HOLISTIC APPROACH FOR SUSTAINABLE PRODUCT DEVELOPMENT AND SERVICE

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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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July 2021

Copyright Statement

Abstract

Sustainability can be achieved by developing products that are more sustainable than the existing status. A systematic sustainable solution should cover sustainable development and sustainable service to achieve the triple bottom line (TBL) of sustainability. However, current research in this area have not given enough attention to the full TBL and whole product life cycle.

This research aims to develop and implement a holistic approach to facilitate sustainable innovation that covers the whole life cycle of the product as well as the TBL of sustainability. This aim is achieved by developing a sustainable product development and service (SPDS) approach. Interdisciplinary methods and tools were integrated into the approach. Distinct from other counterpart methodologies, this approach: (1) addresses TBL of sustainability (2) enhances the interaction between product development and product service phases to advance sustainability performance. (3) Covers the whole life cycle stages of a product, from design, manufacture, distribution, retail to use, maintenance and repair, and EoL (4) demonstrates the suitability for universal product innovation instead of case-specific ones. The approach is further demonstrated with three case applications, including domestic lighting products, industrial lighting products and services, and flooring products. The Products developed by adopting this approach are proved to have superior sustainable performances as well as embracing prominent product functions.

This research contributes to the body of knowledge of sustainable innovation methodology.

The proposed approach supports life cycle management and the implementation of sustainable product and service development, and facilitates enterprises to reform the profit model solutions towards sustainable production and consumption. Thus, it can be concluded that the SPDS approach is effective in developing product and service that advances the TBL of sustainability, which is novel in the subject area.

Acknowledgements

I would like to express my sincere gratitude to my Director of Studies, Professor Daizhong Su, co-supervisors, Professor Anton Ianakiev and Professor Shifan Zhu, for their guidance, support and encouragement throughout the research and my PhD studies.

I also would like to acknowledge the support provided by EU H2020 CIRC4Life project, the project 'Environmental Protection Flooring Products Made from Composite Materials' supported by the international collaboration programme of the Science and Technology Ministry of China, Kosnic Lighting Ltd., ONA PRODUCT SL and Yuntianhua Co., Ltd. Chongqing Branch, which made this research possible.

Finally, I would like to thank my families, for their unconditional love and support.

List of Publications

- Wang, S., Su, D, Ma, M., Kuang, W., 2021. Sustainable Product Development and Service Approach for Application in Industrial Lighting Products. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2021.04.003.

- Wang, S., Su, D., Wu, Y., Zhu, S., Zhang, Q., 2020. Comparative life cycle assessment of raised flooring products. In: D. SU, D.Z. ed., Sustainable product development: tools, methods and examples. Cham: Springer, pp. 293-310. ISBN 9783030391485. https://doi.org/10.1007/978-3-030-39149-2_14.

- Wang, S., Su, D., Wu, Y., Chai, Z., 2020. Application of life-cycle assessment to the eco-design of LED lighting products. Euro-Mediterranean Journal for Environmental Integration. 5, 1-10. https://doi.org/10.1007/s41207-020-00180-0.

- Wang, S., Su, D., Wu, Y., Zhu, S., Kuang, W., 2021. Environmental and Social Lifecycle Assessments of an Industrial Lighting Product. Environ. Impact. Assess. Rev. (under review).

- Wang, S., Su, D., Wu, Y., Zhu, S., Kuang, W., Ma, M., 2021.Environmental Impact Analysis through the Industrial Lighting Product Life Cycle. In: Ksibi M. et al. (eds) Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions (2nd Edition). EMCEI 2019. Environmental Science and Engineering. Springer, Cham. pp 239-243. https://doi.org/10.1007/978-3-030-51210-

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List of Abbreviations

LCA/E-LCA	Life Cycle Assessment
SETAC	Society of Environmental Toxicology And Chemistry
ISO	International Standards Organization
TBL	Triple Bottom Line
SDGs	Sustainability Development Goals
NGOs	Non-Governmental Organisations
SM	Sustainable Manufacturing
LCM	Life Cycle Management
PSS	Product Service System
S-LCA	Social Life Cycle Assessment
BoM	Bill of Materials
SPDS	Sustainable Product Development and Service Approach
CAD	Computer Aid Design
LED	Light-Emitting Diode
CFLs	Compact Fluorescent Lamp
VOCs	Volatile Organic Compounds
UNEP	United Nations Environment Programme
SLCIA	Social Life Cycle Impact Assessment
PDS	Product Design Specifications
IL	Incandescent Lamp
DfS	Design for Service

SfD	Service Feedback for Design Improvement
FEA	Finite Element Analysis
SMEs	Small and Medium Enterprises
EoL	End of Life
DC	Design Concept
B2B	Business to Business
LCIA	Life Cycle Impact Assessment
AHP	Analytical Hierarchy Process

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Chapter 1 – Introduction

1.1 Research background

Environmental impact and climate change, socioeconomic issues, sustainable innovation, and consumption are some of the key challenges of our time and future efforts (Pettersen, 2015). Sustainable development has been agreed upon among countries and organisations after the 'sustainable development' concept was brought out from the Brundtland Report in 1987, which defined the term as the "development that meets the needs of the present generations without compromising the ability of the future generations to meet their own needs" (Brundtland, 1987). The United Nations released 17 sustainable development goals (SDGs) in 2015, including goals addressing the environmental impact and climate change, socioeconomic issues, sustainable innovation and consumption, which provide support to governments to adapt with their national development plans and policies towards the SDGs (UNDP, 2015).

Reduction of ecological footprint by responsible production, efficient management of resources and waste are highlighted in SDGs and the United Nations Climate Change Conference COP21. In the same year (2015), the UK Government committed to achieving the UN's SDGs, which emphasised that tackling climate change is one of the most urgent goals to achieve by 2030 (Lunn, 2019). Further in 2019, the UK became the first major economy to legislate to achieve net zero greenhouse gas (GHG) emissions by 2050, which is also a great challenge to reduce emissions by 80% (Harrabin, 2019).

Many of these objectives are an integral part of the UK Industrial Challenge Research Fund (ICRF) goals. As an exemple, to meet the environmental policy commitments and improve

Parliament's environmental performance, both Houses have agreed the following targets (based on 2008/09 baselines) by 2020/2021 to reduce: absolute carbon emissions by 34%, water consumption by 50%, the weight of waste generated by 30%, to recycle 75% of waste generated.

Following on from the financial crisis of the first decade of the millennium, the national and international economic environment was clearly already under strain as being potentially unsuitable for long term sustainability, and the COVID-19 Pandemic further reveals the need to re-boot the national economy in a green and sustainable way. In addition, to achieve long-term sustainability, socio-economic aspects have increasingly been recognised as crucial. The SDGs has encouraged the decision-makers (policymakers, organisations, non-governmental organisations-NGOs) to implement the social, economic and environmental strategy to reach the sustainability goals by 2030. The need for wider stakeholder discussions has been recognised and is embodied in, for example, the membership of the UK-wide UK Stakeholders for Sustainable Development (UKSSD), while the UKSSD focuses on how business can engage with the SDGs.

The consumers, who could, and, the evidence is, would (at least for the younger members) drive the economy in the direction of sustainability, if only they were sufficiently empowered to be able to model the impact of the whole range of their behaviours, purchasing and work. What is needed interactions with consumers and providing them with the ability to engage with this national agenda in a meaningful manner. In this regard, sustainable products and services are increasingly important to global markets (Neff, 2012).

1.2 Research motivation

Under the current challenging circumstances, states all put regulatory instruments and green fiscal instruments to tackle the imbalanced issues between economic growth and environmental degradation, biodiversity loss, global warming and vulnerabilities linked to health and social exclusion, such as taxations, and cap-and-trade permits, offset systems, etc.

In recent years, green fiscal policy, which is to rearrange government spending and revenue with the goal of advancing sustainable development objectives of countries, is preferable among government and policymakers. Public spending, which accounts for an average of 12%-30% of GDP in different countries, wields enormous purchasing power towards more sustainable goods and services, which can help drive markets in the direction of innovation and sustainability (UNEP, 2020). Under the sustainable consumption and production (SCP) policies and sustainable public procurement (SPP), countries tend their consumers and producers to choose among goods and services, which help to realise sustainable consumption and production, providing opportunities for product and service which perform well on environmental and social sustainability (Pacheco-Blanco and Bastante-Ceca, 2016; Rick LeBlanc,2018).

In addition, many surveys and studies show that a growing percentage of consumers, especially millennials, are willing to pay an extra price for sustainable products and services, and they expect companies to be more responsible for environmental and social aspects, like fair trade and employee welfare. (Tighe,2020; consumer council, 2016; Nielsen, 2015).

Under both opportunities and challenges, increasing numbers of companies consider sustainability in environmental and social issues, as parts of the agenda of their new product development, reputation building, and overall corporate strategy (McKinsey, 2010; Murto et al., 2014). Furthermore, on a cost-effective level, companies have realised that sustainable production with a circular business model has economic benefit, which is another key reason for them to adopt sustainable programme (CountryProfiler,2018).

However, there are barriers in taking proactive approaches to manage sustainability issues, including:

- The lack of technical know-how within companies can prevent companies from adopting alternative sustainable actions. The barrier including knowledge background and tool utilisation. Interdisciplinary knowledge and tools are required during sustainable development or decision-making process; many designers are lacking information about the usage of tools; that supporting life cycle approaches, such as assessment tools, have impeded the implementation of life cycle thinking and product innovation (CIRC4LIFE, 2018).

- A Lack of systematic long-term business strategy/solution (Bocken and Geradts,2020; Brockhaus et al., 2016).

- A Lack of clear and comprehensive approach, especially on value creation (Petersen, 2017; Alblas et al., 2014; Haubensak, 2020; Bocken and Geradts,2020).

1.3 Why does development of sustainable product matters?

Sustainability can be achieved by developing products that are more sustainable than the existing status (Charter, 2001; Boks and McAloone, 2009; Seuring, 2008). As 80% of the product's total environmental impact is determined at the product design stage (Charter, 2001), more attention should be paid by companies to address sustainability issues at the product development stage. In addition, from the Life cycle management (LCM) perspective, the product development stage determines the materials, supplier, manufacturing methods and cost as well as the value chain actors during the service phase, which is the most controllable and effective stage to prevent potential sustainability risks and reduce cost (Agudelo et al. 2017).

1.4 Triple bottom line of sustainability in product and service

Triple bottom line (TBL) is a sustainability-related framework that incorporates three dimensions of performance, i.e. social, environmental and financial. Driven by sustainability, TBL provides a framework that expresses the expansion of the environmental agenda in a way that integrates the economic and social lines (Elkington, 1997). In this definition of TBL, the terms profit, people, and the planet are used as the three lines for measuring sustainability performance.

Under the framework of TBL sustainability, the scope and cognition of sustainable product development have been extended. The product development includes two stages, design and manufacture. The design methodologies to address sustainable development in the early the 90s emerged as the 'green design' and 'eco-design', which aim to 'reduce, reuse and recycle' on the material level of a product; whilst, as the methodology evolves, the interpretation of 'sustainability' of a product is beyond an eco-friendly material, or even a product itself.

Sustainable product design was then defined as an interdisciplinary concept to switch the consumption habit towards a sustainable manner for creating new products and generate value and innovation to best meet consumer's needs, dealing with environmental, social and economic perspectives with the best possible balance. However, barriers have been observed to achieve TBL sustainability solely by implementing sustainable product design. As an instance, the traditional product-sale business mode hinders the consideration of the potential impact of product's other life cycle after sale activities. As suppliers benefit from simply selling the products, there is no interest in prolonging the product lifetime or reuse/repair, consequently increasing the consumption and disposals more than it should. Similar issues have arisen in sustainable manufacturing (SM), it has consented among researchers that the TBL should be addressed during the sustainable development stage, where the focus should not only on the product itself but also on the product life cycle level in the future research (Gbededo et al.,2018; Malek and Desai, 2020).

Sustainable products need to be consumed by consumers to fulfil their sustainability; therefore, sustainable consumption is an important bridge between sustainable products and a sustainable lifestyle. A product service system (PSS) integrates aspects from the physical product side (goods) with an intangible service offering, such as after-sale service including maintenance, repair, and end of life service, usually the service is based on the particular established product. It has the great potential to facilitate sustainable production and consumption (Tukker and Tischner, 2006) as well as achieving customer satisfaction.

Thus, a comprehensive sustainable solution within the product life cycle and its supply chain should cover the sustainable development and the sustainable service to achieve TBL of sustainability. Nevertheless, there is limited research that addresses three pillars of sustainability during product innovation; when it comes to product development towards the TBL, product developers are still 'dancing in the dark' (Petersen and Brockhaus, 2017). Furthermore, practices and studies on sustainable PSS are mostly from the economic domain, which are usually based on established products, and separated from the product development process. The connection between sustainable product development and sustainable product services has not been given enough attention in existing research and practices regarding product sustainability.

1.5 Aims and objectives of the research

The aim of this research is to develop and implement a holistic approach to facilitate sustainable innovation that covers the whole life cycle of the product with consideration of the environmental and socio-economic aspects of sustainability.

In order to achieve the aim, the research had accomplished the following objectives:

- Develop a systematic and harmonized conceptual framework that allows interdisciplinary methods and tools to be integrated to enable new product innovation to address TBL of sustainability issues through the product's whole life cycle. This framework had to enhance the interlinks between the product and its service to synchronize pathways that advance sustainability performances.

- Investigate the relationships between environmental and socio-economic performances in a product's life cycle. Identify the issues and opportunities as well as the interrelationships between both aspects, and integrate the findings in improving new sustainable innovation.

- Develop methods that are generally applicable to identify and tackle environmental and socio-economic issues through the product development processes/stages. These methods emphasised providing solutions to a) how to construct a sustainable product design specification? b) how to combine product design to product service to achieve better sustainability performances? c) how to integrate interdisciplinary methods and tools into the product design process to guarantee sustainable performances? d) how to validate the sustainability performance?

- Demonstrate the framework and methods with different industries and application scenarios. The research had to apply the proposed framework and methods to develop product and/or service in different industries (different product categories, such as energy consumption product, general consumer products, etc.) to prove its efficiency. Different application scenarios, i.e. for cases with variant sustainability development goals, had to be taken into consideration and proven applicable.

1.6 Structure of the thesis

This thesis is divided into eight chapters (Fig. 1.1): 1) Introduction, 2) Literature review, 3) The sustainable product development and service approach, 4) Integration of environmental and social lifecycle assessments to sustainable industrial lighting product and service conceptual construction, 5) Development of sustainable industrial lighting product and service, 6) Development of an environmentally sustainable domestic led lighting product, 7) Development of an eco-friendly and cost-effective flooring product, 8) Conclusions.

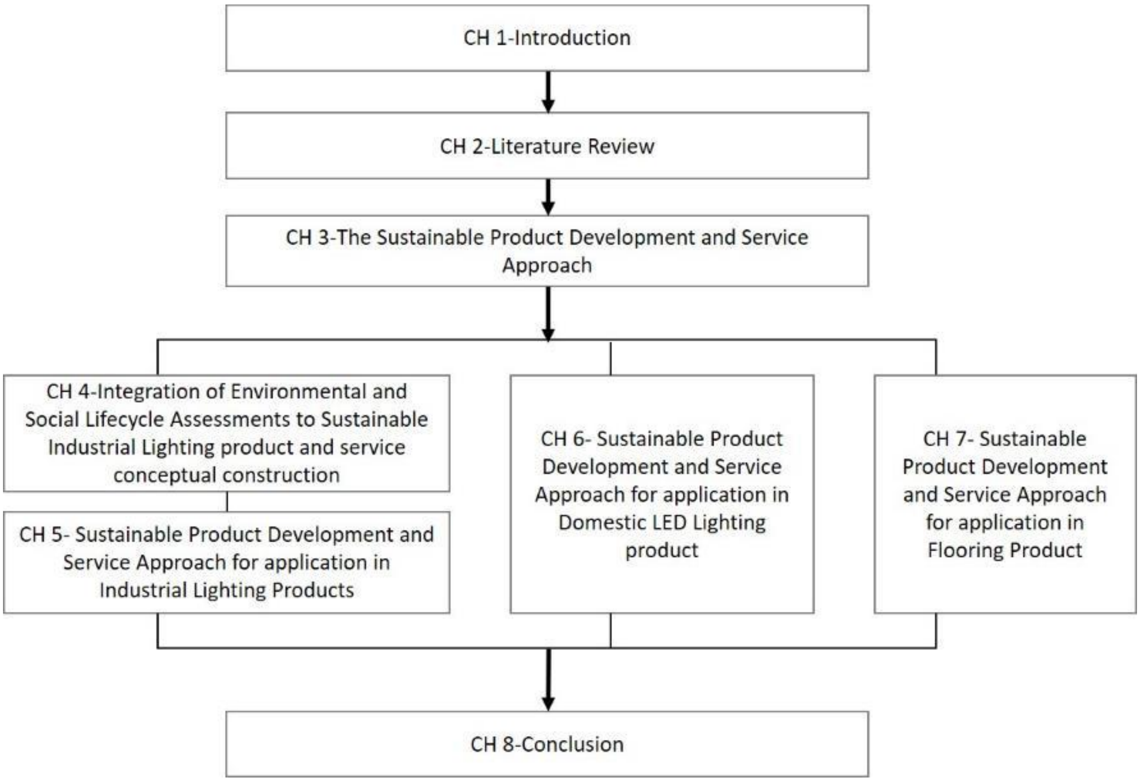


Figure 1.1 Structure of the thesis

Chapter 1 introduces the background, motivation, aim and objectives of the research. Chapter 2 reviews: sustainability in product development, life cycle approaches and practices, product-service systems, and sustainability assessment and the applications in products and services.

Chapter 3 explains the methodology developed and utilised in this research. Chapter 4 presents how to inform sustainable products and services by integrating environmental and social life cycle assessment methods and techniques in the early development stage (industrial lighting product as an example). Chapter 5 demonstrates the case study of the proposed approach that emphasises the development of the sustainable industrial lighting product and the service as a bundle. Chapter 6 presents a case study of developing an environmentally sustainable domestic LED lighting product by utilising the proposed approach. Chapter 7 demonstrates the case study with emphasis on the development of eco-friendly and cost-effective flooring product (static product), and chapter 8 summarises the contributions to knowledge, and points out areas for further research.

Chapter 2 - Literature Review

2.1 Sustainability in product development

2.1.1 Environmental sustainability in product design

Research Studies addressing the environmental aspect of sustainability of product emerged in the late 90s, methodologies and approaches such as 'Green Design' (Dowie, 1994) or 'eco-design' (McAloone, 2009) have been brought out, which had laid the theoretical foundation of sustainable design (SD). At the same time, Life cycle assessment (LCA) , which was initially a methodology in the Environmental Engineering field, had been introduced to product design subject for measuring product's or service's life cycle environmental profile by the Society of Environmental Toxicology and Chemistry (SETAC) (Fava et al., 1991) and International Standards Organization (ISO) (ISO, 2006). Environmental impact assessment software tool based on the LCA method have been developed, such as Simapro (PRé Consultants, 2015), Gaibi (Thinkstep, 2015) and OpenLCA (GreenDelta, 2017), which made conducting LCA increasingly accessible and feasible. Subsequently, the life cycle impact result from LCA has been considered as an evidence-based reference in decision-making during sustainable product development, such as choosing materials and design concepts as well as in eco-labelling scheme and environmental declarations (Baumann, 2004, ISO, 2006).

In recent years, studies on sustainable product development method and sustainable design support tool are thriving. These methods and tools emphasise: eco-friendly material selection and assessment (Zarandi et al., 2011, Sakundarini et al., 2013, İpek et al., 2013, Andriankaja et al., 2015); product development innovation study with integrated eco-design tools (Zhang et al., 2015, González-García et al., 2012, Spangenberg et al., 2010, Bovea and Pérez-Belis, 2012);

decision-making support tool and evaluation criteria for sustainable design (Besharati et al., 2006, Buchert et al., 2015, Heintz et al., 2014). Those studies provide case-specific approaches which aim to reduce the specific product's negative environmental impact. However, as the interpretation and dimension of sustainability evolves, the interpretation of sustainable product is beyond a product with 'recyclable material' or 'green exterior', but an interdisciplinary concept to create new products or services that generate product/ service that best meets consumer's needs, while dealing with environmental, social, and economic perspective with the best possible balance. Therefore, a comprehensive sustainable solution within the product life cycle and its supply chain are necessary, social, and economic aspects are also essential aspects that require to be considered in sustainable design (Manzini,2007; UNGA, 2005). Nevertheless, there is limited research address three pillars of sustainability during the product innovation process.

2.1.2 Social aspects in product development

Social sustainability is the least defined in TBL, and has not received enough attention (Santillo, 2007; Onat et al., 2017) as it should be. According to the Western Australia Council of Social Services (Partridge, 2014):

"*Social sustainability occurs when the formal and informal processes; systems; structures; and relationships actively support the capacity of current and future generations to create healthy and liveable communities. Socially sustainable communities are equitable, diverse, connected and democratic and provide a good quality of life*."

The Sustainability Development Goals (SDGs) has encouraged the decision-makers (Policy makers, Organisations, Non-Governmental Organisations-NGOs) to implement the social, economic and environmental strategy to reach the sustainability goals by 2030. In recent years, social sustainability dimensions are being considered in the decision-making processes (D'Eusanio et al.,2019). Even though, the development of social sustainability has been less considered in the literature (Hutchins and Sutherland, 2008; Vachon and Mao, 2008; Fallahpour et al., 2017; Yawar and Seuring, 2017), it covers an essential role in achieving the economic performances of companies (Carter and Rogers, 2008; Krause et al., 2009; Yawar and Seuring, 2017). A recent review shows that only 16% (46 out of 279) sustainability-related indicators addressing social performance whist 61% (170 out of 279) measuring environmental performance (Kravchenko et al., 2019).

Furthermore, there are limited studies capturing social performance for 'product development' intention, which can be integrated in informing new sustainable product or product-service system development (Kravchenko et al., 2019). On one hand, this may be due to the 'intangible' and 'complex' nature of social aspects and their inter-relationships (Chou et al.,2015; Costa et al., 2015). On the other hand, when it comes to product development towards the triple bottom line of sustainability, product developers are still 'dancing in the dark' (Petersen and Brockhaus, 2017), especially with the question of how social aspects are integrated and how social assessment results can inform product/service design remains challenging. Hence, it is necessary to explore issues and opportunities in both social and environmental perspectives to inform product and service design, so that potential risks can be mitigated in a more holistic perspective among different stakeholders.

2.1.3 Sustainable manufacturing

Sustainable manufacturing (SM) is a new concept, it emerged under the current circumstances since it's a crucial and inevitable sustainability issue amongst industries, especially the environmental sustainability aspect (Bogue, 2014). SM can be described as an extension and implementation of sustainable design. The definition of SM is various according to researchers without a universal agreement. Most of the definitions emphasise the environmental sustainability related to the manufacturing process and the trade-offs between environmental and economic factors (Song and Moon,2016; Malek et al., 2020). For instance, according to the Department of Commerce of US, MS is "the creation of products which use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, consumers and are economically sound" (Chan et al., 2017). Malek et al (2020) described SM as an integration of environmental aspects into economical aspects of business, which aims to reduce the negative impacts during the manufacturing processes.

The majority of research and studies regarding SM emerged during the past seven years. Those studies tended to explore the qualitative aspects, most of which focus on one specific aspect or issue as well as industry. The literature from the automobile industry presents the highest as quantity, followed by electronic industry (Malek and Desai, 2020), which may be due to the energy-consuming nature of those industries. There are numbers of review studies regarding SM topic, which can be found in (Rashid et al., 2008; Ball et al., 2012; Gupta et al., 2016). Energy efficiency is the most reviewed topic of SM, followed by sustainable accounting and auditing. Topics on product design for remanufacturing and recycling as well as eco-deign are also identified in SM studies.

Ahmad et al. (2018) reviewed various sustainability indicators for the manufacturing sector and the constant utilisation of those indicators.

The only literature found that made efforts of addressing social aspects of SM were published by Gbededo et al. (2018), which conducted a systematic review of the contribution of sustainable manufacturing approaches. The study mainly focused on life cycle sustainability assessment; which as well proposed a road map framework for sustainability assessment of Discrete-event simulation. The authors argued the production process would be evaluated and optimised based on holistic sustainability objectives. However, the choice of assessment indicators is not in compliance with the UNEP guidelines of social life cycle assessment, the critical stakeholders such as ‘workers’ and ‘customers’ are not included. In addition, the framework requires established product and on-site related manufacturing process to obtain the data for the assessment, therefore, the design and the manufacturing process are not easy to be adjusted or optimised according to the assessment result, not to mention the cost of the change.

One of the issues in the existing literature of SM which has been consented by researchers (Gbededo et al.,2018; Malek and Desai, 2020; Ball et al., 2012) is that, compares to environmental and economic dimensions of sustainability, the social dimension of sustainability is under deprived situation. The economic dimension topic is still of the highest quantities of the SM literature. As a part of the framework of sustainable product development, it is another evidence of the need for a holistic approach for sustainable product development (design and manufacturing) that addresses triple bottom line sustainability.

2.2 Life cycle approaches and practices

Life cycle approaches are the aggregation of concepts methods and practices which are based on the life cycle perspective. The aims are to provide theoretical frameworks and methods to address one or more issues within the life cycle stages in order to improve sustainability.

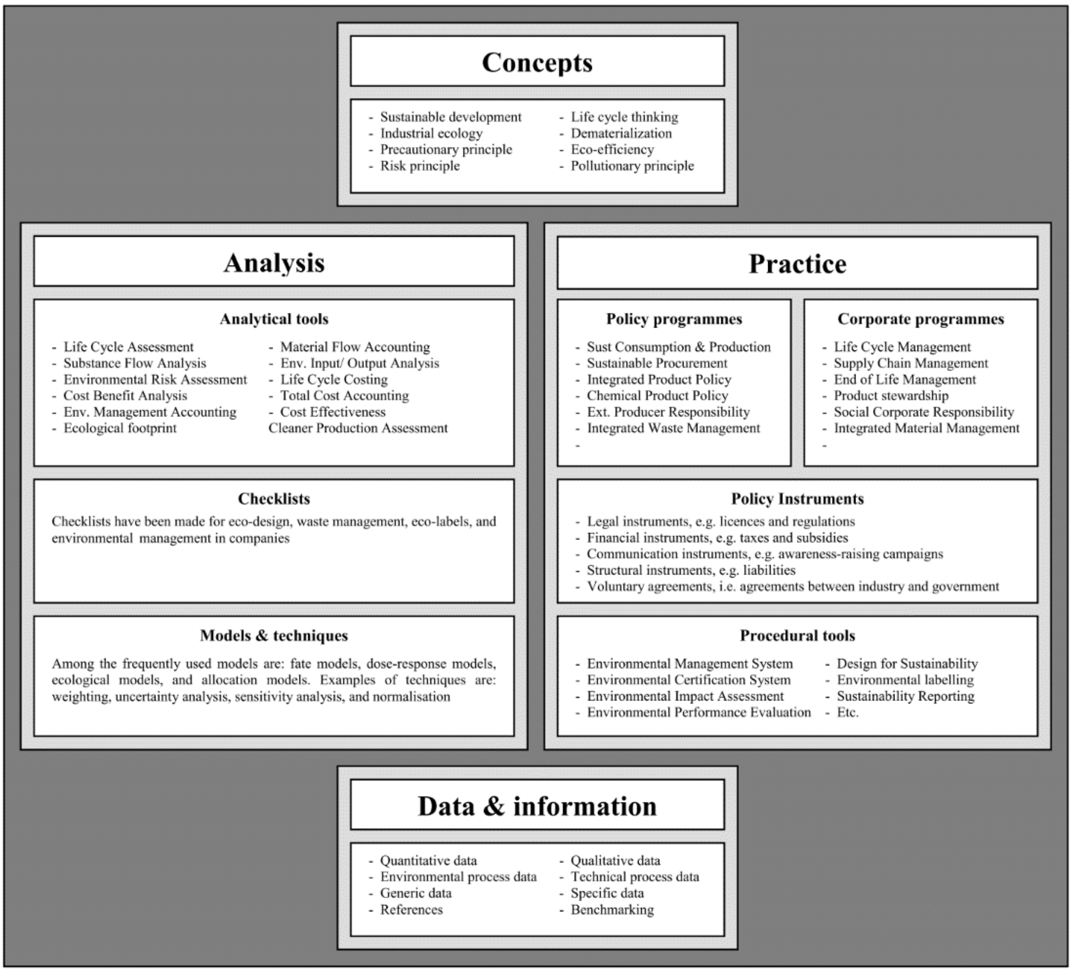


Figure 2.1 Life cycle approaches, consisting of analysis and practice

As shown in Figure 2.1, the role of concepts is to guide analysis and practice. The tools and practice are supported by data and information under the concepts (SETAC, 2005). The most important concept relevant to this research topic are explained in following subsections.

2.2.1 Product life cycle

The International Standard Cognization (ISO) documentation 14001 and 14004 had brought out the 'life cycle perspective' to the wider public, the definition of a product's life cycle is "*Consecutive and interlinked stages of a product (or service) system, from raw material acquisition or generation from natural resources to final disposal. Life cycle stages include acquisition of raw materials, design, production, transportation/delivery, use, end-of-life treatment and final disposal"* (ISO, 2016). According to Life Cycle Initiatives (SETAC, 2005), the number of life cycle stages of a product can vary. A conventional six stages are often defined as follows:

1) Product design

2) Raw material extraction and processing

3) Manufacturing of the product

4) Packaging and distribution to the consumer

5) Product use and maintenance

6) End-of-life management: reuse, recycling and disposal

2.2.2 Life cycle thinking

Life Cycle thinking considers the product or service's life cycle as a whole so that any action could have an effect on the entire system of the product or service itself. In which, the key societal actors cannot limit their responsibilities to those phases of the life cycle of a product, process or activity in which they are directly involved. On the contrary, the scope of their responsibility is expanded to include environmental implication along the entire life cycle of the product, process or activity (SETAC, 1997).

2.2.3 Eco-efficiency

The term eco-efficiency was brought out by the Business Council for Sustainable Development (BCSD, 1993) for Sustainable Development (WBCSD). The concept is defined as followed:

"Eco-efficiency is the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, whilst progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level in line with the Earth's estimated carrying capacity". Eco-efficiency has become a synonym for a management philosophy towards sustainability; in short, eco-efficiency means producing more with less. Eco-efficiency as concept can be applied as a practical but qualitative guiding principle for life cycle approaches."

Those life cycle concepts are supported by analysis tools such as qualitative analytical tools, checklists, and model and techniques. The tools mentioned Figure 2.1 covers environmental evaluation tools, environmental management or economic accounting tools based on a life cycle thinking framework, the complete explanations of the tools can be found in (SETAC, 2005.) Tools and method for social aspect evaluation were addressed limitedly mainly due to the time frame of the publication, still, it reflects that the social aspect of sustainability is not well addressed compares to other aspects in sustainability. The sustainability assessment methodology and research status will be reviewed in the later section in detail, where the assessment of social performance (social life cycle assessment) will also be explained in detail.

2.3.4 Life cycle management

Life Cycle Management (LCM) can be described as the application of life cycle thinking in practice under the Life cycle approach (SETAC, 2005). It has been mainly considered as a business management concept aiming to enhance the overall sustainability performance of the business and its value chains in general. However, there is not an agreed definition of LCM, the concept still needs to be developed. There are researchers and organisations that made their effort to define the LCM concept (Figure 2.2).

Reference	LCM definitions
Linnanen (1995)	Life cycle management consists of three views: (1) the management view – integrating environmental issues into the decision making of the company; (2) the engineering view – optimizing the environmental impact caused by the product during its life cycle; and (3) the leadership view – creating a new organizational culture
Fava (1997)	Life cycle management is the linkage between life cycle environmental criteria and an organization's strategies and plans to achieve business benefits
Finkbeiner et al. (1998)	A comprehensive approach towards product and origination related environmental management tools that follow a life cycle perspective
Heiskanen (2002)	LCA-based ideas and tools can be viewed as emerging institutional logics of their own. While LCA makes use of many scientific models and principles, it is more a form of accounting than an empirical, observational science. Thus, the life cycle approach implies a kind of "social planner's view' on environmental issues, rather than the minimization of a company's direct environmental liabilities"
Hunkeler et al. (2004)	Life cycle management (LCM) is an integrated framework of concepts and techniques to address environmental, economic, technological and social aspects of products, services and organizations. LCM, as any other management pattern, is applied on a voluntary basis and can be adapted to the specific needs and characteristics of individual organizations
Baumann and Tillman (2004)	LCM is "the managerial practices and organizational arrangements that apply life cycle thinking. This means that environmental concerns and work are coordinated in the whole life cycle instead of being independent concerns in each company"
Remmen et al. (2007)	LCM is a product management system aiming to minimize environmental and socioeconomic burdens associated with an organization's product or product portfolio during its entire life cycle and value chain
UNEP/SETAC (2009)	"… a business management approach that can be used by all types of businesses (and other organizations) to improve their products and thus the sustainability performance of the companies and associated value chains" "It can be used to target, organize, analyze and manage product-related information and activities towards continuous improvement along the life cycle"
Jensen (2012)	"… a systematic integration of life cycle thinking in modern business practice with the aim to provide the societies with more sustainable goods and services and to manage the total lifecycle's of an organizations product portfolio towards more sustainable production and consumption"

Figure 2.2 Different definitions of life cycle management (Sonnemann et al., 2015)

The triple bottom line (TBL) integrates the three demotions of sustainability namely environmental, social, and economic sustainability (Remmen et al., 2007). In the late 90s, the definitions of LCM only addressed the environmental aspect of sustainability. Until the early

00s, the social aspect and the whole sustainable concept were included in the LCM definition, which broadens the depth and width of sustainability that the concept covers so that the tools and methodologies according to the adjusted LCM concept can be developed and adapted.

LCM is an integrated framework concept that connects various tools and methods for implementation. Companies use LCM to support their goals of providing products that are as sustainable as possible. Since the concept is under the pillar of Life cycle approach, therefore the techniques and analytical tools are all applicable, such as life cycle assessment depending on the level of ambitions of the enterprise. Remmen et al. (2007) lists the possible tools including policies, strategies, systems, programs, see Figure 2.3. The aggregation of the choice of tools provides an overall picture of the implementation of LCM, yet still not clear enough for the implementation of conducting LCM. However, for enterprises, the barrier in implementing the LCM is frequently not their ambitions of a continuous improvement of their sustainability. The barriers often cluster in the financial avenue of the change; lack of technical know-how; and difficulties in organising and cooperating value chain actors, organisations, and communications between functional departments inside the enterprise.

On top of the barriers, there is a need to explore and develop step-by-step LCM approaches that can be adapted to small and medium enterprises' sustainable development goals, also can be applied for the large enterprises which require a stricter sustainability need.

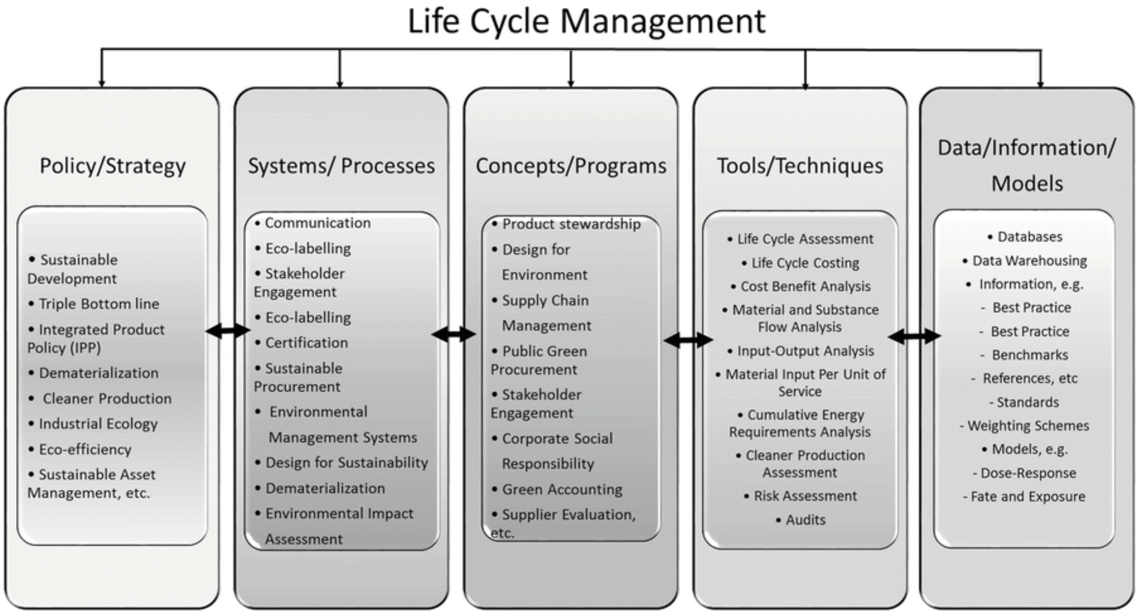


Figure 2.2 Choice of tools within LCM context (Remmen et al., 2007)

2.3 Product service systems

2.3.1 Definition of product service system and the classification

Product service system (PSS), defined as a system that combines marketable product and services to fulfil specific consumer needs (Goedkoop et al., 1999). A PSS integrates aspects from the physical product side (goods) with an intangible service offering, such as after-sale service including maintenance, repair, and end of life service or likewise, usually the service is based on the particular established product. It has the great potential to facilitate sustainable production and consumption (Tukker and Tischner, 2006) as well as achieving customer satisfaction. Studies have also proved that PSS can create benefit for environmental sustainability, which is especially true for resource-consuming industries (Mont, 2002; Roy, 2000). The characteristics of PSS can be summarised as follows (Mont, 2002; Helo et al., 2017):

- Point-of-sale services. Services such as personal assistance in shops, financial schemes for customers, explanations regarding products and their use, as well as marketing.

- Concepts of product use. Use oriented where the utility of a product is determined by the user. Result oriented (utility provider determines product utility for the user).

- Maintenance services. Product servicing aimed at extending the life span of a product, including maintenance and possible upgrades.

- Revalorisation services. Services that aim at closing the material cycle of a product. This can be realized by, e.g., taking products back, reusing certain parts of new products, or recycling materials if reuse is not possible.

Various classifications of PSS have been pro-posed (see e.g. Behrend et al., 2003; Brezet et al.,2001; Zaring et al., 2001). Three major types of PSS have been identified and most cited, namely Product-oriented PSS, Result-oriented PSS, and Use-oriented PSS (Tukker, 2004), as shown in Figure 2.4.

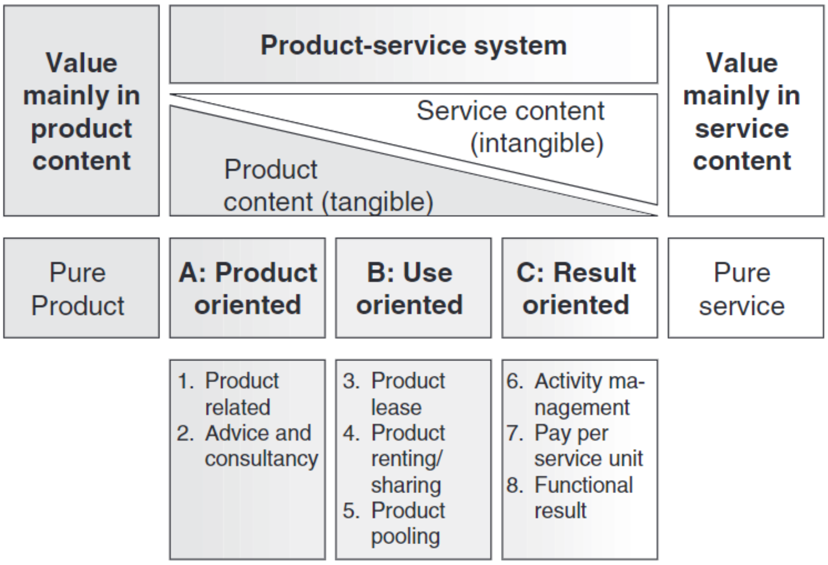


Figure 2.3 Classification of PSS (Tukker, 2004)

According to Tukker (2004), product-oriented PSS characterised as services providing added value to the product life cycle where the business model remains as the product-sales, but some extra services are added. Result-oriented PSSs are services providing 'final results' for customers. In this PSS type, the traditional product still plays a central role, but it is beyond just selling products where the ownership of the product stays with the provider. The provider is usually responsible for maintenance, repair and control. The user pays a regular fee for the usage of the product and the related services, the forms of serving can be various in including product lease, product renting and sharing, and product pooling, which includes sharing and renting but in a simultaneous way.

For use-oriented PSS services, it is providing 'enabling platforms for customers' where the client and provider agree on a result, and there is no pre-determined product involved. This type of PSS involves less product selling but emphasises providing intangible result as the services. The user no longer buys the product but the output of the product according to the level of use, while the producer maintains the ownership of the products.

2.3.2 Sustainable product to sustainable product service system

As stated in the early sections, the trend of sustainable product design is beyond the choice of more eco-friendly materials, but a more stringent interpretation requires a system innovation approach. In fact, researchers have observed that product Life Cycle Design or Eco-design implementation meets obstacles in traditional supply models of product sale (Stahel 2001; Lindhqvist 2000; Goedkoop et al.1999; Vezzoli, C. et al., 2014). A more significant scope in which to act to promote radical changes for sustainable consumption seems to lie in widening the possibilities for innovation beyond the product: commonly referred to in this context as Product-Service Systems (PSS)(Vezzoli, C. et al., 2014).

2.3.3 Sustainability in Product service system

The reduction of environmental impact is the most recognized as the benefit of PSS, 62% of the PSS topic articles (Annarelli et al., 2016) have agreed upon this effect, which is also one of the main reasons behind the development and implementation of a PSS. The PSS concept has been suggested as a way to address and contribute to system-level improvement (Goedkoop et al.,1999). PSS is designed to have a prolonged products' lifetime and its utility so that it allows better exploitation of resources and less waste production. The prolonged life span of products promotes the energy efficiency during the consumption phase from the customers' perspective, also reduce cost related to the consumption.

For business providers and industries, there have been notable policy-driven reasons to conduct sustainable consumption innovation (Backhaus et al., 2017), such as interest in the sustainable business model for shared value creation. PSS reduces mass production which led to a cost reduction of manufacturing. With the added value of the service, the PSS providers can be competent than traditional product provider in many ways, such as revenue increase, consumer engagement and loyalty as well as new market development. Those advantages are built upon the achievement of consumer satisfaction which boosts socioeconomic sustainability.

From the perspective of design for sustainability, it suggests that the environmental impacts of products and associated services should be addressed already at the product and process design stage, while special attention is given to the possibility of reducing environmental impact from the use phase by providing alternative system solutions to owning products (Mont, 2003), in this regard, PSS also facilitates sustainable consumption.

2.4 Sustainability assessment and the applications in products and services

2.4.1 Environmental life cycle impact assessment

Life cycle assessment (LCA or E-LCA when compare environmental life cycle assessment to social life cycle assessment) is ‘A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle'(ISO 14040). Although LCA studies were carried out in the 1960s, it was only in the 1990s that SETAC initiated the standardization process that led to the ISO 14040 and 14044 series

(Hoogmartens et al., 2014).

LCA enables the comparison of different options, produce evidence-based references on the impact performance of each option so that priorities can be identified more transparently and inclusively. LCA methodology is the most acceptable methodology in assessing product or services' life cycle environmental profile. Execution of LCA and LCA based results are mostly integrated nowadays in decision-making processes, such as selection of materials, sustainable design, selection of complex supply, policymaking, green procurement or eco-labelling schemes.

2.4.1.1 Environmental life cycle impact assessment procedure and tool

The assessment scope including a 'cradle-to-grave' approach, which covers impacts includes the extraction of raw materials; manufacturing and fabrication of the product; the transportation or distribution of the product to the consumer; the use of the product by the consumer; and the disposal or recovery of the product after its useful life. According to ISO 14040, 14044, the procedure of conducting an LCA consists of four steps:

- "*Goals and scope definition in which system boundaries and unit of the analysis are set;*
- *Life cycle inventory (LCI)—the collection of all elementary flows of input and output from and to the system in terms of resource used and emission;*
- *Life cycle impact assessment (LCIA)— the assessment of the impact associated with the flows in the inventory, covering a wide variety of environmental impact categories (such as climate change, acidification, ecotox icity, etc.). The different impacts may be associated with three Area of Protections (AoP): human health, ecosystem health, natural resources; and Interpretation.*"

- *Interpretation.* Finally, the conclusions that are result from the process can be shared in interpretation phase, the conclusions are entirely affected by scope, and goals defined in the first part of the process.

There are many LCA-based tools, both qualitative and quantitative (software tools). The mainstream of conducting an LCA is by utilising software tools with the support of databases, such as for policymaking or declarations. The most applied LCA software tools include Simapro (PRé Consultants, 2015), Gabi (Thinkstep, 2015) and OpenLCA (GreenDelta, 2017) and simplified tools such as Sustainable Minds (Sustainable Minds, 2015).

Simapro and Gabi are commercial software tools that facilitate the simulation of complex LCA models, and also to conduct complex end of life (EoL) scenarios.

OpenLCA gains its application during recent years, it’s an open resource software with open codlings provided, which enables advanced users or developers to modify or create their own version of the LCA tool. The software itself is free, which gains its advantage and popularity of research students and academics. The software is compatible with the majority and the most preferable databases and life cycle impact assessment (LCIA) methods.

Sustainable Minds is a simplified LCA tool that mainly supports the sustainable /eco-design process, i.e. to compare different design concepts easily. It is less sophisticated than the commercial software above and not able to conduct multifaceted and detailed assessments with complex EoL scenarios.

Other computer aid design tool such as Solidworks contains features called ‘sustainability’, the main purpose is also to aid eco-design. But the focus is on material and energy consumption in concept selection rather than assessing the full scale of a product's environmental profile, therefore cannot be referenced in formal declarations or likewise purpose. The advantage of Sustainable Minds and Sustainability function in Solidworks is that the simplicity of creating the Bill of Materials (BoM), the software itself will obtain the material information from the product model; for Sustainable Mind, the BoM can be imported from CAD software, which reduces the complexity for designers in conducting LCA.

This research utilised openLCA (Greendelta, 2017) and Online LCA Platform (http://h2020.circ4life.net/) to practice LCA due to several reasons. OpenLCA is an advanced software tool for practicing complexed LCA, its compliances with ISO standards such as ISO 14000 and 14040 and provide several databases and LCIA method options. The software tool is also aid easier comparison between products with variant parameters. In addition, compares to other commercial software tools, openLCA software itself and the LCIA methods are free and some of the databases are free to researchers and non-profit parties which is more accessible. Online LCA platform is developed by CIRC4Life project to enables geographically dispersed users to calculate and share the LCA results online. The Platform provides LCA modelling and assessment functions with user-friendly interfaces. The platform is in line with the international LCA code of conduct ISO 14040 with the incorporation of the well-recognised database, mainstream life cycle impact assessment (LCIA) methods, including ReCiPe midpoint, endpoint and CML are built-in for the impact calculation (detailed in section 6.2.4.5). The online tool was initially developed to support industrial practices including the electrical and food industries which fit for the case studies in this research.

2.4.1.2 Status of life cycle assessment of lighting product towards sustainable design

There are a number of studies addressing environmental topics of LED lighting products, such as (Tähkämö et al., 2012; Principi and Fioretti, 2014; Wang et al., 2020). Most of the literature are comparison studies LED products and demonstrate energy efficiency and environmental sustainability among different technology or LED lighting products. Tähkämö et al. (2012) highlighted that modern light sources (CFLs and LEDs) are more environmentally friendly than conventional sources. Principi and Fioretti (2014) conducted a comparative life cycle assessment of luminaires for general lighting for the office, the results showed that the environmental impacts of using LED luminaire in the office were significantly reduced mainly due to high energy efficiency in the use stage. More LCA studies of lighting product are listed in Table 2.1.

Table 2.1 LCA studies of lighting products

Name of the article	**Lighting category**	**Assessment method**	**Key points summary**
LCA Case Study to LED Outdoor Luminaries as a Circular Economy Solution to Local Scale (Lozano-Miralles et al.,2020)	outdoor	EPS 2000 method& CML	EPS 2000: Human toxity and Exhaustion of resources are the most affected impact categories; CML: human health and Exhaustion of resources are the most affected

Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products (Scholand and Dillon, 2012)	Incandescent lamp/CFL /LED		The "use" phase of all three types of lamps accounted for 90 percent of total life-cycle energy, on average, followed by manufacturing and transport. (based on 10 existing lighting-product LCAs that included academic publications as well as manufacturer and independent-research reports.) The light source that performed the best was the LED lamp (2017) whose impacts are expected to be about 50 percent lower than the 2012 LED lamp and 70 percent lower than the CFL.
Analysis of the performance of domestic lighting lamps (Aman et al., 2013)	incandescent lamp (IL), fluorescent lamp (FL) and compact fluorescent lamp (CFL). Light emitting diodes (LED) based lamp	energy efficiency	"with the current technology, the use of FL and LED lamp is beneficial for utility as well as for consumer."
Assessment of Light Emitting Diodes technology for general lighting: A critical review (Nardelli et al., 2017)		primary energy demand	the lifespan of an LED bulb was equivalent to that of 25 incandescent bulbs and 2.5 compact fluorescent lamps. During the manufacturing and use phases, the energy consumption was 667.9 kW h for the LED bulb, 678.2 kW h for the compact fluorescent lamp and 3305.3 kW h for the incandescent bulb. Less than 2% of primary energy demand over the full life cycle was used for manufacturing. The major contributors to these results were the metals – aluminium, copper and

			gold – and the chemicals used in the composition of the LED chip.
Assessment of Light Emitting Diodes technology for general lighting: A critical review (Nardelli et al., 2017)	LED		Compact fluorescent lamps and LED lamps are more likely to produce an impact on human health and ecosystems. natural resources depletion. The main environmental benefits of LEDs compared to conventional light sources are low carbon dioxide emission and absence of filaments and mercury.
Life cycle assessment of road lighting luminaires e Comparison of light-emitting diode and high-pressure sodium technologies (Tähkämö and Halone, 2015)	high-pressure sodium (HPS) and light-emitting diode (LED) luminaire s. (road lamp)	CML-IA,eco-indicator 99	LED (364pt), HPS(433pt)the use caused the majority of the environmental impacts: 96% in HPS and 87% in LED luminaire over 30 years of operation, while manufacturing accounted for 4% and 13%, and end-of-life less than 1%, respectively. the LED luminaire caused 26% or 17% lower average environmental impacts than the HPS luminaire. defining functional unit under assessment is crutial for lighting comparative study.
Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis (Welz et al., 2011)	Tungsten lamp Halogen lamp Fluoresce nt lamp Comp. fluoresce nt lamp	the cumulative energy demand (CED), the global warming potential (GWP) and the Eco-Indicator'99 (EI99) were	A comparison with the values from the various old studies appears rather difficult, as a broad variety of different impact indicators is used in the various studies. The oldest studies partially use LCIA indicators that are even not in use anymore today — making a comparison with today's result almost impossible. Another difficulty comes from the fact that the functional units vary considerably from one study to the other. Nonetheless,

A comparative life cycle analysis of low power PV lighting products for rural areas in South East Asia (Durlinger et al., 2012)	PV lighting	ReCipe	functional unit: with luminous flux of100 lumens, for 3 h a day, over a period of 1 year. Solar PV lighting products have a lower environmental impact than conventional lighting solutions, such as lighting services from kerosene lamps and powered by car batteries. The environmental profile of small size PV lighting products can be improved by 10 up to 50% by recycling of the batteries.
Mitigating the greenhouse gas emissions from urban roadway lighting in China via energy-efficient luminaire adoption and renewable energy utilization (Chang et al., 2021)	road lighting (HPS and LED)	GHG emissions calculation	used a bottom-up approach to estimate GHG mitigation potential associated with replacing current high-pressure sodium (HPS) lamps with light-emitting diode (LED) lamps and deploying solar-wind hybrid street lights, solar street lights, and wind street lights in China.
The Effect of Consumer Behaviour on the Life Cycle Assessment of Energy Efficient Lighting Technologies (Yu et al., 2016)	CFL and LED	CML2001	Current LEDs and CFLs available on the market have similar total impacts in the use phase and are both suitable replacements for household incandescent lamps if electricity savings are desired. lamp efficiency (lumens per watt) still remains the largest influence on the environmental impact of the lamps
A comparative life cycle assessment of luminaires for general lighting for the office e compact fluorescent (CFL) vs Light Emitting Diode (LED) e a case study (Principi and Fioretti, 2014)	CFL (62W) and LED (23W)	ILCD 2011 midpoint	The life cycle assessments show that the LED luminaire allows the environmental impacts to be significantly reduced (reduction of 41-50% of greenhouse gas emission and cumulative energy demand), mainly due to high energy efficiency in the use stage. The Cumulative Energy Demand (CED) assessed for the CFL was 11.9 MJ and was 71.3 MJ for the LED

			luminaire; percentage between 96 and 99% is due to the use stage of the luminaires,
Exploring Cost and Environmental Implications of Optimal Technology Management Strategies in the Street Lighting Industry (Dzombak et al., 2020)		LCA,LCC	examine the cost and environmental implications of technology management decisions in the context of the street lighting industry, employing life-cycle assessment and a Markov Decision Process model. The goal of the research is to determine a policy that minimizes expected costs and emissions for the system over a fixed time horizon thus reducing uncertainty for managers.
Balancing technological innovation with waste burden minimization: An examination of the global lighting industry (Dzombak et al., 2019)	focusing on waste (Incandes cent, CFL, Disruptive LED, Best Case LED)	N/A	The results quantify the waste burden of high-performance lighting and further motivate the development and implementation of recycling programs and policies to prevent waste diverted to landfills by consumers. The results also confirm that attention must be paid to how to reduce the waste burden of LED lighting products through improved design and lighting as a service model.
Life Cycle Assessment of Incandescent, Fluorescent, Compact Fluorescent and Light Emitting Diode Lamps in an Indian Scenario (Sangwan t al.,2014)	Fluoresce nt, Compact Fluoresce nt and Light Emitting Diode Lamp	CML, eco-indicator 99	Functional unit selected for this study is lumen–hours.

However, these studies are conducted by LCA experts, not aiming to guide sustainable LED lighting product design. One comparative LCA study (Casamayor et al. 2018) regarding the design perspective of LED lighting was found, in which the environmental impact was assessed and compared between a newly designed eco LED product and a commercialised LED-based product. The newly designed product proved to have less (60% less) environmental impact than the existing lighting product in all scenarios, and recommendations for the eco-design of LED lighting products are proposed.

2.4.1.3 Status of life cycle assessment in Flooring product

According to the literature, there are limited researches regarding the LCA of flooring products. In the early years, studies were mainly regarding the topic of LCA comparison of floor covering materials to guide environmentally sound and emission-free purchase (Potting 1995; Jönsson,1997; Jönsson 1999).

A series of Swedish studies (Jönsson,1997; Jönsson 1999) compared the environmental impact of three general flooring materials namely linoleum, vinyl and solid wood under the scenario of Sweden. The study based on a processed LCA, the results revealed that the solid wood flooring was the most environmentally preferable choice, followed by linoleum and vinyl; and the TVOCs emitted by floor coverings during the use phase are of much the same magnitude as the TVOCs emitted in the rest of their life cycle, except for solid wood flooring.

Nicoletti et al. (2002) conducted a comparative LCA between conventional ceramic and marble tiles, the key environmental impact categories were identified as well as the key life cycle phases of two flooring tiles. The results indicated that the impacts of ceramic tile are over twice as bad as the marble tile, and the improvement solutions for the two products were proposed.

Similar studies were found in recent years, Reza et al. (2011) compared three kinds (concrete, clay and expanded polystyrene) of construction flooring systems based on AHP LCA; according to the result, expanded polystyrene EPS is the most environmentally sound flooring system amongst the three. A recent LCA case study (Sangwan, Choudhary, and Batra 2017) assessed the environmental impact of a ceramic tile supply chain, Umberto NXT LCA software was utilised with an updated database and assessment method, and the manufacturing stage was identified as the key environmental impact stage.

Geng et al. (Geng, Zhang, and Yang 2017) compared a kind of wood flooring with traditional ceramic tile from a greenhouse gas reduction and cost-effective points of view, which proved the advantages of wood flooring tile.

The existing studies discussed above clustered on comparing the environmental impact of general flooring materials to guide material selection. Additionally, some of the studies did not apply LCA software in the early years due to the technology limitation; different evaluation methods were applied so that the accuracy of the assessments remains controversial.

2.4.2 Social life cycle impact assessment

The discussion of integrating social aspects into Life Cycle Assessment (S-LCA) started in the 1990s (O'Brien et al., 1996). The United Nations Environment Programme (UNEP) and the

Society of Environmental Toxicology and Chemistry (SETAC) published 'Guidelines for Social Life Cycle Assessment of Products' (UNEP/SEAC, 2009; UNEP/SEAC, 2013), which explains the rationale regarding social impacts for the product and provides a solid social impact evaluation framework. Five types of stakeholders and 23 social and socio-economic subcategories (topics) are introduced in the guideline. A stakeholder category is a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. The stakeholder categories provide a comprehensive basis for the articulation of the subcategories (Benoît et al., 2010) The Five stakeholders are: Workers, Local community, Society, Consumers, and value chain actors.

Impact Categories used in S-LCA will correspond to the goal and scope of the study and represent social issues of interest that will be expressed regarding the stakeholders affected and may cover health and safety, human rights, working conditions, socio-economic repercussions, cultural heritage, and governance. While impact Indicators act as the bridge that links the data with subcategories and impact categories, guiding the data collection process.

S-LCA assesses the social and socio-economic impacts found in the life cycle (supply chain, including use phase and waste) and provides general data and specific data. It is different from other assessment methods, the scope of which is the entire life cycle. The social and economic and social aspects assessed in S-LCA are those that may directly or indirectly affect the positive or negative aspects of the stakeholders in the product life cycle (UNEP, 2009). The four steps of conducting S-LCA is as the same as it of E-LCA:

Goal and scope. The definition of the goal and scope has to be clearly specified in the first step of the study to ensure the study will fulfil the intended application. The goal and scope are directly determining the depth and breadth of the study. Determine the stakeholders considered in the study and the life cycle stages included, the data in S-LCA are always case-specific.

Life Cycle Inventory Analysis. The inventory is the phase of an S-LCA where data are collected, the systems are modelled, and the LCI results are obtained. The Guidelines (UNEP, 2009) specify three different types of data that can be used in an S-LCA (Parent et al., 2010):

> *(1) the activity variable, which serves to allocate a socially relevant weight to the different unit processes when dealing with qualitative and semiquantitative indicators that cannot be referred to the functional unit directly;*
>
> *(2) the data related to the social conditions or stressors that will be translated into impacts (the inventory data); and*
>
> *(3) the data necessary to compare the local situation to an international set of thresholds (the "Performance Reference Points" to be used in the characterization).*

Life cycle impact assessment. Impact assessment (SLCIA) is the third phase of an S-LCA. The purpose of SLCIA is to aggregate inventory data and cluster them into subcategories and categories. SLCIA methods aim to connect to the extent possible, emissions and extractions of life cycle inventories on the impact pathways to their potential environmental damages. Impact pathways consist of the linked environmental process, and they express the casual chain of subsequent effect originating from emission or extraction (Parent et al., 2010).

Life Cycle Interpretation. According to the guideline, the interpretation of S-LCA results including identification of the significant issues; evaluation of the study (which includes considerations of completeness and consistency) and making conclusions, recommendations, and reporting.

2.4.3 S-LCA methods

There are four main methods available to assess a product's social performance through its life cycle, namely Checklist Method, Scoring Method, Database Method and Empirical Method. Amongst the methods, the Database Method is the most recent and the trend of social performance calculation.

The checklist impact assessment method uses the tick sign to measure an impact. Franze and Ciroth (2011) utilised this method and compared the social life cycle impacts for rose flowers from the Ecuador and Netherland, with focuses on production and packaging stages. The assessment was conducted and measured with five levels of colours in a spreadsheet format. The impact category with the most '√' will be marked the darkest colour in the row assessment box. The impact category row with the least '√' will be marked the lightest colour in the row assessment box. The darker the colour is, the more impact the category possesses, and vice versa.

The Scoring Method uses scores to measure an impact. A variety of scoring methods and standards have been developed to apply in the implementation of product S-LCA. Foolmaun and Ramjeeawon (2013) investigated the social impacts of four solutions for recycled PET bottles by utilising this method. The percentages have been marked for each subcategory based on the established scoring standards, the total scores can be calculated for each subcategory for different solutions for comparison. In addition, scoring with values, such as 1-6, has been also found in S-LCA practices (Ciroth and Franze, 2011).

The database method is the most recent and the trend of social performance calculation. There are two databases available to date for S-LCA practices: Social Hotspot Database (Norris, Aulisio and Norris, 2012) and PSILCA (Ciroth and Eisfeldt, 2017). Both databases comply with the categories and indicators framework that is defined by the UNEP Guidelines (Benoît et al., 2010). Global governmental and organizational statistics, as well as non-profitable organizational data, are the main sources for the two databases. Both databases cover data by different sector in hundreds of nations and regions. Using the database to model the product system for S-LCA and conduct the evaluation is timesaving and reduce the uncertainty of the assessment. This research applied the database method to calculate the life cycle social impact, PSILCA database was selected with the industrial case study, which is detailed in 4.4.4.

The empirical method uses empirical formulas or rules in order to assess social impacts. This method has been practised mostly for individual case studies. Labuschagne and Brent (2006) developed a quantitative method to assess social life cycle impacts based on the South Africa Resource Impact Indicator approach. Feschet et al. (2013) used Preston Pathway to evaluate the health, education, employment impacts related to the banana industry in Cameroon.

2.4.4 S-LCA study and integration in sustainable product

The understanding and application of S-LCA methodology are advancing during the past decade, whether on the amount or extensiveness of the publications on this area. Publications were ascending in addressing social and socio-economical topics after the UNEP/SETAC guidelines were brought out in 2009. Furthermore, it can be detected as a fact that among the existing literature, the number of case studies on S-LCA began to surge since 2012, in contrast, literature before were more on a theoretical level. Similar support statics can be found in several publications such as Arcese et al. (2008). The guidelines are considered to have a positive effect on life cycle sustainability assessment as well (Ciroth et al., 2011). However, the concern is raised regarding the S-LCA method lacks standard and code of practice (Arcese et al., 2018; Agyekum et al. 2017). Despite UNEP/SETAC guidelines provide an important benchmark of the S-LCA framework.

There are several studies that integrated social life cycle assessment (S-LCA) with environmental life cycle assessment (E-LCA) to assess product/product-service systems' (PSS) sustainability performance. Jørgensen et al. (2008) conclude the S-LCA study into three categories: 1) S-LCA which aims to identify social hot spots; 2) S-LCA which aims to evaluate the social impacts caused by choosing among several scenarios/options and; 3) S-LCA for marketing and communication purpose.

Franze (2011) and Ciroth (2011) identified both environmental and social hotspots through a notebook's life cycle and rose production processes, which are pioneer examples showing early efforts in the combination of E-LCA and S-LCA. These studies indicate that the E-LCA and

S-LCA results might be completely different so that both environmental and social dimensions need to be assessed to understand holistic sustainability.

Foolmaun and Ramjeeawon (2013) conducted a comparative E-LCA and S-LCA of used polyethene terephthalate (PET) bottles in Mauritius to identify a suitable method of disposing of used PET bottles. A software tool was applied for E-LCA while three stakeholder categories and eight sub-category indicators were included in the S-LCA study. The analysis finally detected that the solution with 75% flake production and 25 % landfilling is the best solution for the case.

Agyekum et al. (2017) created a simplified S-LCA approach that combines a comparative LCA of bicycle frameworks with a simplified S-LCA due to the data limitation.

Chongyang et al. (2019) conducted a comparative environmental and social LCA of manual and mechanical harvesting of sugarcane in Brazil, in which mechanical harvesting showed a better end-point environmental and social impacts.

In a most recent case study, Khorassani et al. (2019) developed an S-LCA operational model based on UNEP/SETAC's guideline and demonstrated together with a standard E-LCA to identify the environmental and social hotspots in cultural heritage restoration. However, those studies focused on the comparative assessment of past actions (an established product or activities) and their outcomes (Pope et al., 2017), there is limited study capturing social performance for 'product development' which can be adapted in informing new sustainable product or product-service system development (Kravchenko et al., 2019). On one hand, this may due to the ‘intangible’ and ‘complex’ nature of social aspects and their inter-relationships (Chou et al.,2015; Costa et al., 2015). On the other hand, when it comes to product development towards the triple bottom line of sustainability, product developers are still ‘dancing in the dark’ (Petersen and Brockhaus, 2017), especially with the question of how social aspects are integrated and how social assessment results can inform product/service design remains challenging. Hence, it is necessary to explore issues and opportunities in both social and environmental perspectives to inform product and service design, so that potential risks can be mitigated in a more holistic perspective among different stakeholders.

2.5 Gaps of current literature

According to the literature review conducted above, the TBL has not been fully addressed in research and practice, there is a need to address sustainability issues from a holistic perspective, i.e. from TBL perspective. Current research focuses on one or two dimension(s) of sustainability issues, environmental and economic sustainability are most addressed in the literature, but the social aspect is lack of attention among current studies, whether on the conscious or application level. The lacking reflects on:

- Applications of conducting social life cycle performance evaluation of product and services.
- Applying the social factors to sustainable innovations towards developing products and services.
- The implementation as decision-making criteria of sustainability issues related to

‘sustainable design’, ’sustainable manufacturing’ and the contents of ‘life cycle management ’.

Systematic Approaches for universal implementation which address holistic sustainability is lacking. Current literature focuses on solving specific case problems, the methods and approaches developed from the case-specific studies are usually suited for specific conditions or enterprise/ case, therefore are difficult to implement as a universal approach. PSS has the potential of integration of TBL od sustainability, however, the application is mainly from the business point of view. There are several efforts made by studies to provide systematic approaches, such as the ‘System design for sustainability’ (Vezzoli, C. et al., 2014). Despite the method can be varied for the goal of the applications, the method still emphasises the service part rather than product development. In addition, the current methods towards systematic sustainability design are qualitative methods, amongst which quantitative techniques are lacking. For those which sustainability assessment-based approach/ frameworks, the choice of assessment indicators and the integration of assessment results into decision-making or product/service development concept optimisation remains controversial.

Systematic sustainable innovation is lacking. In the existing research and practice about product sustainability, the connection between sustainable product development and sustainable product services has not been given enough attention. Sustainable design development and sustainable PSS in service has frequently been studied separately by research in different domains. The product service is mainly developed after the base product is established, therefore there are limitations in this pattern for considering the product and service as a whole to achieve its sustainability goal from a life cycle perspective. Therefore, the combination and consistency of product development and service need to be addressed. From a life cycle thinking perspective, the product and service should be developed and considered as a whole for sustainable innovations.

The methodology that supports preventing the potential environmental and social risks in the early development stages is lacking. Sustainability assessment is a useful and effective methods technique to indicate sustainability performances as a decision-making reference. Yet the nature of the assessment requires quantitative data which often can be conducted by the end of the development process, where the concepts are well developed and difficult to change. Thus, controlling the negative impact in the early design stage is key. From the LCM perspective, the product/service conceptualisation could decide the choice of materials, supplier, manufacturing methods and cost as well as the value chain actors during the service phase, which is the most controllable and effective stage to prevent potential sustainability risks. However, difficulties for designers and engineers are detected in the construction of the sustainable Product Design Specifications (PDS) due to the ambiguities of the sustainable requirements. Other difficulties including the methods to control and predict early impacts in early design stages which needs more research attention.

Chapter 3 - Sustainable Product Development and Service Approach

3.1 Overview of the approach

Sustainable product development and service approach (SPDS) aims to support sustainable product and service through a systemic innovation underpinned by interdisciplinary methods and tools. The SPDS approach covers the whole life cycle of the product, and is conceived to address three detentions of sustainability in the product development and service, i.e. to reduce the environmental burdens, address the social issues while achieving the economic and competitive interest of providers. This approach is applicable to enterprises, sustainability consultancies, engineers/designers and researchers. The approach was conceived to addresses three detentions of sustainability (environmental, social and economic) but adjustable according to the individual needs (to address environmental aspects only, etc.) of the enterprise/practitioner.

Figure 3.1 illustrates the framework of the sustainable product development and service approach. The approach covers the whole product lifecycle stages: design, manufacture, distribution, retail, use, maintenance and repair, and end of life; amongst which the first two stages, design and manufacture, are covered by the sustainable product development phase, while the rest stages are covered by sustainable product service phase. The approach is supported by various techniques and tools including sustainable product design and manufacture, life cycle analyses, sustainability assessment, and sustainable service.

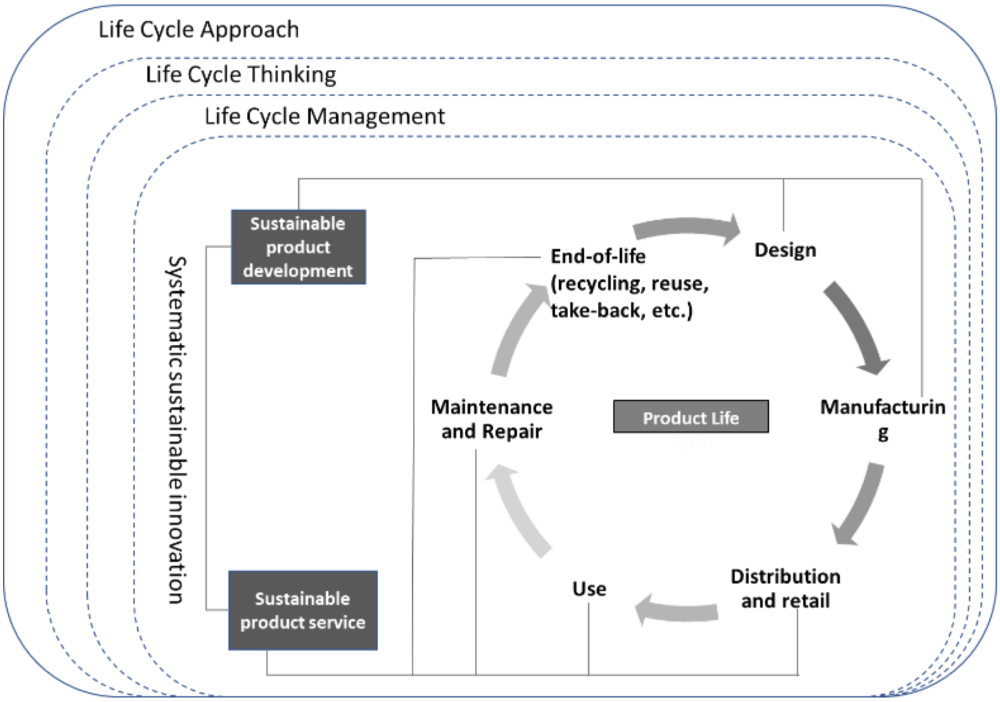


Figure 3.1 The sustainable product development and service approach

This approach is a Life cycle approach under the Life cycle thinking and LCM framework (see chapter 2 for detail) and is supported by sustainable product development and PSS methodology (Goedkoop et al., 1999). The scope of the approach is beyond a physical product, but throughout all the life cycle stages of the product's life cycle. The objectives are to provide systematic solutions not only to reduce the environmental burden but also to achieve economic and social values.

However, for a radical improvement of holistic sustainability of product and service, the existing frameworks and concepts have gaps on the implementation level for sustainable innovation. As a business management concept (UNEP/SETAC, 2009), LCM pays close attention to the implementation of the supply chains to target, organize, analyse and manage product-related information and activities (Remmen et al., 2007); yet lacks specific methods regarding sustainable product development. In addition, the PSS focuses on business models by adding a service component to a physical product (Aurich et al., 2009), such as an after-sale service of the existing product, which only brings incremental innovation to products but not a complete change in the manner to develop the system (Maussang et al., 2009). For those reasons, the approach proposed by this research adopts the framework of LCM but advanced than the existing LCM frameworks and PSS applications, aiming at a radical improvement of sustainability by the development of the sustainable product and the service as a bundle in the same stage to construct a systematic sustainable innovation.

The proposed SPSD embraces the following key features:

- As a life cycle approach further developed from the existing frameworks and approaches, the SPDS is more advanced than the existing LCM and PSS applications.
- Covering the whole life cycle stages of a product, from design, manufacture, distribution, retail to use, maintenance and repair, and EoL.
- Addressing the TBL of sustainability in products and services.
- Enhancing the interaction between product development and product service phases to advance sustainability performance.

3.2 Interactions between product development and service

3.2.1 Design for service (DfS) and service feedback for design improvement (SfD)

In order to achieve effective interaction between the two phases, the product development and product services need to be considered, therefore the connection between product development phase and product service phases needs to be enhanced. This is achieved by 'design for service (DfS)' and 'service feedback for design improvement (SfD)', enabling the two phases to interact and support each other.

The DfS is to address the service factors at the design stage, for the product to achieve sustainable functions at relevant stages within the product service phase. An example of such DfS methods is the modular design which facilitates the repair and recycle/reuse of products when they reach the EoL. DfS is derived from the fact that the majority of a product's sustainable impacts are determined at the product design stage and form the LCM perspective, and the design stage is most controllable and cost-effective in improving sustainability (Agudelo et al. 2016).

The SfD is to deal with the issues encountered in the product services phase, which are related to the product performance/functions, to provide useful feedback for the improvement of the product. As illustrated in Figure 3.2, such feedbacks are used to refine the product design specifications, which govern the design and manufacture, to ensure the improvement of the product performance/functions, including the product sustainability.

3.2.2 Implementation of DfS and SfD in product and service system

The objectives to implement this approach are to reduce the environmental impact through the product life cycle and to address related social and economic issues. The objectives are to be achieved by implementing sustainable product development and sustainable product services.

Within the approach, the sustainable product development phase and the sustainable product service phase are interrelated and support each other. The interaction of product development and product services take place at different stages in the SPDS. For example, the ability of service is considered as one of the criteria in the evaluation of potential design concepts; in the detail design stage, the product features are particularly addressed to guarantee the successful operation of the product service, see chapter 5 for application in lighting product. A conceptual construction method is proposed in response to SfD and aims to conceptualise product and service opportunities towards TBL sustainability at the conceptual design stage, in which, the sustainability performance (E-LCA and S-LCA) of the product(s) in service is to be assessed first to provide feedback on sustainability issues, such as to identify the opportunities for the specific enterprise/case on the improvement of sustainability performance in the new product and service development. The sustainable recommendations are to be given based on the assessment results so that they can be applied to the sustainable product design specification (PDS) construction. The method includes three steps: data collection, conducting sustainable assessment, and deriving recommendations and implications for product and service design. This method is the first step of operating the SPDS as well as reflecting the interaction between service and product development.

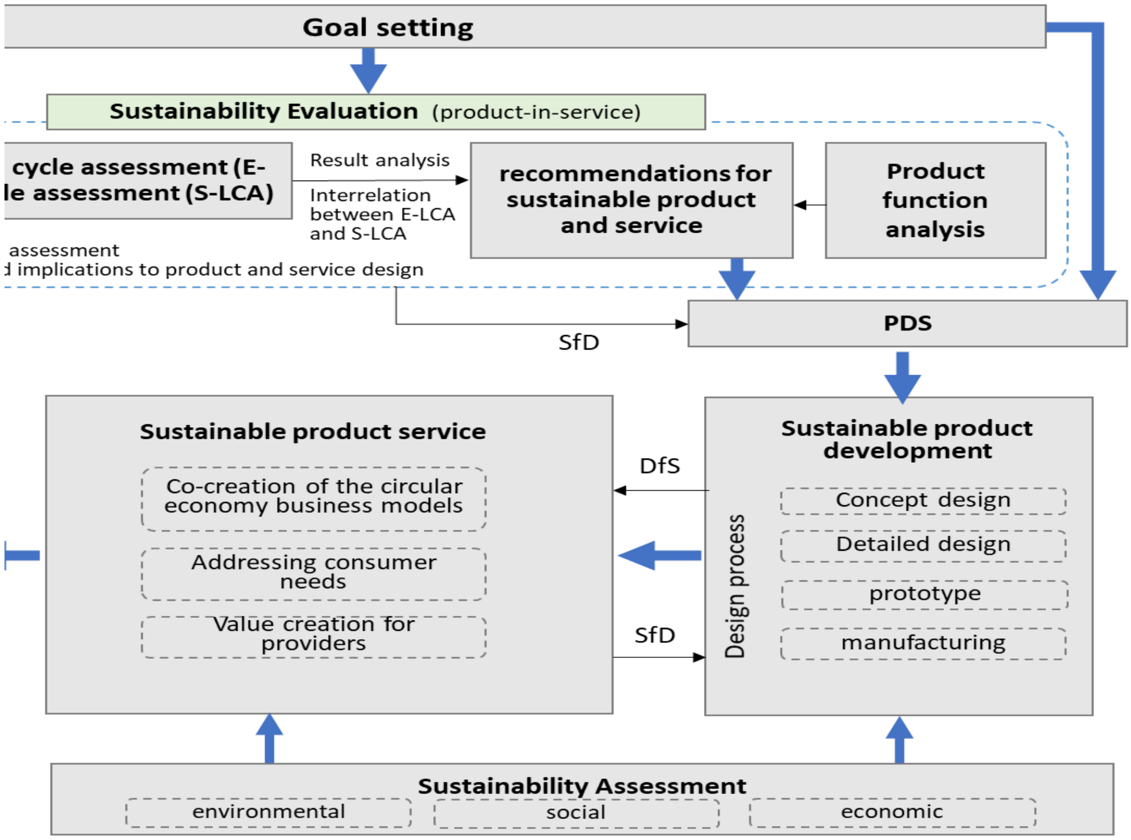


Figure 3.2 The sustainable product development and service (SPDS) approach

In the sustainable product development phase, the DfS and SfD methods are implemented within the design process consisting of product design specification (PDS, the essential definition of what the product is required to provide. The PDS is a statement of what functions or characters the product have to achieve), conceptual design, detail design and prototyping. The PDS is refined by the feedback for improvement resulted in the sustainable product service phase. The product's sustainable features are achieved by making the designed product through the manufacturing process, where related sustainable manufacture methods are applied.

In the sustainable product service phase, the manufactured product goes through the stages of distribution including retail, use (i.e. consumption), maintenance, and end of life (including recycling and reuse). In this phase, co-creation is conducted, with the knowledge of life cycle thinking and lifecycle management, designers, researchers, value chain actors are all involved in the co-creation which aiming at circular economy business model/models. The goal is to construct a service that is better fulfil consumer needs while creating value for the providers with reduced environmental and social impact.

The sustainability assessment is applied in the approach to reveal the environmental and socio-economic performance of the product and service. In which, life cycle assessment technique and software tools are utilised to evaluate the environmental sustainability of the product, while the socio-economic sustainability of the service is analysed as well.

3.3 Sustainable product and service conceptual construction approach

3.3.1 Product conceptualization stage towards sustainability

As 80% of the product's total environmental impact is determined at the product design stage (Charter, 2001), more attention should be paid to address sustainability issues at the product design stage. Sustainable product design is defined as an interdisciplinary concept to create new products or services and to generate value and innovation to best meet consumer's needs, dealing with environmental, social and economic perspectives with the best possible balance. The sustainable design process begins with defining the product design specifications, then move to 'conceptual design' to meet the PDS. From the LCM perspective, the choice of materials, supplier, manufacturing methods and cost, as well as the value chain actors during the service phase, are built-in in this stage, which is the most controllable and effective stage to prevent potential sustainability risks and reduce cost (Agudelo et al. 2017). Thus, controlling the negative impact in the early design stage is crucial.

However, barriers are detected to designers/engineers, such as to convert the ‘uncertain’ sustainable variables in design requirements (Giachetti et al., 1997). The difficulties to designers/engineers in sustainable PDS construction mainly centred on:

- Detecting and conceptualising the tailored PDS towards holistic sustainability;
- Lacking a clear evidence-based design guide for the specific product (Petersen, 2017; Alblas et al., 2014);
- Lacking method or guidelines to integrate social aspects and social assessment results to inform product/service design, and;
- Lacking a comprehensive strategy (Brockhaus et al., 2016).

3.3.2 The integrated method to inform sustainable product and service design

The integration of sustainability assessment aims to detect and guide product and service conceptualisation towards TBL sustainability at the early development stage. In which, the sustainability performance of the product in service is to be also assessed at the beginning of the development process to provide feedback on sustainability issues, which is useful for the conceptualisation of new sustainable product and service. Its application can be broad depending on the sustainability goals (how many sustainability aspects to address, etc.), and according to the goals, the environmental and socioeconomic performances of product-in-service are to be assessed to identify the opportunities (see figure 3.3) for the specific enterprise/case on their improvement of sustainability performance in the development of new product and service. The sustainable recommendations are given based on the assessment results, therefore, are tailored and specified so that they can be applied into the PDS construction.

3.3.2.1 Integrating sustainability assessment to inform product and service design

The integration method is outlined in Figure 3.3. The method includes three steps: data collection, life cycle assessment and recommendations. LCA methods and tools are utilised to assess the product-in-service.

3.3.2.1.1 Data collection

In the data collection step, an investigation in collaboration with the manufacturer to obtain case-specific data is necessary. Given the goal is to address the TBL of sustainability, the sustainability evaluation, therefore, is consisting of E-LCA and S-LCA. There will be three types of data under this circumstance: E-LCA specific data, S-LCA specific data and common data for both E-LCA and S-LCA.

The investigation consists of two parts: the first part is to obtain the E-LCA specific data and common data for both E-LCA and S-LCA through the product life cycle, including production data, supply chain data, and life cycle stages' data. These are quantitative data that can be applied and adapted to the assessment model directly. The other part is to collect the S-LCA specific data that contain information about company social performance regarding different stakeholders through life cycle stages.

Existing literature has pointed out that one of the barriers for engineers/designers to conduct environmental and social life cycle assessment is the difficulties of acquiring inventory data. Therefore, there is a need to apply the constructive method to short the time and reduce the communication barriers between the practitioner and manufacture.

The data collection forms for E-LCA and S-LCA are designed, see figure 3.4, which can be applied during the data collection processes.

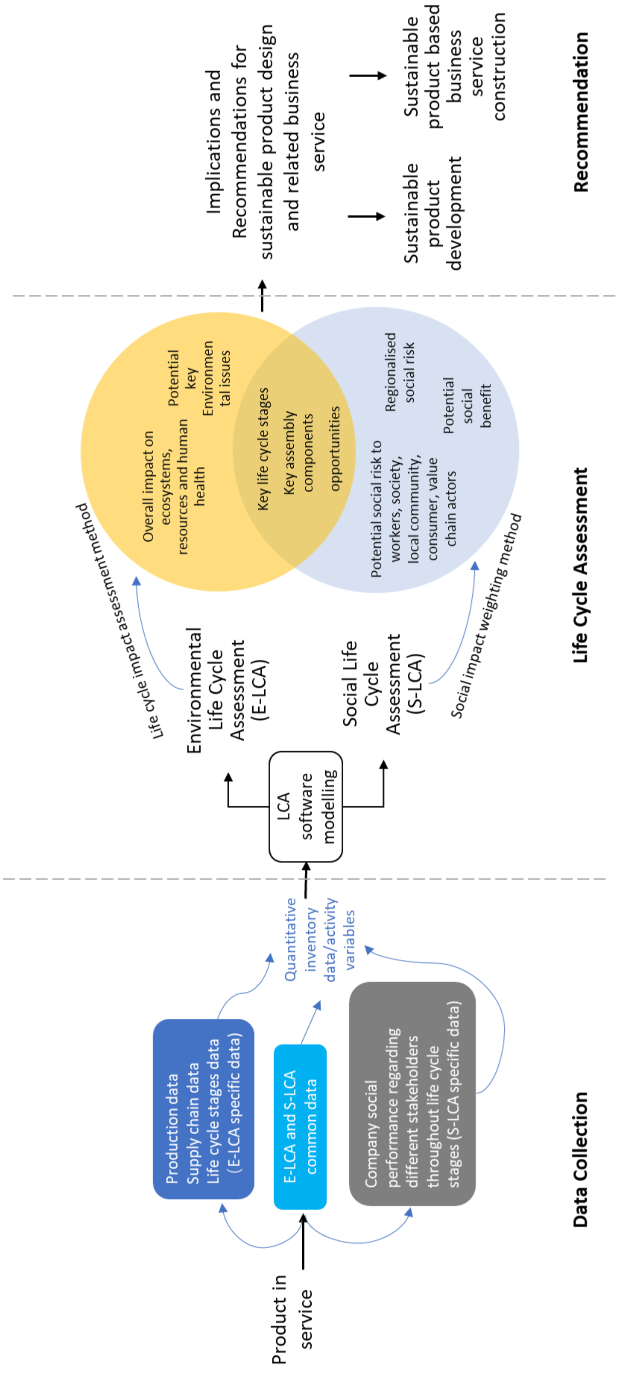


Figure 3.3 The Integrated approach to Inform Sustainable Industrial Lighting Product and Service Design

1. Product General Data	1.1 Product Name/ Model Name	
	1.2 Product Photo (including application photo)	please put all the pictures in the picture folder.
	1.3 Suggest Service Time	
	1.4 Total Weight (kg)	
2. Product Manufacturing Data	2.1 Describe Product Manufacturing Procedure (including time use)	production diagram with brief description, please put all the pictures in the picture folder.
	2.2 Product Assembly inventory data	including product all assembly parts name, number, weight, material , see 'example for 2.2' sheet.
	2.3 Waste Generation During Manufacturing(kg)	eg: solid waste, liquid waste
	2.4 Emissions Generations (kg)	to air
	2.5 Is there harmful waste or emission? If yes, specify the production stage, substances and mass	
3. Functional Unit and Usage Data	3.1 Functional Unit Description	How the product works, how much function could a individual product provide, is it required work with certain amount of the products.
	3.2 Product Explosion Diagram	see 'example for 3.2' sheet, please put all the pictures in the picture folder.
	3.3 Parameters of the Product	
	3.4 Energy Consumption During Use	
	3.5 Is there any maintenance needed during the service time? If yes, specify in detail	
4. Transportation Data	4.1 Manufacture Plant country and Region	
	4.2 Target Market Country or Region/City	
	4.3 Distance between manufactory plant to target market Region/City	
	4.4 Means of Transport	if the transportation includes more than one transportation tool, specify in detail
	4.5 is there other transport activities take place during the manufacturing stage? If yes, specify in detail	
5. End of Life and Disposal Data	5.1 Current disposal method and Mass of product disposal this way	
	5.2 Is there component of the product includes harmful substance which requires special disposal method? If yes specify the disposal method and mass of the component.	WEEE, REACH, RoHS
	5.3 Is there material of the product recyclable? If yes, describe the material and mass.	

	1.1 Place of Production	1.2 If all the assembly members come from China	1.3 if yes, the cost of the members are	1.4 if there is members from other country，please specify the member name, country and cost. ($)	1.5 the cost of electricity during manufacturing the product ($)	1.6 transport cost of production stage ($)	1.7 export or inport cost of the product ($)	1.8 is there other costs, fill the activity name and cost ($)
1. Production Stage								
2. Transportation								
3. Distribution								
4. Use Stage								
5. Disposal								

Figure 3.4 Example of data collection form (E-LCA and S-LCA)

The data collection forms cover the questions regarding the product's life cycle information in segments, such as product general data, manufacturing data, Functional Unit and Usage Data, transportation data and End of Life and Disposal Data. The data collection forms had been used in the case studies in later chapters. Each life cycle segment consists of three to five questions accordingly. The required information is stated as direct questions in the question forms, which are easier for engineers to provide the corresponding information by answering the questions. It is considered as an easy method to interact between the assessor (the one who conduct the assessment) and the industrial partner to shorten the data collection process by explicate the questions in a coherent format and obtain the data with effectiveness. It is also considered as a 'burden relief ' for the industrial partner, as they are usually not clear about the exact information needed for the assessment consequently have trouble providing the right information, which may lead to the misunderstanding between the assessor and the industrial partner and prolong data collection process.

For the S-LCA data collection, it's more complicated to describe as questions, as a complement, interviews with engineers, employee representatives, and company directors can be conducted to obtain the data as needed.

3.3.2.1.2 Conducting sustainability assessment

In the second step, with the data collected from the firsts step, the E-LCA and S-LCA are conducted. LCA is a valuable tool in integrating sustainability into product development and assessment due to its systematic procedures. The E-LCA considers environmental impacts along supply chains, while the S-LCA aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle (UNEP/SETAC, 2009). Both the E-LCA and the S-LCA adopt the same methodology (LCA) which is comprised of four main steps: goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation.

To conduct the sustainability assessment, the E-LCA and S-LCA modelling techniques are required. Assessment models for environmental and social impact assessments are developed via the LCA software tools (see chapter 2 for details). The key life cycle stages, key assembly components, and opportunities are identified on environmental and social aspects. Meanwhile, the potential environmental issues, potential social risk to the stakeholders, namely workers, society, local community, consumer, value chain actors, and potential social benefit are also obtained and analysed.

3.3.2.1.3 Recommendations and implications to product and service design

In the third step, the E-LCA and S-LCA results obtained from the second step are analysed. If applicable, the interrelation between the E-LCA and S-LCA results are also analysed. The insights and findings from the analyses are derived and transformed into applicable sustainable design recommendations and managerial implications, subsequently guide sustainable product development and business service implementation.

The method to detect the interactions can be found in section 3.5. Those recommendations derived from the sustainability assessment of the product in service can be directly applied in constructing the new sustainable product design specification and service conceptualisation. The recommendations are tailored for the specific enterprise with evidence-based (environmental and social performance results based) systemic solutions, including new technologies and sustainability requirements for the new product and the requirements addressing social issues and trade-off with economic interests. Therefore, by integrating the recommendations into sustainable product and service conceptualisation, it is expected that the negative impact can be controlled in the early development stage, and consequently, to improve the overall sustainability of the innovation.

This proposed method can be applied to guide sustainable product and service conceptualisation. However, the interrelationships between the E-LCA and S-LCA results can vary due to the characteristics of different products. The application of the method also depends on the goal and the ambitions of the enterprise towards sustainability, nevertheless, the method can be adjusted accordingly, which will be demonstrated in later sections.

3.4 Methods and tools in sustainable product development stages

This subsection introduces methods that can be applied during the product development stage to support sustainable product development. These methods can be applied selectively depending on the targeting product and identified objectives from PDS. The demonstration of different methods will be presented in the forthcoming case studies. Figure 3.5 illustrates the methods and tools and how they can be integrated in the product design process. The subsections will explain each method and the application process.

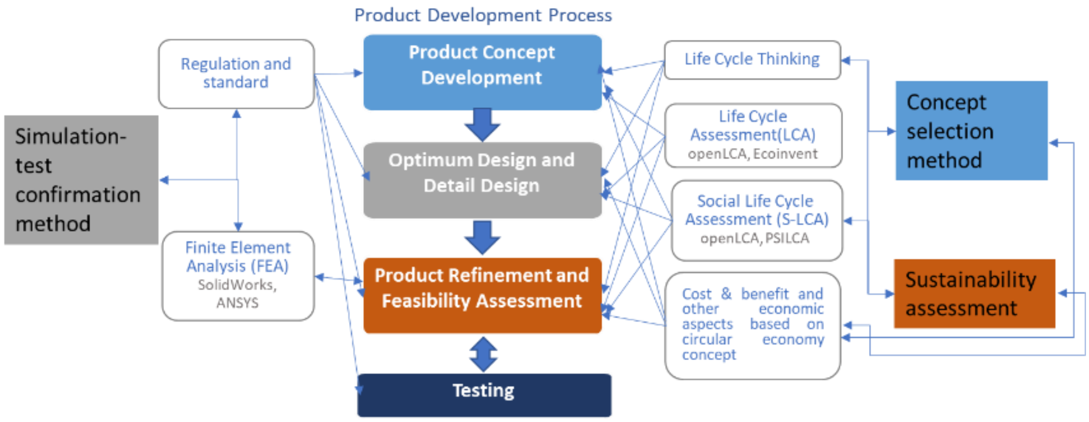


Figure 3.5 Methods and tools in sustainable product development stages

3.4.1 Concept selection method

Concept selection is an activity in the product design process, where alternative concepts are compared and a decision is made to select the alternative(s) which proceed into the later phases of design (Ulrich and Eppinger, 2000). Several authors have agreed that concept selection is one of the most critical issues in design (Pugh, 1996; Ulrich and Eppinger, 2000). The concept selection process is the initial decision-making process that could affect the impact of the product through the selection criteria, those criteria should be formulated in accordance with the PDS with emphasised aspects. For sustainable design, when the product technical characters are guaranteed, environmental and economic aspects also should be addressed and emphasised in the criteria construction (social aspect is hardly be considered at the initial concept selection stage, since the social information is limited at the stage).

This research proposes a concept selection method that aims to grantee the technical standard while minimising the potential environmental impact and cost. In which, all the concepts are evaluated with two types of evaluation criteria, comparative criteria and threshold criteria. The threshold criteria represent the requirements that the concepts must meet. Those criteria are usually derived from the standard and the constraints of the product category. If a concept cannot meet any of the requirement, i.e., the threshold criterion, the concept is then ruled out without further consideration for evaluation. With the comparative criteria, the concepts are evaluated using numerical values, and a higher value represents a better result. To rate the importance of each criterion, the Weight Factors are applied. The values of the weight factors are ranged from 1 to 3, and a higher value indicates more importance of the criteria to which the higher value assigned. To guarantee the eco-friendly features, it is suggested to assign 'weight', 'environmental impact' and 'cost' the highest value '3'. However, the assignment of the weight factor can be adjusted according to the initial PDS. Figure 3.6 illustrates the two criteria.

The comparative criteria cover possible issues that can affect the sustainability (mainly environmental and economic) performance along the product life cycle.

Weight. Product weight is one of the most critical parameters that link to further issues such as transport, installation, etc. It is also proved to be the key parameter to the environmental performance of the product (Wang et al., 2020).

The number of materials. It is another important parameter that links to manufacturing processes, joint methods and costs as well affects the environmental performances (Wang et al., 2020) during the production stage and related to the end of life options.

Ease of manufacturing. This allows the comparison of the design concepts regarding their manufacturing process if the proposed concept is achievable from the manufacturing perspective.

The flexibility of adjustment. This item aims to measure the flexibility of instalment and disassembly/adjustment.

Ease of maintenance. Ease of maintenance refers to the low maintenance required throughout the service time, easy to detect if the product needs to be repaired; as well the operation of the repair or upgrade is either require fewer complex works, easy to reach; or cost-effective.

Life cycle environmental impact. Here is an estimation of the potential environmental impact along the product life cycle, i.e. through the material and manufacturing complexity. Three impact aspects can be considered regarding this item, namely the impact on human health, ecosystem and resources.

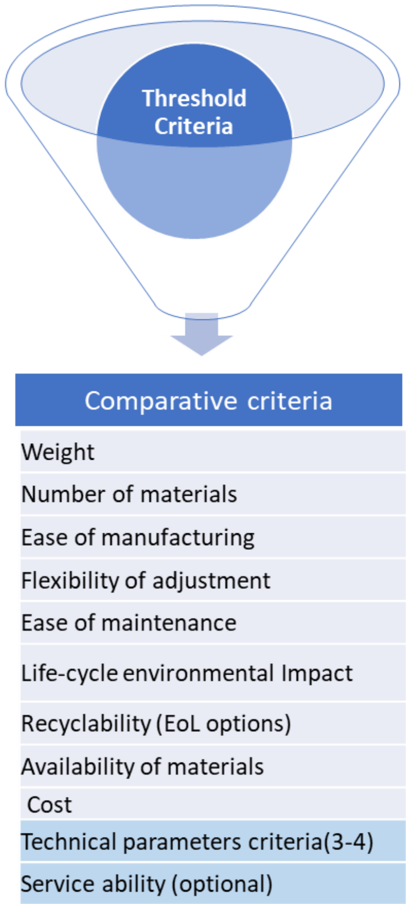


Figure 3.6 threshold criteria and comparative criteria

Recyclability (EoL options) is to address the end of life options if the materials chosen in the concepts are recyclable, or easy to disassemble if the joint methods are preferable when disassembling the product.

Availability of materials evaluates if the materials proposed in the design concepts are easy to reach. This can also affect the production cost of the design concept.

Cost. The objective is to balance the environmental impact but with controlled production cost. This is considered beneficial for the producer to gain market competitiveness.

In addition, optional criteria are included, such as the evaluation items regarding technical parameters and serviceability. The additional technical parameters criteria aim to pick the preferred characters of the product under development. The serviceability is to indicate and support the potential product service related to the product, user can consider this item when there is a service goal to achieve.

3.4.2 Simulation-experiment confirmation method

Finite Element Analysis (FEA) is a simulation tool that can be used to predict how a product or system will react in numerous scenarios. For the product that needs to comply with a strength standard, FEA is useful to simulate the stress and deformation and obtain the response data under a certain load.

The simulation of experimental test with FEA techniques is necessary before the product prototype is ready. It is considered a time-effective and cost reduction method in the detailed design stage. The simulation model of the product and the experiment instrument is to be developed and the simulation of the load/position should be set according to the physical experiment, which in turn complies with the related technical standards. This combination of method can be applied by repeat attempts which are continued until success, or until the attempt stops.

If the FEA results meet the chosen standard, they can be processed to the next development stages, where the prototype can be made then the experiment can be carried out. Finally, the

FEA results will be compared to confirm the physical experimental test results.

Under the circumstances when the detailed design concept under FEA is failed to meet the requirement, it is suggested to be redesigned/refined. It needs to be noticed that the FEA results, in theory, is slightly lower than those of a real experiment environment. In this case, by limiting the fixed parameter (usually the technical standard or goal), and keep trying with different dimensions (thickness, height, etc.), the simulation tool could finally detect the breaking point so that the designer/ practitioner refines readjust the preferable dimensions that meet with the chosen standard's requirement. This method is particularly applicable in developing a product with load-bearing capacities, such as furniture, transportation products, aiding products and constructing products, etc.

3.4.3 Sustainability evaluation

The sustainability evaluation is applicable as a sustainable decision-making method throughout the product and service development process. The evaluation including life cycle assessment; social sustainability evaluation, and cost and benefit and other economic aspect evaluation. According to the goal set at the beginning of the development, the assessment can be chosen accordingly. For example, if the goal is set to achieve the holistic sustainability, then the three evaluation needs to be conducted in the detailed design stage to check if the goal is met, while if the goal is emphasising on the environmental aspect, then the life cycle assessment should be focused throughout the development process. Nevertheless, cost-efficient is a universal target that will be addressed during the decision-making process. The evaluation can be an iteration process until the sustainability goal is achieved, i.e. the environmental impact is reduced, the social issues are well addressed (it varies between cases).

Life cycle assessment is a widely accepted method to evaluate the environmental performance of products and services. In this research, the integration of life cycle assessment is on two folds: the initial sustainability performance assessment, where the impact of product-in-service is assessed to obtain and derive the PDS, see early this section for detail. The other fold is to conduct comparative LCA to obtain the environmental performance of the new design with the reference product/products. The reference product can be the product that under assessment initially, or other typical product that can be compared as benchmarking objectives or reference values in related standards.

Social sustainability evaluation. The evaluation focuses on the social effect along the supply chain of the product and service, where stakeholders (i.e. provider of the supply chain, end-user/consumer, workers, etc.) benefit along the life cycle stages will be evaluated. Social issues such as job boosting, consumer satisfaction, etc. will be covered. This evaluation will be conducted in the detailed design stage, however, unlike LCA data, the socio-economic information is hard to collect for an S-LCA. Nevertheless, the social sustainability analysis and evaluation will cover as much of the stakeholders and social issues as possible.

Cost and benefit and other economic aspect evaluation. This evaluation can be integrated into many development stages, such as concept selection, decision-making in detailed design stage prototyping and manufacturing. The goal is to achieve cost-effective also create extra value from the sustainable product to enhance the profit of the provider while achieving sustainability goals with their products.

3.5 Operation of the approach

An overview of the operation process of the product service approach is presented in Figure 3.7.

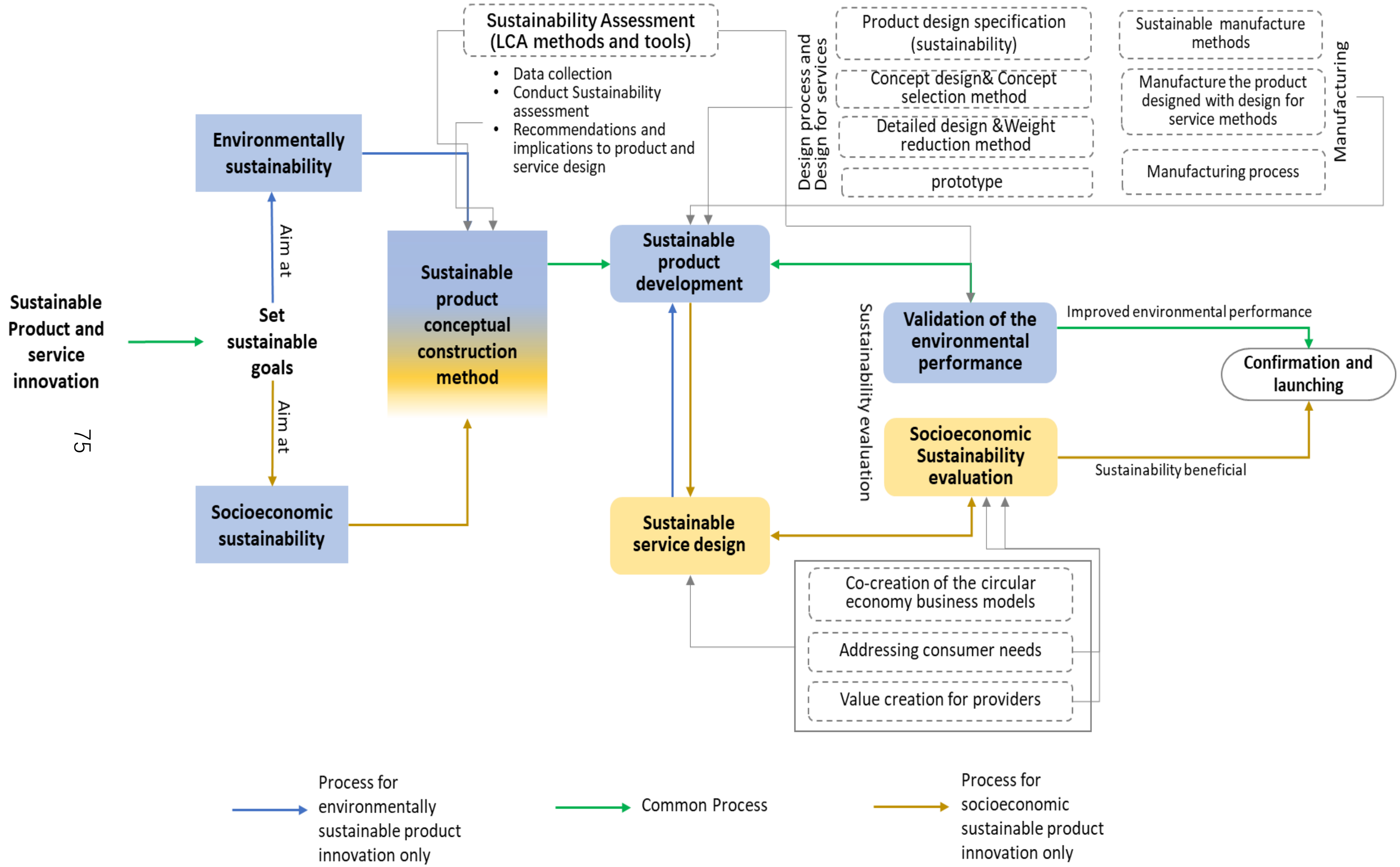

Sustainable Product and service innovation
Set sustainable goals
Aim at
Aim at
Environmentally sustainability
Socioeconomic sustainability
Sustainable product conceptual construction method
Sustainability Assessment (LCA methods and tools)
• Data collection
• Conduct Sustainability assessment
• Recommendations and implications to product and service design
Design process and Design for services
Product design specification (sustainability)
Concept design& Concept selection method
Detailed design &Weight reduction method
prototype
Manufacturing
Sustainable manufacture methods
Manufacture the product designed with design for service methods
Manufacturing process
Sustainable product development
Sustainable service design
Sustainability evaluation
Validation of the environmental performance
Socioeconomic Sustainability evaluation
Improved environmental performance
Sustainability beneficial
Confirmation and launching
Co-creation of the circular economy business models
Addressing consumer needs
Value creation for providers
Process for environmentally sustainable product innovation only
Common Process
Process for socioeconomic sustainable product innovation only

Figure 3.7 Operation process of the approach

The approach consists of several steps with optional and common processes and supported by interdisciplinary methodologies and tools. The methodologies can be selectively applied according to the nature of the product/service and the sustainability goals. In figure 3.7, the processes filled with blue refer to the activities link to the development of an environmentally sustainable product, while the processes filled with yellow refer to the activities that link to the development of a socioeconomic sustainable product. The processes linked with green are the common processes that apply to all purposes.

The approach starts by setting the sustainable goals and identifying the sustainable goal for the certain product and/or service by the case enterprise or by the practitioners for a research project. For a sustainable innovation, the goal can be set to achieve one or more perspective of sustainability. Environmental sustainability is the fundamental goal to achieve, nevertheless, this approach is designed to achieve the TBL of sustainability initially. Thus, it is encouraged to set the sustainability goal to cover both environmental and socioeconomic sustainability where it's applicable. However, there are also barriers to set a goal for holistic sustainability, the practitioner needs to consider several aspects in this step, such as timeframe, available resources, technical know-how and cost, etc.

Secondly, the 'sustainable product conceptual construction method' can be applied. In this stage, sustainability evaluation will be conducted to a product-in-service. The purpose is to detect the sustainable issues from both environmental and social perspectives, also to derive recommendations and implications for sustainable product and service conceptualisation. Life cycle assessment methodology, including both environmental life cycle assessment (E-LCA) and social lifecycle assessment (S-LCA), are utilised in the stage as the evaluation method and tool. During the evaluation, the key life cycle stage (hotspot) and process, as well as the key issues are identified from environmental and social perspectives. After analysed and interpreted the results, opportunities and recommendations which address the key issues for sustainable product and service design are derived and applied the conceptualisation of the product and service. After the assessments, the results need to be analysed and the interlink between the E-LCA and S-LCA results can be identified. This step aims to identify the evidence-based objectives and opportunities for the specific enterprise/case so that sustainable recommendations are tailored and specified. Those overlapped E-LCA and S-LCA results are the key opportunities to improve the overall sustainability, thus will be directly applied into sustainable product and service conceptualisation, whilst individual S-LCA findings will be addressed in service conceptualisation. The S-LCA and related analysis can be eliminated for only environmental sustainability-oriented innovations.

Moving on to the next step, in this stage, sustainable product development and sustainable service will be developed as a bundle. The sustainable product development stage including product design and manufacture. Subsequently, according to the tailored recommendations derived, the standard product design process is conducted while the product service concepts are proposed building on the newly designed sustainable product with a coherent solution for sustainable product development, the recommendations are applied in the product design specification, and go through the design iteration process supported by proposed design methods that enhancing eco-features, such as concept selection method, simulation-experiment confirmation method as well as sustainability evaluation. The product's sustainable features can then achieve by making the designed product through the manufacturing process, where related sustainable manufacture methods are applied.

The sustainable service includes 'distribution', ''use', 'maintenance' and 'end of life (EoL)' stage. In the product and service development stage, the new product should address the potential service activities in the early development process such as conceptual design and vice versa. Take take-back service (take back the EoL product from a customer for reproduction, etc.), design for disassembly and recyclability as instances, the new product under development should consider/optimise the EoL options (by modular design and/or choosing the recyclable material) for the easy operation of the further potential taking-back service; similarly, the service under construction requires to consider what the product traits need to be fulfilled to realise the service in the design stage. In the sustainable product service phase, the manufactured product goes through the stages of distribution including retail, use (i.e. consumption), maintenance, and end of life (including recycling and reuse). Since the development of sustainable product and service requires interdisciplinary knowledge, therefore, in this phase, co-creation might be needed to facilitate the development processes. With the knowledge of life cycle thinking and lifecycle management, designers, researchers, value chain actors are expected to be involved in the co-creation which aiming at circular economy business model/models. Such an inter-disciplinary team shall consist of researchers within the organisation itself (between people from different disciplinary backgrounds) or outside the organisation. The goal is to construct a service that is better fulfil consumer needs while creating value for the providers with reduced environmental and social impact.

To validate the sustainability performance of the new sustainable product and service, comparative environmental impact assessment is conducted underpinned by the LCA method and tool, as well as the socio-economic sustainability. For the product without a service, the socio-economic performance is not expected to change much, due to the product still manufactured from the same company and the supply chain is similar to other products of the company, therefore the socioeconomic evaluation can be eliminated at the stage. After validating the sustainability performances, finally, the proposed product and service bundle can be confirmed and processed to the next phase.

3.6 Addressing the TBL of sustainability in products and services

The TBL is addressed throughout the development process. For the environmental and social aspects, those were initially addressed via the sustainability assessment, in which, environmental impacts regarding resources, human health and ecosystem are assessed, and five types of stakeholders including ‘workers’, ‘society’, ‘value chain actors’, ‘consumer’ and ‘local communities’ are covered in line with UNEP guideline (UNEP/SETAC,2009). The recommendations which contain environmental and social aspects are then integrated as the development goals in PDS of product and service conceptualisation to guarantee the identified issues are addressed in the innovation. Furthermore, during Concept Selection and Detailed Design, the sustainable features are strengthened by selection through comparative criteria and weighting method. The criteria including ‘weight’, ‘number of materials’, ‘ease of manufacturing’, ‘flexibility of adjustment’, ‘ease of maintenance’, ‘life cycle impact’, ‘recyclability’, ‘cost’, ‘serviceability’ and technical parameters. The weighting factors are ranged from 1 to 3, and a higher value indicates more importance of the criteria to which the higher value assigned.

The economic aspect is addressed in ‘contribution to economic development’ under the assessment of ‘society’ stakeholder, and also is involved in the trade-off with the environmental issues in the implications. In addition, cost-effective is one of the comparative criteria with the highest weighting factors. In the product service phase, the profit competitiveness is also is addressed, such as in the added value analysis, payment plan, etc. Finally, the sustainability assessment is once again applied in the approach to reveal the sustainable performance of the proposed product and service.

3.7 Demonstration of the approach

To demonstrate and validate the effectiveness of the approach, three case studies will be presented. The case studies consist of sustainable innovation in lighting products and flooring products, which represents the product of energy consumption and static product. The three studies emphasis on different perspectives to present the applicability of the approach, which is explained as follows.

A sustainable industrial LED lighting product and service will be developed by utilising the proposed sustainable product and service approach. This case study aims to implement the utilisation of the approach to combine sustainable product development and sustainable service as a bundle through the product life cycle and achieve holistic sustainability. In this case study, the product development part consists of sustainable design, environmental and social lifecycle assessment, and sustainable manufacture. The sustainable product service part includes distribution, support for sustainable consumption, maintenance and repair, and services related to product end of life such as recycling, reuse and take-back. The case study addresses sustainability in both environmental and socio-economic aspects by applying the process and methods in the proposed approach to the development of an industrial lighting product and the design of its subsequence services with sustainable features. The case study also demonstrates how the approach can provide consultations and solutions for enterprises which aim to bring out sustainable product and service towards a circular economy. An industrial lighting manufacturing company was joined for implementation of the consultation results on their sustainable product and service innovation. The approach and its application in the industrial LED lighting industry are further detailed in the following chapters (chapter 4 and 5) of this thesis.

An environmentally sustainable (eco-friendly) domestic LED lighting will be developed. This case study is designed to demonstrate the alternative application of the approach, i.e. when environmental sustainability is the goal of the product innovation. The sustainable product conceptual construction methods for domestic lighting product will be demonstrated in detail. This case study also aims to demonstrate how small and medium enterprises (SMEs) in the energy consumption industry can apply the method. A domestic LED lighting design and manufacturing company was participated in this case study on the design and manufacture the sustainable lighting product results from the study.

Finally, a sustainable flooring product will be developed to demonstrate the application of the approach using a static (no energy-consuming during the use stage) product as an example.

This case study is designed to demonstrate how the derived PDS can be meet by utilising the supporting methods and tools. This case study emphasises the sustainable product design process and integration of the interdisciplinary methods to meet its sustainability goal (environmental-friendly and cost-effective). The proposed sustainable product conceptual construction methods, concept selection method, and simulation-experiment confirmation method will be utilised and explained in detail.

Chapter 4 - Integration of Environmental and Social Lifecycle Assessments to Sustainable Industrial Lighting Product and Service conceptual construction

4.1 Introduction

4.1.1 Overview of the chapter

This chapter demonstrates the first and second steps of the holistic approach, i.e. setting sustainability goals and sustainable product and service conceptual construction approach (detailed in section 3). This study presents how to inform sustainable product and service by integrating environmental and social life cycle assessment methods and techniques in the early development stage.

According to the operation process explained in chapter 3. In this chapter, after the identification of the sustainable goals, with the data collected from the firsts step, the E-LCA and S-LCA are conducted. LCA is a valuable framework in integrating sustainability into product development and assessment due to its systematic procedures. The E-LCA considers environmental impacts along supply chains. The S-LCA aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle (UNEP/SETAC, 2009). Both the E-LCA and the S-LCA adopt the same framework which is comprised of four main steps: goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation. Assessment models for environmental and social impact assessments are developed via the LCA software tool, openLCA. The key life cycle stages, key assembly components, and opportunities are identified on environmental and social aspects. Meanwhile, the potential environmental issues, potential social risk to the stakeholders, namely workers, society, local community, consumer, value chain actors, and potential social benefit are also obtained and analysed.

This chapter illustrates the goal identification, identified the key issues and opportunities from environmental and social perspectives. The interrelationships between both assessment results are analysed and detected, and the recommendations are derived from the results subsequently integrated into the new sustainable product and service design specifications. An industrial lighting product-in-service (existing product in the market) is a case product under study.

4.1.2 Sustainability goals of the case company

Kosnic Lighting Ltd is an independent British company that incorporates design, manufacture and bespoke lighting solutions. The company is well recognised for its good practice in providing innovative, robust lamps and luminaires that deliver quality, cost-effective and environmentally responsible lighting solutions for residential, commercial and public sectors alike. Research and innovation are important for the focal company in continuously delivering prominent product and service, it recently participates in the EU H2020 research project CIRC4Life as an industrial partner, the main task in the project of the company is to develop a sustainable LED lighting product with integrated sustainable product design methods, which dedicated to maximising the energy-efficient and cost-saving potential of LED technology; and demonstrate its application in a circular economy based business context to form the triple bottom line of sustainability in their product and service.

The objective of the focal company is to develop a sustainable product and circular economy-oriented business model that covers the triple bottom line of sustainability, i.e. environmentally reduce the material and energy consumption, socially benefit the society and stakeholders, and economically create value and profit. The aim of developing the sustainable product and service bundle is to reduce the environmental burdens, address the social issues while achieving the economic and competitive interest of providers (stakeholders in the supply chain), i.e. to achieve the holistic sustainability of the industrial LED lighting through the innovation.

4.1.3 Industrial LED lighting products

The lighting industry is one of the high resource-consuming sectors. Lighting consumes 18% of the UK's electricity, roughly 58,000 terawatt-hours per year, and commercial lighting accounts for seven-tenths of this electrical consumption (Statista, 2013). Lighting products, and LED lighting products in particular, sustain our modern lifestyles and have been widely used nowadays. Light-emitting diodes (LEDs) have been developed to a level of performance and light quality that enables the replacement of most conventional light sources (GLA, 2020). One of the new paradigms for lighting industry is to provide product efficiency and longer lifetime and the new trend is to implement circular economy and materials efficiency (GLA, 2020), which are in accordance with the key Sustainable Development Goals (SDGs) brought out by the United Nations.

In this case, the LED lighting product under study industrial LED lighting product. Industrial lighting products are widely used in warehouse, factory, manufacturing areas, barns, etc. (see

Figure 4.1 for example of the application scenario) with a usual installation height of 4 to 12 meters. This kind of LED lighting products is of High power (>100W) and High efficiency (>120lm/W) which is considered an energy-saving for industrial application. Figure 4.1 shows an example of such product application.

Figure 4.1 Industrial LED lighting application scenario.

4.2 Data collection

In the data collection step, an investigation is conducted in collaboration with the manufacturer of the LED luminaire to obtain case-specific data. One of the barriers for engineers/designers to conduct environmental and social life cycle assessment is the difficulties of acquiring inventory data. In order to shorten the time and reduce the communication barriers between the practitioner and manufacturer, three types of data are identified before interaction with the manufacturer, i.e. E-LCA specific data, S-LCA specific data and common data for both E-LCA and S-LCA.

After the identification of the data types, it is considered there are two parts of investigation need to be conducted. The first part is to obtain the E-LCA specific data and common data for both E-LCA and S-LCA through the product life cycle. Those data including production data, supply chain data, and life cycle stages' data. These are quantitative data that can be applied and adapted to the assessment to build the simulation life cycle model directly.

The other part is to collect the S-LCA specific data. Those contain information about company social performance regarding different stakeholders through life cycle stages. It is more complex to collect the S-LCA related data since most of them are qualitative and semi-qualitative data which are more subjective.

The proposed data collection forms for E-LCA and S-LCA are applied during the data collection processes. Figure 4.2 and 4.3 are the data collection forms for E-LCA and S-LCA respectively. The required information is stated as direct questions in the question forms, which are easier for engineers to provide the corresponding information by answering the questions. The forms also including examples for how the manufacture could provide clearer information for assessment.

Product Data Collection Form (Kosnic)

1. Product General Data	1.1 Product Name/ Model Name	
	1.2 Product Photo (including application photo)	please put all the pictures in the picture folder.
	1.3 Suggest Service Time	
	1.4 Total Weight (kg)	
2. Product Manufacturing Data	2.1 Describe Product Manufacturing Procedure (including time use)	production diagram with brief description, please put all the pictures in the picture folder.
	2.2 Product Assembly inventory data	including product all assembly parts name, number, weight, material , see 'example for 2.2' sheet.
	2.3 Waste Generation During Manufacturing(kg)	eg: solid waste, liquid waste
	2.4 Emissions Generations (kg)	to air
	2.5 Is there harmful waste or emission? If yes, specify the production stage, substances and mass	
3. Functional Unit and Usage Data	3.1 Functional Unit Description	How the product works, how much function could a individual product provide, is it required work with certain amount of the products.
	3.2 Product Explosion Diagram	see 'example for 3.2' sheet, please put all the pictures in the picture folder.
	3.3 Parameters of the Product	
	3.4 Energy Consumption During Use	
	3.5 Is there any maintenance needed during the service time? If yes, specify in detail	
4. Transportation Data	4.1 Manufacture Plant country and Region	
	4.2 Target Market Country or Region/City	
	4.3 Distance between manufactory plant to target market Region/City	
	4.4 Means of Transport	if the transportation includes more than one transportation tool, specify in detail
	4.5 is there other transport activities take place during the manufacturing stage? If yes, specify in detail	
	5.1 Current disposal method and Mass of product disposal this way	

Figure 4.2 E-LCA data collection form_KMSD100LLBE

S-LCA Data Collection Form _KMSD100LLBE								
1. Production Stage	1.1 Place of Production	1.2 If all the assembly members come from China	1.3 if yes, the cost of the members are	1.4 if there is members from other country，please specify the member name, country and cost. ($)	1.5 the cost of electricity during manufacturing the product ($)	1.6 transport cost of production stage ($)	1.7 export or inport cost of the product ($)	1.8 is there other costs, fill the activity name and cost ($)
2. Transportation								
3. Distribution								
4. Use Stage								
5. Disposal								

Figure 4.3 S-LCA Data Collection Form _KMSD100LLBE

For E-LCA data collection, the process is smooth, the manufacture provided several documents regarding the product under study, including pictures, drawings technical data, manufacturing processes, etc. Those are valuable for the assessment, however, during the first data collection, there are a few remain questions and data that needed to be clarified and further provided. The remaining questions are asked through phone calls and complimented by online searching, such as the distance of the transportation between the manufacturer and retailing location.

For S-LCA, the data which can be easily answered in a form are listed in Figure 4.3. The manufacturer sent back the information comparatively sooner since the information of their supply chain is well managed and easy to find. However, Interviews with engineers, employee representatives, and company directors were also carried out to obtain the company's social condition related information. The information including the well-being and welfare of the employees, working conditions, the importance of the social impact indicators to the company, etc. The qualitative and semi-qualitative information collected for S-LCA cannot be directly input into the calculation since impact calculation requires qualitative methods. Those data are converted into ‘active variables’ (quantitative value) which will be explained in detail in the S-LCA section.

4.3 Environmental life cycle assessment

A detailed LCA is conducted to evaluate the environmental impact of the industrial LED lighting product in the market, taking into account all life cycle stages of the product. The environmental analysis is conducted in accordance with the international standards ISO 14044 (ISO, 2006), as detailed below.

4.3.1 Goal

The goal is to evaluate the environmental impacts and to identify the hotspots (A life cycle stage, process or elementary flow which accounts for a significant proportion of the impact of the functional unit) of the LED lighting product through the product’s whole lifecycle. It also aims to seek opportunities to derive design recommendations that can improve the overall environmental performance of the product.

4.3.2 Functional unit

The assessment target is one unit of a KMSD100LLBE lighting product for general industrial use, which is a 100W LED low bay luminaire from Kosnic Lighting LTD (UK), as shown in Figure 4.4. The luminaire is an energy-saving, high-performance product which is usually applied in general industrial areas, such as manufacturing workshops, warehouses, leisure facilities, and retail environments. The luminaire consists of three parts: housing, electronic device, and fastening members. The housing is the shell of the luminaire that provides a space for the configuration of the core electronic devices. The electronic device is the vital part providing the feature functions, which includes two LED drivers, one LED panel, one junction box, and one electronic press button. All the assembly parts are jointed with the fastening members. The technical specifications of one functional unit product are listed in Table 4.1.

Table 4.1 Technical Specifications of KMSD100LLBE

Product Code	**KMSD100LLBE-W65-WHT**
Power (W)	100
Voltage	220-240Vac 50-60Hz
Current (mA)	448
Protection	Class I, IP20
Power Factor	0.97
Luminous Flux (lm)	11500

Beam Angle (°)	120
CCT (K)	6500K Day Light
CRI	83
Lifetime (h)	40000
Dimmable	No
Switching Cycles	50000
Start Time (s)	0.35
Warm-up time to 60% (s)	Instant full light
Diffuser	Frosted polycarbonate.
Length (mm)	600
Width (mm)	327
Depth (mm)	84
Mercury (mg)	0

Lumen Maintenance Factor at Lifetime	0.75
Ambient Temperature (°C)	-20 to 40
Optional Sensor	No

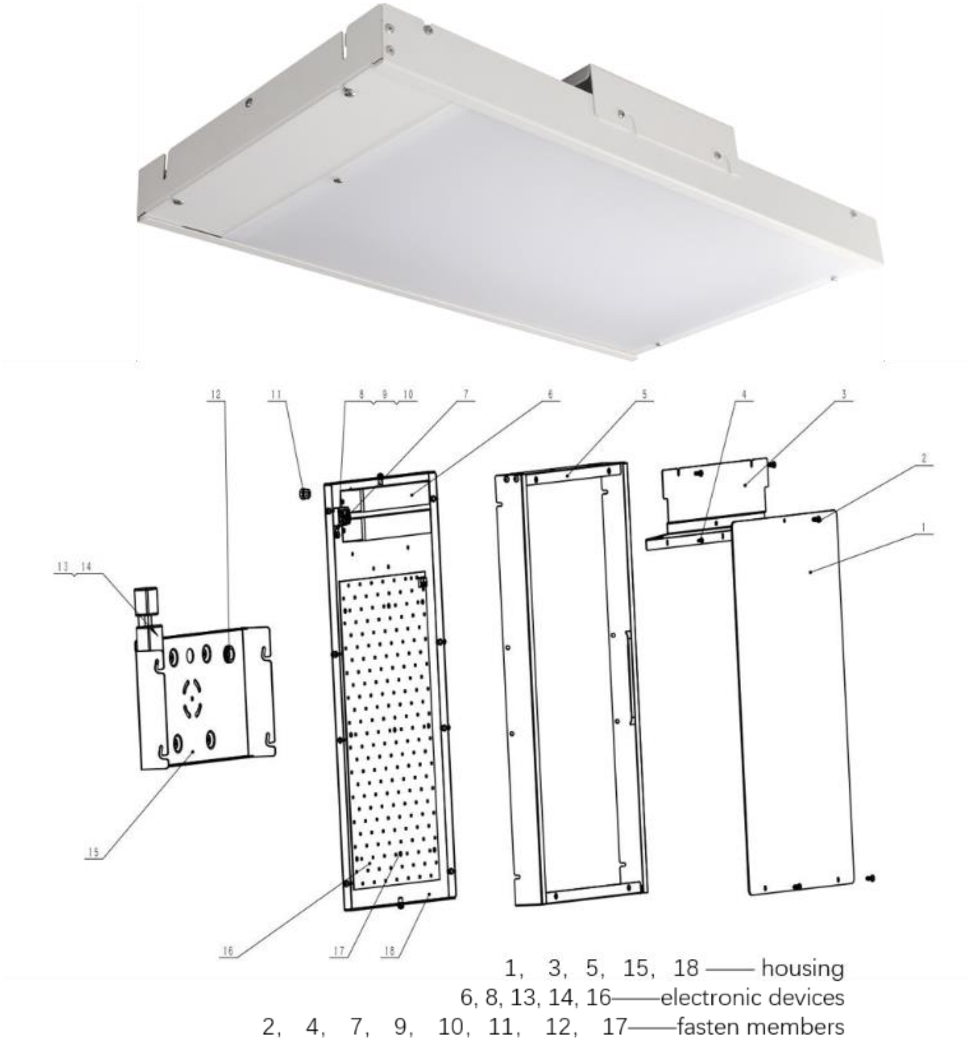


Figure 4.4 The 100W LED Low Bay Luminaire Under Assessment

4.3.3 System boundary

All life cycle stages are considered in the system boundary, including raw material extraction, production of basic materials, production of the components, LED lighting assembly, packaging, distribution (transportation) and end-of-life (EoL) treatment. In the manufacturing stage, components and sub-systems production and assembly are considered, including raw material acquisition, the product assembly, energy consumption, waste/emissions generation and disposal during manufacturing. The packaging and transportation activities during production are within the boundary as well. The LED lighting product is manufactured in China (Hangzhou) and then shipped to the UK for wholesaling. Energy consumed during the use stage was also taken into account, it assumes that the LED lighting product would serve until the end of its useful life (40000 hours).

4.3.4 Life cycle inventory

The data of material use, energy consumption, waste is provided by the lighting company through the data collection process. The background data, such as raw material extraction and production of the basic materials are derived from the Ecoinvent 3.5 database (Ecoinvent, 2018).

The inventory data are listed in Table 4.2. As most of the inventory data are provided by the manufacturer, the data quality is considered satisfactory with low uncertainty. During the usage of the product, the required electricity was calculated by multiplying the products' power with useful time. The shipping distance from Hangzhou to London is obtained by consulting Google Map.

Table 4.2 Inventory data of KMSD100LLBE

Assembly Component	Material	Amount	Unit
Housing	Plastic	0.29	kg

	Steel	2.199	kg
	Aluminium	1.1	kg
LED driver	Plastic	0.172	kg
	printed circuit board	0.688	kg
LED lighting board	LED	0.32	kg
	Aluminium	0.012	m2
Junction Box	Plastic	0.02	kg
Press button	Plastic	0.007	kg
Fasten members	Steel	0.07838	kg
	Plastic	0.0016	kg
	printed board box	1.17	kg
Packaging	plastic film	0.0003	kg
	paper	0.0004	kg
	plastic form	0.066	kg
Electricity		4000	kWh
Shipping		56451.96	kg*km
Solid waste		5.3207	kg
Waste paperboard		1.8537	kg

4.3.5 Life cycle impact assessment

The E-LCA assessment model of the LED lighting product system is developed with OpenLCA (Greendelta, 2017) software, in line with the Ecoinvent 3.5 database (Ecoinvent, 2018). The environmental impact categories can be varying when practising with different assessment methods and weighting methods, which mainly depends on the aim and scope of the assessment. The aggregation and weighting of different environmental categories are controversial since a subjective judgment on the priority of different impact categories are applied in the weighting process (Benoit and Rousseaux, 2003).

The ReCiPe Hierarchist method (Goedkoop, 2009) is selected for the E-LCA due to its following major advantages: it is one of the most recent and harmonized LCIA approaches available (Huijbregts et al. 2016). The method can combine LCA results as a single score via weighting, which allows user to easily compare the environmental impact of different products or scenarios (Kalbar et al. 2017). Unlike other methods (such as Eco-Indicator 99, EPS Method, LIME, and Impact 2002+), ReCiPe does not include potential impacts from future extractions in the impact assessment but assumes such impacts have been included in the inventory analysis (Huijbregts et al. 2016). In this study, endpoint and midpoint assessments were conducted. The endpoint assessment is based on the three endpoint impact categories, namely ecosystems, resources and human health, while the midpoint assessment is based on 18 indicators to identify specified environmental problems. Sensitivity analyses were also carried out regarding different lifetime scenario and three EoL options to validate the results and seek opportunities to improve the environmental profile.

4.4 Social life cycle assessment

The United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) published 'Guidelines for Social Life Cycle Assessment of Products' (UNEP/SEAC, 2009; UNEP/SEAC, 2013), which explains the rationale regarding social impacts for the product and provides a solid social impact evaluation framework, 5 types of stakeholders and 23 social and socio-economic subcategories (topics) are introduced in the guideline. The S-LCA was carried out in accordance with the UNEP/SETAC guideline. S-LCA methods and the applications were under investigation as well to select the suitable calculation method, i.e. checklist method, scoring method, database method and empirical method (Ekener et al., 2018; Foolmaun and Ramjeeawon, 2013; Franze and Ciroth, 2011; Weidema, 2006). The review shows that in the recent studies, more attention has been paid to apply database method in S-LCA evaluation, also, the database method enables to assess more comprehensive social and socioeconomic issues. There are two established databases available to practice at the time when the research is conducting, namely Social Hotspot Database (Norris, Aulisio and Norris, 2012) and PSILCA (Eisfeldt, 2017). PSILCA 2.0 (GreenDeLTa, 2017) was selected for this study as it's the most updated available data source with transparent risk assessment (Mancini et al. 2018). The database is also compatible with commonly used aggregation and calculation tools such as OpenLCA and SimaPro. In addition, it provides more impact categories/subcategories which are suitable for the study.

4.4.1 Stakeholders and subcategories

From the initial set of subcategories, identification of suitable subcategories for the S-LCA study was carried out (see Table 4.3). The selection of stakeholders and subcategories was based on criteria of relevance, data availability, and bibliography validation. National-, sector-, and company-specific data and comments for each subcategory in all five stakeholder categories were collected from Kosnic, then the collected information was verified if data is available for all the subcategories. Finally, S-LCA related literature was consulted to validate those subcategories, which includes the findings of one of the most cited paper in the field (Jørgensen, et al., 2008), an updated S-LCA review (Siebert, et al., 2018), and the most recent report on S-LCA done by the Joint Research Centre in 2018 (Mancini, et al., 2018), the three studies provide a total of 24 S-LCA cases that serve to identify the most relevant social indicators by their frequency of use.

All the five types of stakeholders, namely ‘workers’, ‘local community’, ‘society’, ‘consumers’ and ‘value chain actors’ were taken into consideration. 16 subcategories were covered to assess the social sustainability of the LED lighting product’s supply chain: ‘fair salary’, ‘working time’, ‘discrimination’, ‘health and safety’, ‘social benefits’, ‘legal issues’ ‘workers´ rights’, ‘fair competition’, ‘promoting social responsibility’, ‘supplier relationships’, ‘contribution to economic development’, ‘promoting social responsibility’, ‘supplier relationships’, ‘contribution to economic development’, ‘Access to material resources’, ‘Safe and healthy living conditions’, ‘Local employment’, ‘Health and Safety’, ‘Transparency’, and ‘End of life responsibility’.

Table 4.3 Stakeholders and subcategories selection

Stakeholder	PSILCA Subcategory	Relev-ance	Data availability	Bibliograph-y validation	Resul-t
Workers	Child labour	NO	NO	8	NO
	Forced labour	NO	NO	7	NO
	Fair salary	YES	YES	20	YES
	Working time	YES	YES	15	YES
	Discrimination	YES	YES	20	YES
	Health and Safety	YES	YES	20	YES
	Social benefits, legal issues	YES	YES	5	YES
	Workers´ rights	YES	YES	18	YES
Value Chain Actors	Fair competition	YES	YES	0	YES
	Corruption	YES	NO	1	NO
	Promoting social responsibility	YES	YES	0	YES
	Supplier relationships	YES	YES	0	YES

Society	Contribution to economic development	YES	YES	13	YES
	Health and safety	YES	NO	0	NO
	Prevention and mitigation of conflicts	YES	NO	0	NO
Local Community	Access to material resources	YES	YES	0	YES
	Respect of indigenous rights	NO	NO	1	NO
	Safe and healthy living conditions	YES	YES	6	YES
	Local employment	YES	YES	5	YES
	Migration	YES	NO	1	NO
Consumers	Health and Safety	YES	YES	0	YES
	Transparency	YES	YES	0	YES
	End of life responsibility	YES	YES	0	YES

4.4.2 System boundary

KMSD100LLBE is designed, final assembled (production) by Kosnic Lighting Ltd., which shares the same functional unit with E-LCA. The simplified life cycle process flowchart of the product is illustrated in Figure 4.5.

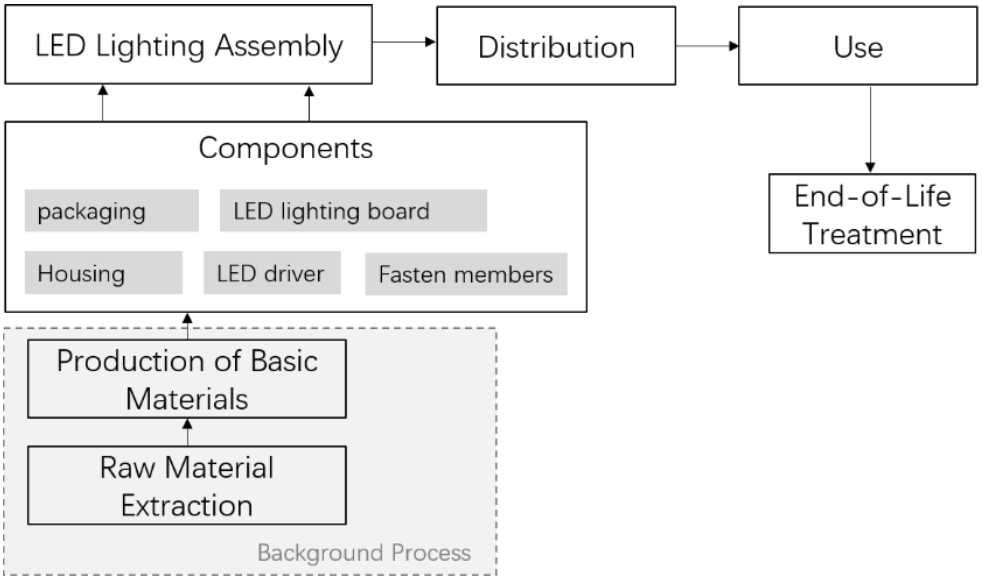


Figure 4.5 Simplified life cycle process flowchart

All the stages are taken into account in the assessment. In the production/assembly stage, 18 main components as well as packaging materials are included. The components are categorised into 5 parts: LED lighting board, housing, LED driver, fasten members, and packaging. Background production related processes, such as the production of basic material and extraction of material, are covered in the assessment as well. The transportation, useful life and EoL scenarios are also considered.

4.4.3 Social life cycle inventory data

For the social life cycle inventory, inputs are expressed in monetary terms, where 1 GBP equals 1.34 USD, 1 USD equals 6.8 CNY. The final price of the product covers capital items, overheads, wastes, materials, and labour cost associated with the production of one functional unit. The time frame of data source is from 2018 to 2019. Considering the data quality, the study reaches sufficient data for modelling the product system. The data availability for the S-LCA study is overall satisfactory to the assessment goal and scope. Case-specific data were collected, all reference costs were estimated by the final product company. However, generic data were also applied where the case-specific information was unavailable. The background process data were retrieved from the PSILCA database. The social life cycle inventory data of the final product is presented in Table 4.4.

Table 4.4 social life cycle inventory data of the final product

Assembly component	Supplier company	Supply country	Material	Price per unit (USD)
Housing	Qike New Energy Technology (Changzhou) Co., Ltd.; Jiangxi Shenghui Optical and Technology Innovation Co., Ltd	China	Plastic Steel Aluminium	2.841
LED driver	SuZhou Kosnic Lighting Technology Co., Ltd.	China	Plastic printed circuit board	10
LED lighting board	Shanghai Oulang Electronic Technology Co., Ltd.	China	LED Aluminium	5.95
Junction Box	multiple companies	China	Plastic	0.925
Press button	multiple companies	China	Plastic	0.22
base module	multiple companies	China	Aluminium	5.2085
Packaging	Suzhou Ritu Packaging Materials Co., Ltd.	China	printed board box plastic film paper	2.701

			plastic form	
labour cost	SuZhou Kosnic Lighting Technology Co., Ltd.	China	—	4.958
Shipping	—		—	4.69
Electricity	—	UK		643.2
End of life		UK		Generic data in PSILCA

The final product manufacturing company (Kosnic) gains prominent recognition in the corresponding industry sector regarding social responsibility and product quality. Kosnic joined the elite group of Accredited Suppliers to The Carbon Trust, the market-leading scheme for high-quality energy-efficient equipment and renewable technology suppliers worldwide. The company works with and conforms to the management system of the British Assessment Bureau standard ISO-9001. The company also associates with the Electrical Distributors Association, the Lighting Industry Association, and the British Assessment Bureau (KOS, 2019). The information of the supplier companies for the main components are list as following:

- Shanghai Oolang Electronic Technology Co., Ltd. was established in 2005, mainly engaged in technical services, technical development, technical consulting, computer network engineering, etc. The company is the first level distributor of Taiwan's Yiguang Electronic (EVERLIGHT) in mainland China.

- Qike New Energy Technology (Changzhou) Co., Ltd. The company was called Wujin District Hutang Machinery Co., Ltd., it was focusing on manufacturing metal products. It then changed its name to Qike New Energy Technology (Changzhou) Co., Ltd. was established in 2017. The company's business scope includes: solar technology research and development in the field of solar science and technology; machinery and equipment, folding electric vehicles, electronic components research and development, manufacturing; plastic products, tooling, mold, sheet metal parts manufacturing, processing; Electric car sales, etc.The company swtich the main production to electrical bike, 70% of the products are exported. Besides, the company have its own website.

- Jiangxi Shenghui Optical and Technology Innovation Co., Ltd. was jointly invested by the leading domestic traffic reflective materials company Jiangxi Shengfulai directional reflective Materials Co., Ltd and Shanghai Fosun Group, the first private high-tech group enterprise in Shanghai. Registered capital of 80 million, has invested 100 million yuan.Is a professional engaged in optical thin films, LED light display backlight module film and sheet and other products, is a collection of research and development, production, management as one of the high-tech companies.

- SuZhou Kosnic Lighting Technology Co., Ltd. The company design and produce its own LED driver of this model, the driver is the key component of the LED lighting.

The manufacturing factory of Kosnic is based in Suzhou, China, where the lighting product KMSD100LLBE is produced, it comprises research and design, production, and quality testing departments, see Figure 4.6 and 4.7 (by courtesy of Kosnic Lighting Ltd.). There are 53 employees (15 males and 38 females) in the factory. The majority of female employees work on the assembly line, while male employees mainly work in design or technical positions.

Figure 4.6 - Working Condition of the Assembly Line

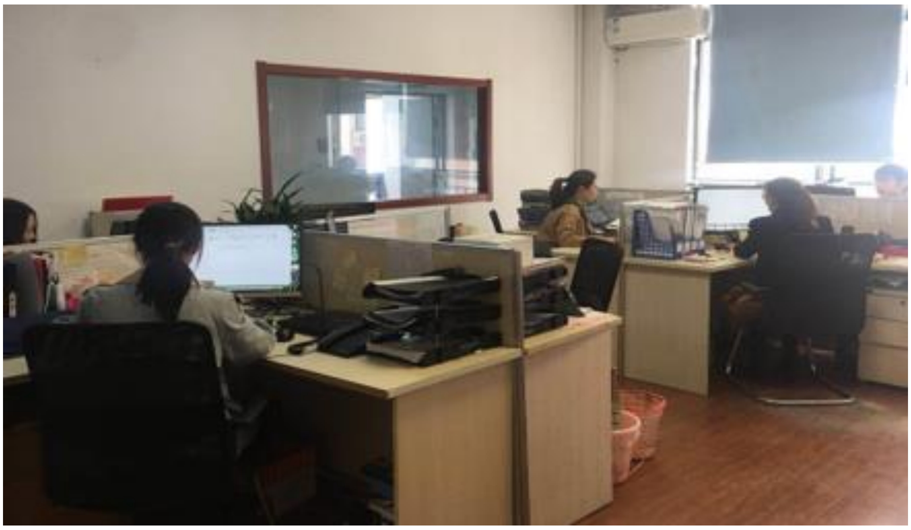


Figure 4.7 Working condition of the office

The monthly average wage of all employees is 7153 CNY (approx. 1052 USD) which is higher than that in Suzhou 2018, i.e. 6719CNY (NSSN, 2018). It is needed to highlight that the wage of male employees is 1.5 times higher than that of females in the lighting company. The company uses a 13-month payment system with additional bonus scheme. All employees receive paid annual leave, and national holidays are also guaranteed. The average working time is 40-48h per week, and overtime pay is provided. In addition, there are open and transparent channels for employees to pursue promotion and salary rise.

There are no fatal or serious accidents involved in the production process as the main activities in production are to assemble the components of the products. The components do not contain open hazardous substances, and therefore, the assembly process does not cause a health risk.

The energy type for assembly line is electricity. The average electricity bill is approximated 2941 USD per month.

The price of the final product is 361.2 USD and the labour cost for one unit of the product is 4.958 USD. The product comprises of 18 components and packaging materials, which were categorised into five modules: LED lighting board, housing, LED driver, fasten members and packaging. The total transportation cost per unit product is approximately 4.69 USD. The electricity cost during the expected life (40000h) is 643.2 USD, which is obtained by the UK national statics (Statista, 2019).

4.4.4 Social life cycle impact assessment

PSILCA adopts a multi-regional input/output database, which comprises 189 countries' data 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 (Eisfeldt, 2017). As an Input-Output database, Eora uses money flows to link processes. All process inputs are given in 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. PSILCA provides 88 qualitative and quantitative indicators in total, the indicators are measured in different units such as single values or percentages, while some are also qualitative. The indicators/sub-indicators are organised in clusters describing 25 social and socio-economic subcategories (topics). The complete stakeholders, subcategories, and indicators covered can be found in PSILA documentation (Eisfeldt, 2017).

Based on the selection of the stakeholders and inventory development, the social life cycle assessment of the reference products was conducted. The case-specific social data collected from the company and sector were used to assess the level of risk for each selected indicator. 'worker hours' have been utilised as the 'Activity variable' to ‘reflect the share of a given activity associated with each unit process’ (UNEP/SETAC, 2009) in PSILCA, which is calculated as follows (Eisfeldt, 2017):

$$Worker\ hours = \frac{Unit\ labour\ costs}{Mean\ hourly\ labour\ cost\ (per\ employee)}$$

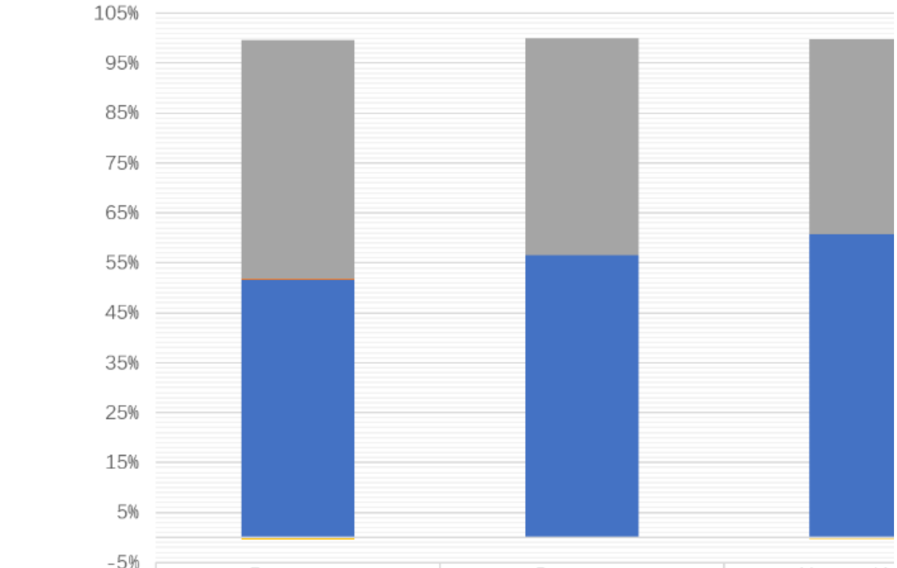
Subsequently, life cycle simulation models for social assessment were constructed in software tool OpenLCA. The simulation model is made based on self-construct processes supported by the built-in industries and commodities data under the database of the country, e.g. ‘electronic element and device-CN’. Social LCIA method (GreenDelta, 2020) was utilised to calculate the social performance.

4.5 Results

4.5.1 Environmental aspects

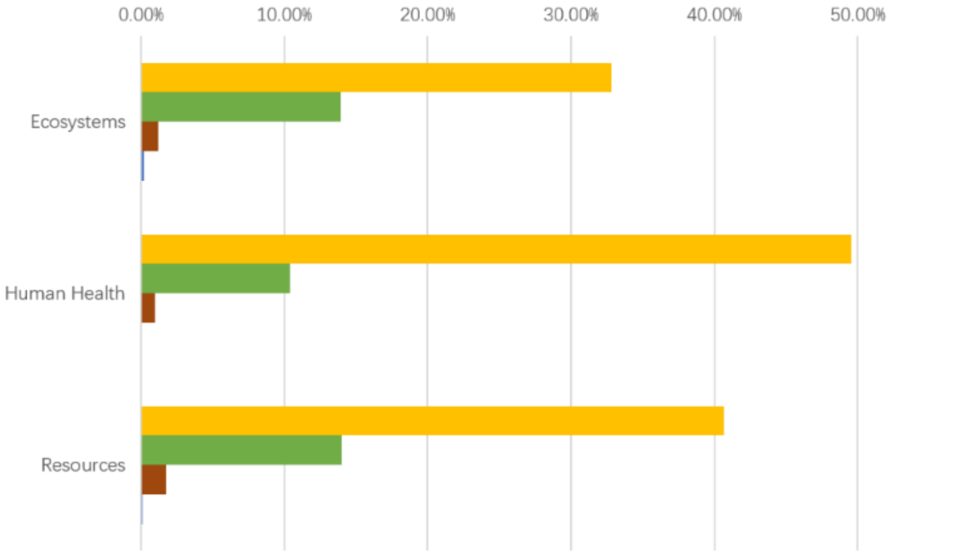
In the first part of the analysis, the endpoint assessment was conducted to identify the overall environmental performance of the lighting product and the key life cycle stage. The key life cycle stage was analysed separately to obtain the hotspot processes. Then the midpoint assessment was conducted to identify the key environmental issues and its deriving processes. Different life cycle scenarios, i.e. EoL options, lifetime scenario, were analysed and discussed in order to seek opportunities to improve the environmental profile.

The production stage is identified as the key stage of the environmental impacts within the product life cycle. On the contrary, transportation and EoL stages contribute very limited impacts on the total environmental profile, EoL shows a small number of positive effects. It was detected that more than 50% of the impacts are generated from the production stage (52%, 56%, 61% to ecosystem, resources and human health respectively), see Figure 4. It is due to the production stage is the input-output intensive stage where the main consumption of materials and energy take place. A further analysis of the production stage suggests that the manufacture of the electric devices, including the LED driver (accounts for 40%, 49% and 32% of production stage's impact on ecosystem, resources and human health respectively) and LED light panel (13%, 10% and 13% impact on ecosystem, resources and human health respectively), are the key contributors to the impact of production/assembly stage, see Figure 4.8. It is also consolidated by the midpoint assessment results that except for 'electricity production', LED driver and LED lighting board, which contributed by 'wire printed board production' and 'light emitting diode production' processes respectively, are the two key components to the overall environmental performance of the assessed product, see Figure 4.9. The analyse of the background results linked to the both flows implied that the extraction of raw materials, especially precious materials, such as gold and silver, transportation, fabrication, and processes during the production of the wire printed board and light emitting diode are the major ascriptions. In addition, the emissions and processed water of those components mostly contain heavy metals that are hazardous and consequently cause potential damages directly or indirectly to the ‘marine ecotoxicity’, ‘freshwater ecotoxicity’, ‘human toxicity’ and ‘freshwater eutrophication’. An alternative production scenario considering use the post-consumer materials were assessed and analysed in later this section. Production of other assembly members, such as housing, fastening members and packaging, account for a very small percentage of the total impact in each category.



	Ecosystem	Resources	Human He
EoL	-0.41%	-0.02%	-0.22%
Use	48.19%	43.43%	39.11%
Transportation	0.10%	0.07%	0.10%
Production	52.13%	56.51%	61.03%

Figure 4.8 Contribution percentages of each life cycle stage on the three endpoint impact categories



	Resources	Human Health	Ecosystems
LED driver	40.68%	49.57%	32.82%
LED panel	13.99%	10.39%	13.93%
Housing	1.73%	0.99%	1.22%
other	0.11%	0.08%	0.22%

Figure 4.9 Components' contribution tree of production stage in endpoint categories

The use stage also plays a noticeable role in the environmental burden (43%, 39% and 48% to resources, human health and ecosystem respectively), which is due to the electricity consumption. From midpoint perspective, 'electricity production' process is the main ascription for the top three impact categories (see Figure 4.10): 64% of 'marine ecotoxicity', 65% of 'freshwater ecotoxicity', and 26% of 'human toxicity'. However, it is noticed that different ways of producing the electricity will affect the total impact of the product, which is also stated in previous LCA studies on lighting products (Longo et al., 2014; Principi and Fioretti, 2014). However, the goal of this LCA study is to seek opportunities to derive design recommendations that can improve the environmental performance; therefore, different electricity production methods were not analysed. Nevertheless, another lifetime scenario (50000h) was assessed to compare the difference of the environmental performance results. The result (Figure 4.11) shows a 22% impact reduction (from 4.31E-03 to 3.38E-03) on the total impact and three endpoint categories. This means that prolong the product serve time is an effective opportunity in improving environmental performance. Other opportunities in the use stage could be achieved by increasing the luminaire efficiency.

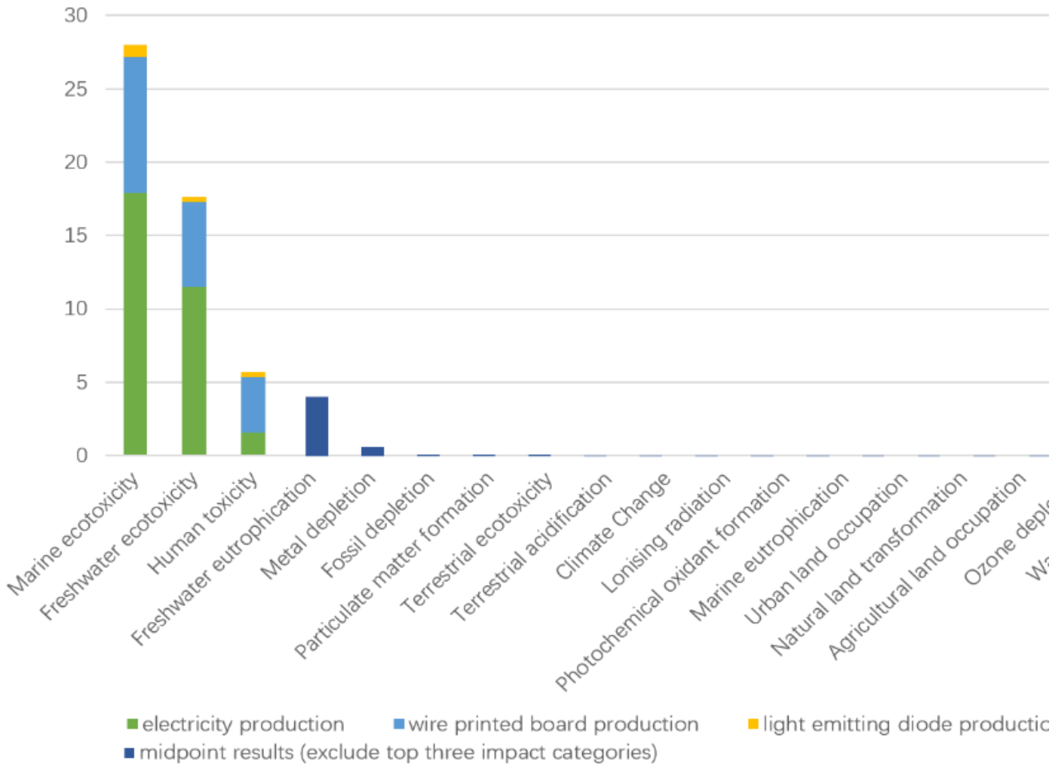


Figure 4.10 Midpoint results and the top three impact categories' key contribution flow

The EoL results show a small number of positive effects (Figure 4.8) under the default EoL scenario, which is assumed that the EoL LED lighting product is processed in compliance with WEEE directive, in which, electrical devices in the LED lighting product are disassembled from the product and placed in a recycling waste bin, then sent for material recovery. Other parts of the lighting product are disposed as general solid waste. Packaging waste is separated from the general waste bin, then incinerated. In addition to the default EoL scenario (S1), two alternative EoL scenarios (S2, S3) were considered and assessed to examine if: the performance varies by disposing and treating electrical devices separately; and if the post-consumer materials used for remanufacturing can affect the total performance. S2 and S3 are described as follows:

- Scenario 2 (S2): It assumes that the entire EoL LED lighting product is directly sent to a waste bin as solid waste and goes with the corresponding processing method, i.e. landfill. The waste packaging materials are processed in the same way as in the base scenario.

- Scenario 3 (S3): It assumes that the LED lighting product producer and distribution company, i.e. Kosnic, operate a take-back scheme, in which the EoL lighting products will be collected by the company for further processing: the product will be disassembled, and the electrical devices repaired and refurbished for producing new LED lighting products. Other useful materials in housing, such as aluminium, steel, and plastic are recycled or upcycled. The paperboard for packaging is remanufactured as new packaging material. The remaining materials from the used lighting product are treated as general solid waste.

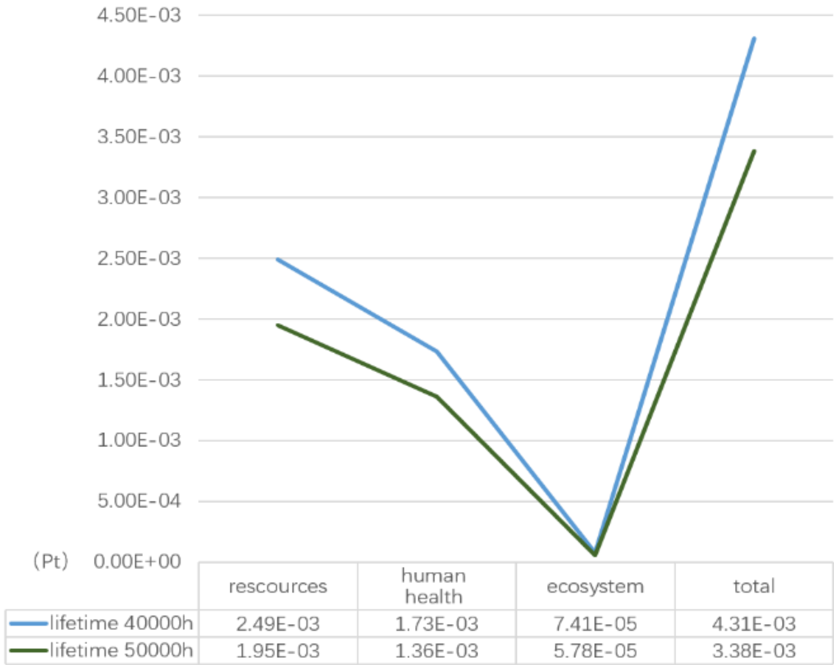


Figure 4.11 Environmental assessment results under different functional unit settings

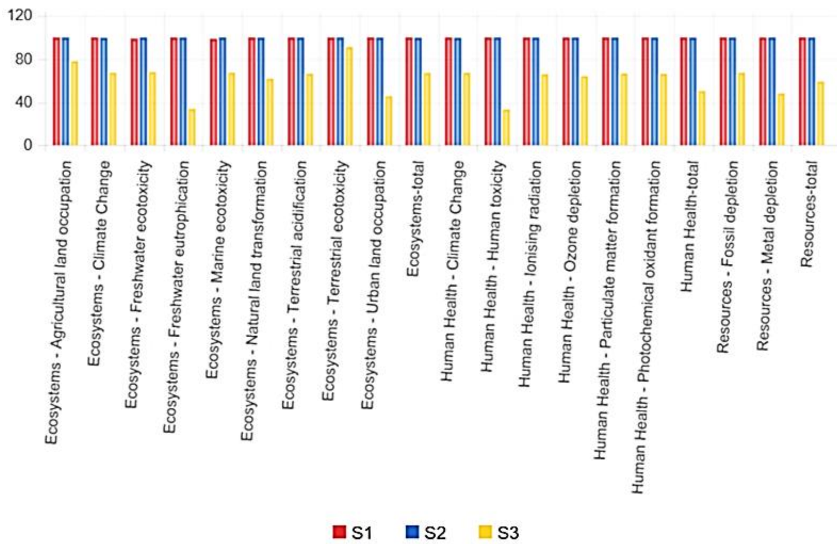


Figure 4.12 Relative results of the three EoL scenarios

The analysis results of the three EoL scenarios are shown in Figure 4.12, it shows that among the relative impact category results, the impact of S3 drops dramatically in comparison to the other scenarios. S2 and S1 have very small differences in each corresponding subcategory per unit process. It indicates that there is no evident change on the total environmental impact regardless of the disposal of electronic devices are independently or not. The results only show a dramatic improvement on the environmental performance if the post-consumer materials/components can be reused, i.e. the electronic devices can be repaired and reused as an assembly part in new products; or the packaging materials can be recycled and reproduced.

4.5.2 Social aspects

The social life cycle impacts were obtained and compared to electronic industry in China as the production plant is in China as well as its components suppliers. The comparison results show that from a whole perspective, the reference product presents a better social performance on 30 out of 49 impact categories, which are marked in green in Table 4.5. However, common key issues are identified (marked in blue in Table 4.5), namely 'association and bargaining rights', 'sanitation coverage', 'public sector corruption', and 'pollution'. Among these, 'sanitation coverage' and 'pollution' are under major risk to the stakeholder of local communities, due to the extraction of metal materials to produce electrical components. A high risk linked to sanitation and polluting problems during the extraction and manufacturing processes were identified, which is also the ascriptions of the environmental burden in the local communities; Austria, China, and Netherland are the main affected countries by the environmental burden along the supply chain. Besides, 'Industrial water depletion' is detected as a risky social issue, which relates to the local communities were producing the electricity and electric devices. Worker right issue 'Association and bargaining rights' was identified as a risk in the material supply country. However, this may be due to the political system rather than being a company level problem. Comparison results suggest that attention could be paid to improve worker's health and safety measures in the production line of metal and plastic components; and to promote fair salaries related to extraction works as well as reducing the gender wage gap to ease the risk of 'worker' stakeholder. Another major issue laid in 'value chain actor' under the compared results is 'public sector corruption', this issue, however, is difficult to improve by taking actions on the company level. Nevertheless, better implementation could be achieved by tackling the social responsibility risks along the supply chain, since distribution activities and electricity supply chains in the UK were noticed to have relation to slightly irresponsible social behaviours.

Table 4.5 S-LCA impact result with reference of electriconic industry of China

Impact category	**Electronic industry (CN)**	**Referenced product**	**Unit**
Active involvement of enterprises in corruption and bribery	0.0559152	0.08897	AI med risk hours
Anti-competitive behaviour or violation of anti-trust and monopoly legislation	0.0964823	0.05	AC med risk hours
Association and bargaining rights	56.219	53.30298	ACB med risk hours
Biomass consumption	0.739048	1.06511	BM med risk hours
Certified environmental management system	20.858	14.83369	CMS med risk hours
Child Labour, female	5.10977	4.85197	CL med risk hours
Child Labour, male	5.12282	6.05678	CL med risk hours
Child Labour, total	5.11025	4.85192	CL med risk hours

Contribution to economic development	-3.35925	-4.10638	CE med risk hours
Contribution to environmental load	7.30327	9.75208	CS med risk hours
DALYs due to indoor and outdoor air and water pollution	0.0513837	0.04733	DALY med risk hours
Drinking water coverage	0.0525511	0.12178	DW med risk hours
Education	5.18211	4.83548	E med risk hours
Fair Salary	6.35658	11.96347	FS med risk hours
Fatal accidents	0.065749	0.04914	FA med risk hours
Fossil fuel consumption	0.0055012	0.00726	FF med risk hours
Frequency of forced labour	0.00555091	0.0065	FL med risk hours
Gender wage gap	0.498243	1.70625	GW med risk hours
Goods produced by forced labour	0.255223	0.08265	GFL med risk hours
Health expenditure	1.76866	1.57533	HE med risk hours
Illiteracy, female	0.511776	0.47665	I med risk hours
Illiteracy, male	0.0515712	0.04764	I med risk hours
Illiteracy, total	0.0517942	0.04969	I med risk hours
Indigenous rights	0.574942	0.51225	IR med risk hours
Industrial water depletion	1.12619	4.03145	WU med risk hours
International migrant stock	0.165058	0.43032	IMS med risk hours
International migrant workers (in the sector/ site)	0.109396	1.51289	IMW med risk hours
Life expectancy at birth	0.00655237	0.00506	LE med risk hours
Men in the sectoral labour force	0.00523568	0.01112	M med risk hours
Minerals consumption	5.1657	4.89121	MC med risk hours

Net migration	0.0105308	0.01946	NM med risk hours
Non-fatal accidents	0.0753911	0.39495	NFA med risk hours
Pollution	51.0922	46.5373	P med risk hours
Presence of business practices deceptive or unfair to consumers	0.161019	0.0262	CONS med risk hours
Public sector corruption	51.5248	48.18288	C med risk hours
Safety measures	0.973351	1.321858	SM med risk hours
Sanitation coverage	51.3308	48.07471	SC med risk hours
Social responsibility along the supply chain	7.86053	7.89106	SR med risk hours
Social security expenditures	5.45725	4.77722	SS med risk hours
Trade unionism	1.19609	1.31958	TU med risk hours
Trafficking in persons	5.12111	4.85702	TP med risk hours
Unemployment	0.0518463	0.18575	U med risk hours
Violations of employment laws and regulations	1.0585	1.19236	VL med risk hours
Weekly hours of work per employee	0.212007	0.15446	WH med risk hours
Women in the sectoral labour force	0.00766246	0.19455	W med risk hours
Workers affected by natural disasters	5.24794	5.99472	ND med risk hours
Youth illiteracy, female	0.01	0.00638	YI med risk hours
Youth illiteracy, male	0.01	0.00711	YI med risk hours
Youth illiteracy, total	0.01	0.00638	YI med risk hours

Further analysis of the spotted social issues from the social impact results demonstrated that the production/assembly stage is the key contributor to the social performance among all life cycle activities and processes of the reference product. Activities related to the production of housing, LED driver, and LED panel, as well as electricity, in particular, are identified as the key opportunities to improve the social performance of the reference product. Figure 4.13 particularly highlights the key processes to the important social issues identified. Production for housing components contributes the most risks to the important social issues. Besides, the production of LED driver and LED panel are the main contributors to the major social risks. Electricity supply chain during the use phase is identified as the main contribution of 'social responsibility along the supply chain', 'industrial water depletion', and 'contribution to environmental load' risks. As the use stage is defined to be taken place in the UK, it is suggested that more attention should be paid to ease the risks generated during electricity production processes on the local communities and value chain actors. Production of plastic components and distribution activities present to have minor impacts on the impact of social issues.

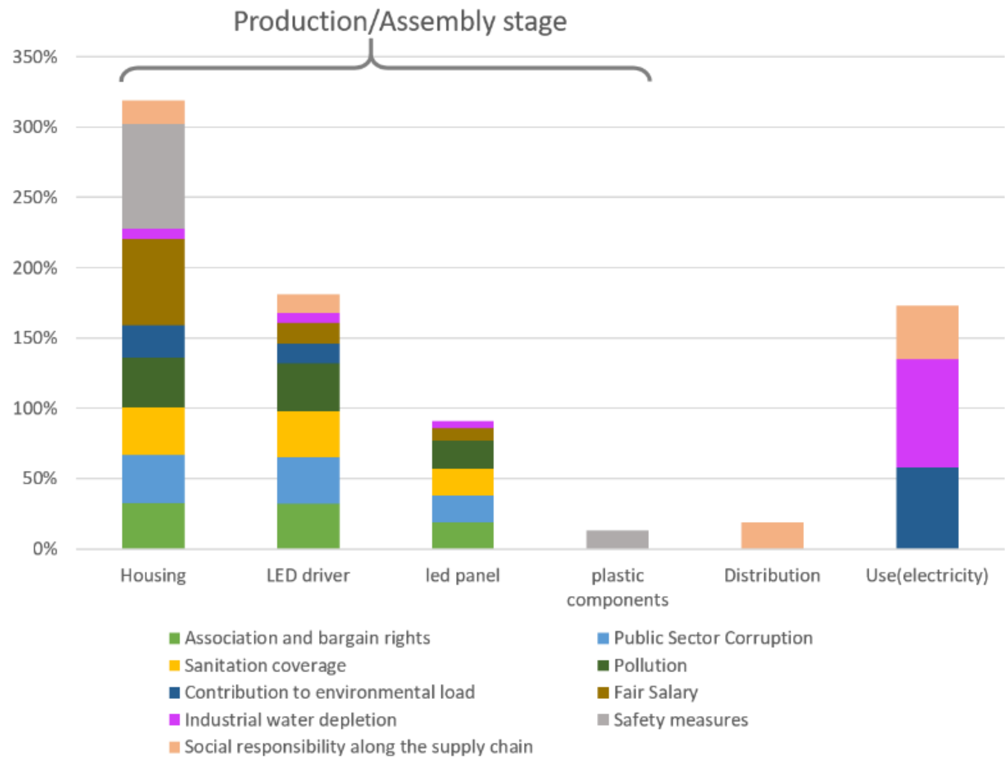


Figure 4.13 Key processes to the important social issues

There is no outstanding social issue in stakeholder allocated in the 'society' or 'consumers'. On the contrary, an 18% more superior positive social effect (around -4.1 per unit) was detected under category 'contribution to economic development' in comparison with the results of the referenced industry in China. Currently, it's the only indicator that assesses positive social impact in PSILCA database, therefore the result presents a '-' to differentiate the positive effect between other impacts. As shown in Figure 4.14, manufacturing activities account for the most positive effects, production of LED driver (37%), housing (31%), and LED panel (22%) are the main contributors which link to the economic contribution. China is the country that benefits the most from the positive effect since it's the country where the main manufacturing processes were taken places in.

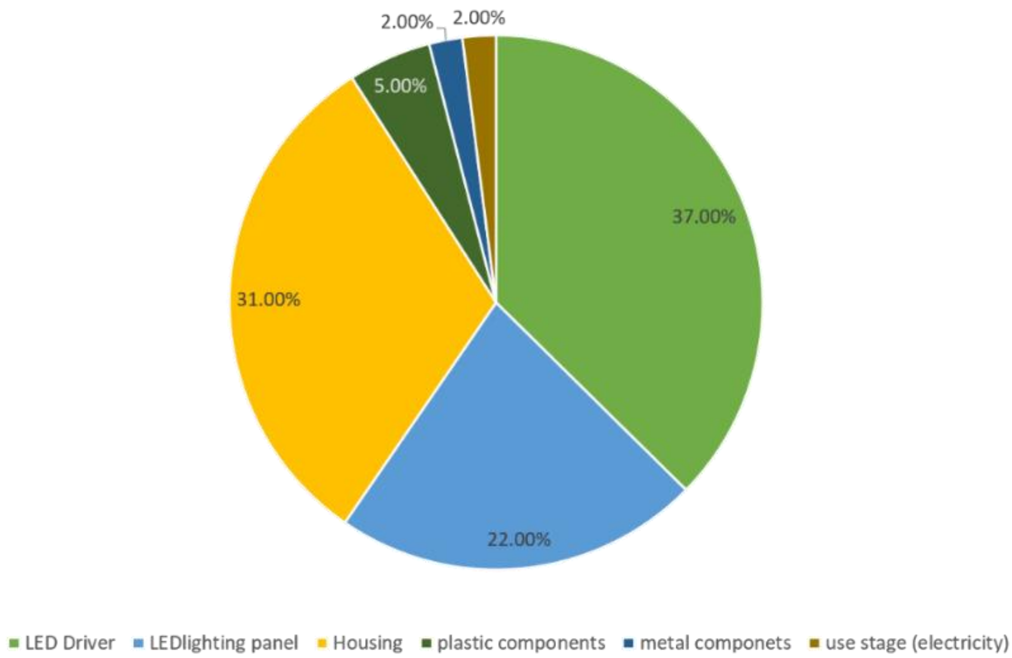


Figure 4.14 Process contribution to positive social impact

4.5.3 Limitations

The E-LCA was conducted in compliance with the ISO14040 while S-LCA was conducted according to UNEP guidelines. The overall data sources and reliability were satisfied within the scope, and the aims of the study have been achieved. However, there are still limitations within the study.

In the E-LCA, the sensitivity study was conducted based on the assumption of the EoL scenarios which are rather optimistic in comparison to the real circumstances. In addition, assumptions were also made for the calculation of the inventory data, which might cause uncertainty of the results.

Different from E-LCA, it is difficult for S-LCA to have numerical scores and consequently it is difficult to draw a conclusion of social performance based on a single product, thus analysis results are more comparable when two or more similar products or product services are under study. Secondly, the case-specific foreground S-LCA data in the other stages were difficult to access, therefore assumptions were also made in this regard. Furthermore, the social impact is relatively subjective in comparison to the E-LCA. Despite the fact that the choice of impact categories and/or the risk levels were based on facts and data gathered from the company under assessment, a certain amount of uncertainty still exists regarding the result of the social performance.

4.6 Interactions between E-LCA and S-LCA results

The E-LCA and S-LCA results inform the challenges and opportunities in improving the sustainability performance of the reference product's life cycle from different perspectives. Figure 4.15 outlines the important E-LCA and S-LCA results and their interrelations. The E-LCA related results are marked in blue while the S-LCA results in yellow, the overlapped key life cycle stages and processes are marked in grey. The production stage is the 'hotspot' life cycle stage revealed by both assessments which responsible for the major potential environmental and social risks. In terms of the overall processes, the production of LED driver and LED panel, and electricity are revealed as the key components/processes by both assessments which are crucial for improving the sustainability performance. Those overlapped life cycle stages and processes are considered as the starting point to form recommendations, subsequently, can be directly applied to constructing sustainable product and service concepts.

Furthermore, the sensitivity analysis results from EoL and lifetime scenarios complement or validate the opportunities that support to formulate the design recommendations. The results from the comparison of three EoL scenarios indicate that there is no evident change in the total environmental impact regardless of the disposal of electronic devices independently or not; dramatic impact reduction occurs only if the post-consumer materials/components can be reused for reproduction. Meanwhile, the lifetime scenario analysis results show a 22% impact reduction on the total impact with an additional 10000h lifetime. Those results reveal that prolong the product serve time, EoL treatment towards remanufacturing are effective opportunities in improving environmental performance. Other opportunities relate to electricity could be achieved by increasing the luminaire efficiency.

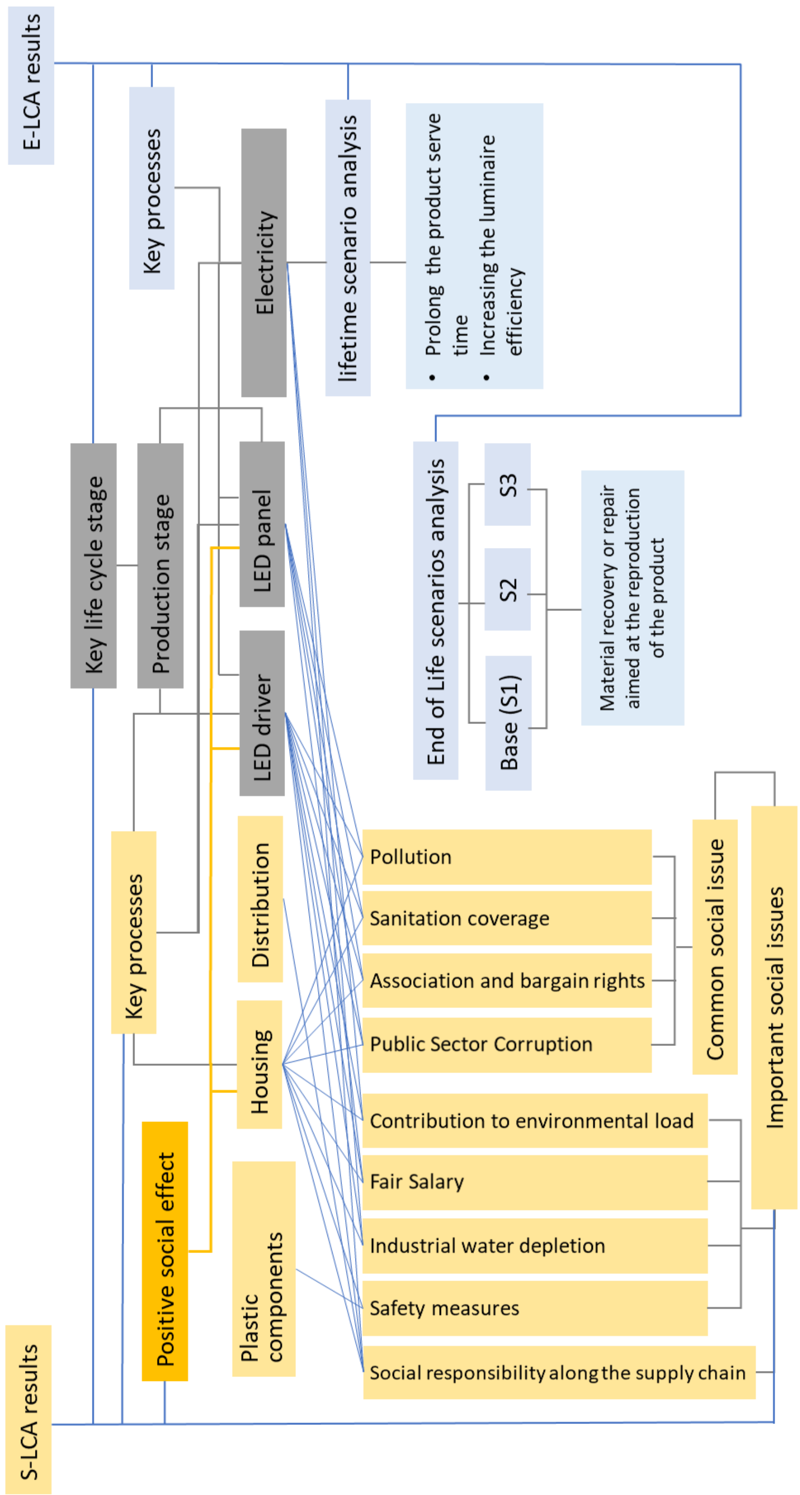


Figure 4.15 E-LCA and S-LCA results and interrelations in brief

It is noticed from S-LCA results that, apart from LED driver, panel and electricity, which are the overlapped key processes, production of housing is the main ascriptions to most of the important social issues as well, especial to the important social issues including common social issues (between the product and the referenced sector in China).

Nevertheless, those activities (linked with yellow lines) are also detected as the main contributors to the positive effect that links for boosting the regional economy. In this case, finding a mitigating solution to reduce the environmental impact and social impact whilst facilitating the positive socio-economic effect (boosting the regional economy) related to the key process is essential. However, the S-LCA results are less direct for design integration and being notified as social improvement via comparison assessment. This is due to the intangible and semi-quantitative nature of S-LCA. Nevertheless, S-LCA findings are more preferable on guiding life cycle thinking for product-service design. Potential business models based on the sustainable redesign are proposed to trade-off the environmental impact with the socio-economic benefit.

4.7 Recommendations and implications to product and service design

4.7.1 Recommendation for sustainable industrial LED lighting product design

Based on both assessment results and analyses, the recommendation aims at guiding industrial lighting product with longevity and energy reduction features. In addition, adaptability of related product service is also considered in the proposed recommendation, which is stated as follows:

- Design of the LED driver. An LED driver is the most important and problematic part of an LED lighting product. It is suggested to re-design the circuit board, eliminate or reduce the precious metal inputs within components by substituting with other materials. A more compact and efficient driver design is suggested, preferably, the modular design is encouraged to enable the change of the damaged module(s) without affecting other functional modules and therefore reduce the maintenance time and cost.

- Improve energy efficiency. High efficiency is considered crucial for industrial LED lighting product, improve energy efficiency means the lighting product provides more brightness by consuming the same amount of electricity, which can reduce energy consumption related impact in a given area, as well as reduce energy cost. This can be achieved by replacing the light emitting diode with a higher luminous efficiency product, and refine the arrangement of the LED optics; improving the power control system and; design with a high-efficiency lampshade, e.g. change diffuser to lens, etc.
- Prolong the lifetime. Prolong the lifetime is proven (section 5.1) to have less impact on environment. A lighting product with longer lifetime means it needs to have high reliability and upgradability, especially under an industrial application circumstance. It is suggested to implement a modular design and enable easy access to electronic components to change/upgrade if necessary while remaining the housing construction to prolong the lifetime.
- Reduce housing material and refine the product’s dimensions.
- Use recycled packaging material (80% post-consumer cardboard and 50% recycled

plastic materials).

- Design for easy assembly and disassembly for all the components.
- Use recycled plastic material, making sure chlorine content in the plastic parts is not greater than 50%.

4.7.2 Recommendation for service based on sustainable lighting product

Based on the implementation of the proposed sustainable redesign of the industrial LED lighting product, possible product services for the company that follows circular economy principles are also recommended:

- Establish a take-back scheme. Major environmental and social risks are detected in relation to raw material mining for manufacturing the important components, e.g., LED driver and LED light Panel as well as the Housing. Nevertheless, they are also identified with links in boosting the economy. Therefore, it is suggested a take-back scheme could mitigate the negative environmental and social risks in mining for new materials by means such as using the post-consumer recycled materials to remanufacture. The results of the EoL scenario (S3) also proved the environmental improvement of initiating the potential scheme.
- Leasing service. Leasing service is a kind of product services system, in which the end-users do not own the lighting product but benefit from the lighting service provided by the company for a contracted time, including the maintenance and take back of the lighting products. By providing the energy-efficient luminaire with longer lifetime as

well as the take-back service, it is expected to improve the sustainability performance along the supply chain and benefit a broader range of stakeholders.

The services proposed are based on a sustainable LED lighting product that enables a longer lifetime and energy efficiency. With providing the service, it is more predictable in material flow from a stewardship perspective. By creating value from waste, recycling responsibility in mind, the manufacturer will need to focus more on reusability, EoL options in the product design stage, which minimises waste disposal. The collaboration of all partners under the proposed services aim for the best user experience so that is marketable. Meanwhile, a broader range of stakeholders are benefited along the supply chain, new job roles are needed, and all stakeholders benefit with a healthy recurring profit stream, which is sustainable.

Chapter 5 - Sustainable Product Development and Service Approach for Application in Industrial Lighting Products

5.1 Introduction

This chapter is an application and demonstration of the proposed approach which emphasis on the development sustainable product and the service as a bundle using industrial lighting as an example. The product development part consists of sustainable design, environmental and social lifecycle assessment, and sustainable manufacture, while the sustainable product service part includes distribution, support for sustainable consumption, maintenance and repair, and services related to product end of life such as recycling, reuse and take-back. Building on the results learned from the second step, i.e. sustainability study which presented in chapter 4. This chapter demonstrates the integration and implementation of the implications and recommendations (result from sustainability assessment) in the development of the new sustainable lighting product and service. Standard product design process is conducted while the product service concepts are proposed coherent with the newly designed sustainable lighting product. Environmental and socioeconomic aspects of sustainability are addressed then evaluated. The comparative life cycle assessment results indicate that the lighting product developed with the approach shows a 46% lower environmental impact (detailed in section 5.4.1.6). The product and service benefit multiple stakeholders, such as promoting workers' welfare, cutting cost for manufacturer and end users with prominent services, and a healthy recurring profit stream for all stakeholders.

5.2 Sustainable product development

The aim of developing the sustainable product and service bundle is to reduce the environmental burdens, address the social issues while achieving the economic and competitive interest of providers (stakeholders in the supply chain), i.e. to achieve the holistic sustainability of the industrial LED lighting through the innovation.

5.2.1 Conceptual design

The E-LCA and S-LCA results indicate the key life cycle stage and key process of both environmental and social performance are overlapped. Environmentally and socially, production stage is identified as key life cycle stage; LED driver and LED panel are the key components and, the production of electricity is the key process to improve the overall sustainability performance of the assessed product. The interrelation between both results are analysed and, finally, those overlapped E-LCA and S-LCA results were directly applied to sustainable product and service recommendations and conceptualisations, while individual S-LCA findings were addressed in the conceptualisation of product-service. The detailed assessments and analyses can be found in chapter 4.

Incorporating the recommendations based on sustainability assessment results and analysis into practice, a sustainable PDS for new industrial LED lighting was brought out. Several key characters were emphasised in the PDS to develop a sustainable LED lighting product with superior functions, where the objectives of product service were also taken into consideration to support the superior function and operation of the potential PSS. Possible product services recommendation for the case company are also proposed according to the assessment results and analyses, it was recommended that the company could start a leasing service and establish a take-back scheme, which will be elaborated in next section.

The sustainable LED lighting to be developed is suggested to incorporate the following features:

- Design of the LED driver. Design the circuit board, eliminate or reduce the precious metal inputs within components by substituting with other materials. A more compact and efficient driver design is suggested.

- Improve energy efficiency. Improve energy efficiency means the lighting product provides more brightness by consuming the same amount of electricity, which can reduce energy consumption related impact in a given area, as well as reduce energy cost. This can be achieved by improving the power control system and design with a high-efficiency lamp shade.

- Prolong the lifetime. Prolong the lifetime is proven to have a less environmental impact. It is suggested to implement a modular design and enable to change electronic components if necessary while remaining the housing construction to prolong the lifetime.

- Reduce housing material and refine the product’s dimensions.

- Use recycled packaging material (80% post-consumer cardboard and 50% recycled plastic materials).

- Design for easy assembly and disassembly for all the components.
- Use recycled plastic material, making sure chlorine content in the plastic parts is not greater than 50%.

Conceptual design concepts were brought out by the case company. Since the derived PDS is tailored specifically towards sustainability improvement, therefore the two design concepts were narrowed down and proposed by the case company. The two concepts both have the same objectives, which is to deliver modular designed industrial LED lighting product.

Figure 5.1-5.3 shows the design concept 1(DC1) which embraces the following features:

- polygonal column shaped with extra attached emergency module.
- Each LED engine has its own dedicated driver, each luminaire can contain up to 6 independent LED lighting units.
- Any component failure will only affect the corresponding lighting unit and not result in complete product failure.
- Only the faulty module (light engine or driver) is replaced when it's not functioning, minimising unnecessary waste.

- Each individual piece can be assembled /disassembles to ease the manufacturing process, assemble/disassemble and installation processes

- The LED lighting panel and its module can be adjusted for different angle and application needs.

- An emergency back-up energy design was added in order to implement the leasing service with upgraded functionalities.

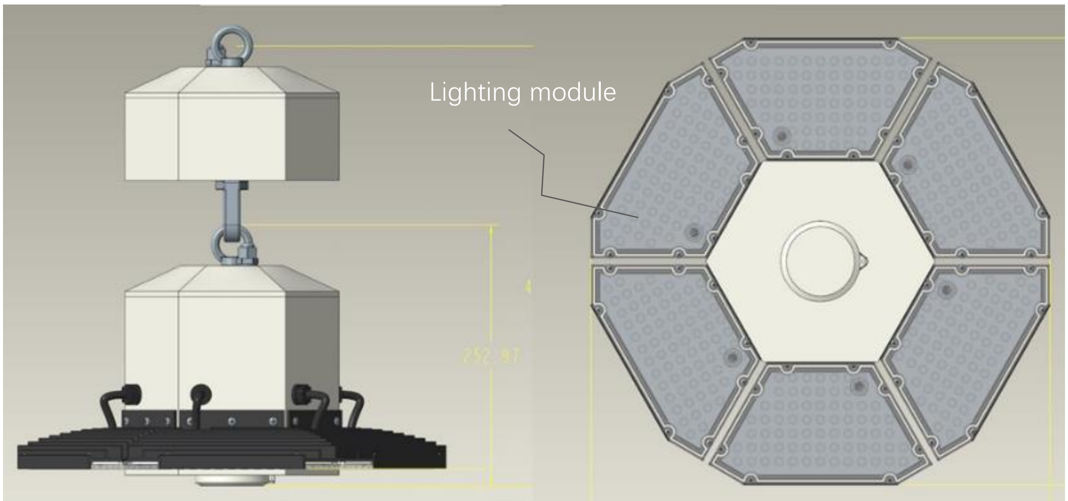


Figure 5.1 Overview of design concept 1

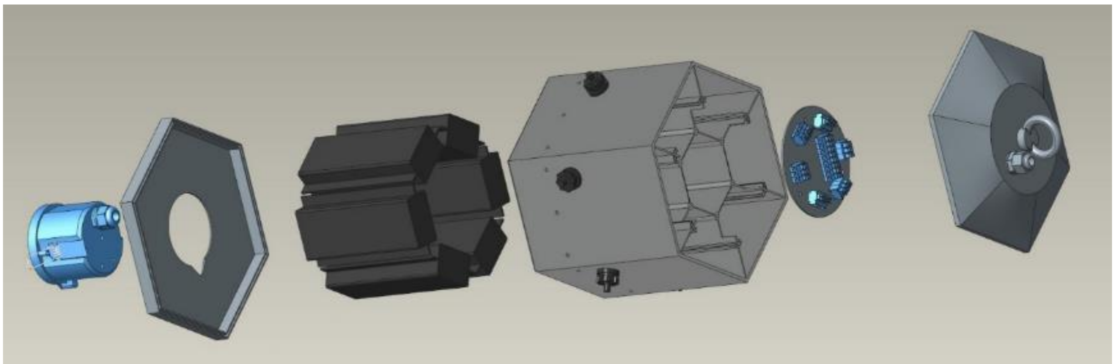


Figure 5.2 explosion figure of design concept 1 (main structure)

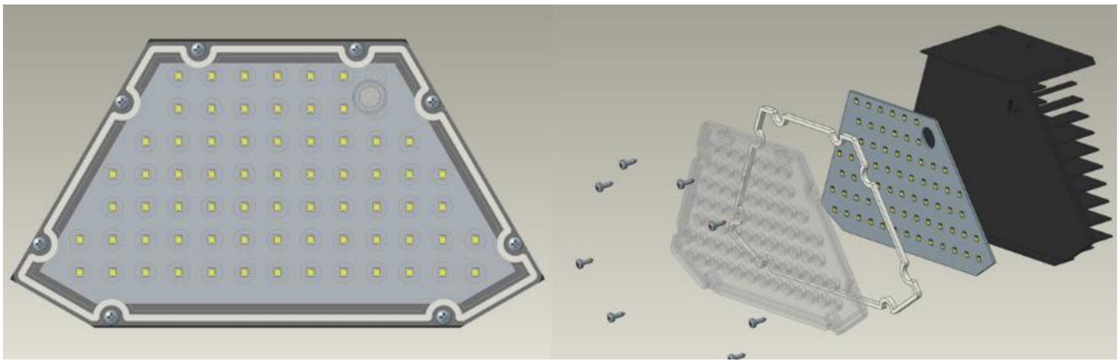


Figure 5.3 structure of the light module of Design concept 1

Figure 5.4 presents design concept 2 (DC2). This concept employs the traditional ceiling-mounted structure, the main functional features are the same as design concept 1 which are mentioned above. It can be considered as an improved design DC1, the main difference is that the structure of DC2 is flat with reduced components, therefore reduce the joint members (screws) and the manufacturing process. In addition, the main electrical devices are design to be amounted in the same module which is considered easier to control when errors occur. This concept reduces the total material required, also a reduced weight and dimension.

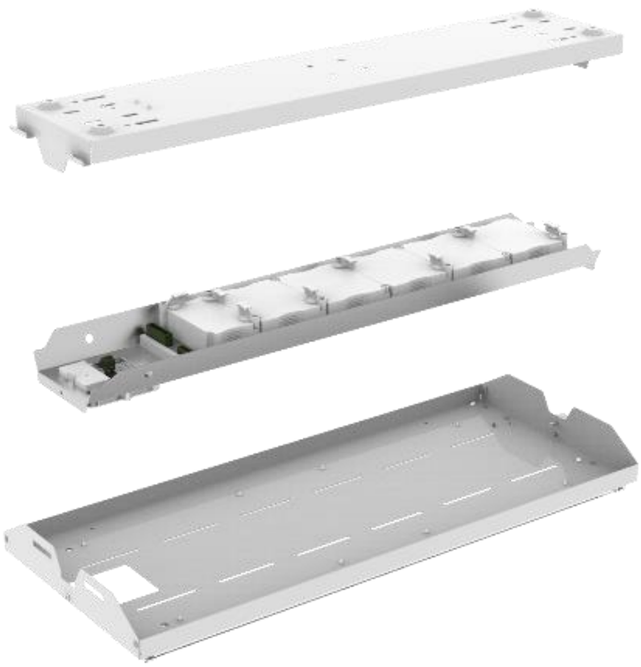


Figure 5.4 Design concept 2

The concept selection was carried out according to the 'concept selection method' (detailed in section 3.4), 12 criteria were finalised and compared between the two design concepts (DC1 and DC2). The concept selection payed special attention on the impact throughout each life cycle stages and the impact of the potential service, such as the environmental impact of the material, ease of manufacturing, ease of installation and disassembly, ease of transportation, cost, and recyclability, etc. Weighting factors to each comparative were applied according to the importance, from 1 to 3, which is aiming to guarantee the key eco-friendly features in the early design stage and the successful operation of the potential service. Finally, the total evaluation score of DC1 was 91 whilst it of DC2 was 118, which indicates DC2 has the higher score therefore was the selected DC for detailed design, see Table 5.1.

Table 5.2 Concept evaluation with comparative criteria

No.	**Comparative Criteria** (Low/Expensive = 1; High/Cheap =5)	**Design concept (DC1)**	**Design concept (DC2)**	**Weight factor (low=1, high=3)**
1	Weight	3	5	3
2	Number of materials	2	4	3
3	Ease of manufacturing	3	5	2
4	Flexibility of adjustment	4	5	2
5	Ease of maintenance	5	5	2
	Life-cycle environmental Impact	4	5	2
6	Recyclability (EoL options)	4	4	2
7	Availability of materials	5	5	1
8	Cost	3	4	3
9	Upgradability	3	4	2
10	Lighting efficiency	4	4	1
11	Emergency back-up	4	4	1
12	Service ability	4	5	2
	Total evaluation score	91	118	

5.2.2 Detailed design

The final design (ARCUS-II) is shown in Figure 5.5 and 5.6, it embraces an entire modular LED low bay with emergency and sensor options. This model features an overall modular design and an ultra-high efficiency with high adaptabilities, including the efficiency of 123lm/W, optional emergency and microwave sensor version, stand-by dimming and daylight threshold conduit, trunking or surface mounting. The key features of the industrial low bay luminaire and the implementation of sustainable design are lists in Table 5.2.

Table 5.3 Key Features and Implementation of sustainable design.

Sustainable Design Features	Benefit Life Cycle Stages	Implementation of Recommendations
Modular design	Production, use and maintenance (installation), EoL treatment	√
Innovative design of the LED driver	Use and maintenance	√
High energy efficiency design	Use and maintenance	√
Compact design	Production, distribution(transportation)	√
Design for long lifetime and high reliability	Use and maintenance	√

Figure 5.5 Detailed design of ARCUS-II

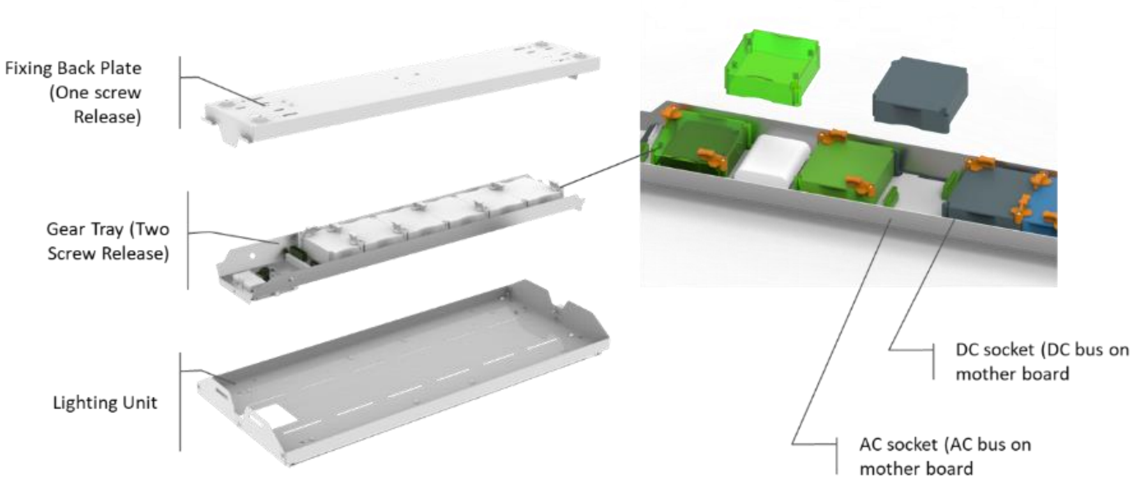


Figure 5.6 Detailed design of ARCUS-II (explosion graph)

Modular design. Overall modular design is the paramount novelty of this model, which gains superior adaptability and upgradability of the model for potential activities, e.g. leasing service. The structure of the low bay luminaire consists of three main parts with concise fastening method, namely fixing backplate, Gear tray as well as lighting unit, each part can be joined with one or two screw(s). In addition, inside the gear tray, the control module including the driver, sensor and the emergency module are plugged individually on its motherboard. As shown in Figure 6, the modular design of the housing and control module eases the processes of production, assembly/disassembly, installation, maintenance, and end-of-life (EoL) treatment. There are different version options regarding the power (100W/150W/200W) and function (if with sensor and emergency function) preferences, the structure of the luminaire remains the same regardless of functional preference changes. The control module and LED optical panel are the most delicate parts of a LED lighting product, the modular design enables the change of the problematic module(s) without affecting other functional modules and therefore reduce the maintenance time and cost.

Innovative design of the LED driver. Taking the design recommendations derived from the LCA studies into PDS, the new design brought out a completely new design of driver with concertation of prolonging the service time. One of the drawbacks of the driver in the old model (ARCUS-Compact) is that the individual driver which provide the whole power of the LED could be overheated during usage consequently increases the chance which can lead to an entire breakdown of the luminaire. The new design of the driver is more compact and efficient since the control system consists of more than one driver (depending on the power of the luminaire) so that the other driver(s) are not affected despite one driver operates wrong therefore prevent complete failure. In addition, redundant design is applied to reduce the operational risk of the driver, thus the lifetime of the driver is expected to be prolonged. Furthermore, the sensor version could achieve a stand-by dimming which also protects the driver from risks.

High energy efficiency design. The previous model employs a diffuser (see picture in Table 5.9) shade, also there is only one LED light panel where all the LED optics arranged onto. In order to improve the light efficiency, the new model utilises two lenses and two separate LED panel, the lenses are polarized that can provide different options of beam angle with reduced LED optical arrangement, therefore reduce the cost of LED optical with improved efficiency. The new model has a 7% efficiency improvement (from 115lm/W to 123lm/W) thanks to the optimise design of panel and shade.

Compact design. The new design reduces the housing dimensions and the usage of housing materials owing to the compact design. As a result of the compact design and modular design, the manufacturing processes are simplified, the housing material is a steel sheet which is a highly approachable and recyclable material.

Design for long lifetime and high reliability. One of the feedbacks from service is to make the lighting equipment easy for maintenance and more reliable for the consumer. With consideration of the feedback, the new model provides an optical emergency version which could detect potential driver deficiency and automatically operates a dimming to prevent entire luminaire break-down, which adds high reliability to the product. Furthermore, the modular design eases the maintenance without changing functional parts (including housing) and enhance the upgradability which is advantages for a longer lifetime as well as for the proposed service.

5.2.3 Manufacture and test

The manufacturing procedure of ARCUS-II is briefly illustrated in Figure 5.7. The housing components are made of steel sheets, which are manufactured by laser cutting and bending, then are coated by automatic spray machine. The electrical devices are made through the manufacturing line and are then assembled into the housing to form the final product. The modularly designed units are manufactured accordingly and mounted to the product, which significantly simplifies the assembly process and speed-up the assembly, and hence the assembly cost is reduced to about 30%. More detailed information about the manufacturing process can be found in (CIRC4Life, 2020). The quality of the product is ensured by following the product quality assurance procedure including, quality checking through the production line, the early failure prevention conducted at the test station, and maintenance experiment implemented in the lab.

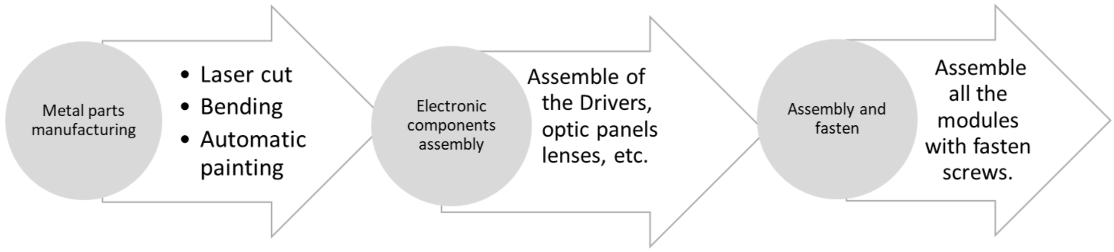


Figure 5.7 Manufacture procedures in brief

5.3 Sustainable service

5.3.1 The sustainable product service system

Kosnic Lighting Ltd is an independent British company which incorporates design, manufacture and bespoke lighting solutions. The company is well recognised for its good practice in providing innovative, robust lamps and luminaires that deliver quality, cost-effective and environmentally responsible lighting solutions for residential, commercial and the public sectors alike. Research and innovation are important for the focal company in continuously delivering prominent product and service, it recently participates in the EU H2020 research project CIRC4Life as an industrial partner, the main task in the project of the company is to develop a sustainable LED lighting product with integrated sustainable product design methods, which dedicated to maximising the energy-efficient and cost-saving potential of LED technology; and demonstrate its application in a circular economy based business context to form the triple bottom line of sustainability in their product and service.

The objective of the focal company is to develop sustainable product and circular economy-oriented business model that covers the triple bottom line of sustainability, i.e. environmentally reduce the material and energy consumption, socially benefit the society and stakeholders, and economically create value and profit.

Taken the recommendations from social performance study (Wang et al., 2020) into consideration, the product-service bundle between the sustainable product and possible service implementation is explored. With the knowledge of life cycle thinking and lifecycle management, designers, researchers, value chain actors were brought together co-creating the PSS aiming at circular economy business model/models, see Figure 5.8 and 5.9.

Figure 5.8 Co-creation of business model-group discussion

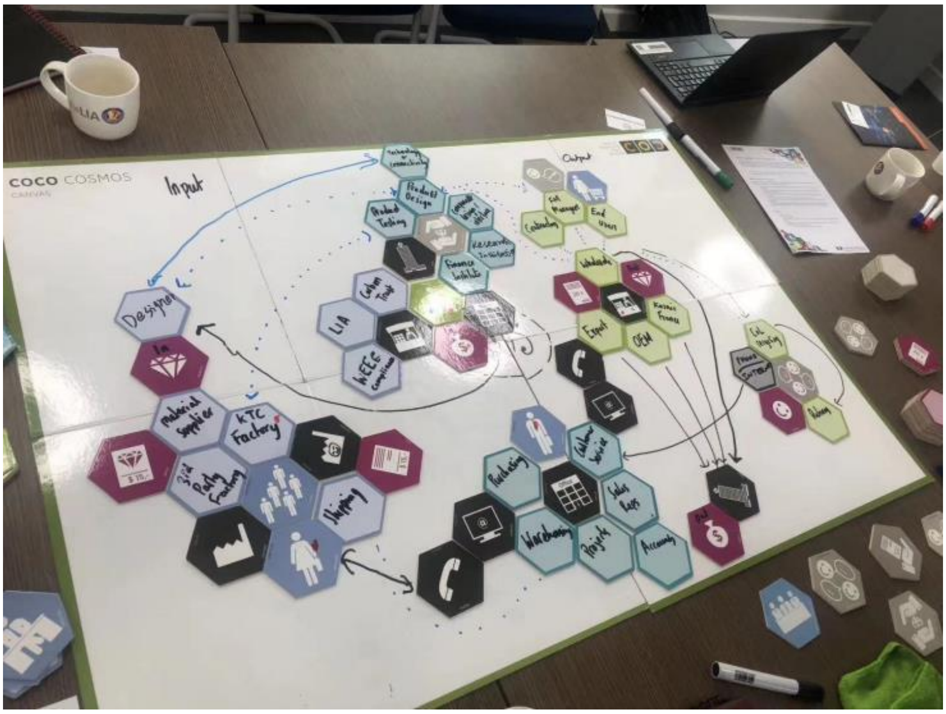


Figure 5.9 Example of the group discussion results

Consumer needs and the potential added value were analysed, the goal is to construct a service that is better fulfil consumer needs while creating value for the providers with reduced environmental and social impact. Currently, the focal company adopts a classic product-sale business model, in which the company is the manufacturer without distribution, a wholesaler is entitled to connect the end users and other stakeholders, e.g. the subcontractors of installation, maintenance via a liner route of distribution. In this case, profit and margin are added at every stage of the supply chain without the responsibility to the product's whole lifecycle, which may cause inadequate products being applied. Such products require frequent repair and replacements that creates a significant inconvenience, such as dealing with the problems, outage period whilst waiting for the replacement, and further cost for the end user to ensure the lighting products in good operating condition. As all suppliers currently benefit from simply selling the products, there is no interest in prolonging the product lifetime or reuse/repair, consequently increasing the number of waste disposals than it should. It is recognised the need to search for additional value related to the product longevity and energy reduction, therefore the focus was on creating the added value of innovative services throughout LED lighting's lifetime for consumer satisfaction.

5.3.2 The leasing services

The proposed leasing service is a use-oriented PSS (Cook et al.,2006; Williams, 2007), which customer satisfaction implies enjoying the function of products or services rather than enjoying the ownership (Chou et al., 2015). The proposed service focuses on how the best benefit and most effective illumination plan can be gained for the end user in a contracted time. Figure 8 illustrates the eco-system of the LED lighting product leasing service, in which the wholesaler brokers and managers leasing service to the end user, the manufacturer supplies the lighting equipment and parts, the contract is responsible for installation and maintenance company looks after the equipment. The manufacturer uses WEEE service to recycle and dispose the faulty and EoL products.

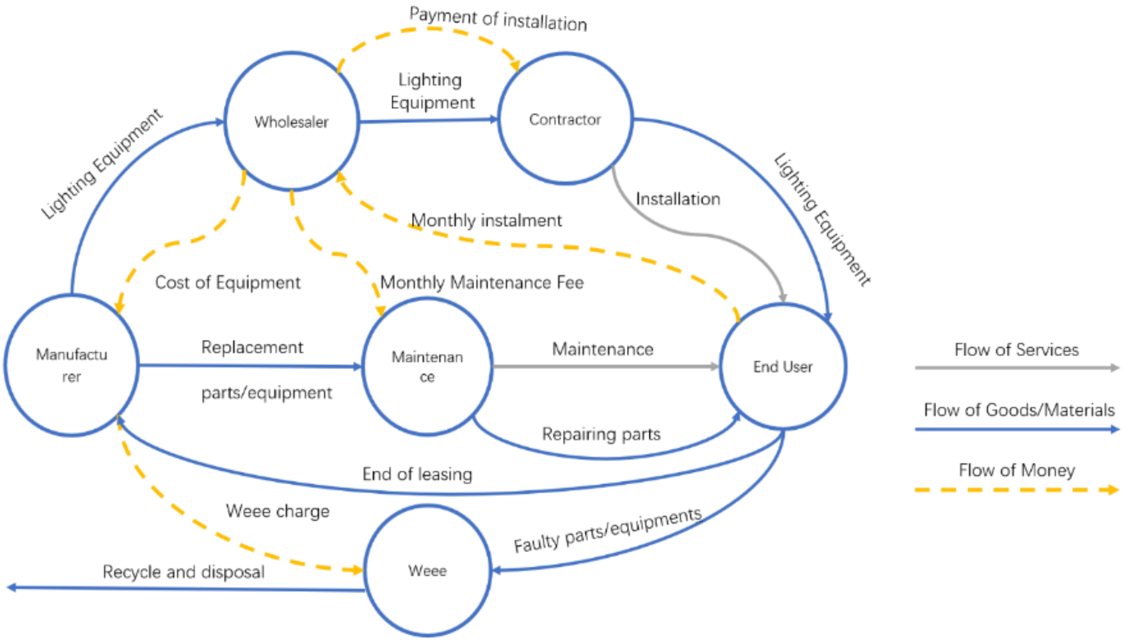


Figure 5.10 The eco-system of the PSS

The PSS includes design, providing the lighting equipment, installation, maintenance and end-of-life take back services. The case company will work with technical know-how to come up with a bespoke plan, such as define the lighting equipment required, which will best suit the application and conform to all necessary standards and regulations. The wholesaler leads the commercial activities in finding local business opportunities. Once the leasing contract is agreed, the electrical wholesaler works with other partners to deliver the equipment and services accordingly.

The payment (instalments) is collected by the wholesaler, who in turn pays the other business partners. Figure 5.11 and 5.12 show two types of payments plans: stepped payment plan and flat payment plan, respectively, which are proposed to offer to our leasing customers. A full leasing cost of £240 for typical industrial lighting and 5 years leasing contract term with payment over 20 quarters is used as an example for illustration purpose.

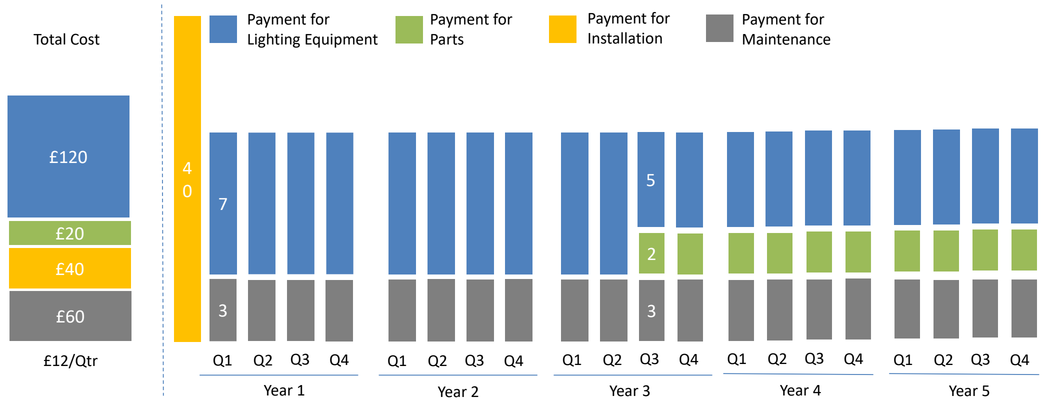


Figure 5.11 Stepped payment plan

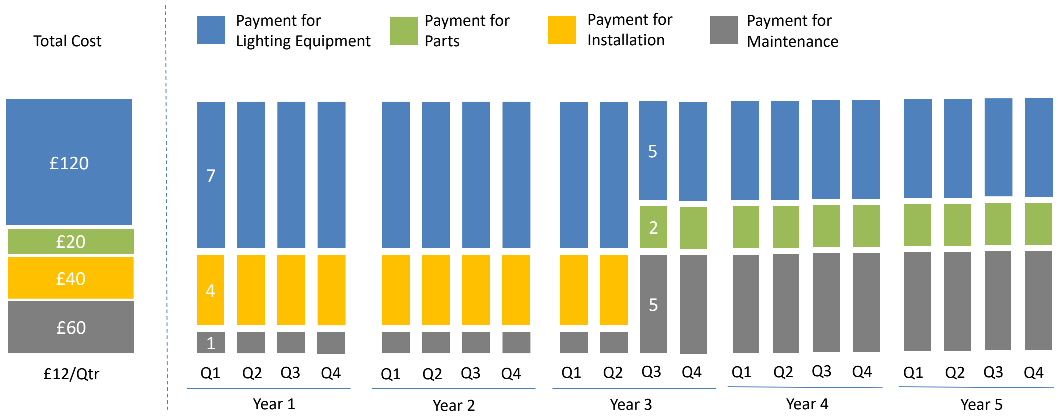


Figure 5.12 Flat payment plan

As an example, a leasing cost of £240 consists of £120 product cost, £20 parts, £40 installation fees and £60 maintenance charge, in which financial cost of leasing such as interest and profit for each party of lessor side have already taken into consideration. For stepped payment plan, £40 cost of installation fees are paid in full at the start of the leasing contract, the remaining cost is spread over 5 years term with quarter payment of £10, whilst a fixed £12 quarter payment is applied for whole leasing term for a flat payment plan. The customer only needs to pay a small number of quarterly instalments instead of a much big payment in one go for both payment schemes with a small proportion of installation cost at the beginning for the stepped payment plan, which provides a very flexible financial plan and a peace of mind for lighting maintenance for the customers, and extra financial cost for leasing service is supposed to be covered by energy bill saving due to high energy efficiency design, leading to more potential business opportunities and extra revenues as the customer is willing to initiate those lighting projects which are thought to be expensive in term of financial planning, now become affordable because of leasing service.

For leasing service, the owner of the lighting equipment belongs to Kosnic, at the end of the leasing contract, Kosnic will take back the lighting equipment, due to its novel modular design, more components can and will be recycled, reused or re-engineered to extract the maximum residual value of the used lighting equipment, and a cost cut of WEEE charge is expected due to much fewer parts of the light equipment for disposal.

A multi-party leasing contract is proposed to ensure that every stakeholder in eco-system of the PSS shown in Figure 5.10 fulfils its role. The flow chart of the leasing contract is shown in Figure 5.13, in which an update is permitted during the term enabling the customer to take advantage of continual improvement of LED efficiency and update to the latest lighting technology with incentive discount whilst an extra charge as a penalty is applied to cover the remaining financial cost if the leasing contract is terminated before the term, and the customer is strongly recommended to take new leasing contract with a latest and most efficient products at the end of the leasing agreement with an option for the customer to continue to use the leasing equipment with a flat maintenance charge.

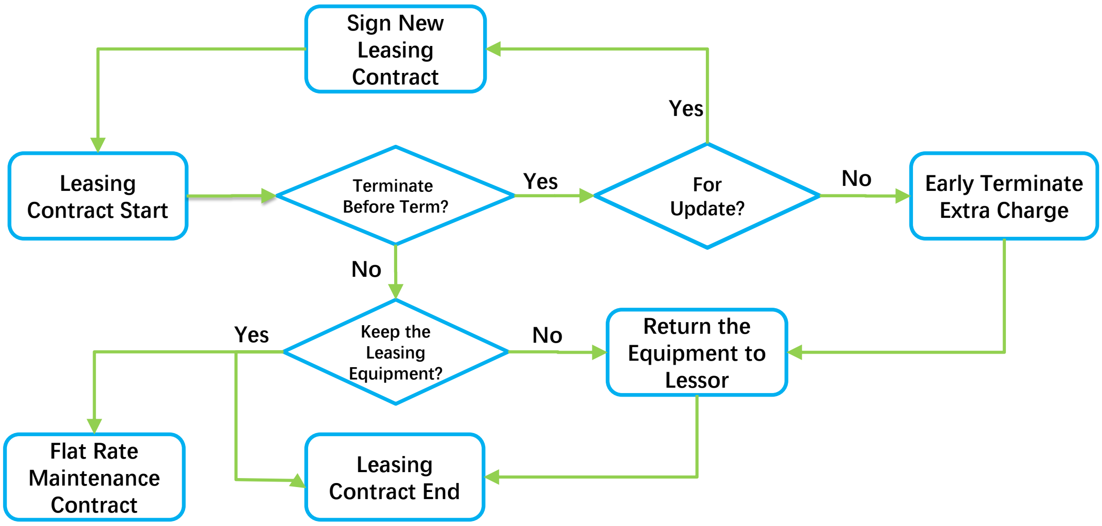


Figure 5.13 Leasing contract flow chart

In summary, leasing service shall provide the following benefits:

- Reduces capital requirement for business, especially small and medium enterprises with limited cash flow.
- Results in more business opportunities and revenue growth due to a flexible financial plan for the end user.
- Affordable leasing service as its financial cost will be covered by the energy bill saving by using the latest LED technology.
- Increasing the user experiences regarding the maintenance and upgrading of the lighting equipment.
- Increases the recycling rate and lift cycle of lighting equipment.

- Reduces the manufacturer's waste recycle and disposal cost.

- Reduces the energy consumption due to the high efficiency of the lighting product using the latest LED technology

- The contract is flexible for adjusting and terminating regarding different business needs.

A range of leasing service activities is planned to finalise and implement this new business model, including:

Business partner identification. The case company will attend the largest lighting equipment fair ('Light+ building 2020') held in Frankfurt aims to showcase the newly designed sustainable product (Arcus II) and promote the leasing and get initial feedback to finalise the business plan (Rescheduled due to Covid-19).

Business to Business (B2B) customer identification. The focal company will also attend Facilities Show (Rescheduled to 18–20 May 2021 due to Covid-19) aiming to market the leasing service and identify the potential customers.

5.4 Sustainability Evaluation

5.4.1 Life Cycle Assessment

5.4.1.1 Goal

The goal is to compare the overall environmental performance between the previous and newly designed LED lighting products (ARCUS-Compact and ARCUS-II) and obtain an understanding of how the environmental profile affected by adopting a sustainable design.

5.4.1.2 Functional unit

The functional unit under comparison is environmental impact under 1 unit of both luminaires' lifetime (40000h). The luminaires under study including two industrial LED low bays from Kosnic Lighting LTD (UK), one is an existing product in the market (ARCUS-Compact), the other one is newly developed product (ARCUS II) with sustainable design methods. Both of the luminaires can be applied in general industrial areas, such as manufacturing workshops, warehouses, leisure facilities, and retail environments. The technical specifications are listed in Table 5.3.

Table 5.4 Technical specifications of comparative LCA

Product Name	ARCUS II	ARCUS-Compact
Power	100W	100W
Voltage	200-240V 50-60Hz	200-240V 50-60Hz
Beam Angle	polarized	120
CCT (K)	6500	6500
Luminous Flux (Lm)	12000lm	11500lm
Detentions (Mm)	681*87*74	600*327*84

CRI	>83	>80
Lifetime (H)	40000	40000
Power Factor	0.96	0.95
Ambient Temp (°C)	-20 to 40	-20 to 40

5.4.1.3 System boundary

All life cycle stages are considered in the system boundary, including raw material extraction, production of basic materials, production of the components, LED lighting assembly, packaging, distribution (transportation) and EoL treatment. In the manufacturing stage, components and sub-systems production and assembly are considered, including raw material acquisition, the product assembly, energy consumption, waste/emissions generation and disposal during manufacturing. The packaging and transportation activities during production are within the boundary as well. The LED lighting product is manufactured in China (Hangzhou) and then shipped to the UK for wholesaling. Energy consumed during the use stage was also taken into account, it was assumed that the LED lighting product would serve until the end of its useful life (40000 hours).

5.4.1.4 Inventory data

The data of material use, manufacture processes, and energy consumption were acquired from the manufacturer. The background data, such as raw material extraction and production of the basic materials were derived from the Ecoinvent 3.5 database (Ecoinvent, 2018). The input data are listed in Table 5.4. The electricity usage scenario is referred to the UK context as well as the EoL treatment, which is considered in compliance with the WEEE directive. The shipping distance, Hangzhou to London (UK), is obtained using Google Map information.

Table 5.5 Inventory data of compared industrial LED products

Product	Assembly Component	Material	Amount	Unit
ARCUS-II	Electronic control unit	LED optics	0.25	kg
		Aluminium	0.035	kg
		Plastic (junction board)	0.013	kg
		Steel (base module)	0.545	kg
		Wire board	0.42	kg
		Plastic (LED driver)	0.033	kg
	Fasten member	Nickel coated iron	0.0734	kg
	Housing	Steel sheet (housing)	1.525	kg
		Plastic sheets (plastic members)	0.2212	kg
		Plastic (lens)	0.4	kg
	Packaging	Paper printed board box	0.96	kg
		Plastic film	0.0003	kg
		Paper	0.0004	kg
		Plastic form	0.054	kg
	Electricity		4000	kW*h
	Shipping		52896	kg*km
	Recycle	Steel	2.07	kg
		Plastic	0.6212	kg
	Electric devices		1.1	kg
	General waste		0.099	kg
	Housing	Plastic	0.29	kg

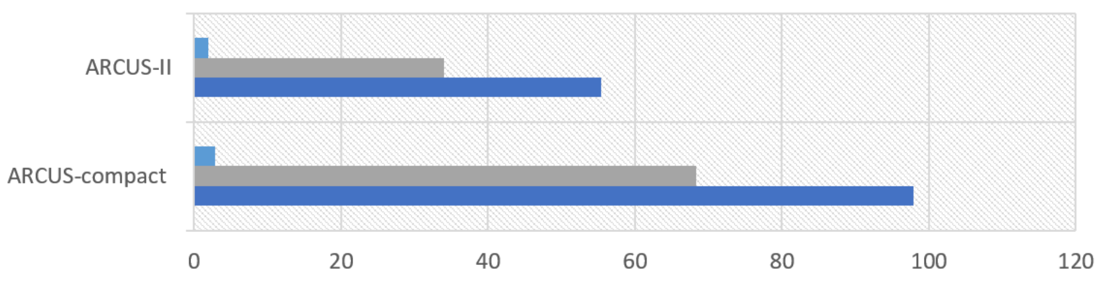
		Steel	2.199	kg
ARCUS-compact		Aluminum	1.1	kg
	LED driver	Plastic	0.172	kg
		Printed circuit board	0.688	kg
	LED lighting board	Led	0.32	kg
		Aluminum	0.012	m2
	Junction Box	Plastic	0.02	kg
	Press button	Plastic	0.007	kg
	Fasten members	Steel	0.07838	kg
		Plastic	0.0016	kg
	Packaging	Printed board box	1.17	kg
		Plastic film	0.0003	kg
		Paper	0.0004	kg
		Plastic form	0.066	kg
	Electricity		4000	kW*h
	Shipping		56451.96	kg*km
	Solid waste		5.3207	kg
	Waste paperboard		1.8537	kg

5.4.1.5 Life cycle impact assessment

The assessment models of are developed with openLCA in line with the Ecoinvent 3.5 database (Ecoinvent, 2018). ReCiPe Hierarchist (Goedkoop et al., 2009) is selected for the comparative LCA study since it’s one of the most recent and harmonized LCIA approaches available (Huijbregts et al., 2016), also, it can combine LCA results as a single score via weighting, which allows user to easily compare the environmental impact of different products or scenarios (Kalbar et al., 2017). In addition, unlike other methods (such as Eco-Indicator 99, EPS Method, LIME, and Impact 2002+), ReCiPe does not include potential impacts from future extractions in the impact assessment but assumes such impacts have been included in the inventory analysis (Huijbregts et al., 2016). Endpoint assessments were conducted which is based on the three endpoint impact categories, namely ecosystems, resources and human health. Normalisation and weighting methods are applied, i.e. 'World ReCiPe H/A (person/year)', the single score of the three categories are gained and aggregated as the overall environmental impact score of each assessed unit.

5.4.1.6 Results and discussions

The Environmental Impact Assessment results indicate the environmental performance of the newly designed product (ARCUS-II) improved by 46% compares to the existing product (ARCUS-Compact), from 169 Pt to 91 Pt (by aggregating the endpoint single scores, e.g. 55.46+34+1.87=91.33). The environmental impact on the three categories of the new model is 55.46, 34 and 1.87 for Resources, Human Health and Ecosystems impact category respectively, which improved 43%, 50% and 35% on the impact categories accordingly in comparison to those of ARCUS-Compact. Figure 5.14 presents the single score results of the three impact categories of the two variant products. Among the three impact categories, 'resources' is most affected (key impact category), which contribute 60% and 57% of the total impacts of ARCUS-II and ARCUS-compact respectively, followed by 'human health', 'ecosystems' is least affected revealed from the assessment results.



	ARCUS-compact	ARCUS-II
Ecosystems	2.89	1.87
Human Health	68.32	34
Resources	97.93	55.46

Figure 5.14 Endpoint single score results

A Further analysis inside the contribution tree of 'resources' are presented in the Sankey diagram with 10% cut-off (Figure 5.15), the allocation of impact contribution varies within the two products. The key impact category is dominated by production/assembly and use stage for both products since the two stages are high energy and material consumption stage. In the existing product (ARCUS-Compact), production/assembly stage has a higher contribution to its total impact in comparison of use stage, i.e. about 58% to 42%, which mainly due to the production of electronic devices. In contrast, the main contributor (75%) to the impact on resources within the newly designed product (ARCUS-II) is electricity production during usage, only about 25% of the impact is contributed form production/assembly stage. A similar pattern is also laid in other endpoint impact categories. Given the use scenario and the production method of the electricity is the same for both variants yet accounted for different percentage of those product's total impact (42% for ARCUS-compact and 75% for ARCUS-II), thus the impact of ARCUS-II has a significant drop from the production stage (58% to 25%) compared to ARCUS-compact, that is, the LED lighting product developed utilising sustainable method has an outstanding overall environmental improvement owing to the impact reduction during the production stage.

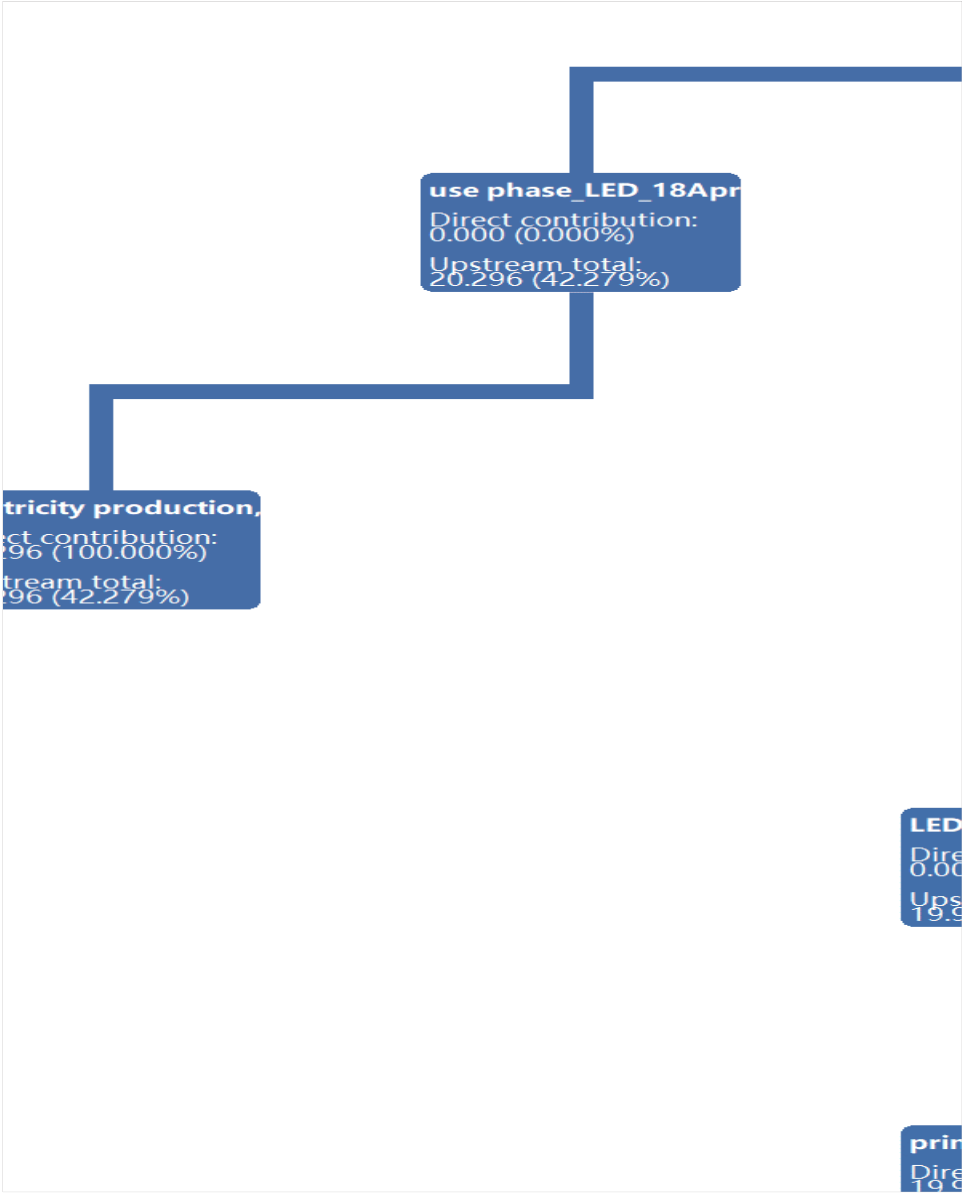


Figure 5.15 Sankey diagram under impact category 'resource' of the compared products (10% cut-off)- ARCUS-compact

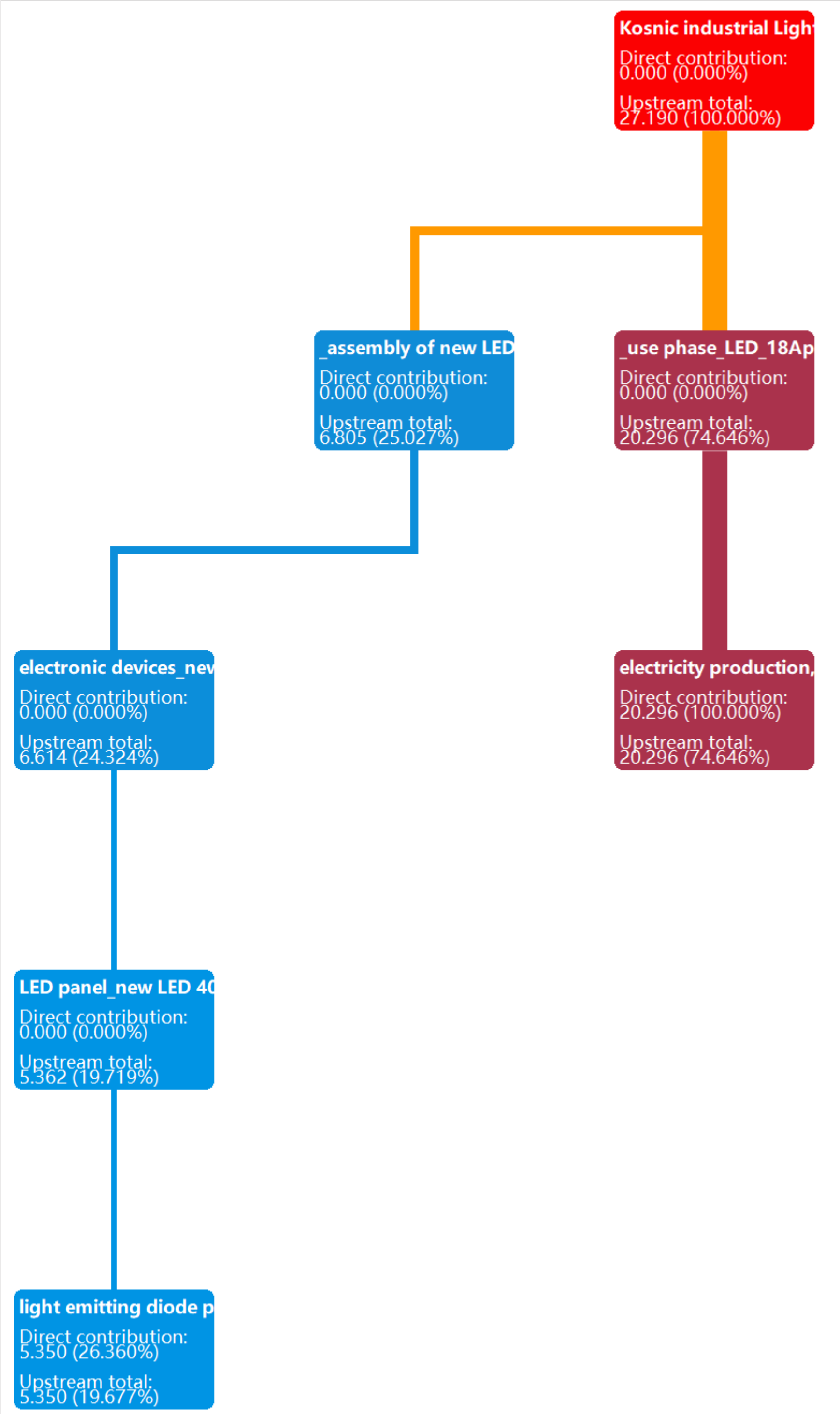


Figure 5.16 Sankey diagram under impact category 'resource' of the compared products (10% cut-off)- ARCUS-II

The standard version of ARCUS-II is selected in this comparison LCA. It is expected that in a real application context the newly designed product will perform a better environmental profile in a longer given time, because it might merely need to change few components whilst the former product has no changing option but to replace the entire luminaire if failure accrues. In addition, some qualitative eco-features are unable to convert to a numeric value, and, consequently, cannot be assessed in an LCA process, such as easy to transport, easy to disassemble and repair, reduction of delivering space and packaging material, etc. These eco-features have enhanced the overall sustainability on a great scale. However, these features are unable to be taken into account in the assessment due to the quantitative nature of LCA methodology.

5.4.2 Socio-economic sustainability

There are studies that attempted to put forward the frameworks and methods for the evaluation of sustainable PSS, yet the application of those methods remained limited (Maxwell and van der Vorst, 2003; Chou et al., 2015; Omann, 2003). The leasing service was initially proposed based on the results and analysis of the environmental and social life cycle assessment to address the risks identified, therefore, theoretically, the product and service are expected to be environmentally friendly and socioeconomically beneficial by implementing the proposed service. Indeed, the proposed sustainable product and service achieve the 3BL of sustainability which supported by the following reasons.

The leasing service is based on a sustainable industrial LED lighting product that enables a longer lifetime and higher energy efficiency. With providing the service, it is more predictable in material flow from a stewardship perspective, subsequently maximize material and energy efficiency from a lifetime perspective, which also consented in several environmental evaluation studies of PSS (Mont, 2003; Roy, 2000). In addition, leasing of LED lighting product is considered within the scope of 'green lease', which aims to ensure the renting property has been constructed and managed with sustainable technologies (CMS, 2011).

Indeed, the new sustainable product and service achieve the TBL of sustainability, an example is presented where a site was looking to change the existing illumination plan for the new sustainable LED lighting products (Arcus-II) and its service. Table 5.5 lists the environmental and economic benefits for the new product and service system.

Table 5.5 Environmental and economic benefits for the new product and service system

	Existing Illumination Plan	**Illumination Plan with Proposed Sustainable Product and Service**	**Savings Per Year**
Cost of Electricity Per Kw*H	£0.15	£0.15	
Hours Per Year	3,000	3,000	
Area	Warehouse 1	Warehouse 1	
Quantity	50	50	
Replacement LED Fitting Type	4 x 54w Fluorescent T5 Low Bays	150w Arcus II - KLBA150L1	
Replacement LED Fitting Wattage	236	150	**4300**
LED Fitting Life Hours	12,000	40,000	
LED Electricity Per Year £	£5,310.00	£3,375.00	**£1,935.00**
LED Fitting Costs Per Year	£402.50	£277.50	

LED Fitting + Electricity Costs Per Year	£5,712.50	£3,652.50	**£2,060.00**
LED Kilowatts Per Year	35,400	22,500	**12,900**
Environmental impact in CO_2	18,833	11,970	**6,863**

	Year 1	**Year 2**	**Year 3**
Existing Costs (Lamps & Electricity)	£5,712.50	£5,712.50	£5,712.50
LED Costs (Purchase in Year 1 + Elec Costs)	£6,825.00	£3,375.00	£3,375.00
Payback Period Months		**18**	
Saving Per Year		**£2,337.50**	
Saving over life of the LED		**£31,166.67**	

For the same illumination effect, changing the existing fitting to the proposed lighting leasing service can have multiple direct benefits, for instance, it can save the warehouse 12900 KW energy consumption which accounts for £1935 electricity bill and 6863 CO2 emissions; up to £2337.5 per year and £31166.67 over the life of the LED can be saved when adopting a 3-year payment plan.

Furthermore, social dedication and socio-economic aspects have been addressed by the company and the product and service. The company gains prominent recognition in the corresponding industry sector regarding social responsibility and product quality. Kosnic joined the elite group of Accredited Suppliers to The Carbon Trust, the market-leading scheme for high-quality energy-efficient equipment and renewable technology suppliers worldwide. The welfare of the employees in the case company is valued as satisfactory. Thanks to the modular design, the assembly process has been significantly simplified and speeded-up, and hence the assembly cost is reduced to about 30% while the workload of the workers is relieved. The cradle-to-cradle life cycle development approach enhances the socio-economic benefits along with the value chain actors within the sustainable innovation. New jobs are created due to the new roles required by the PSS, and all stakeholders benefit with a healthy recurring profit stream. By creating value from waste, recycling responsibility in mind, the company has been enhancing the reusability of materials, tools and facilities, which minimises waste disposal. It encourages its sub-contract manufacturer to dedicates sustainable product/service innovation and provide the best possible solutions with reliable products. The collaboration of all partners under this leasing model aims for the best user experience of the client, with the bespoke illumination plan, the interactions between the manufacturer and end user are much closer.

For the end user, a significant amount of cost saving is achieved by adopting the proposed product service thanks to the cost reduction of energy, maintenance and EoL disposal. The end user could also entitle to declare a certificate regarding the sustainability of the property results from the energy reduction during the contracted period. In addition, it removes all the hassles, financial uncertainties, technical knowledge gaps and out of service risks from them. Finally, the sustainable product and service facilitate the end user adopting a responsible and sustainable consumption, which is a key bridge between sustainable product/service and the implementation of sustainability.

5.5 Concluding remarks

A case study is conducted and presented utilising the proposed approach, a sustainable industrial LED lighting product and its product service are developed. The main contents and findings in this chapter are summarised as follows:

- Applying the approach to the development of the sustainable product and the service as a bundle in the same stage. The case study demonstrated how to link between product development and product service, how to 'design for service' and how the sustainable product can be integrated in the sustainable service are brought out and demonstrated.

- A sustainable industrial LED lighting product and service are developed by utilising the proposed approach. The sustainable lighting product has an innovative modular design and ultra-high efficiency and longevity, which is designed for its service. There is no such product in the market, which is unique.

- The sustainability performances of the sustainable LED lighting product and service are assessed. The environmental assessment results indicate that the sustainable LED lighting product developed with the proposed approach (ARCUS-II) presents a 46% lower environmental impact. The sustainable service based on the sustainable LED lighting product is evaluated as environmentally friendly and socioeconomically beneficial. The proposed product and service has the capacity of benefit multiple stakeholders, such as promoting workers' welfare, cutting cost for manufacturer and customers (end users) with prominent services and, all stakeholders benefit with a healthy recurring profit stream.

Chapter 6 - Sustainable product Development and Service Approach for Application in Domestic LED Lighting Products

6.1 Introduction

This chapter is a case study of developing an environmentally sustainable domestic LED lighting product by utilising the proposed sustainable product and service development approach. This case study aims to demonstrate the approach with an alternative sustainable goal, i.e. environmental aspect of sustainability, including eco-design and eco-production, is the paramount goal for the case company. In the chapter, the sustainable product conceptual construction approach is applied and demonstrated particularly, of which, LCA of five domestic lighting products that currently available in service of the case company are conducted. Based on the LCA results, the sustainability requests for lighting products are derived and then embedded in the product design specification to ensure the eco-design features of the product to be developed. A new sustainable lamp is designed according to the PDS and manufactured; the environmental performance of the new product is evaluated. Comparing the LCA results of the new product with those of the existing ones, the newly designed lamp presents a better environmental performance, i.e. from 27% to 58% lower impact than the existing ones.

6.2 Application of Sustainable product conceptual construction approach into environmentally sustainable domestic LED lighting product

6.2.1 Innovation goal of the case company

ONA PRODUCT SL (ONA), is a Spanish SME manufacturer of lighting products, specialising in domestic and contract lighting for hotels, premises of leisure, office, and public places (https://ona.es/). The goal of ONA is to develop domestic LED lighting products that have superior eco-friendly features than their existing products, achieve sustainable production and eco-shopping of domestic LED lighting products on their company-owned website.

6.2.2 Application of sustainable product conceptual construction approach

After defining the sustainable innovation goal, the operation processes and methods are adapted according to the goal, which is outlined in Figure 6.1. First, evaluation of the environmental profile of five existing LED lighting products available in the online shop (by the time of the research conducted, there are five products available on their website), including Embolic, Panau, Marble, Ele and Cobalt, were conducted by utilising E-LCA methodology and technique. According to the results and interpretation, design reflections aiming at environmentally sustainable LED lighting product design are brought out and integrated in the PDS in conceptual design. Subsequently, the eco-design of LED lighting product is carried out in accordance with product design procedure. Finally, the design can be confirmed if the environmental performance of the new product is prior to the previous products via LCA techniques and tools.

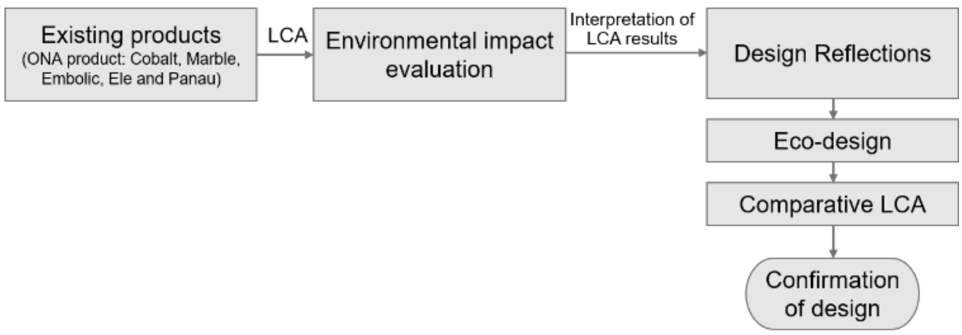
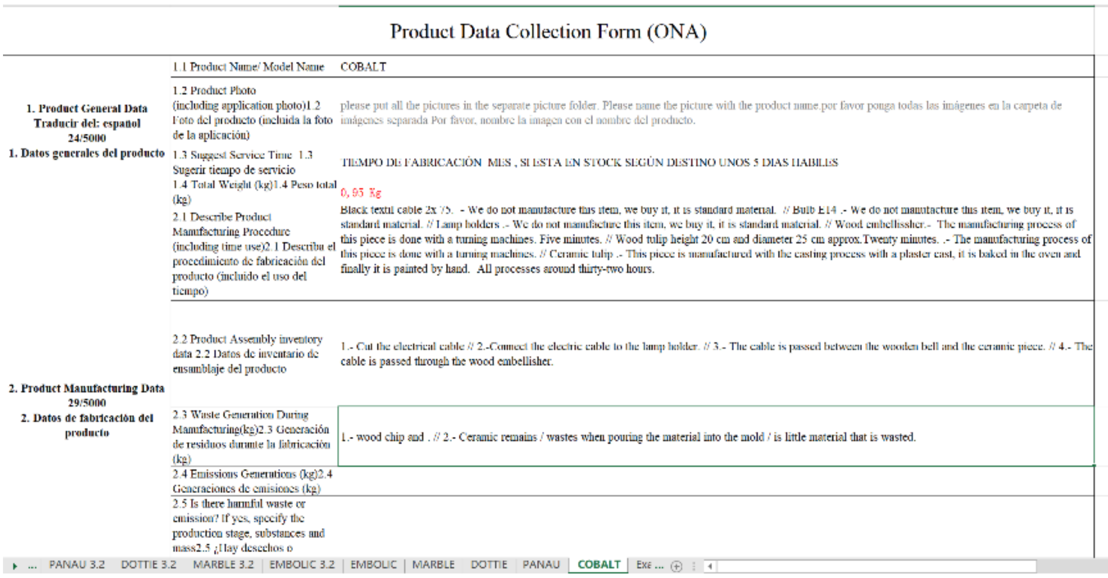


Figure 6.1 The research process and method applied in developing environmentally sustainable domestic LED lighting product

6.2.3 Data collection

The data of material use, information of pre-product, manufacture process, technical parameters that are related to the environmental assessment and energy consumption of the five LED lighting product were collected. The data collection method and forms (detailed in chapter 3) were utilised, the data collected formation including the answers to the questions in the data collection form and technical drawings and descriptions for each product. Examples of the returned (completed) data collection information are shown in Figure 6.2 and 6.3, the detailed inventory data for assessment is presented in Table 6.2.



Product Data Collection Form (ONA)

1. Product General Data Traducir del: español 24/5000 1. Datos generales del producto	1.1 Product Name/ Model Name	COBALT
	1.2 Product Photo (including application photo)1.2 Foto del producto (incluida la foto de la aplicación)	please put all the pictures in the separate picture folder. Please name the picture with the product name.por favor ponga todas las imágenes en la carpeta de imágenes separada Por favor, nombre la imagen con el nombre del producto.
	1.3 Suggest Service Time 1.3 Sugerir tiempo de servicio	TIEMPO DE FABRICACIÓN MES , SI ESTA EN STOCK SEGÚN DESTINO UNOS 5 DIAS HABILES
	1.4 Total Weight (kg)1.4 Peso total (kg)	0, 95 Kg
	2.1 Describe Product Manufacturing Procedure (including time use)2.1 Describa el procedimiento de fabricación del producto (incluido el uso del tiempo)	Black textil cable 2x 75. - We do not manufacture this item, we buy it, it is standard material. // Bulb E14 .- We do not manufacture this item, we buy it, it is standard material. // Lamp holders .- We do not manufacture this item, we buy it, it is standard material. // Wood embellissher.- The manufacturing process of this piece is done with a turning machines. Five minutes. // Wood tulip height 20 cm and diameter 25 cm approx.Twenty minutes. .- The manufacturing process of this piece is done with a turning machines. // Ceramic tulip .- This piece is manufactured with the casting process with a plaster cast, it is baked in the oven and finally it is painted by hand. All processes around thirty-two hours.
2. Product Manufacturing Data 29/5000 2. Datos de fabricación del producto	2.2 Product Assembly inventory data 2.2 Datos de inventario de ensamblaje del producto	1.- Cut the electrical cable // 2.-Connect the electric cable to the lamp holder. // 3.- The cable is passed between the wooden bell and the ceramic piece. // 4.- The cable is passed through the wood embellisher.
	2.3 Waste Generation During Manufacturing(kg)2.3 Generación de residuos durante la fabricación (kg)	1.- wood chip and . // 2.- Ceramic remains / wastes when pouring the material into the mold / is little material that is wasted.
	2.4 Emissions Generations (kg)2.4 Generaciones de emisiones (kg)	
	2.5 Is there harmful waste or emission? If yes, specify the production stage, substances and mass2.5 ¿Hay desechos o	

... PANAU 3.2 | DOTTIE 3.2 | MARBLE 3.2 | EMBOLIC 3.2 | EMBOLIC | MARBLE | DOTTIE | PANAU | COBALT | Exe ...

Figure 6.2 Example of data collection form

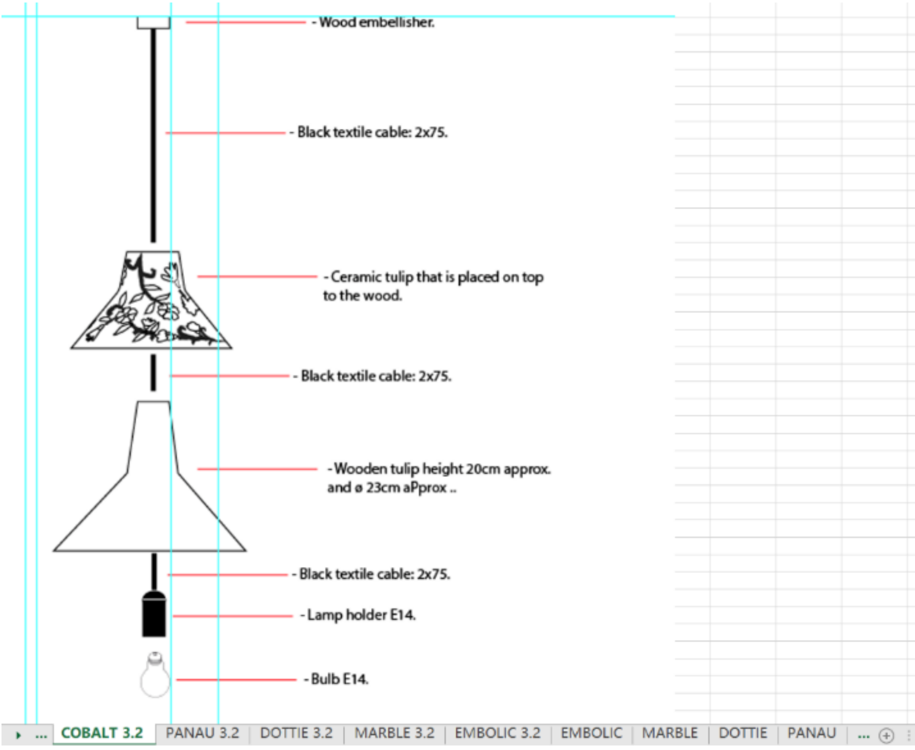


Figure 6.3 Example of data collection form-technical drawings

6.2.4 Environmental life cycle assessment

LCA is an effective tool that facilitates the evaluation of environmental impact through a product's lifecycle and plays a significant part in environmentally responsible product innovation. In this study, five current LED lighting products from ONA were assessed by utilising screening LCA techniques in order to identify issues and opportunities to implement into domestic LED lighting eco-design.

6.2.4.1 Goal

The goal is to evaluate the overall environmental impacts of ONA's current LED lighting products through their product lifecycles, identify key processes and key varieties behind the results.

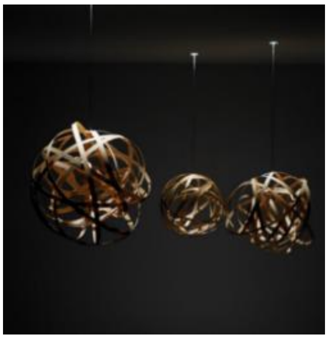
6.2.4.2 Functional Unit

The functional unit under assessment are one unit of each of the five LED lighting products, namely Embolic, Panau, Marble, Ele and Cobalt. The five LED lighting product are all domestic lighting product including ceiling lights and table lamps, the product information is shown in Table 6.1.

Table 6.6 Product information of the LED lighting product under assessment

Name	Product Figure	Description	Specification
Cobalt		Cobalt is a Pendant lamp in which wood and ceramics are combined. The combination gives this lamp a seal of distinction. With the floral drawing in blue of the ceramic is inspired by the Valencian ceramics.	• Light body height: 20cm. • Diameter: 23cm.

Marble		Table lamp of large dimensions joined with a cylindrical foot of black marble veined in white and a large glass tulip, both elements make this piece sculpture with great strength and personality.	• Total height: 54cm. • Diameter base of marble: 13.5cm. • Diameter glass diffuser: 21cm.
Panau		Pendant lamp made with natural fibres. With an original design, this lamp is suitable for any corner of a house, providing a great personality to the room and pleasant light.	• Height: 50cm. • Finish: natural. • System: E27.

Embolic		Good craftsmanship with offering a warm and magical product that skims the sculptural object. The point of light illuminates the tangle creating unique environments among its shadows. The tangle is solved by randomly interlaced wooden slats suspended from a steel wire illuminated from the ceiling.	• Height of the led spotlight: 8cm. • Diameter of the wooden tangle: 40-45cm.
Ele		The aesthetics of this table lamp is characterized by its simplicity. Designed with straight lines and	• Height: 43cm • Width: 40cm. • Screen height: 22cm. • Finishing

	with a shape that reminds us of the consonant L, it makes it a great looking luminaire in an apartment where it is placed.	structure: matt metal. • Finishing screen: white parchment.

6.2.4.3 System Boundary

All life cycle stages were taken into consideration in the assessment, including raw material extraction, production of basic materials, production of the components, assembly, distribution (transportation) use stage and end-of-life (EoL) treatment.

6.2.4.4 Inventory Data

The lighting products were manufactured and assembled in ONA's plant, Spain. The data of material use, information of pre-product, and energy consumption were acquired through the data collection form and interviews with the company engineers and managers. The background data, such as raw material extraction and production of the basic materials were derived from the Ecoinvent 3.1 database, the inventory data are listed in Table 6.2. It is assumed that the LED lighting products will serve until the end of their useful lives (i.e. 40000 hours).

Table 6.7 Inventory data of the five LED lighting products

Marble		Embolic		Panau		Cobalt		Ele	
marble base	2.13 kg	wood	1.136 kg	wood	1.136 kg	wood piece	0.025 kg	Aluminum	3.755 kg
glass tulip	2.2kg	cable	0.7kg	cable	0.7kg	cable	0.058 kg	Cable	0.094 kg
cables	0.15kg	road transportation	674.5 kgkm	plastic	0.025 kg	ceramic part	0.542 kg	Plastic	0.316 kg
metal parts(steel)	0.155 kg	Electricity, low voltage	280kW/h	metal piece	0.05kg	wood part	0.291 kg	lamp frame	0.028 kg
road transportation	1547.8kgkm	end-of-life (multiple waste treatment)	1.836 kg	Road transportation	674.5 kgkm	lamp holder	0.013 kg	steel parts	0.014 kg
Electricity, low voltage	400kWh			Electricity, low voltage	400kW/h	road transportation	1355 kgkm	Electricity, low voltage	400kWh
end-of-life (multiple waste treatment)	4.36kg			end-of-life (multiple waste treatment)	1.836 kg	Electricity, low voltage	400kWh	Road transportation	1493.5kgkm
						end-of-life (multiple waste treatment)	0.95kg	end-of-life	4.307 kg

6.2.4.5 Life cycle Assessment

The Online LCA Platform (http://h2020.circ4life.net/) is an online software tool that utilised to develop the assessment models, see Figure 6.4. The Platform is developed by CIRC4Life (CIRC4Life,2018) research project to provide simplified and user-friendly LCA calculations, which especially to support industrial practices including electrical and food industries. The platform is developed in line with international LCA code of conduct ISO 14040 (ISO 2006) with the incorporation of the Ecoinvent database 3.1 (Ecoinvent 2007). Mainstream life cycle impact assessment (LCIA) methods, such as ReCiPe and CML are build in for the impact calculation.

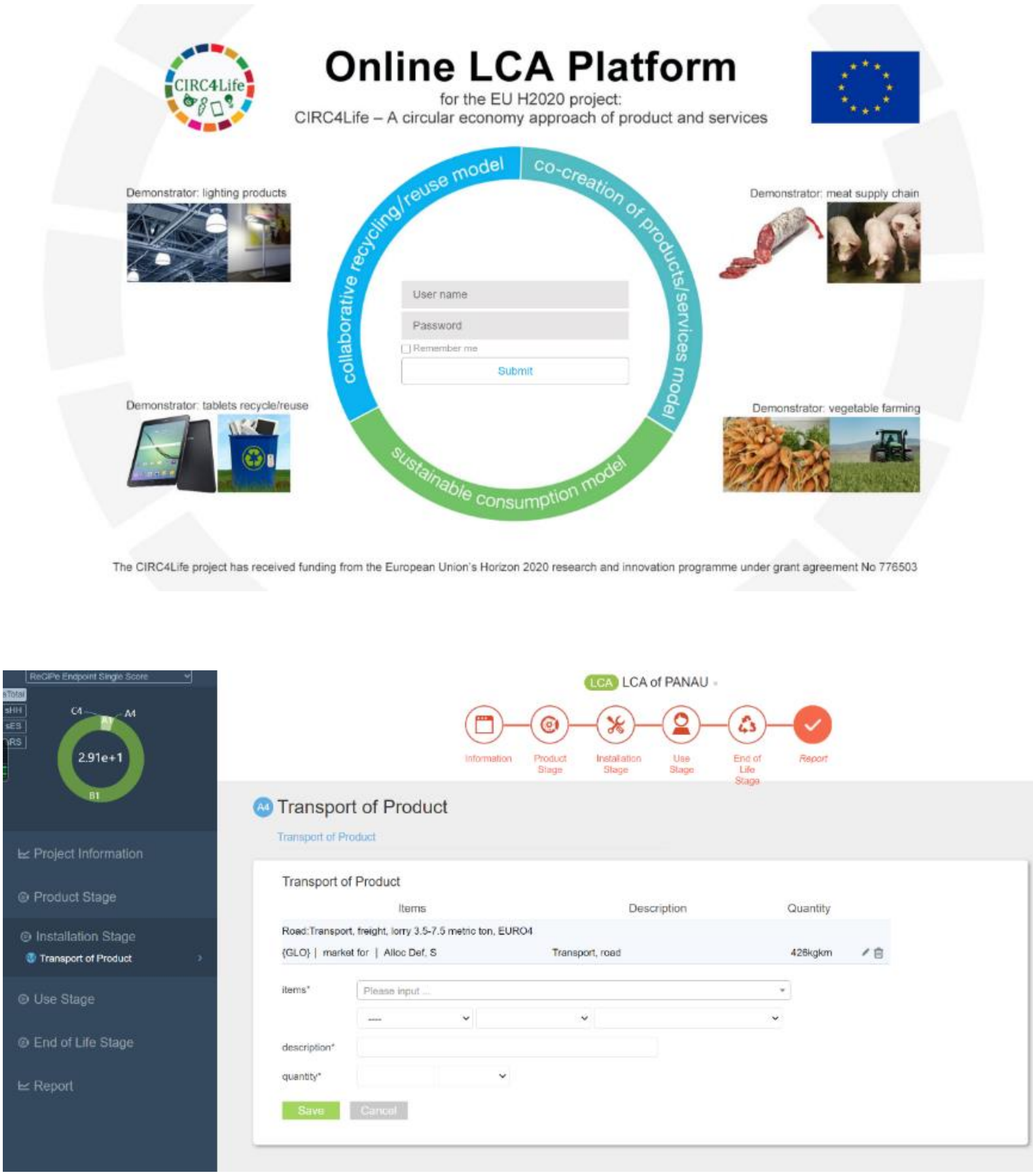


Figure 6.4 The online LCA platform

Case-specific data were adapted to the database to develop the assessment models. LCIA were conducted by using ReCiPe (midpoint and Endpoint) method (Goedkoop et al. 2009). The endpoint method characterizes 17 midpoint environmental categories into three endpoint impacts, namely Ecosystem, Human Health, and Resources via weighting and normalisation.

Then the single score results were adopted for easy comparison, in which scores of the three impact categories were added up to obtain one single score to represent the total environmental impact of a product.

6.2.5 Results interpretation and reflection

6.2.5.1 Results

Table 6.3 and Table 6.4 show the midpoint results and the single score results respectively. The results show that Ele has the highest negative score (39 Pt) amongst the five LED lighting products, followed by Panau and Marble (37.7Pt and 37.6 Pt respectively). Cobalt and Embolic have relatively fewer impacts, which are 22.5 Pt and 27.4 Pt respectively. It is considered the results have interrelations to weight and the number of materials used, see the later section for interpretation.

Table 6.8 Midpoint results of the five LED lighting product

Explanation	Unit	Panau	cobalt	marble	embolic	Ele
Climate change Human Health	kg CO2 eq	3.26E+02	1.96E+02	1.98E+02	4.04E+02	7.38E+01
Ozone depletion	kg CFC-11 eq	6.03E+01	1.83E+01	3.99E+01	2.20E+02	4.57E+02
Human toxicity	kg SO2 eq	5.64E+00	2.18E+00	4.44E+00	1.72E+01	4.28E+01

Photochemical oxidant formation	kg P eq	1.83E-01	1.10E-01	1.18E-01	5.54E-02	1.08E-01
Particulate matter formation	kg N eq	1.15E+01	5.20E+00	5.70E+00	2.55E+01	1.39E+02
Ionising radiation	kg 1,4-DB eq	1.35E+02	8.01E+01	8.67E+01	7.16E+01	2.35E+02
Climate change Ecosystems	kg NMVOC	1.93E+04	7.75E+03	9.78E+03	4.35E+04	4.61E+05
Terrestrial acidification	kg PM10 eq	1.13E+00	6.58E-01	6.81E-01	8.95E-01	4.27E-01
Freshwater eutrophication	kg 1,4-DB eq	2.01E-02	1.17E-02	1.45E-02	2.06E-02	5.88E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	1.03E+01	6.24E+00	6.50E+00	3.07E+00	7.78E+00
Freshwater ecotoxicity	kg 1,4-DB eq	9.13E+00	5.53E+00	5.64E+00	2.82E+00	6.82E+00
Marine ecotoxicity	kBq U235 eq	5.56E+01	3.22E+01	3.45E+01	3.01E+01	5.19E+01
Agricultural land occupation	m2a	1.48E+01	8.90E+00	8.92E+00	5.68E+00	4.89E+00

Urban land occupation	m2a	1.99E+00	1.21E+00	1.27E+00	3.48E+00	1.48E+00
Natural land transformation	m2	4.06E-02	2.35E-02	2.35E-02	2.98E-02	8.24E-02
Water depletion	m3	2.40E+00	1.44E+00	1.45E+00	7.23E-01	9.60E-01
Metal depletion	kg Fe eq	2.09E+01	1.01E+01	1.13E+01	3.66E+01	1.67E+02
Fossil depletion	kg oil eq	8.01E+01	4.83E+01	4.85E+01	7.81E+01	1.87E+01

Table 6.9 Endpoint single score result of each product

Product Name	**Single score result（Pt）**	**Product mass（kg）**	**Number of materials used**
Cobalt Lamp	22.5	0.95	4
Marble Lamp	37.6	4.36	4
Panau Lamp	37.7	1.1	4
Embolic Lamp	27.4	1.84	2
Ele	39	4.39	4

The total environmental impacts were predominated by the use stage in comparison to other life cycle stages, which result from the production and consumption of electricity during the use stage. As shown in Figure 6.5-6.9, the widest strips in each sub-figures represent the impact percentage that the electricity production contributed to the corresponding products, which accounts for 97%, 95%, 88%, 94% and 97% of Cobalt, Marble, Embolic, Ele and Panau's total impact respectively.

Table 6.10 Key processes contribution of each LED product (exclude electricity)

Ele		Panau	
Process	Contribution %	Process	Contribution %
Aluminium alloy	66.46	Cable	90.27
Base (Aluminium)	20.44	Municipal solid waste	4.15
Cable (including socket)	11.61	Transport, road	2.4
plug	1.11	plastic lamp holder	1.36
Lamp frame	0.38	Steel, unalloyed	1.24
Embolic		**Cobalt**	
Process	Contribution %	Process	Contribution %
tangle wood part	57.49	Cable	49.72
Cable	40.35	Ceramic part	26.53
Municipal solid waste	1.31	Transport, road	15.73
Transport	0.85	Municipal solid waste	6.25
		Wood part	1.65
Marble			
Process	Contribution %		
Cable	31.45		
glass lampshade	30.22		
multiple waste treatment	25.71		
Transport	10.28		
metal parts	2.15		

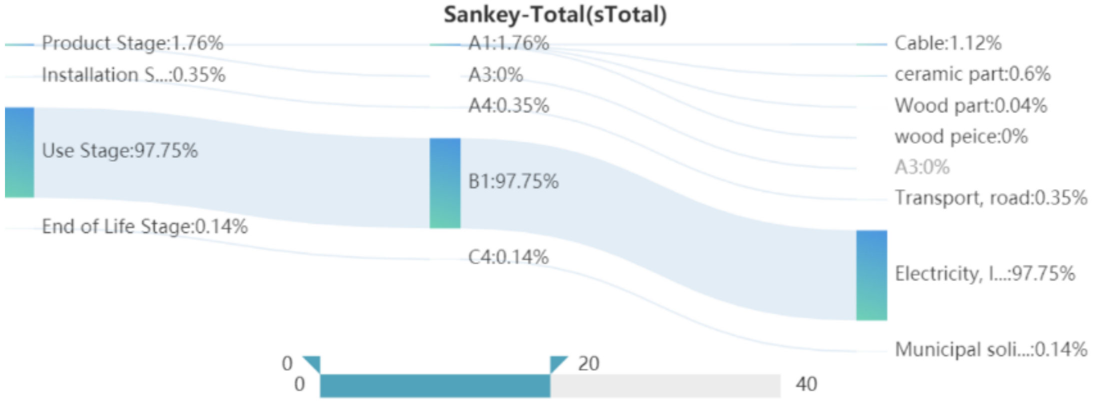


Figure 6.5 Sankey diagram of Cobalt

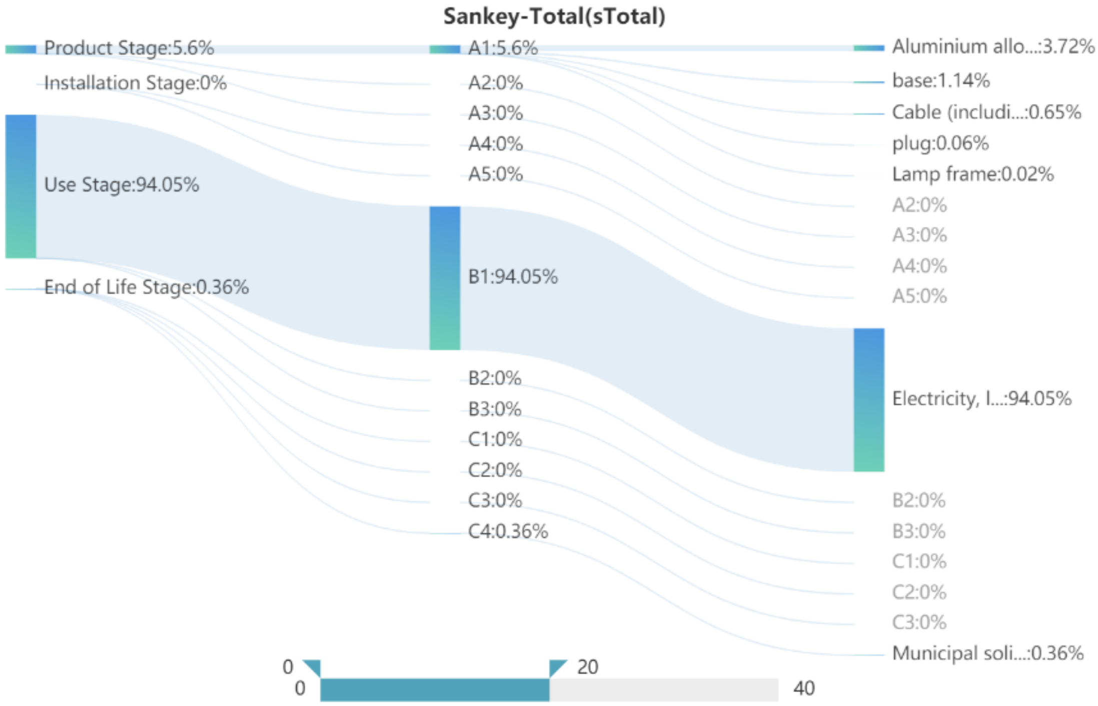


Figure 6.6 Sankey diagram of Ele

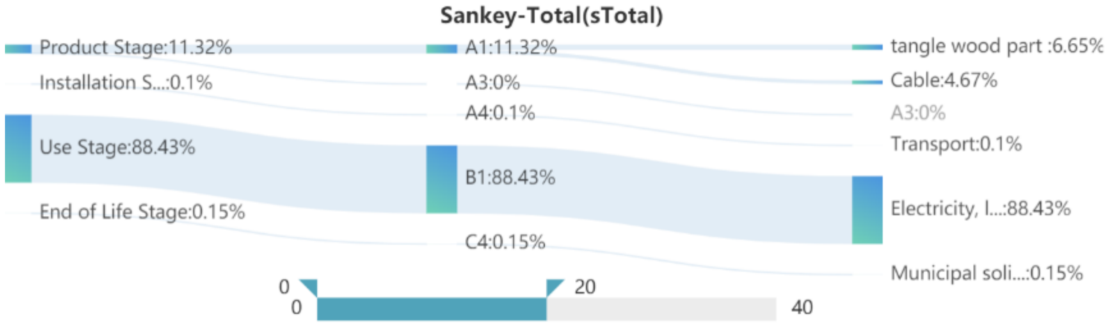


Figure 6.7 Sankey diagram of Embolic

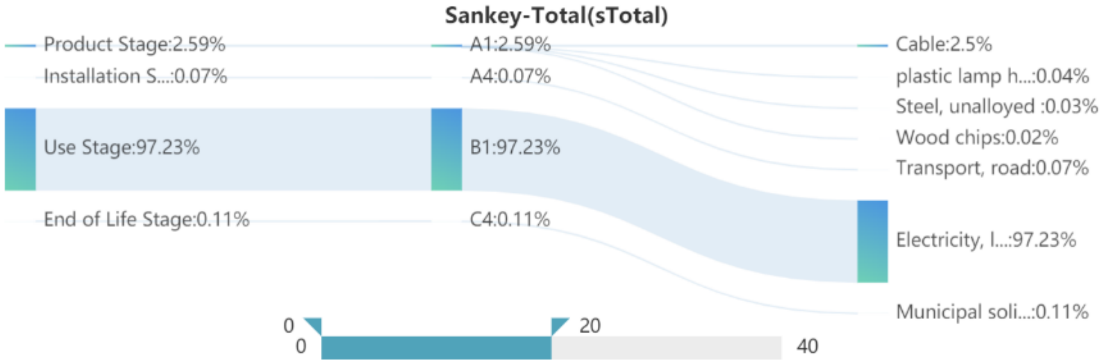


Figure 6.8 Sankey diagram Panau

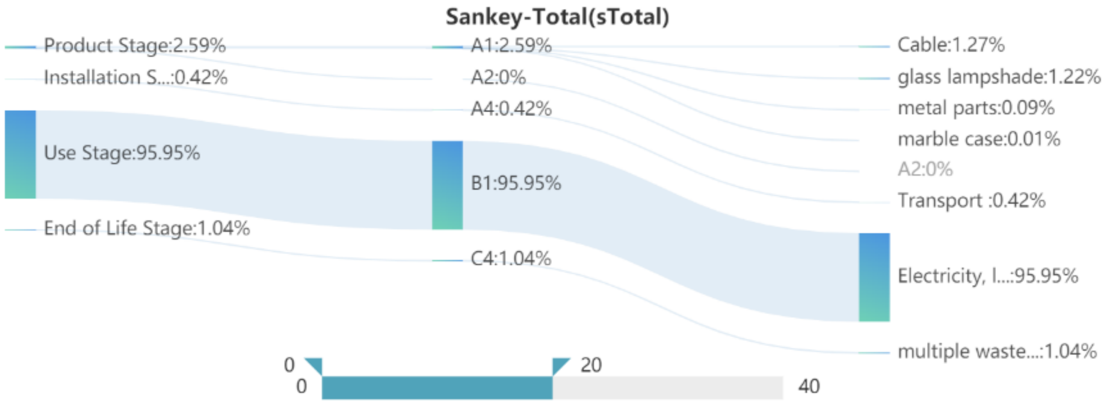


Figure 6.9 Sankey diagram Marble

However, the allocation of impact within the life cycle stages is considered reasonable for LED lighting products and has been proved as the key environmental stage among LED specialised studies (Paolo and Roberto 2014; Jose et al. 2017). Moreover, in the LCA, electricity consumption is calculated by multiplying the service time and the power, therefore the longer the product serves, the more electricity consumption the product requires, and vice versa. In addition, this study aims to identify opportunities to improve product sustainability via product design. Therefore, it is important to set preferences to identify the key processes apart from the use stage.

Table 6.5 lists the key process contribution of LED products excluding the electricity usage. For Ele, the aluminium production including the manufacture of the base parts accounts for the majority of the total impact (80.9% together), followed by cable (11.61%) and other components including plug and lamp frame (1.49%).

In Panau, production of communication cable accounts for significant impact (90.27%), while disposal of the lighting product also plays a role (4.15%) in contributing the total impact due to the light usage of plastic, steel and wood, the impact generated from those materials are minor (2.18% in total).

The tangle wood part and production of cable are the key processes of Embolic's impact, which is 57.49% and 40.35% of the total impact. It is noticed that, apart from the cable which accounts for 49.72% of Cobalt's total impact, the production of the ceramic part, wood part as well as transportation and disposal of the post-consumer product also contribute to more than half of its total impact (50.28%).

Similarly, for Marble, the production of the glass lampshade (30.22%) and end-of-life treatment of the products (25.71%) are the key processes as well as cable production

(31.45%). Transportation of the product is another noticeable process that accounts for 10.28 % of the whole impact due to the product weight and packaging method.

6.2.5.2 Interpretation and Reflection

The LCA results indicate the issues/potential risks behind current products of ONA:

Use a diversity of materials. As seen in Table 6.4, each lamp under assessment consists of 4 kinds of main materials except for Embolic (2 kinds of materials). Although diversity material contrast could help in achieving the aesthetic goals from a design perspective. However, as seen in the results, Embolic has relatively fewer impacts thanks to the simplicity of the material usage (made of 2 kinds of materials) compares to other lamp products in the study. In addition, potential issues may link to the diverse usage of materials which can affect the total environmental sustainability. For example, it might affect choosing the joint method of different assembly parts; increasing the complexity of manufacturing; and the ability of assembly and disassembly.

Complex to manufacture. According to the assessment results, Marble and Panau have almost the same impact (37.6 and 37.7 respectively) which are both consist of 4 kinds of materials. However, due to the complexity of production, Panau shows slightly higher impacts despite the weight is nearly four times less than Marble (1.1 kg and 4.36 kg separately). The energy consumption during production procedures is the main ascription to the high environmental impact.

Product weight. Total lamp weight is another variable that confluences total environmental performance. The results show Marble and Ele have relatively higher impacts (39 and 37.6 respectively) due to heavy in comparison to other lamp products. In contrast, cobalt presents to have the best environmental performance (22.5) amongst the five lamps owing to the lightweight.

Hard to assemble or disassemble. According to ONA, all the lamps are pre-assembled and transported as a whole. In addition, it might increase the complexity of production and hampered the possibility of recycling/ reuse, for instance, it is unable to recycle/reuse if the assembly parts are undetachable despite the material itself is recyclable/ reusable. Furthermore, hard to assemble/disassemble indicates there is a low possibility to repair thus may shorten the service time. It also decreases the efficiency of transportation, which increases transportation costs.

Lacking end-of-life consideration. Lack of end-of-life consideration reflects on choosing the material, joint method, as well as the finishing. Currently, the EoL method for all the lamp products (housing materials) is to dispose at the end-user side. Better EoL solutions of the post-consumer housing materials can be achieved in the design stage which can increase the possibility of recycling/reuse.

6.3 Eco-design of LED Lighting Product

6.3.1 Concept design

Taking the assessment results and reflections into account, product design specifications of the eco-lighting to be designed was brought out in accordance with standard PDS requirement (Pugh 1999) the key characters are listed below in the PDS:

- Low energy consumption during the manufacturing stage (easy to manufacture).
- Prolong the lifespan by enabling repairability, it is expected to have a 10-year lifespan.
- Modular design.
- Easy to assemble/disassemble (consumer can assemble the lamp by themselves).
- Made from low impact materials. Post-consumer/recycled materials are preferred.
- Refine the dimension of the product to reduce weight.
- Fully recyclable at end of life.
- Flat packaging.

Based on the PDS, the new design concepts (DC1, DC2 and DC3) are developed, the proposed eco-features were embodied in the new product with modular-design housing, as shown in Figure 6.10-6.12. The concepts are expected to reduce the environmental impact through design and manufacture; for the materials consideration, the post-consumer or remnants of material that generated from ONA's suppliers in their manufacturing processes is considered to be used as the source of the manufacturing material, the housings are mainly based on the idea of taking as many advantages of the manufacturing/post-customer wastes as possible. In addition, from easy to manufacture and cost-effective as well as eco-friendly points of view, the structure of the lamp housing should be as simple as possible to avoid energy/material input as well as the manufacturing time. The modular design of the poles is the solution to enhance the availability of material options so that more advantage can be taken of the remnants. For those reasons, the housings of three DCs consist of modular strips to avoided complex shapes while achieving a certain aesthetic standard.

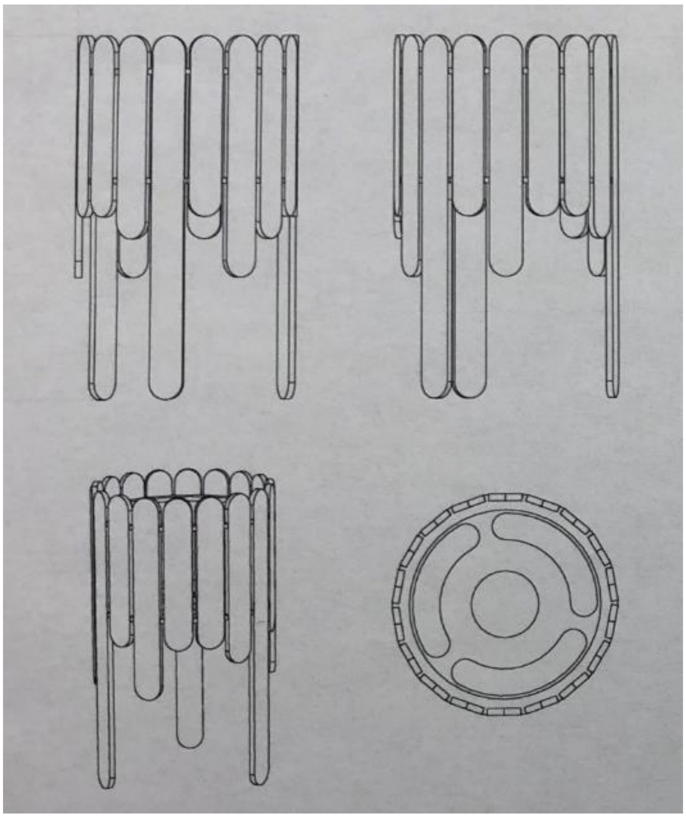


Figure 6.10 DC1 of domestic LED lighting

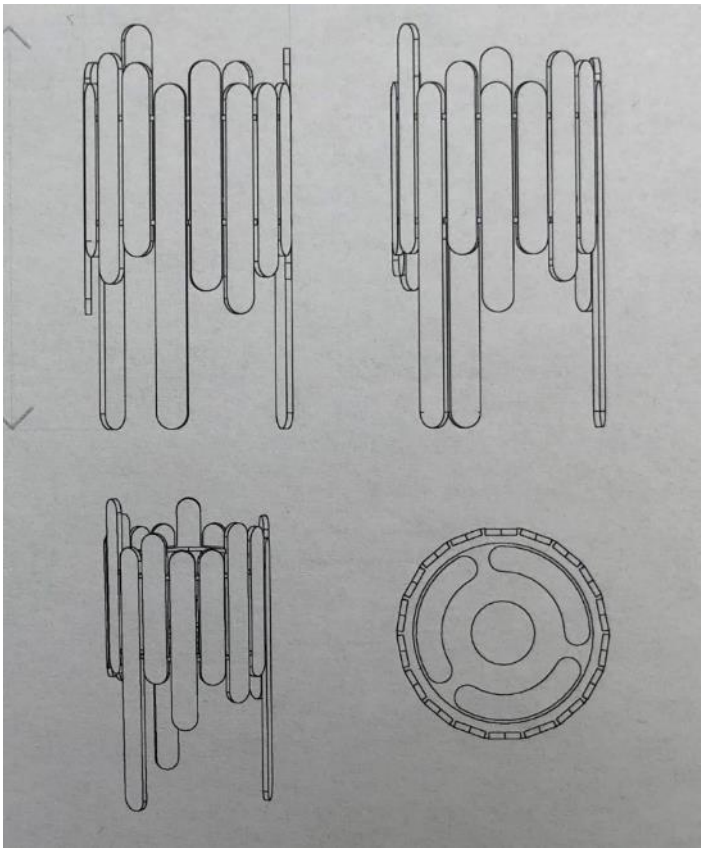


Figure 6.11 DC2 of domestic LED lighting

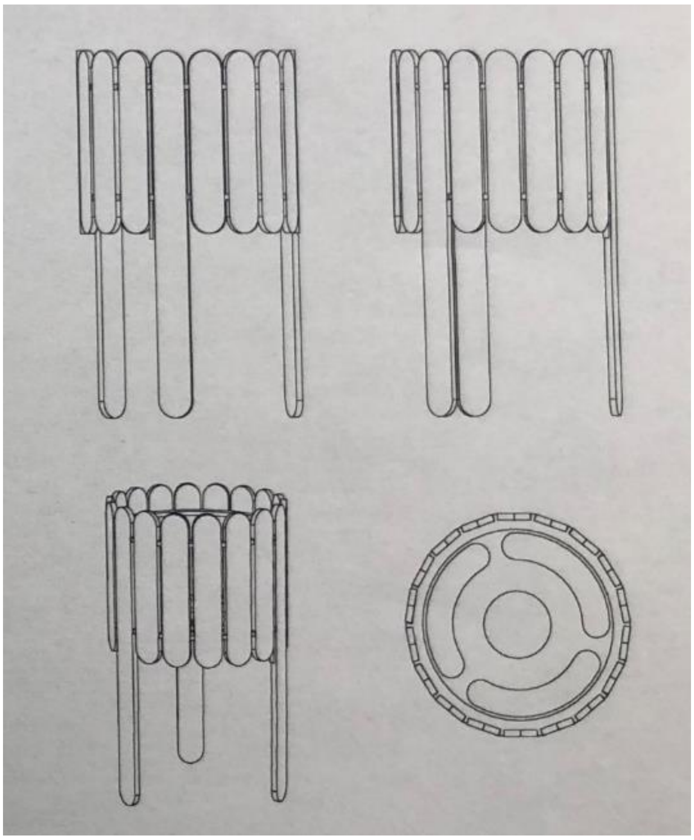


Figure 6.12 DC3 of domestic LED lighting

The three DCs have similar shapes but varies in the length of the modular components which are the main module of the lamp housing. The consideration behind the three versions is from the aesthetic perspective, as the lighting product under development is consumer lighting product that fits in domestic application, therefore the aesthetic factor is as the same importance as the eco features to achieve the marketing target subsequently facilitating the sustainable consumption.

Considering the similarity of the structure and the functionality of the three DCs, the decisive comparative criteria to select the concept for detailed design is between aesthetic and environmental impact, including material usage and ease of manufacture and assembly & disassembly of the potential products. For the above reasons, DC3 is selected for detailed design owing to the concept requires least material and manufacturing complexity compares to the DC2 and DC1.

6.3.2 Detailed design

DC3 then has been further designed, the detailed drawing of DC2 is illustrated in Figure 6.13. The modular-design housing is entirely made of extruded post-consumer recycled materials. There are three additional material options i.e. wood, glass metal, and different size options to meet consumers' need, as shown in Figure 6.14. The electric devices are designed to be compliant with RoHS inclusive of the LEDs and the driver: 2 Correlated Colour Temperature (CCT), including 3000 K° (warm light) and 5000K° (cold light) are applied alternately, while a dimmable feature is also embraced with driver circuit control. The prominent eco-features are explained as follows:

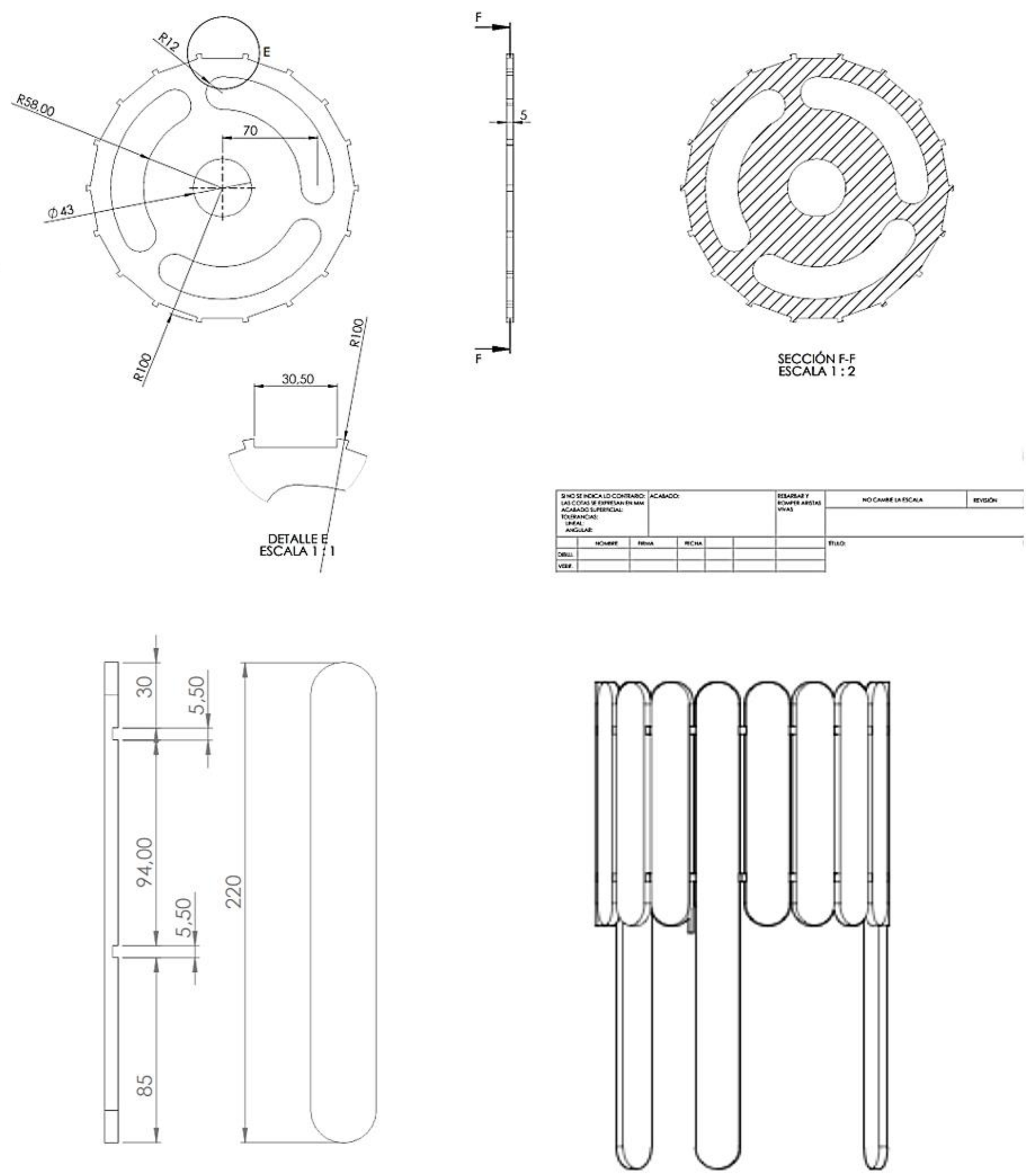


Figure 6.13 Detailed design drawings of the environmentally sustainable domestic LED lamp

Figure 6.14 material and size alternatives of the environmentally sustainable lamp

High availability material. The default material is post-consumer plastic, as descripted above, the source of material will be mainly source from manufacture or post-consumer wastes. There are three additional material options to meet wider customer needs such as wood, metal and glass. The chosen materials are all common materials which have high availabilities.

Modular designed structure. The goal of the eco-design is to achieve a simple structure with less variety of materials usage yet visually appealing to consumers. The structure is configured by chips of the same size to form the housing of the lamp. The pieces are joined by two inner ring-shaped parts in a circular shape. The two ending edges of the pieces are designed in curve shape for safety and aesthetic reasons. The modular structure also enables: 1) Easy to assemble/disassemble (consumer can assemble the lamp by themselves). 2) Easy access for repair and maintenance.

Easy to manufacture. The main pieces are all processed with the laser cut technique. No joint members (screws) are required thus reduce the complexity of manufacturing procedure such as assembly time. In addition, the energy consumption from the manufacturing since the materials requires no other treatment such as coating; the waste during manufacturing is minimised owing to the precise laser cut technique. Alternatively, a special adhesive is used to join the pieces. It is also novel to find the solution to the adhesives by applying a special dissolution so that potential problem regarding disassemble and recycle is avoided.

High recyclability/ reusability. The whole lamp made from one unite material without an additional joint member (applicable to the three material options). Therefore, it can be recycled as a whole so that additional disassemble pressure is reduced when it comes to EoL treatment. Figure 6.15 illustrates the easy steps for end of life recycle.

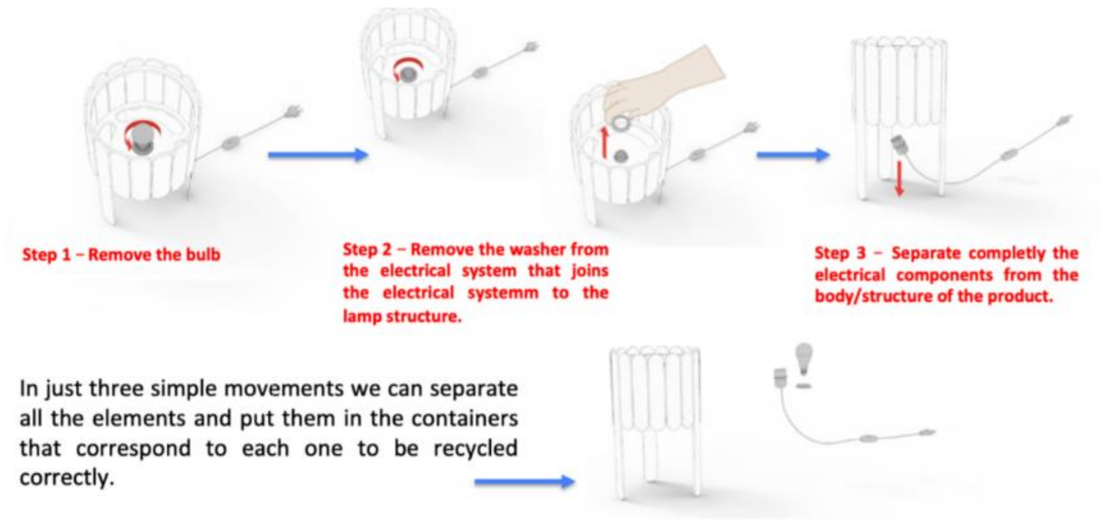


Figure 6.15 The disassembly steps for recycle

6.3.3 prototyping and manufacture

The housing of the lamp consists of three parts which is shown in the detailed design section, namely Poles, upper rim and inner rim. The manufacturing processes for ONA domestic lighting product could be defined in the following steps: (1) material selection (2) cutting (3) mechanize (4) assemble.

Material selection. As explain in previous section, this design is based on the post-consumer or remnants of material that the suppliers of the company generated in their manufacturing processes. For this reason, the pieces are selected from the containers or the area segment destined for this type of piece. Since the housing of the concept is mainly consists of material strips, the material selection process is easier since the eligible remnants are increased due to the size restriction.

Cutting. The selected material will be taken to the laser machine of numerical control to perform the cutting process. The laser cut is able to execute accurately and effectively so that the waste of the material is reduced. The processing time of a whole set of the product is of 15 to 25 minutes depending on the material and is applicable to all material options.

Mechanize. The only material that requires this step after the cutting process is the metal (aluminium) components due to the technique reasons. The CNC laser machine which used for cutting pieces cannot process the slots at the same time, since different from the plastic pieces, marks on aluminium with the CNC laser machine is not possible, etc.

Assemble. At last the housing pieces and the electrical components can be assembled. The electrical components such as the LED, driver, switches and electrical wires are pre-manufactured and purchased from ONA's suppliers.

6.4 Validation of the environmental performance

One unit of the eco-designed LED lighting with default material (plastic) was assessed using the same life cycle impact assessment (LCIA) method. It was assumed taht the new product has the same transportation distance, and the service time is as same as the current products, which is 40000h; the whole lamp housing will be recycled after service life.

Table 6.6 shows the endpoint results from the online LCA platform. The total impact of the eco-design lamp is 16.4 (Pt), human health is the most affected impact category (10.9 Pt), followed by resources (4.98 Pt). The impact on the ecosystem is minimum which is 0.528 Pt.

Table 6.11 Endpoint single score results of the newly designed lamp product

Characterization	**Explanation**	**Value （Pt）**
sTotal	Total	16.4
sHH	Human Health	10.9
sES	Ecosystems	0.528
sRS	Resources	4.98

Figure 6.16 illustrates the comparative results regarding environmental impact score from endpoint assessment, product weights and variety of material usage of the five products. The newly designed lamp presents the lowest impact scores (16.4 Pt) which are 27% less than Cobalt's and 58% less than Ele's. It also has the smallest quantities of material usage (0.8kg in weight and made from only one kind of material) amongst the five products.

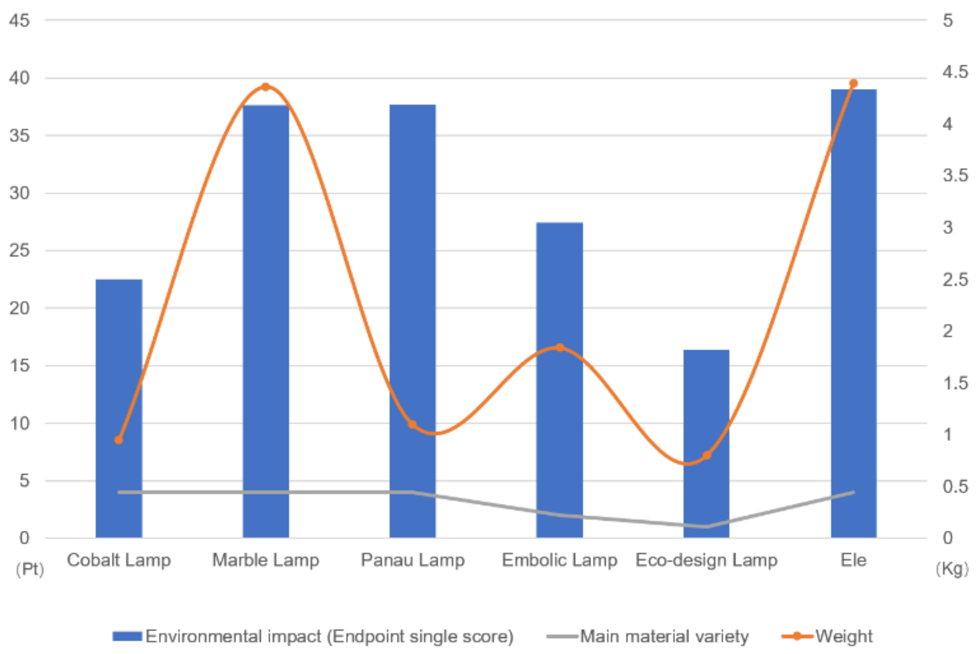


Figure 6.16 Comparative LCA results with reference of material and weight

However, LCA is a quantitative method in evaluating the numeric process data. Some qualitative eco-features are unable to convert to a numeric value, and, consequently, cannot be assessed in an LCA process. For instance, the eco-design lamp product embraces other eco-features such as easy to transport, easy to disassemble and repair, reduction of delivering space and packaging material. These eco-features have enhanced the eco-performance of the proposed product on a great scale, also have a meaningful act on saving energy or provide user-friendly usability in applications. However, these features are unable to be taken into account in the assessment due to the nature of LCA which mentioned above.

6.5 Concluding remarks

This study presented the approach when the alternative sustainable goal is identified, i.e.

environmentally sustainability is the paramount goal for the case company. The sustainable product conceptual construction approach is adaptively applied, and LCA of five lighting products that currently available in the market has been conducted. Issues and opportunities in improving environmental performance have been identified. Evidence-based reflections have been brought out and integrated into the eco-design of domestic LED lighting products. It is indicated that the newly designed lamp has a better environmental performance as well as other eco-features in comparison to existing products.

The environmental assessment results showed that Ele has the highest negative score (39 Pt) amongst the five LED lighting products, followed by Panau and Marble (37.7Pt and 37.6 Pt respectively), while Cobalt (22.5 Pt) and Embolic (27.4 Pt) have relatively lower impacts. Consumption of electricity during the use stage was the predominant process which averagely accounted for more than 90% of the total impacts of the five products.

The analyses were also conducted to identify the key variables behind the corresponding impacts regarding the current products. It is identified that: 1) Use a diversity of materials 2)Complex to manufacture 3) Product weight 4) Hard to assemble or disassemble and 5) Lack of end-of-life consideration are the main potential issues related to their current product's environmental profiles that required to be addressed in the eco-design innovation.

Eco-design of an LED lamp product was conducted with the integration of the design reflections into PDS. Several eco-features of the lamp were demonstrated, especially on reducing the use of materials and manufacturing complexity. Comparative LCA results indicated that the eco-designed Lamp presented a better environmental performance by resulting in the lowest impact scores (16.4 Pt) which are 27% less than Cobalt's and 58% less than Ele's. Additionally, the new lamp has the smallest quantities of material usage (0.8 kg in weight and made from only one kind of material) amongst the five products.

It can be concluded that it is effective in improving LED lighting product's environmental performance by integrating LCA results as a reference into product design, in developing PDS and decision-making processes particularly.

Chapter 7 - Sustainable Product Development and Service Approach for Application in Eco-friendly and Cost-effective Flooring products

7.1 Introduction

7.1.1 Overview of the chapter

This chapter is a case study of the proposed approach with emphasis on static product (product that normally requires no energy input, i.e. flooring product). The flooring product under development is a raised flooring product (detailed in later this section) which is expected to be eco-friendly and cost-effective. A number of sustainable features that reduce environmental impact, cost, as well as achieve the designed function will be delivered. The chapter includes the following contents:

- 'Sustainable product and service conceptual construction approach' is utilised. The environmental impact evaluation is conducted with two kinds of most popular types of flooring product in service (product in the market) to identify environmental issues throughout raised flooring products' life cycle. Analysis with the results and detection of key improvement factors. Reflections and recommendations are applied to the product conceptualisation stage. Literature review and a market survey were conducted and presented, as well as the collection of technical information including product standards, quality assessment standards, patents related to the floor products.

- Possible concepts combining the materials with the manufacturing process for flooring products are proposed. The materials selected have environmentally friendly features and easy to manufacture. The concepts are evaluated by applying the ‘concept selection method’ (see section 3 for detail).

- Detailed design, together with the material parameters, fire resistance classification, material cost and propose manufacturing method are covered in the chapter.

- Based on the outcome of the above task, a ‘simulation-experiment confirmation method’ is applied to simulate the technical test of the detail designed product. Finite Element Analysis (FEA) method and simulation technology are applied and compared with the physical experimental test results.

- Sustainability assessment. The product's sustainability is assessed through the product lifecycle, including material attraction, manufacture, end-of-life, reuse/recycle, and disposal. The product supply chain, resource efficiency and waste reduction through the product lifecycle are particularly addressed. A model to assess the sustainability of the flooring product is developed with LCA software tools.

7.1.2 Raised flooring products

Raised floor systems, also known as access floor systems, were initially developed to offer a way of installing and accessing the massive power and communication cables required in computer installations(MARVIN, JACK et al. 1984)(Marvin et al., 1984); also to provide airflow in a computer room in order to keep its systems in a safe operating temperature (Catalfu, 2006). The system now has been widely applied not only in computer rooms, but also in office buildings, commercial buildings, courts, institutions (schools) and, telecommunication rooms or likewise. Installing a raised access floor system provides various advantages. Unlike similar ceiling products, it enables wires routing and equipment (ventilation, fireproof, etc.) installing by elevating floors while providing easy accessibility and reconfigurability with less material required. Moreover, studies have shown that raised floor system has a positive influence on minimizing the impact vibration performance as well as environmental impact performance (by increasing the energy-using effectiveness) of a building (Reynolds at al., 1998; Srinarayana et al., 2012). Recently, increasing attention has been paid to raised access floor (integrated with underfloor air distribution) to meet the related criteria of gaining a green/sustainable building certificate in its assessment processes.

A traditional raised floor system consists of panel, stringer, pedestals, and fastening members. The pedestals(4 for a module) are rigid adjustable columns made of metal located beneath the corner of panels to provide support, traditional access floor pedestal's height usually varies ranging from 51mm to 1200mm according to application requirements; low profile raised floor could be about 30mm to 150mm in height (some low profile raised floor do not have pedestals as they are directly on the subfloor) with only cable and electricity wire arrangement underneath (NETFLOORUSA, 2014). To decentralize the pressure on the panel corner, stringers are often provided on top of pedestals connected between edges, however, the stringer is an optional member as it will not be needed in low profile raised floor systems. Floor panels are mostly manufactured 600mm×600mm in size, rectangular in shape. These panels are supposed to fix onto the stringers and pedestals with fastening members in order to support loadings and activities on the surface, which makes them an essential element of a raised floor system.

A raised floor panel often consists of several materials with various fabrication technologies accordingly, choosing materials becomes vital as it is directly related to the formation of the structure, function, cost and so forth of the raised floor system.

There is fruitful literature regarding raised floor panel and materials thereof. Literature of early invention and application indicate that wood composition sheets, namely chipboard, blackboard or plywood are favourable materials, this may have been due to wood material's inexpensiveness, lightweight and easily manufacture features. However, wood panels were soon have showed defects such as inferior in fire resistance, strength issues, hence, efforts have been made on both optimizing wooden materials' performance by integrating multi-materials, multi-layers or reasonable precautions; and on identifying other appropriate fabrication materials. Nowadays, Aluminium, steel, cement/concrete, and synthetic materials are widely used raised floor panel materials in order to fit certain situations and functions.

Metal materials like aluminium and steel are of good characteristics in forming an access floor panel, their panel relatively light-weighted than concrete-core steel panels or barely concrete panels yet with high strength. With these characteristics, metal panels are able to be shaped into various structures. Planar metal sheets were used initially as reinforcements on the upper side and over the lower side of another material panel (often with wood)(Robert, 1990). HALE. J. disclosed a type of floor panel with sandwich anticlastic cellular core structure, which provides a structural decoupling and noise attenuation between such outer face sheets, improving the rigidness of the panel unit at the same time. The merits of the structure had been referenced by several scholars including T. KOBAYASHI, sandwich floor panel structure with solid core infilled had been invented. Similar examples are patent No. 8401062 with entitled “Access Flooring Panel”, U.S. patent 2004177589, 4085557, etc. Sandwich structure panel, which consists of a metal tray, metal lid and core material, has been the most widely used panel material-and-structure worldwide. The panel core could be infilled with various materials, namely wood, vegetable fibre, cement and so forth (Table 7.1). ALTENBERG M. J. even came up with a sandwich panel structure with polyurethane foam and/or glass fibre core and assumed such kind of combination was rigid and cost-effective.

Table 7.1 Core materials in sandwich raised floor structure (steel panel)

Core Material	**Main Feature**	**Drawback**
Cement	• most common used • high ultimate load capacity • high fire resistance	• heavy in mass • could have hardship and potential safety issue in installation, replacement, and removal • high environment impact
Wood (chipboard, wood fibre)	• recyclable material • light weight • material easy to get	• limited load rating capacity • inflammable material
vegetable fibre	• natural, sustainable material • light weight • good acoustic properties	• limited load rating capacity • inflammable material
None (hollow steel)	• light weight • available in traditional and low-profile floors	• limited load rating capacity • may create hollow sound when walked upon

	• easy to handle	
Polyurethane foam and/or glass fibre	• Assumed to have high load rating capacity • cost-effective	• Unknown

There are also perforated or grated panels, which use metal (all steel or all aluminium) as fabrication material, those kinds of panels permit a large amount of airflow between the subfloor and room. It can be used in combination with other traditional raised floor panels or independently. Examples could be seen in FAHY's invention (Fahy et al., 2001). Moreover, studies have indicated that perorated tile, especially those with underfloor air distribution (UFAD) systems, have proved to have a positive impact on ventilation effectiveness and controlling the thermal performance of computer room, data centre or airflow required places (Schiavon et al., 2010).

Other panel material could be wood, concrete, plastic and polymeric material. Despite the defects of wood panels which mentioned above, the wood panel are popular due to its other advantages. However, such a panel often has been improved with several measurements: glazed metal clad covering, rigid material padded underside, metal stringer supported, anti-crunching edge trim protection, etc.; as a similar measure as its concrete counterparts (Butch, 2015). Plastic and/or polymeric material panel can be found in low profile raised floor system. Low profile raised floor were designed to fit automated office buildings and display places where have needed to locate cabling throughout open areas; it is also an objective to reduce the floor and ceiling heights while maximizing ducting capacity. Plastic and high strength polypropylene are commonly used in such panels and considered more eco-friendly because of their versatile features: high strength, fireproof, extremely lightweight, recyclable; easy to install and transport and, incorrigible (Micro-Mesh, 2015; ShowDeck, 2015). These panels are usually constructed in hollowed structures and modular duct setting space and integrated with junction box; details and examples are shown in U.S. Pat. No. 5057647, 5263289 (Bogden et al., 1991; Boyd, 1993).

Panel finishes and covering are universally applied for aesthetic, functional and comfortable purposes. Myriad materials have been used for floor coverings, including stone, cement, High-Pressure Laminate, vinyl sheets, paint, carpets, to name just a few. On the one hand, there are similarities in finishing/covering methods between conventional flooring decks and raised floor panels; on the other hand, raised floor panel has distinguishing features (depending on specific environmental and functional need) that influence its choice on finishing and covering method. Acoustic problems (unpleasant sound generated when walked on) has been one of the most intractable issues thereof. Recent studies conducted by Chiang, C.M. et al. (2001) and Asdubali and Alessandro (2008) have concluded that panel material, surface finish, damping materials could be the key elements in optimizing acoustic performance. Asdubali et al. (2008) also carried out LCA on sustainable materials' acoustical applications (2008), turned out that material like coco fibre, cork, expanded polystyrene, etc.; sandwich panel made of coconut fibres, foam and fabric have good properties on acoustic insulation. Also, panels with soft rubber, fibre pads, and carpet coverings are considered effective in reducing the impact vibration performance or zone peak cooling load in an office building.

Figure 7.1 Perforated floor (LFAF, 2015)

Figure 7.2 Wood panel

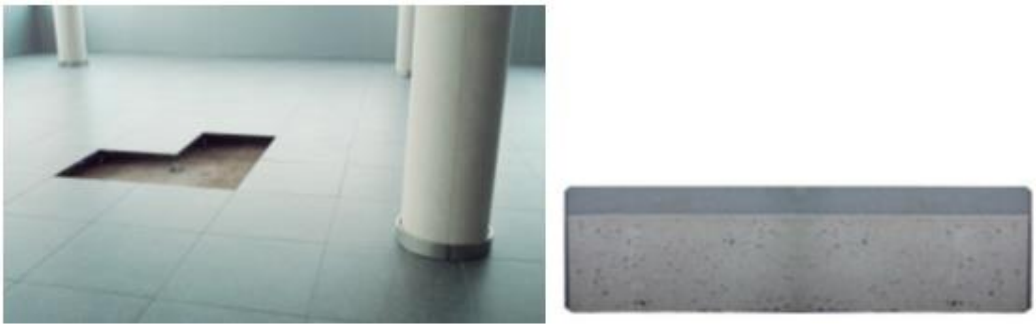


Figure 7.3 Concrete panel (Butch, 2015)

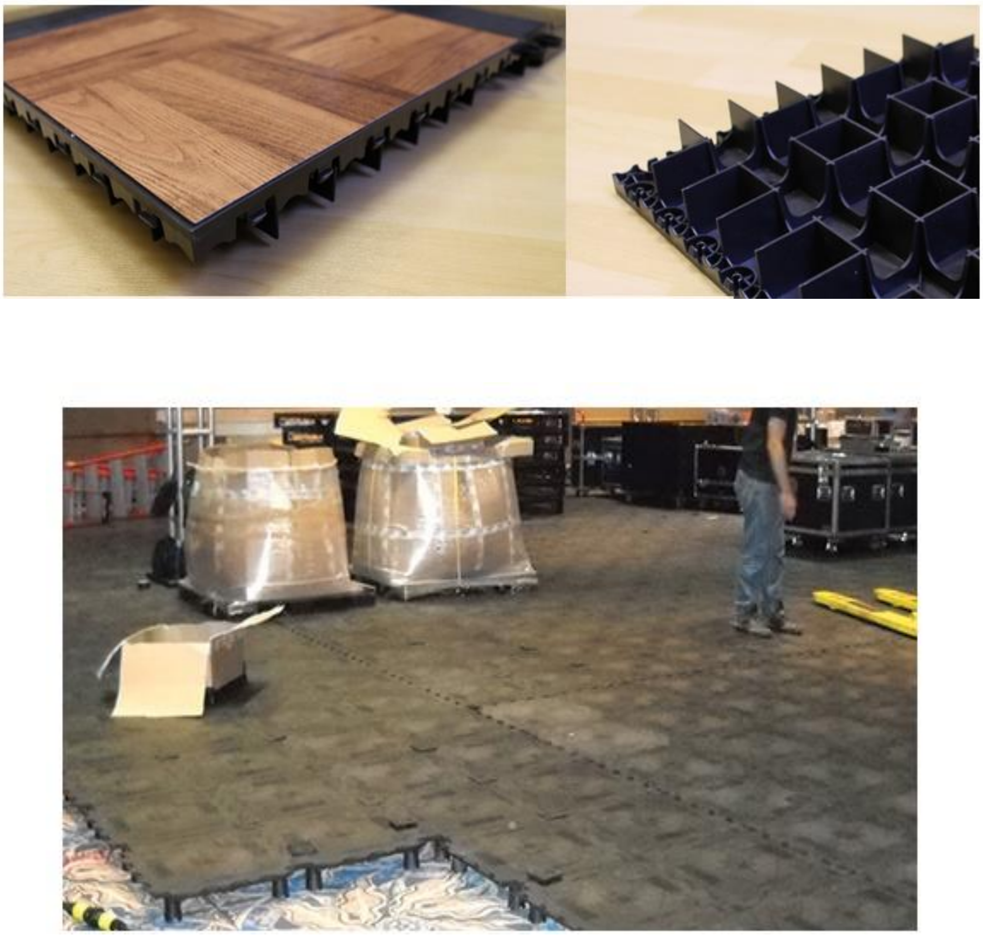


Figure 7.4 Plastic low profile raised floor panel (EFS, 2015a, b)

The production of manufacturing the existing raised access floor panels involves three stages, these are galvanised steel coil cutting, forming press and assembly process of the raised access floor panels, where pre-cut chipboard is encapsulated in the steel.

The fabrication of the galvanised steel with 0.4 mm thickness includes two types of processes, these are galvanised steel coil cutting followed by the forming press to form the lids and trays of galvanised steel for the raised access floor panel. The galvanised steel coil is placed on the galvanised steel coil machine to cut into thin galvanised steel sheet with the length and width required for the fabrication of lids and trays of galvanised steel. Then, the forming press will be taking place after thin galvanised steel sheet has been cut into the length and width required for the raised access floor panel. The mechanism of forming press can be hydraulic, mechanical or pneumatic and forming press machine required to perform the forming of lids and trays of galvanised steel is between 1 to 30 tons.

7.2 Environmental impact evaluation of typical raised flooring product in service

7.2.1 Goal and scope

The goal is to evaluate the environmental impact of the chosen flooring products throughout the product's whole lifecycle to identify the key environmental impact stages or processes. The evaluation results can be used to identify opportunities for improving the environmental performance, eco-design and guide innovation of raised flooring products.

7.2.2 Function unit

The products under evaluation are cement injected steel sandwich raised floor (FP1) and wood-based raised floor (FP2), see Figure 7.5. The raised flooring products have the same panel dimension, thus function provided in given area is equal. 100 items of flooring products are defined as the function unite under assessment, 1 item includes a panel, and stringer and pedestals.

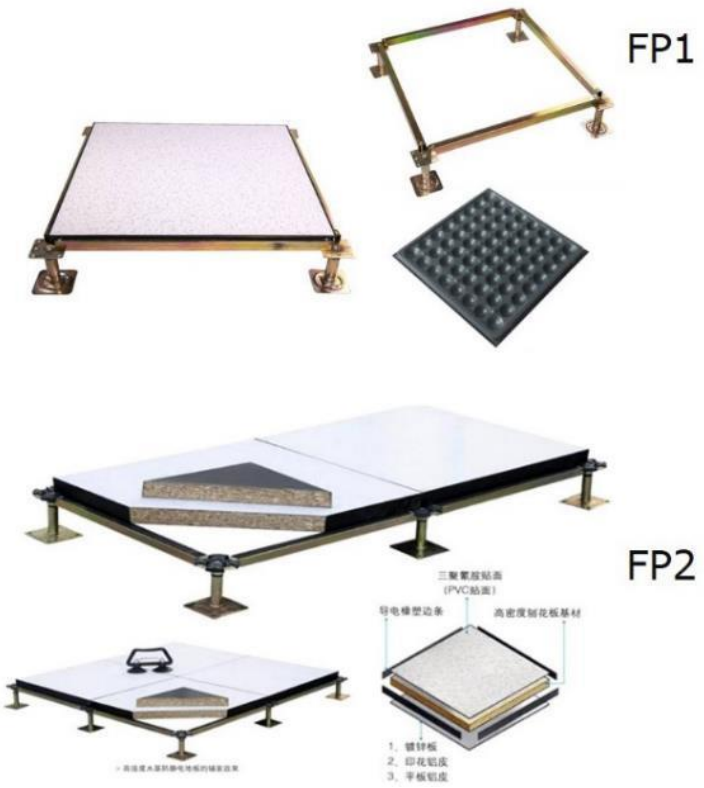


Figure 7. 5 Flooring products under evaluation

As shown in Figure 7.5, FP1 consists of a sandwich-structured panel, a stringer, fastening members and pedestals. The panel is made of cement core wrapped with steel sheets and PVC finishing. The stringer is made from steel tube in a squared shape to support the panel as well to enhance the strength. Three pedestal height options are available which determined by consumer preference. Similarly, structure configuration of FP2 is as same as its counterpart

FP1. The flooring panel is mainly made from chipboard with special thickness (40mm), the steel sheet is placed (glued) on the top and bottom of the chipboard to ensure the fire resistance and strength performance. Four edges are sealed with conductive rubber, and printed PVC sheet is placed on the top of the panel as finishing, the technical parameters are summarized in Table 7.2.

Table 7.2 Technical Parameter of flooring products under comparison

	FP1	**FP2**
Weight (panel & stringer)	24.9 kg	24.5 kg
Component	panel, stringer, pedestals	panel, stringer, pedestals
Dimension (mm)	600*600*35	600*600*40
Material	cement(core), steel sheet, PVC, rubber, steel tube	wood (fiberboard), steel sheet, PVC, rubber, steel tube
Concentrated load	≤3000N	≥3000N
Ultimate loads	≤8000N	≥8000N
Fire resistance	V1	V1

The two sample products have been selected because of their ability to reflect common environmental problems of raised flooring products so that the evaluation results could be widely applied. The products both contain: (1) wood-based panel and sandwich-structured panel, especially panel with cement core, are most commonly used raised flooring panel type. (2) The two products both consist of a panel, a stringer and four pedestals, this structure configuration is in accord with most existing raised flooring products. (3) The flooring products both manufactured in the same region of China (Changzhou) where most Chinese raised floor producers are sited in.

7.2.3 System boundary

As illustrated in Figure 7.6, stages throughout flooring product's life cycle including raw material acquisition, manufacture, packaging, distribution (transportation) and end-of-life treatment are included in the system boundary of the LCA study. Use phase including maintenance during the useful time is excluded from the assessment boundary since information about such activity is out of reach.

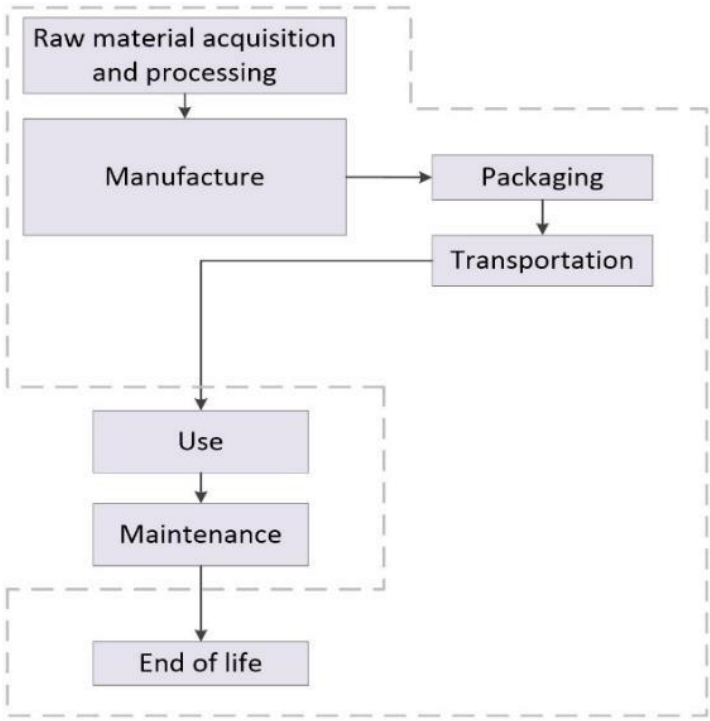


Figure 7.6 System boundary of LCA of typical raised flooring products

Consumption and emission during fabrication, such as raw material acquisition, usage of materials, electricity, waste, transportation during manufacturing and emissions are considered within the boundary.

Packaging stage plays a vital role in contributing product's environmental impact through flooring products' life cycle thus is included in the system boundary. It also helps in identifying the opportunity towards improvement alternatives. Packaging data of FP1 and FP2 were acquired by measuring the final products' packaging which is offered by the producer.

In transportation stage, transport activity through product distribution is taken into consideration. In this study, the flooring products were assumed to be exported from China to the UK, FP1 and FP2 are both produced in Changzhou (China) thus assumed to have the same transport rout: freight road transport from Changzhou to Yi Wu (3541 Km) then to the UK via freight train (12451 Km).

End-of-life activities are considered in system boundary. The flooring products are assumed to have following EoL scenario: for the panel of two products will be landfilled after their use life. The other parts of the floor system such steel stringer is considered sending to recycle/reuse rout of steel waste.

7.2.4 Inventory data

Bill of materials for assessment is listed in Table 7.3. Bill of materials and related mass of FP1 and FP2 are acquired by measuring the final products and inquiring the producer. Method of obtaining transportation and EoL information is explained in System boundary, background data such as process inventory data was selected in Ecoinvent 3.3 database.

Table 7.3 Inventory data of FP1 and FP2

FP1		**FP2**	
Inputs		Inputs	
Materials		*Materials*	
Steel (Pressed Steel Sheet)	3.49kg	High Density Fiberboard	9.85kg
Steel (stringer)	12.3kg	Steel Sheet	1.51kg
Cement	8.52kg	Steel (stringer)	12.3kg
PVC	0.66kg	PVC	0.05kg
Adhesive	0.04kg	Adhesive	0.002kg

Medium Density particleboard	6.77kg	Rubber	0.79kg
Plastic	0.11kg	Plastic	0.01kg
Transport		Wood	0.03M^3
Freight Road Transportation	3541km	Paperboard	0.87kg
Freight Railway Transportation	12451km	*Transport*	
		Freight Road Transportation	3541km
		Freight Railway Transportation	12451km
Output		Output	
Product		*Product*	
Sandwich Steel Panel (Cement Injected)	12.60kg	Wood Based Raised Floor Panel	12.20kg
Stringer	12.3kg	Stringer	12.3kg
End-Of-Life Treatment		*End-Of-Life Treatment*	
Landfill	12.60kg	Incineration	12.20kg

7.2.5 LCA results and interpretation

100 items per each of the two flooring products (FP1, FP2) are assessed using ReCiPe Endpoint H method. The LCA results of three endpoint impact categories as well the total impacts are shown in Table 7.4. As shown, FP1 presents a higher environmental impact than FP2 which is 1941.98 points and 1882.93 points respectively. Among the three endpoint environmental

impact categories, Resources (773.8 and 721.2 points) is identified as the most impact-sensitive category for both of two products, followed by Human Health and Ecosystem. Key environmental impact life cycle stage and "hotspot" process results are shown in Figure 7.7, undoubtedly, production stage is the key lifecycle stage to the total impact contribution of both products since production stage is the input-output intensive stage where the majority consumption of materials and energy have taken place. Production of stringer is identified as the hotspot process for both products.

Table 7.4 Endpoint single score of FP1 and FP2

Impact category	FP1	FP2	Unit
Ecosystem Quality	498.59	573.16	Points
Human Health	669.59	588.55	Points
Resources	773.8	721.22	Points
Total	1941.98	1882.93	Points

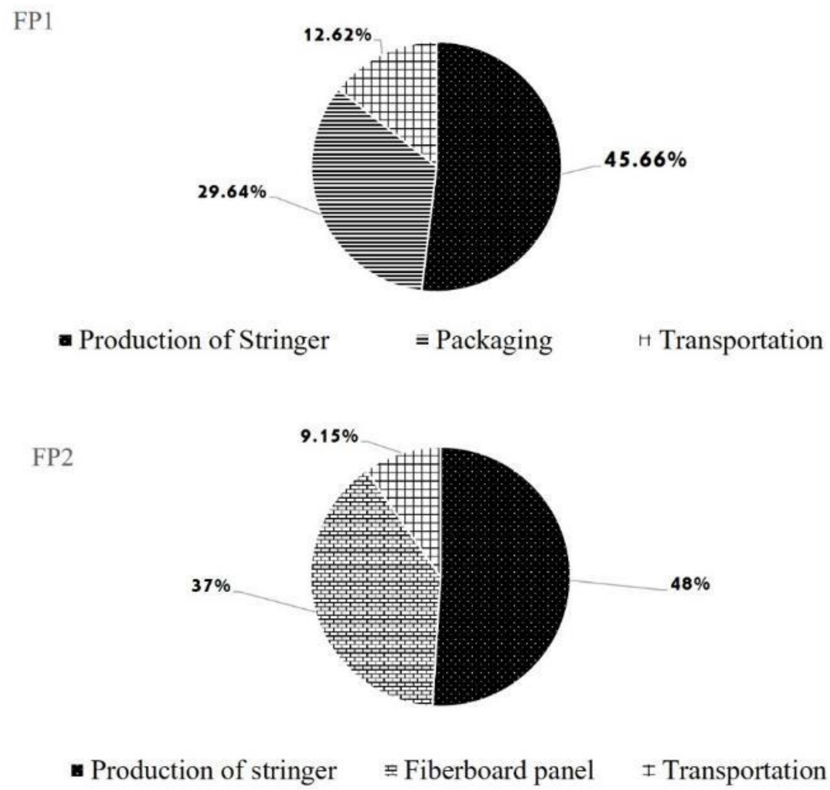


Figure 7.7 Key environmental issue stage (pie chart of LCA results)

Production is the Key environmental life cycle phase of FP1. Production of the stringer is the highest environmental impact process of FP1 which contributes 45.66% of the total impact. The second highest impact phase is Packaging (29.64%) stage. According to the producer, each panel is going to be packaged with wooden (particleboard) materials to ensure product safety during transportation, nevertheless, material usage and mass related factors are increased on impacts of various categories, consequently increased the total impact. Transportation phase of FP1 produced 12.62% of its total impact. In FP2, Production of stringer also is the hotspot process (48%), followed by Fiberboard production (37%). Transportation contributes 9.15% of FP2’s total impacts.

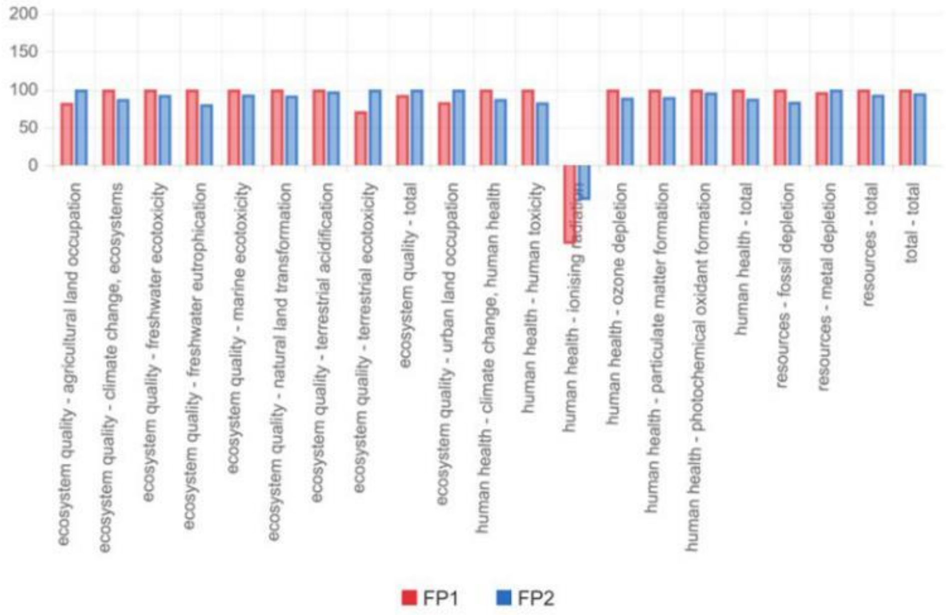


Figure 7.8 Key environmental issue stage (pie chart of LCA results)

Figure 7.8 illustrates the relative impacts in percentage which includes 17 midpoint and 3 endpoint impact categories of FP1, FP2. From an endpoint impact category perspective, Resources is identified as the most impact-sensitive category for both of two products, heavy in mass and the complexity of manufacturing technique (process) have led to massive inputs such as raw material and energy, consequently increase the consumption of resources. In this impact category, FP1 presents a higher score (percentage) mainly attributes to the fabrication of stringer and packaging phase. FP2 presents fewer impacts than FP1 which is 90%. In Human Health category, impact is mainly affected by the complexity of material used in product or product systems, particularly by amount of chemicals consumed. Again, FP1 scores higher than FP2 which is 100% and 90% respectively. For impact on Ecosystem Quality, FP1 is about 90% whilst FP2 is almost 100%. The wood-based material is naturally grown material which effects greatly on Ecosystem Quality category, the two products have used massive wood-based materials in their whole lifecycle which attribute more impact on this category. In which, wood-based material is majorly used as packaging material in FP1 and panel material in FP2, consequently led to large amount of potential impact on ecosystem quality such as on Climate change and Terrestrial acidification as shown in the figure.

7.2.6 Environmental performance improvement opportunities and verification

The LCA results above have revealed that the production stage is the key environmental impact stage throughout life cycle stages of raised flooring products, material fabrication of flooring members, especially production of stringer, is the "hotspot" process which has directly influenced the environmental performance of both product. For FP1, the packaging is the other high environmental impact stage through its lifecycle. According to the result mentioned above, recommendations towards improving the environmental performances of the flooring products should focus on addressing the environmental impact of key environmental stages and hotspot processes:

- For FP1, alternatives are focusing on changing or/and reducing the packaging material and reducing the weight of the stringer. as explained above, the inappropriate usage of packaging material contributes a massive negative impact to FP1's total impact by changing/reducing the packaging material is expected to have a great improvement to FP1's environmental performance. For instance, the total impact of FP1 could be reduced by 45% by merely changing the packaging material as same as its counterpart FP2's. In addition, the production of the stringer contributes greatly to FP1's environmental profile, especially affects the impacts related to resources and transportation. Therefore, reducing the weight of stringer while meeting the product strength standard is the most effective way on improving FP1's environmental performance.

- For FP2, the improvement opportunities lie in reducing the thickness of the panel as well as reducing the weight of the stringer. Wood-based material is an impact-intensive material such as chipboard used by FP2, as mentioned in the previous section, reducing the usage of this kind of material by reducing the thickness of the floor panel is considered the solution to lower the total impact of FP2. Reducing the weight of the stringer is another alternative for the same reason as FP1.

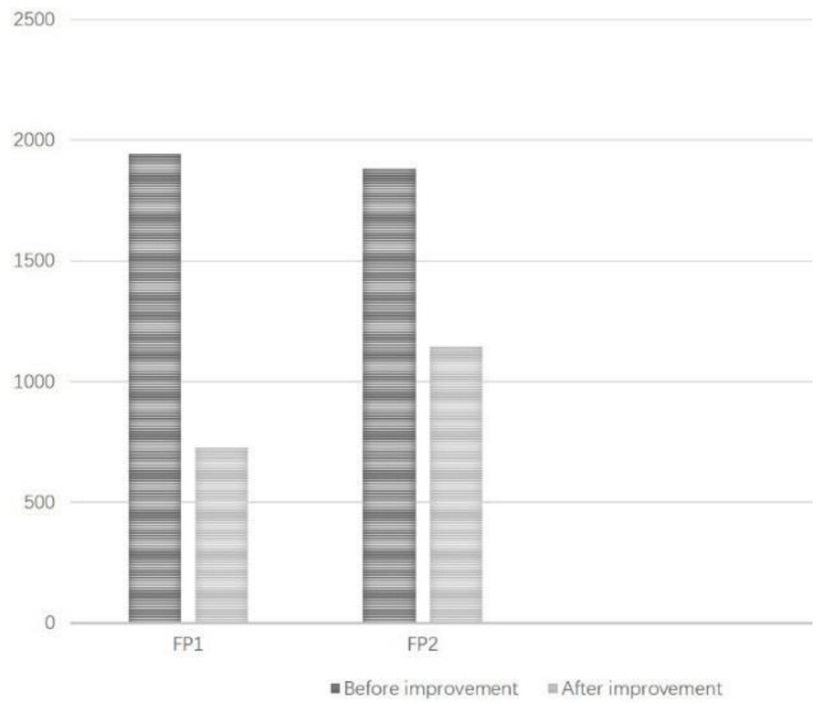


Figure 7.9 LCA results before and after implementing alternatives

To verify the effectiveness of the improvement solutions, alternative scenarios are applied assumed and assessed, including:

- A 5% reduction of stringer's weight to both FP1 and FP2;
- A 5% reduction of FP2's panel weight and;
- An alternative packaging material to FP2 (as the same as FP1).

The alternative scenario results are shown in Figure 7.9. As shown in the figure, the LCA impact score of both flooring products after implementing improvement alternatives have a dramatic drop compares to it was beforehand. FP1 has a 62% impact reduction (728.68 points) while

FP2 reduced 39% (1145.37) after optimisation which proved the effectiveness of the opportunities.

7.2.7 Reflections on development of eco-friendly raised flooring product

Reducing total weight is vital for eco-friendly raised flooring product innovation. As shown from the LCA results after optimisation in Figure 7.9, the total environmental impact score and its sub impact categories are much lower when the total usage of material has been reduced. Thus, it is necessary to use as few materials as possible.

For raised flooring product, reduction of weight includes reducing the weight of both panel and stringer. To implement the reduction of material usage while meeting the product standard requirements, simulation software tool (such as Ansys or SolidWorks) are essential, since the reduction of materials and total product weight are effective alternatives only in the condition of meeting the related product quality standard. Product weight goal can be set in PDS at the beginning of the product development process and reinsure in the concept selection or Refinement stage. By utilising Error Testing Method and strength simulation tool mentioned above, the thickness of panel material, as well as the stringer, can be minimized thus reduced the total weight of the product. Besides, weight reduction also reduces the impact on transportation, and improve the product usability thus improves the sustainability of the product more extensively.

Reducing manufacturing processes by simplifying raised flooring product’s structure. Mass production requires energy, water, resources and generate emissions which are the main contributor to the environmental impact. Optimising product structure to reduce unnecessary member or material in detail design or refinement stage could be effective to achieve this objective, including simplifying the assembly and disassembly process; reducing of the manufacture related cost, thus improves the sustainability.

The optimising of raised flooring product including reduce panel layer; apply structure jointing method instead of using adhesive or additional joint member; reduce the number/type of material usage. Furthermore, design evaluation is particularly important, eco-friendly design concept is achievable by setting a strict environmental goal during PDS construction and increasing the weighting score of environmental aspects in the design evaluation process.

Modular design. Modular design contributes to several eco-features, for instance, easy to transport, easy to install and disassemble, it also helps with easy maintenance during the use phase.

Recyclability. Choosing recyclable material not only improves the total environmental performance of raised flooring products but also reduce the cost. However, to meet the threshold standard of raised flooring product such as anti-corrosion, fire-proof and strength class, there are difficulties to choose completely recyclable panel material. Also, since the layered design is preferred for the production of this type such as FP2, recyclability is not the only concern of choosing panel material: join method, adhesives and core material are also vital since these factors related to the detachability consequently affect the recyclability.

Life cycle thinking is crucial in eco-product innovation, other life cycle stages also need to be taken into consideration in the product development stage. Other life cycle stages play the important role in contributing negative impact to the total environmental profile, take FP1 as an example, the total impact score reduced by 45% after implementing the packaging alternative. By taking environmental aspect seriously in early design stages, such as Product Specification and Concept Selection is effective implementation of life cycle thinking in a design process.

7.3 Concept design and selection of eco-flooring product

7.3.1 Product design specification and design concepts

Taken the design reflections and recommendations that are derived from the environmental evaluation, which focuses on 6 aspects aiming to improve environmental performance and overall environmental sustainability in new raised flooring product innovation: Reducing total weight is the foremost need for eco-friendly raised flooring product innovation. Secondly, reducing manufacturing processes by simplifying raised flooring products' structure, it's considered not only effective in achieving the impact reduction goal but also lower the manufacturing cost, and enhance the manufacture or assemble effectiveness. Similarly, the modular design improves raised flooring products' sustainability more extensively, such as enhance the effectiveness of transportation, installation, disassembly as well as maintenance. Additionally, life cycle thinking is essential in eco-product innovation, recyclability, end of life treatment and consideration of other life cycle phases as a whole system. The key PDS (excluding the quality performance standards) for the eco-flooring product are listed as follows:

- Lightweight design, the total weight is no greater than 8KG
- Easy to manufacturing
- Simplified structure
- Reduce adhesive usage
- Harmful chemical-free
- Modular design
- Easy to recycle

Based on the PDS and literature review result addressed in the previous sections, a range of materials have been investigated, such as polymer materials, glass fibre, thermosetting materials, thermoplastics, etc. The manufacturing methods considered include compression moulding, extrusion and injection. Combining materials with the manufacturing process for raised access flooring products, the six design concepts of raised access flooring panels were proposed, see Table 7.5.

Table 7.5 DCs of eco-flooring product

Design concepts	Graphic	Description

Chipboard core encapsulated by steel (DC1)

Made of the conventional materials and structure of raised flooring product

Recycled paper core encapsulated by composite material (DC2)

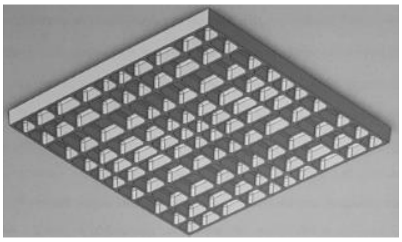
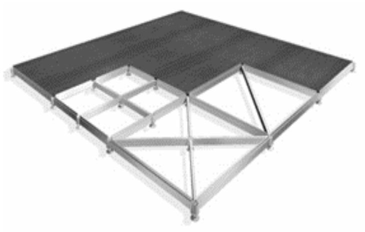
Consists of core material, covering surface, bottom surface, and edge protections. In DC2, the core material is proposed to be a high-density paperboard which is an engineered paper product manufactured by papers recycled. The core encapsulated by composite sheet to substitute the conventional metal sheets such as steel and aluminium

Balsa chipboard encapsulated by composite material (DC3)

In this design concept, the raised access flooring panel is proposed to utilise a light and dense wood chipboard, which is called Balsa, as the core material. Balsa is much lighter and denser than regular wood such as plywood and has good toughness due to its fibre. The covering surfaces and edge protection is made by composite material, which provides a barrier for the humidity and has the mechanical resistance and fireproof.

Foam core encapsulated by composite material (DC4)

The alternative of the core material is foam core, which is light and has good compression. The covering is also made of composite materials.

Sheet moulding composite panel reinforced by rib (DC5)		The whole raised access flooring panel is made of a light-weight composite material composed of glass fibre and polymer material. To further reduce the weight, the flooring panel is to be molded to a ribbed structure, which is processed by compression molding.
Composite material panel supported by steel stringers (DC6)		The panel is completely made of glass fiber composite material so the covering and the core material is reduced. To enhance the strength, a steel stringer is proposed under the panel

7.3.2 concept selection of eco-flooring product

Concept selection was conducted by utilising the 'concept selection method'. All the concepts are evaluated with two types of evaluation criteria, threshold criteria and comparative criteria. With the comparative criteria, the concepts are evaluated using numerical values, and a higher value represents a better result. The threshold criteria represent the requirements that the concepts must meet; if a concept cannot meet any of the threshold criteria, the concept is then ruled out without further consideration for evaluation. The concept evaluation results with comparative criteria are shown in Table 7.7. To rate the criteria, the weight factors are applied and stated on the right side of Table 7.7. The values of the weight factors are ranged from 1 to 3, a higher value indicates more importance of the criteria to which the higher value assigned. In this evaluation, criteria 'weight', 'surface strength', 'environmental impact' and 'cost' are considered the most important criteria according to the development goals, and hence there are assigned the highest value ‘3’. Each concept is rated against comparative criteria with numerical values, ranging from 1-5, of which a higher value represents a better evaluation result. Each evaluation value is then multiplied with its corresponding weigh factor, for example, the score of DC2 under ‘ease of manufacture’ is 6 (3*2=6). The total score of a concept is obtained by adding its weighted (individual values of a comparative criterion multiplies the weight factor) values together. Finally, DC6 obtained the highest score (124) and selected as the detailed design concept, the explanations are detailed as followed.

Table 7.6 The threshold criteria evaluation

No.	Threshold Criteria	DC1	DC2	DC3	DC4	DC5	DC6
1	Fire resistance	Yes	Yes	Yes	Yes	Yes	Yes
2	No harmful emission (formaldehyde, chlorine)	Yes	Yes	Yes	Yes	Yes	Yes
3	Meet the bending strength requirement	Yes	Yes	Yes	Yes	Yes	Yes

Table 7.7 comparative criteria evaluation

No.	**Comparative Criteria** (Low/Expensive = 1; High/Cheap =5)	DC1	DC2	DC3	DC4	DC5	DC6	**Weight factor** (low=1, high=3)
1	Weight	1	4	4	4	4	5	3
2	Surface strength	4	5	5	5	5	5	3
3	Deformation resistance	4	4	4	3	5	5	2

4	Ease of manufacturing	3	3	3	3	5	5	2
5	Erosion resistance	2	4	4	4	4	4	2
6	Flexibility of adjustment	3	3	3	3	4	5	2
7	Ease of maintenance	3	4	4	4	4	3	1
8	Life-cycle environmental Impact	3	4	4	3	5	5	3
9	Recyclability	3	3	3	2	2	4	2
10	Availability of materials	5	3	2	4	5	5	1
11	Performance of sound insulation	3	4	4	4	4	4	2
12	Surface finishing	2	5	5	5	5	5	1
13	Cost	5	2	2	2	3	4	3
	Total evaluation score	**85**	**99**	**98**	**93**	**113**	**124**	

The comparative criteria considered include:

Weight. The weight of a floor panel affects not only the load on the floor and hence the building, but also the cost of transportation. Concept DC1 (the chipboard core encapsulated by steel) is the heaviest one amongst all the concepts, which is of 11Kg per standard panel (600mm X 600mm). In comparison, Concept DC6 (the composite material panel with steel stringers) is the lightest one where the composite material panel is very thin and light. The rest of the four concepts (recycled paper/Balsa/foam core encapsulated by composite materials, and sheet moulding composite reinforced by rib) are ranked to the same score '4', which are lighter than concept DC1. The recycled paper/Balsa/foam core encapsulated by composite materials are light due to the nature of their cores, but the availability and feasibility of manufacture should be further investigated. Concept DC5 (the sheet moulding composite panel reinforced by rib) features a ribbed structure, which reduces the weight of the floor panel.

Surface strength. The surface strength of the floor panel reflects the capacity of resistance to the load applied on the surface of the floor panel. For instance, the surface of the floor panel must have adequate resistance when suffering from sharp or tough substances, such as high heels. The composite material has a higher surface strength than the metal sheet used to encapsulate the chipboard of DC1. Because concept DC2, DC3, DC4, DC5 and DC6 are either encapsulated with or made of composite materials, and, hence, they have a high score '5', while DC1' has a lower score '4'.

Deformation resistance. The capacity of deformation resistance is also a vital criterion for evaluating floor panels. Amongst all the concepts, DC6 (the composite material panel with steel stringers) has the strongest resistance to the deformation of the floor panel, since one of the steel stringers is used to support the floor panel in the centre and hence relieve the deformation. Concept DC5 (the sheet moulding composite panel reinforced by ribs) is also ranked as the highest level of deformation resistance due to the strong ribbed structure with good deformation resistance. DC4 (the foam core encapsulated by composite materials) is subjected to a large deformation when applying the load, for example, in the middle of the surface of the floor panel, so it has the lowest resistance to deformation among all of the concepts.

Ease of manufacturing. There are two types of structure of floor panel to be manufactured in all of the concepts: sandwich structure, and composite. Apart from DC5 (Sheet moulding composite panel reinforced by rib) and DC6 (Composite material panel with steel stringers), the rest of the four concepts (chipboard/recycled paper/Balsa/foam core encapsulated by composite materials) adopt the sandwich structure, which contains core material, surface finish, bottom finish and edge protection; with such a structure, the core materials have to be encapsulated with steel or composite material via compression moulding, which increases the cost of manufacture. Therefore, the four concepts with the sandwich structure are more difficult to manufacture than DC5 and DC6 which do not need the encapsulation of finishes, and, hence, DC5 and DC6 have the highest score ‘5’, while all others have a score ‘3’.

Erosion resistance. Among all of the concepts, concept DC1, the chipboard core encapsulated by steel, has the lowest erosion resistance. That is because the surface finish of the floor panel has to be painted to resist the erosion of steel. The paint of steel finish will be worn off and eroded over time. However, the rest of the concepts (recycled paper/Balsa/foam core encapsulated by composite materials, sheet moulding composite panel, and composite material panel with steel stringers) have the strongest resistance to erosion, which utilise the composite materials as surface finish materials.

The flexibility of adjustment. In some cases, a part of the floor panel has to be cut off in order to fit into a special place, such as a corner, where a standard size panel is too big to fit. The core materials of concepts DC1, DC2 and DC3 are not fire-resistant, which makes it difficult to ensure the cut-panel to meet the fire-resistant requirement. Although the core material of DC4, foam, is fire-resistant, the cut-edge of the panel is weakened. Therefore, concepts DC1, DC2, DC3 and DC4 all have a low score ‘3’. Concepts DC5 and DC6 are made of composite materials, which are fire-resistant. However, both DC5 and DC6 are supported by ribs, and it is a challenge to ensure that the outer edge of the floor panel, when it is cut off between two ribs, meets the standard of strength. In comparison, DC6, the composite material panel with steel stringers, is the most flexible to make the adjustment - the length of ribbed stringers for supporting the floor panel can be adjusted to different size of the floor panel. Therefore, DC5 and DC6 are ranked with scores of‘ 4’ and ‘5’ respectively.

Ease of maintenance. The maintenance work considered includes replacement/removal of the floor panel and as well as those which are placed under the floor panel, such as cables, meters, etc. Concept DC6, the composite material panel with steel stringers, may create difficulties for replacing the materials and equipment under the floor panel, because the stringers probably have to be removed first. Concept DC1, the chipboard core encapsulated by steel is also difficult to maintain, as it is the heaviest one among all the concepts (see the discussion in Weight part) and hence is hard to lift it. Concepts DC2, DC3 and DC4, the recycled paper/Balsa/foam cores encapsulated by composite materials and DC5, the sheet moulding composite panel reinforced by rib are easier to operate and maintain than DC1 and DC6.

Life cycle environmental impact is to measure the negative environmental performance through the whole life cycle (material extraction, manufacture, transport, use phase and disposal) of the six design concepts. This criterion is also considered important (weight factor is 3) for a sustainable floor product from the life cycle assessment point of view. Among the design concepts, sheet moulding composite panel reinforced by ribs (DC5 and DC6) has the highest score due to its uniformed material, fewer manufacturing processes, ease of transport and maintenance. Although DC2 and DC3 consist of lightweight and/or recyclable materials(paper, Balsa, steel), for the extraction phase, different encapsulating and core materials are involved, and manufacture processes are needed hence may cause more negative influence on the environmental impact of the panels. Chipboard core encapsulated by steel (DC1) and Foam core encapsulated by composite material (DC4) have the lowest score (3). Chipboard and foam are not environmentally sound materials; they are both adhesive consuming to keep combined and thus increase material using, emissions and waste. There is also a weight problem in DC1, which influences its transport, use phase parameters.

Recyclability. Although their core materials ‘chipboard’, ‘recycled papers’ and ‘balsa’ maybe recyclable, concepts DC1, DC2 and DC3 are still difficult to recycle because the core materials are encapsulated by steel and composite materials, and it is difficult to separate the encapsulating materials from the core materials with affordable cost, and, hence, all the three concepts (DC1, DC2 and DC3) are ranked with a score ‘3’. The core material ‘foam’ is unrecyclable, and, hence, DC4 is ranked with a score of ‘2’. Composite material is unrecyclable, which concepts DC5 and DC6 are made of, but DC6 is thinner than DC5, and DC6 is supported by steel stringers which are separate from the panel and is recyclable; therefore, DC5 is ranked with a score ‘2’, but DC6 is ranked with a score ‘4’.

Availability of materials. Although recycled papers are available in China, making recycled papers into a board needs special technologies, which is uncertain in China for this evaluation, and, hence, DC2 is ranked with a score ‘3’. Balsa is a kind of flowering plant habitats in northern Bolivia, Brazil, and southern Mexico which makes the material more uncertain in

China, and, hence, DC3 is ranked with a score ‘2’. Although foam is available in China, the technique to make it into a panel encapsulated by composite sheet is unknown for this project at this moment, and, hence, DC4 is ranked with a score ‘4’. Steel, chipboard and composite materials are available in China, and, hence, DC1, DC5 and DC6 are ranked with the same score ‘5’.

Performance of sound insulation. Sound performance (sound response when steps on) differs between materials. There are mainly two factors, which may influence the sound performance of a panel: surface material and panel structure. In this criterion, DC1 has the lowest score ‘3’, because metal surface material like steel often have a poor sound performance than composite materials (carpet covering is not considered in this context) due to its physical property. In addition, hollow structure, such as double-layer structure with no core material, are easily generate a hollow sound when steps on; DC6 also have the lowest score ‘3’, this is due to the metal stringer structure underneath may generate unpleasant squeezing sound between the surface material and stringer when presses on.

Surface finishing. The surface of DC1 is metal, which has to be painted or coated for aesthetics and rust/erosion-resistance purposes, and, hence, increases the cost, as well as has a durability problem; while the surfaces of all the other concepts are of composite materials, which do not need painting or coating, but have a quality surface finishing and have long durability. Therefore, DC1 has the lowest score ‘2’, and all other concepts have a score of‘ 5’.

Cost. The cost considered in this evaluation includes material cost and manufacture cost. Because chipboards and metal sheets are the cheapest materials, and the manufacturing cost is relatively cheaper, concept DC1 is the cheapest amongst all the concepts, and hence has the highest score ‘5’. The composite material is relatively expensive, and the process to encapsulate the core materials with the composite material sheet increases the manufacturing cost, so concepts DC2, DC3 and DC4 are the most expensive and hence have the lowest score ‘2’. Because both concepts DC5 and DC6 do not involve the encapsulating process, their manufacture cost is lower than DC2, DC3 and DC4; in addition, DC6 is thinner than DC5, and hence uses fewer composite materials, therefore, DC5 is ranked with a score ‘3’ and DC6 is ranked with score ‘4’.

7.4 Detailed design

According to the concept evaluation result, the composite material panel supported by steel stringers (concept DC6) was selected as the best concept, this concept was further developed in the detail design stage. A composites floor with ribs reinforced and the stringer combination was proposed as the detailed design concept, see Figure 7.10 and 7.11. To reduce the weight of the flooring product, this design adopts the rib structure, which replaces the solid panel design.

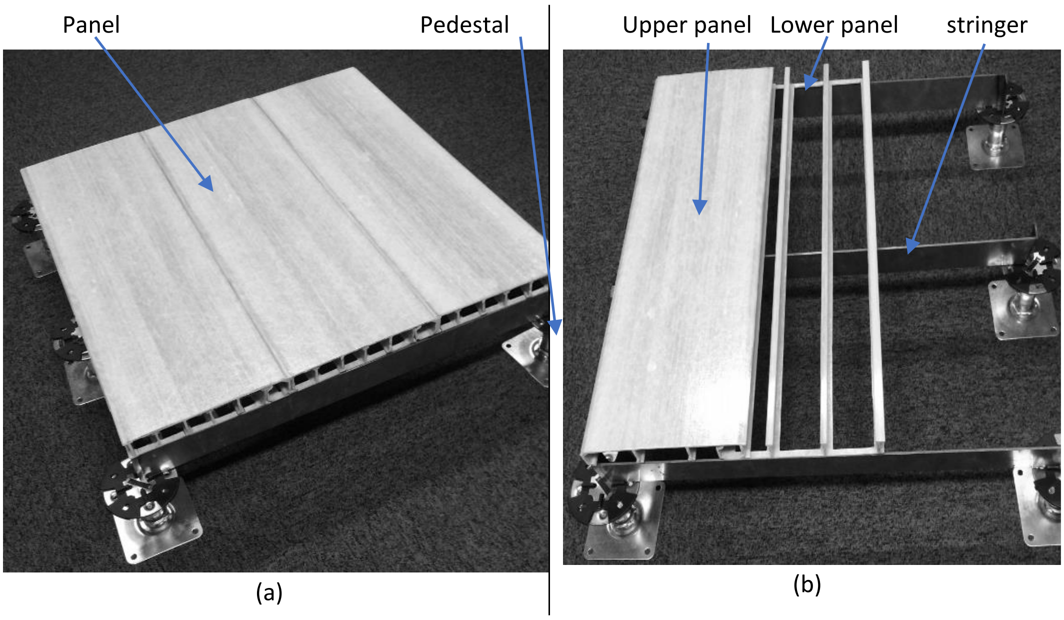


Figure 7.10 Detailed design of eco-flooring product

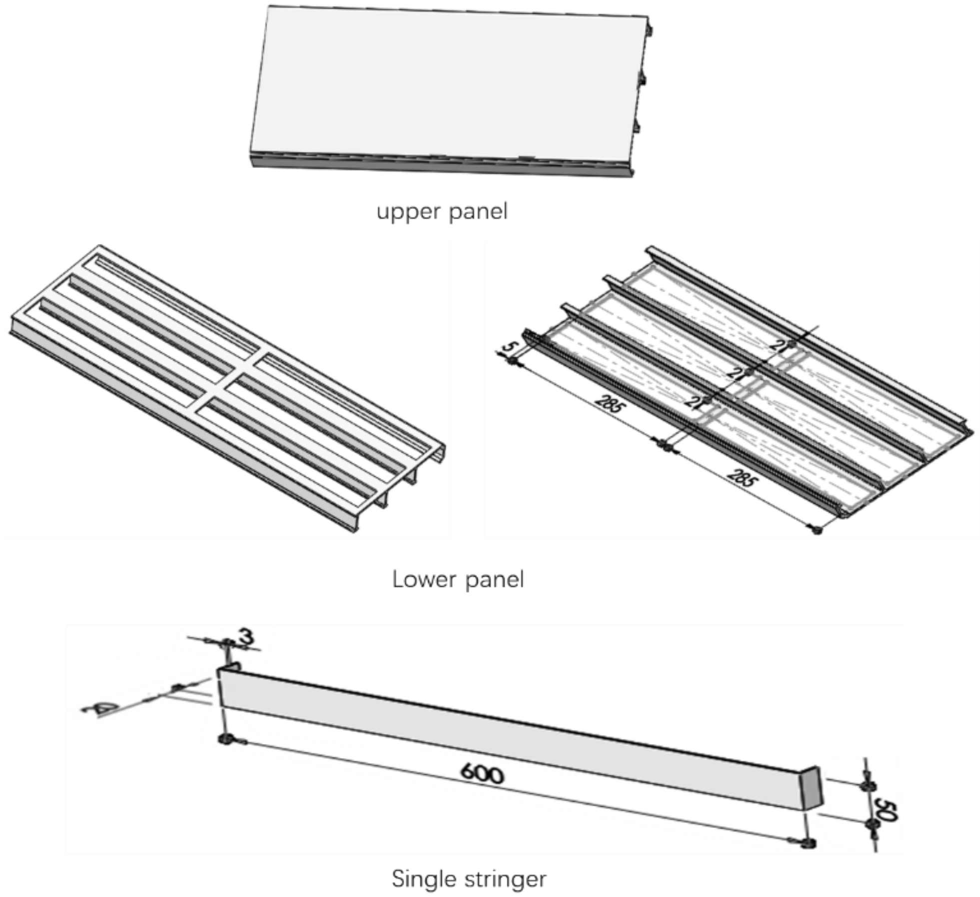


Figure 7.11 modular components of the raised flooring product

The panel is consisting of six 200*600mm panel, the six panels (three top panels and three bottom panels) are stacked, where the ribs are scattered in equal spacing. The lower piece is processed from the upper piece by cutting-off some parts of the flat sheet with the rest remaining with the ribs to reduce the weight of the panel. The stringer is to enhance the strength of the panel along the longitudinal direction, as shown in Figure 7.11, it made of steel sheet which is cross shaped with steel sheets on the four edges. The panel is made of glass fibre enforced PU composite material (25%~30% glass fibre). For the material of stringer, carbon steel is considered as it performs high strength properties and cost-effective as well as high recyclability. Table 7.8 presents the properties of materials of the panel and associated stringer for supporting the panel.

Table 7.8 Properties of materials for panel and stringer of the eco-flooring

Property	**PU 2500-12.3 composites**		**AISI 1045 steel**
Description	Glass fibre enforced PU composites, with the features of superior fabrication efficiency, high strength, and low water absorption, and fire resistance. PU material has different properties in the two different directions. In this research, PU material with 220MPa yielding strength in the direction of 90 degree is considered.		Chosen as stringer material, most applied metal material with high strength properties and cost-effective as well as high recyclability
Mass Density	2070g/cm3		7850g/cm3
Poisson's Ratio	0.3		0.29
Yielding Strength	220MPa (90^o)	1467MPa (0^o)	530MPa
Tensile Strength	70MPa (90^o)	1185MPa (0^o)	625MPa
Elastic Modulus	20.5GPa (90^o)	58.1GPa (0^o)	205GPa
Water Absorption	< 0.09%		Paint required for corrosion resistance

The fire resistance factor is important for the new development of raised floors panel because composite materials are becoming the alternative material replacement for traditional chipboard core and steel plating. The relevant standard of fire resistance test for composite materials is UL 94, "Test for Flammability of Plastic Materials for Parts in Devices and Appliances". The UL 94 Standard provides a method for rating the ignition characteristics of plastic materials. The UL 94 rating that code officials commonly run across is V, such as V-0, V-1, and V-2. According to the above fire-resistant standards, the fire test has been conducted by the material provider, the results of PU 2500-12.3 composites classes as V1, which indicates the material meets a good fire resistance standard.

In addition, the cost of the flooring material is taken into consideration since one of the development objectives is to achieve cost-effective goals. The price per unit for each material is presented as follows:

- PU material: 2.22 GBP/kg (=20 Chinese Yuan/kg based on the rate 1 GBP= 9 Chinese Yuan)

- Carbon steel: 0.22 GBP/kg (=2 Chinese Yuan/kg)

The total weight of the design with PU material is 7.9kg (about 36% less than the average raised floor panel) which is approximately 7.73 GBP, and the cost of carbon steel is about 1.07GBP. Altogether, the design reduces 45% of the material cost compares to other composite material option (with sheet moulding compound costs 16.1 GBP, which is almost twice of the cost compares to it of PU material).

The manufacturing of floor panel utilises the pultrusion method, which is faster than traditional processing methods of floor panels, such as compression modelling. Moreover, because the panel surface is formed during the pultrusion process of the panel material without additional treatment required, the outer layers are not needed for manufacture, which simplifies the processes, and, hence, accelerates manufacturing and decreases the cost.

7.5 Integrating finite element analysis in development of the eco-flooring product

7.5.1 Simulation of the flooring product test

7.5.1.1 Standards and technical requirements of raised flooring product

According to the British Standard for raised flooring product BSEN 12825:2001 (BS EN 12825, 2001) and PSA MOB PF2 PS (PSA, 1992), the floor panel is required to apply working loads of 3000N on a 25mm square of the surface of the panel. The working load is multiplied by the Safety Factor and then obtain the ultimate load. Therefore, a raised access flooring system complied with BSEN standard is defined as follows:

- Working load of 3000N
- Ultimate load of 9000N
- Safety factor goal is 3 (Class 3), which shows the strong possible panel under BSEN Certification with a high Safety Factor.
- Deflection under the Working load is within 2.5mm (Class A).

According to the standards and testing method in both documents, for a standard 600mm x

600mm raised access floor, the load is required to be applied on the area of 25mm of the surface of the panel, of which the capacity should be tested at the positions of the centre and outer edge of the panel, see Figure 7.12.

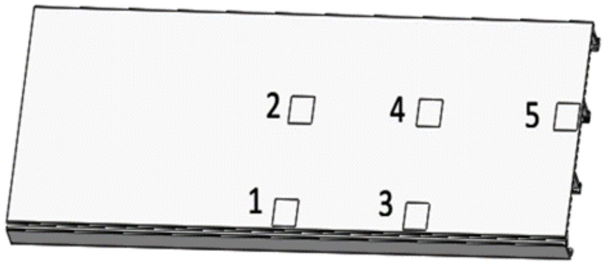


Figure 7.12 Standard testing point of raised flooring product

7.5.1.2 The finite element analysis (FEA)

The FEA was conducted to simulate the experiment before the experiment to have a preliminary evaluation of the strength performance, in this case, if the FEA results meet the technical requirements, then the physical text can be conducted, otherwise, the flooring product will be refined till the results meeting the requirements. Subsequently, the FEA test will be compared to confirm the experimental results. Based on the parameters of material property, the finite element model has been developed for the loading-capacity analysis of the panel. The main material parameters involved in the modelling process include elastic modulus (E), yielding strength, density, and Poisson's ratio. The CAD software, Solidworks Simulation, was utilised to simulate the technical tests.

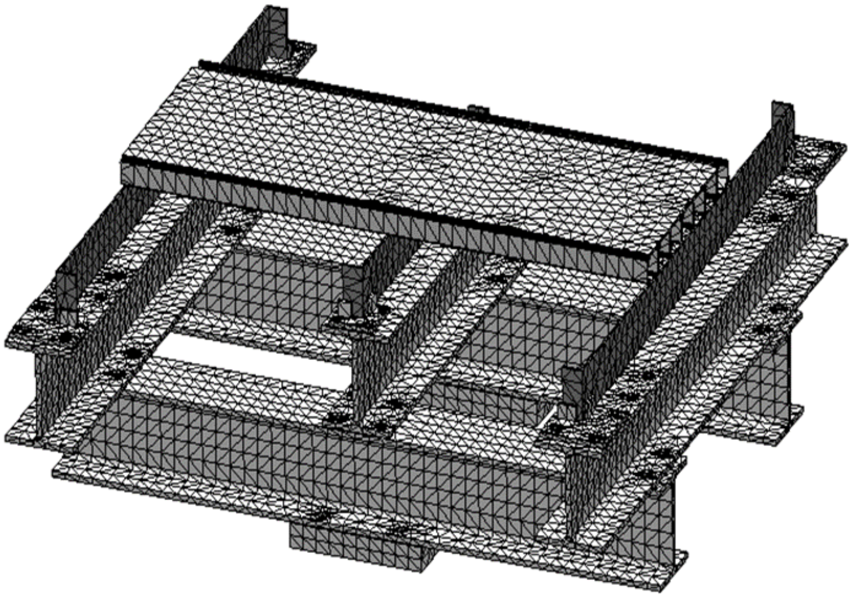
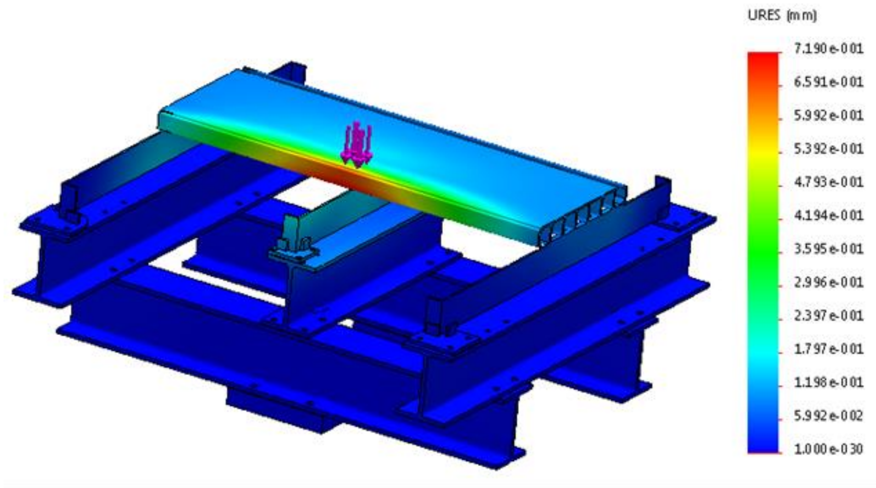
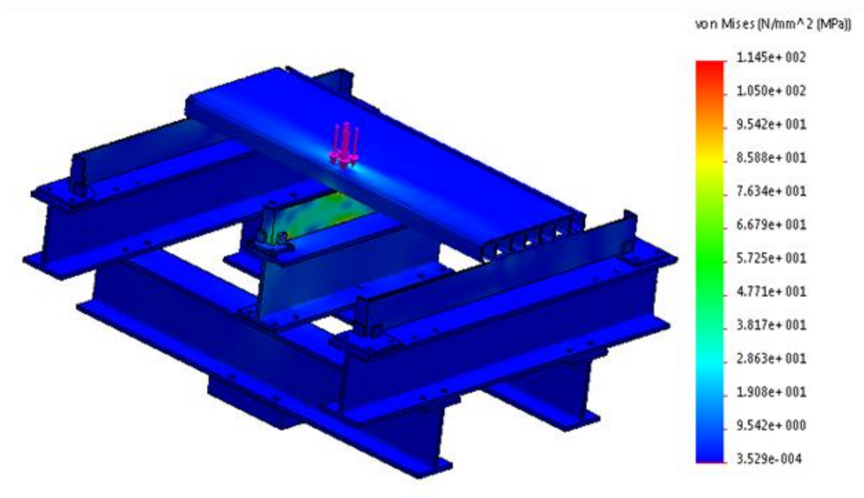


Figure 7.13 Finite element analysis model

The FEA model is shown in Figure 7.13, which is developed based on the CAD model modified from previous work in (Faulkner, 2017). As shown in the FEA model, the components of the experimental system considered in the FEA include two panel pieces (an upper piece and a lower piece), three parallel stringers, six pedestals, beams that support the stringers for testing, and two base supports. The assessment settings are made according to the real physical test, which is shown in the next section. The two panel pieces (an upper part and a lower base) were assembled (in the software) and placed upon the stringers, which are fixed with the experimental beams via the pedestals. For simulation of the deflection (deformation) and yielding stress, at each test points, 3000N working load were applied with a 90° vertical angle in a 25mm^2 square area in the form of distributed forces. Figure 7.14-7.18 show the results of deflection and yielding stress at the five testing locations.

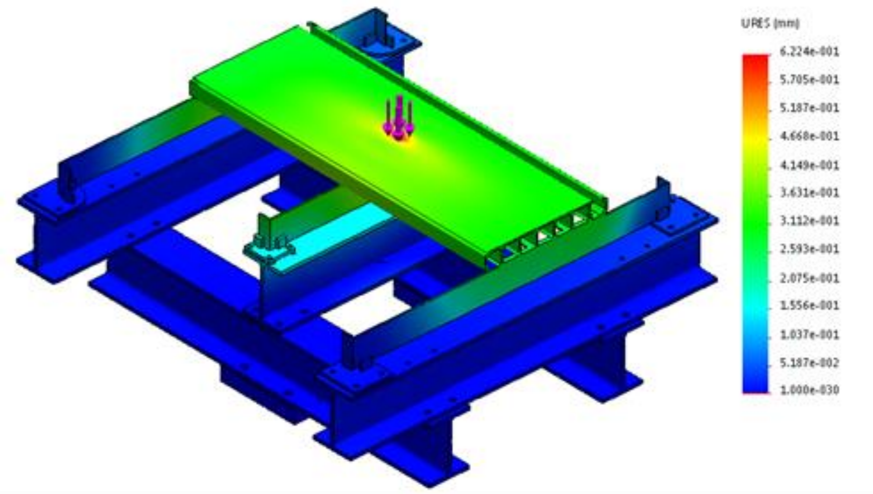


(a)

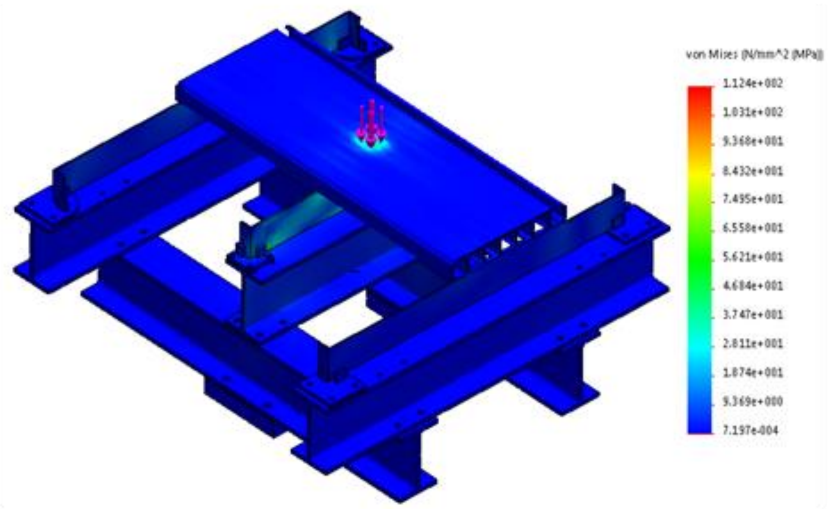


(b)

Figure 7.14 FEA results of position 1 (a) Deflection (b) Yielding stress

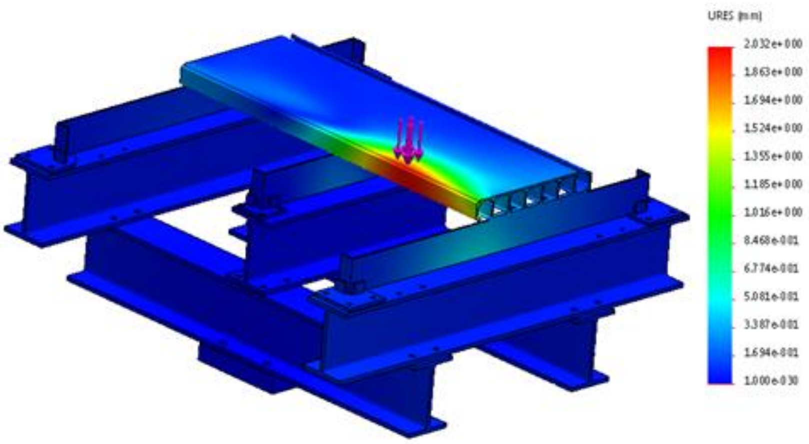


(a)

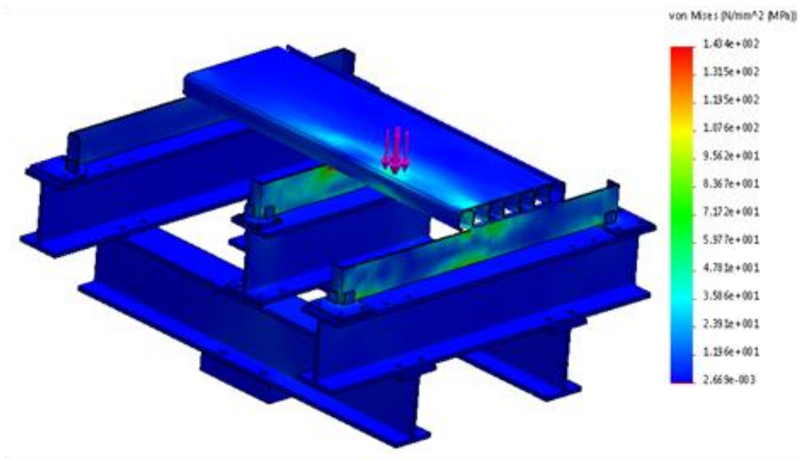


(b)

Figure 7.15 FEA results of position 2 (a) Deflection (b) Yielding stress



(a)



(b)

Figure 7.16 FEA results of position 3 (a)Deflection (b) Yielding stress

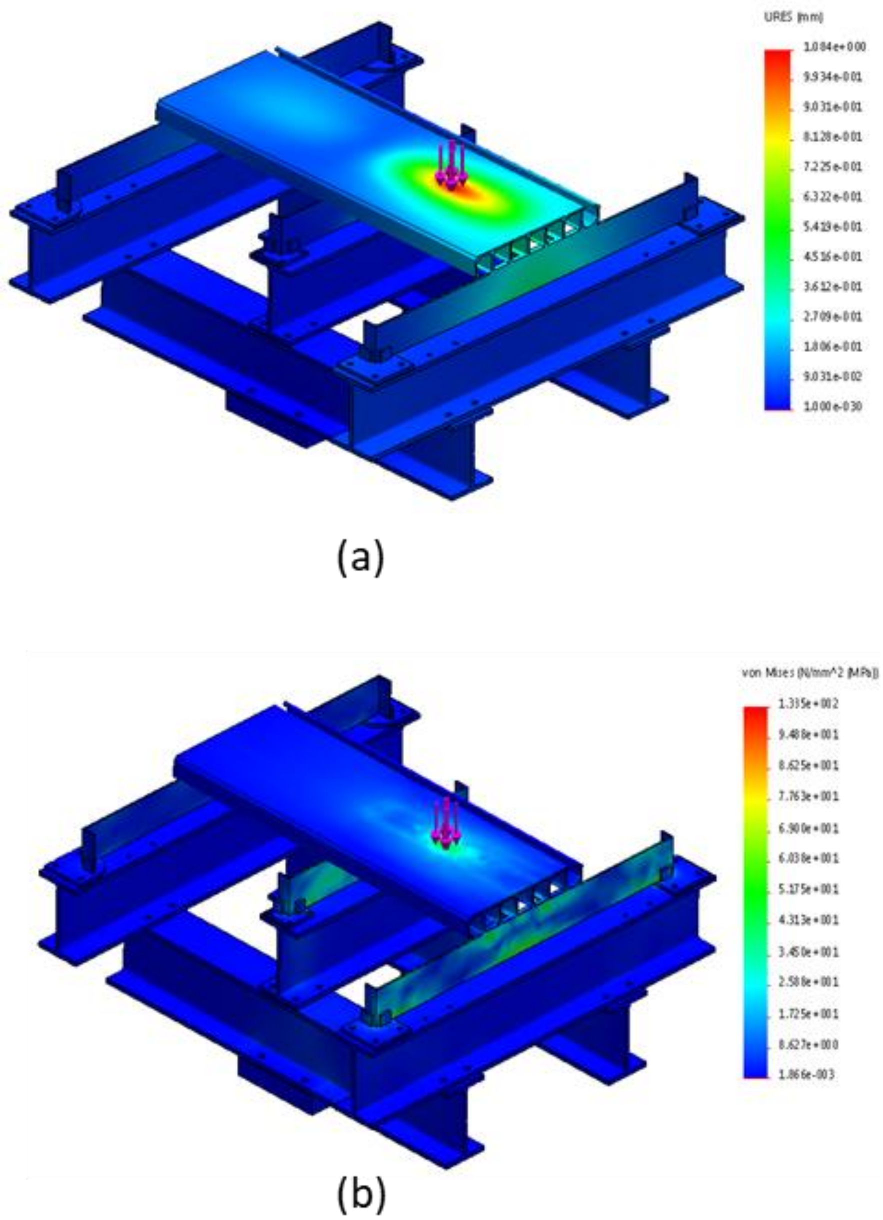
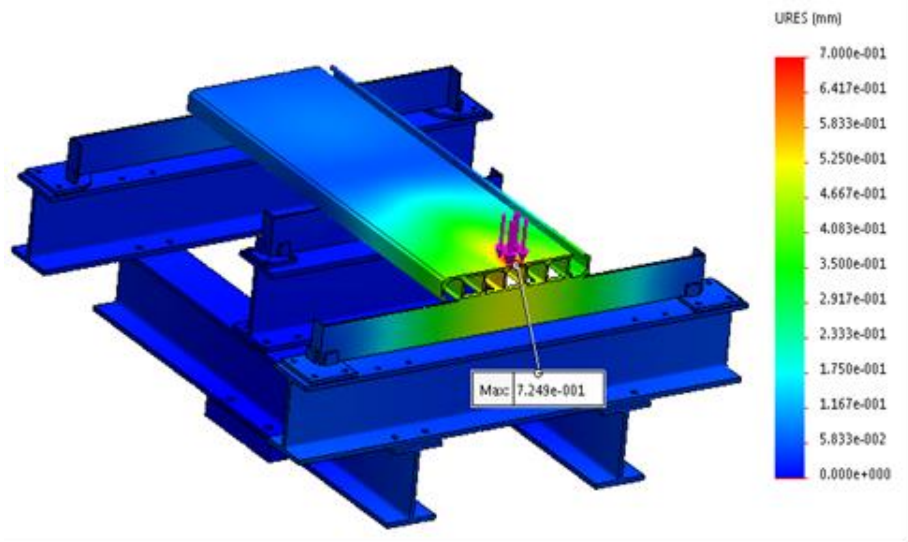
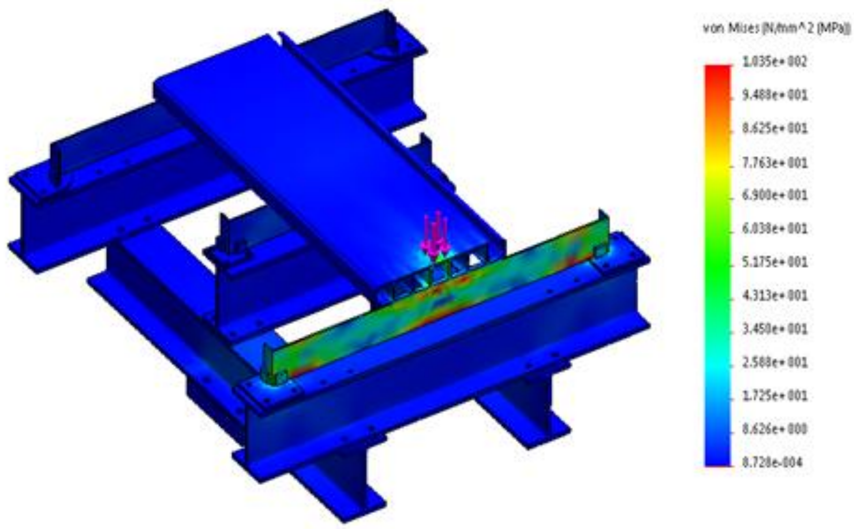


Figure 7.17 FEA results of position 4 (a) Deflection (b) Yielding stress



(a)



(b)

Figure 7.18 FEA results of position 5 (a) Deflection (b) Yielding stress

The values of each test results are listed in Table 7.9. As shown in the table, the deflection of the panel is more than that of the stringer, whilst yielding stress of the panel is less than that of the stringer. The maximum deflection takes place at Position 3 on the panel (2.03mm), and the maximum yielding stress occurs at Position 3 on the stringer (143.4Mpa).

Table 7.9 FEA results of deflection and yielding stress of each testing point

FEA results	**Glass fibre enforced panel**		**Stringer**	
	Deflection	**Yielding stress**	**Deflection**	**Yielding stress**
Position 1	0.71mm	11.45MPa	0.16mm	114.5Mpa
Position 2	0.62mm	11.05MPa	0.14mm	112.4MPa
Position 3	2.03mm	48.34MPa	0.81mm	143.4MPa
Position 4	1.08mm	40.35MPa	0.72mm	133.5MPa
Position 5	0.70mm	21.55MPa	0.08mm	103.5MPa

The results show all the test point were within the requirement value, which is the deflection of the panel is less than 2.5 mm under 3000N working load and yielding stress of the panel is less than 73.3 MPa. Therefore, the physical experimental test was conducted, and the results are to be compared in the next section.

7.5.2 Simulation results compare with experimental test results

The experimental test was conducted with an Instron testing system to apply external loads on the surface of the top panel and monitor the change of the deflection of the panels with the loads. The experimental cite is shown in Figure 7.19, detailed experimental test Procedure can be found in (Su et al., 2021).

(a) (b)

Figure 7.19 Experimental test (a) Test overview (b) Strain gauges on the back of top panel

The comparison of the simulation results and the experimental results are shown in Table 7.10. As shown in the table, the FEA results confirm with the experimental results, which double proves the results of experimental and the FEA are correct. Therefore, the detailed design concept with glass-fibre reinforced PU composite material is confirmed because it has high load-bearing performance and meets all the requirements within the composite material flooring product standards.

Table 7.10 Comparison results of FEA and experimental test

	Deflection of glass-fibre reinforced PU material panel		**Yielding stress of glass-fibre reinforced PU material panel**	
	Experiment	FEA result	Experiment	FEA result
Position 1	0.70mm	0.71mm	12.3MPa	11.45MPa

Position 2	0.65mm	0.62mm	11.8MPa	11.05MPa
Position 3	1.90mm	2.03mm	45.6MPa	48.34MPa
Position 4	1.13mm	1.08mm	42.6MPa	40.35MPa
Position 5	0.70mm	0.70mm	20.1MPa	21.55MPa

7.6 Manufacture

After the detailed design is confirmed, field research was conducted in Chongqing (China), where the composite material manufacturing company and floor sample producer is sited in.

The field research aims to study the manufacturing procedure and related technique of the composite eco-flooring product. The floor sample had been manufactured by Chongqing International Composite Material Co. LTD(CPIC) in China. The manufacturing of floor panel developed in this research utilises the pultrusion method (see Figure 7.20), which is faster than traditional processing methods of floor panels, such as compression modelling. Moreover, because the panel surface is formed during the pultrusion process of the panel material without additional treatment required, the outer layers are not needed for manufacture, which simplifies the processes, and, hence, accelerates manufacturing and decreases the cost. The manufacturing process of the eco-flooring product is illustrated in Figure 7.21.

Figure 7.20 Composite eco-flooring manufacture plant (a) pultruding procedure (b) selecting of materials

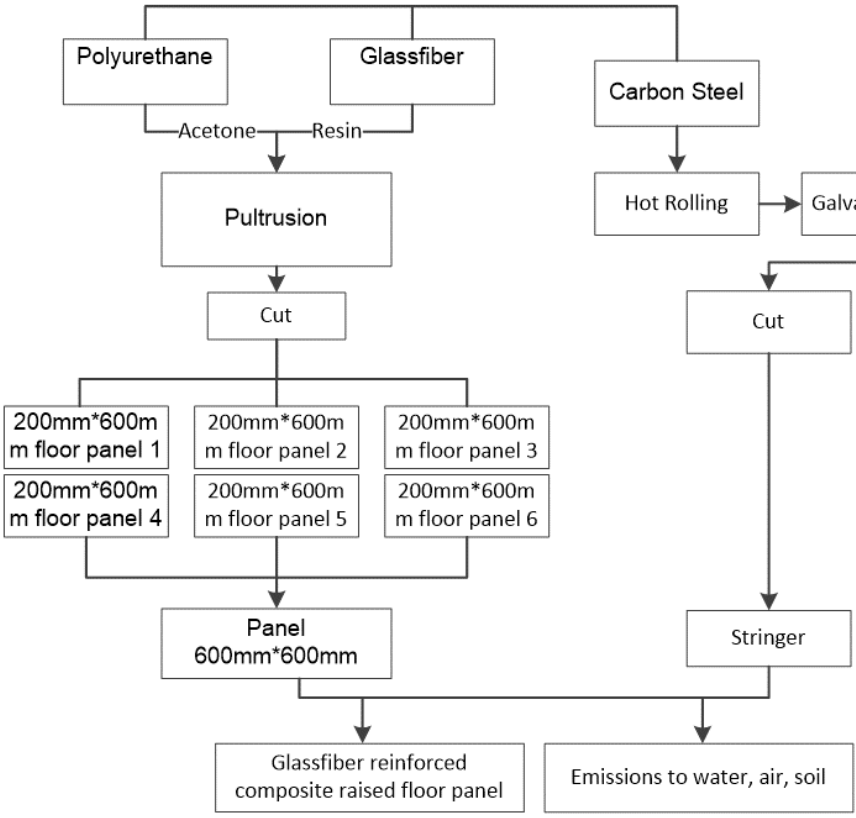


Figure 7.21 Manufacture process of the eco-flooring product

In addition, the field research also aims to collect the inventory data collection for LCA. Input-output data such as material use, energy consumption, waste treatment during the composite floor panel production were acquired in the manufacturing plant by interviewing engineers and staff on plant and/or measure on site.

The visit also including meeting with the producer and potential application company. Meeting with engineers in the production company helps to gather information about the production facilities, materials usage as well as identify the difficulty for companies to conduct eco-friendly product design.

7.7 Comparative life cycle assessment

The life cycle assessment of the eco-flooring product (F1) was conducted then compared with two existing raised flooring products (F2, F3) to evaluate the flooring product's environmental profile. As shown in Figure 7.22, the flooring products under study including composite material raised floor (F1), cement injected steel sandwich raised floor (F2) and, wood-based raised floor (F3). The functional unit of F2 and F3 can be found in 7.2.2 while that of F1 can be found in 7.4.

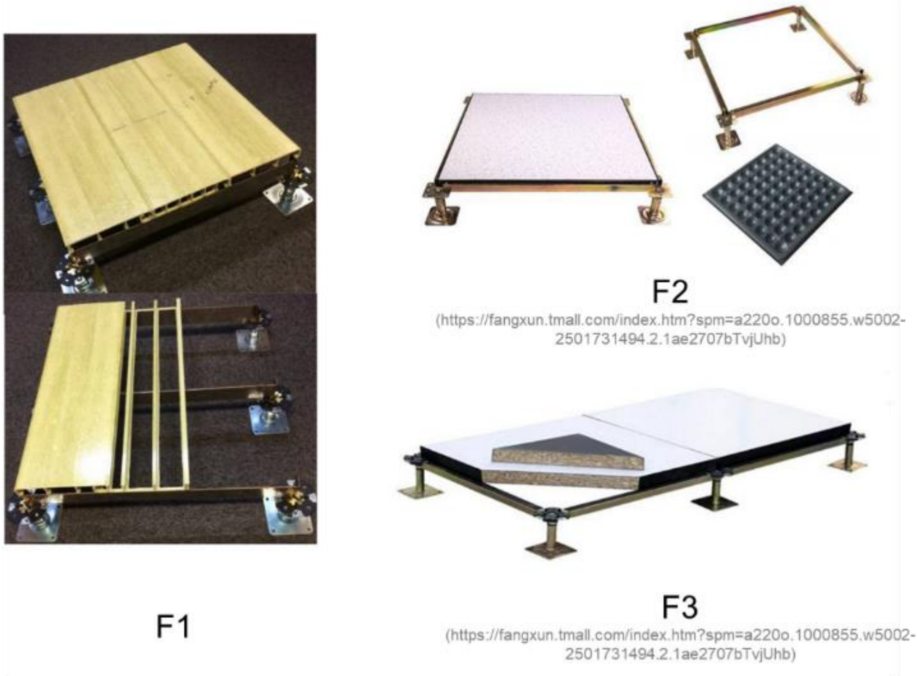


Figure 7.22 Flooring product under comparison

Since the three raised flooring products have the same panel dimensions, the function unit is equal to the three products. Thus, the functional unite defined under this study is 100 items, one item includes a panel and a stringer of the three products.

The system boundary including raw material acquisition, manufacture, packaging, distribution (transportation) and end-of-life treatment are within the system boundary under study. Use phase along with maintenance during the product's service life are excluded from the assessment boundary, it is assumed as a static raised flooring product, the energy consumption of the stage is zero.

Inventory data of F1 is listed in Table 7.11, while that of F2 and F3 is listed in 7.2.4. Input data of F1, such as material use, energy consumption during the composite floor panel production were acquired in the factory of the manufacturing company. Transport distance was assumed according to the direct distance from Chongqing (China) to UK (London). It is assumed that 80% of panel material may send to recycle and 20% shall take to landfill, and all stringer material will be reused.

Table 7.11 Inventory data of F1

Inputs		Output	
Materials		Product	
Polyurethane	2.16kg	Floor Panel	8.34kg
Glass Fiber	8.66kg	Stringer	3.42kg
Acetone	1.20L	Waste	
Resin	0.50L	Solid Waste	1.71kg
Carbon Steel	5.20kg		
Plastic	0.07kg	End-Of-Life Treatment	
Paperboard	1.10kg	Recycle (Composite Material)	7.82kg
Energy		Reuse (Carbon Steel)	4.00kg
Electricity	0.48kw/h	Landfill	4.27kg
Transport			
Road Transport (Material Deliver)	2517km		
Railway (Product Transport)	11477km		

100 items per each of the three variants (F1, F2 and F3) are assessed with ReCiPe Endpoint H method to compare their environmental performances. The results of three individual impact categories as well the total impacts are shown in Table 7.12 and Figure 7.23. As shown, F2 presents the highest environmental impacts of the three variants (1941.98 points), F3 has the second highest impacts (1882.93 points), F1 has the lowest impacts (466.67 points), which is 76% less than F2 and 75% less than F3 that mainly thanks to the feature of light weight and easy to manufacture.

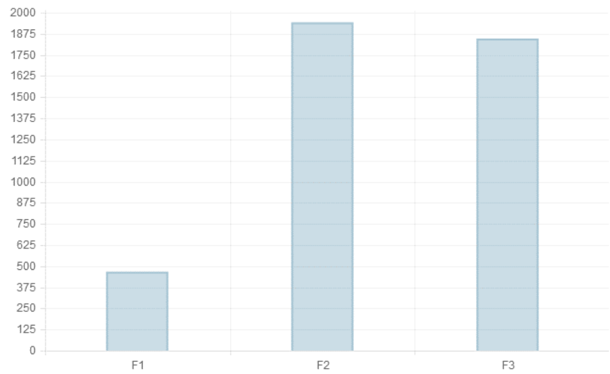


Figure 7.23 Bar chart of single score results (F1, F2, F3)

Table 7.12 Environmental impacts in endpoint category (F1, F2, F3)

Impact category	F1	F2	F3	Unit
Ecosystem Quality	109.62	498.59	573.16	Points
Human Health	149.95	669.59	588.55	Points
Resources	207.1	773.8	721.22	Points
Total	466.67	1941.98	1882.93	Points

The key environmental impact life cycle stages and processes of three products have been identified and demonstrated in Figure 7.24. The production is the key environmental impact stage of all three products throughout their life cycle. For F1, the production of glass fibre is the hotspot process (74.2%) followed by the transportation stage (15.17%) and packaging (10.25%). The production of stringer was identified to be the biggest contributor to the production of F2 (45.66%), while the packaging is the other hotspot stage in F2 (29.64%) due to the material used. For F3, the production of stringer accounts for 48% of the total impact which is the hotspot process. The other key environmental process issue is the production of fiberboard which contributes 37% of F3's total impact. Detailed results and interpretation can be found in (Wang et al., 2020).

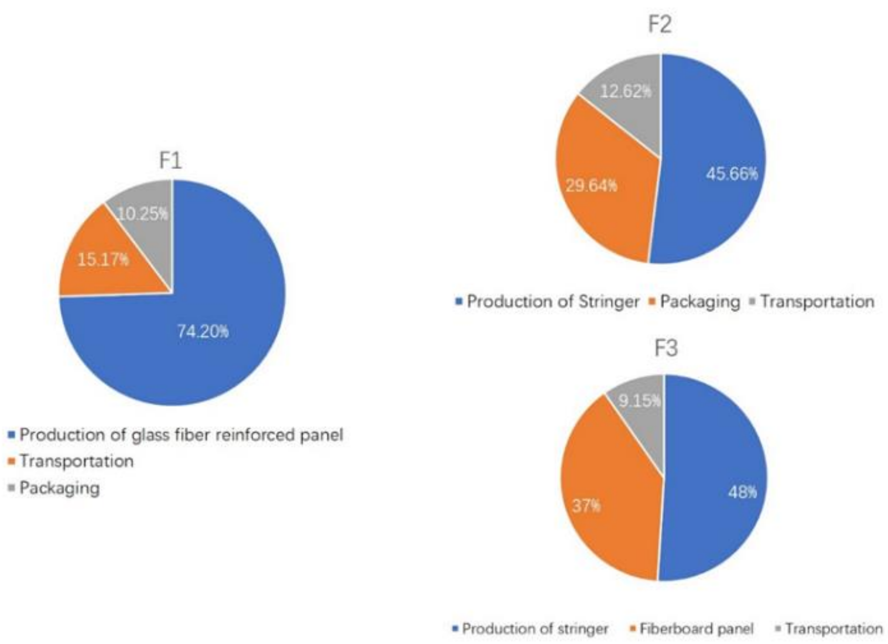


Figure 7.24 Key life cycle stages to F1 F2 F3's environmental profile

The comparative results revealed that, with the consideration of environmental issues in the early stage of product development, the proposed raised floor product (F1) embraces several eco features which have proven to have superior environmentally performance. The proposed raised flooring product can be considered as a benchmark in eco flooring innovation.

Chapter 8 - Conclusion

8.1 Contribution to knowledge of the research

This thesis presents an original research that focuses on methodologies and practices to facilitate systematic innovations of sustainable product development and product service towards the triple bottom line of sustainability. A holistic approach that aims to support sustainable innovation that covers the whole life cycle of the product with consideration of the TBL of sustainability, is developed and demonstrated with variant case applications. Distinct from other counterpart methodologies, this approach:

(1) addresses not only environmental sustainability but also social and economic aspects of sustainability from the product and service development perspective, which is state-of-art.

(2) proposes the methods of developing the sustainable product and the service as a bundle, facilitating the links between product development and product service with the consideration throughout the whole product life cycle, which is novel.

(3) demonstrates the suitability for universal product innovation instead of case-specific ones. Products developed by adopting this approach are proved to have superior performances on environmental, socio-economic levels within their life cycle stages as well as embracing prominent product functions. In addition, the research provides a practical approach to companies, especially SMEs with variant industrial case examples. The approach presented in this thesis supports the implementation of sustainable product and service development, life cycle management, facilitating enterprises' reform the profit model solutions towards

sustainable production and consumption, which, ultimately, contribute to the circular economy and sustainable development, which is state-of-art.

The contributions have made to knowledge of this research are explained as follows:

- A systematic approach, namely 'sustainable product development and service approach', which aims to facilitate sustainable innovation for the whole life cycle of the product with consideration of the environmental and socio-economic aspects of sustainability is developed. Different from the existing frameworks/methodologies, this approach emphasises developing product and service together as well as addressing the TBL of sustainability. The approach facilitates the links between product development and product service and thus enhances the holistic sustainability of products through their whole life cycle. The approach is generally applicable and proved (by the case studies) to be effective in developing product and service with improved sustainability performance.

- The concept 'design for service (DfS)' and 'service feedback for design (SfD)' have been brought out and integrated into the holistic approach. Under the concept, the sustainable product development phase and the sustainable product service phase are interrelated and support each other; the issues encountered and identified in the product services phase, which are related to the product sustainability performance/functions, provide useful feedback for improvement of the product. Such feedback is then analysed and used to refine the product design specifications, which govern the design and manufacture, to ensure the improvement of the product performance/functions, including the product sustainability. DfS is a conceptual framework that supports the integration of the related methods.

- A 'Sustainable product and service conceptual construction approach' is developed and demonstrated. The research detected the importance of controlling the negative impact in the early design stage, and the barriers for designers to transform the 'uncertain' sustainable variables in design requirements. To meet the gaps, the proposed approach builds on the framework of DfS, and aims to detect and conceptualise product and service opportunities towards TBL sustainability at the early development stage (conceptual design stage). The sustainability performance of the product(s) in service is/are to be assessed at the beginning of the product development process to provide feedback on sustainability issues, such as to identify the opportunities for the specific enterprise/case on their improvement of sustainability performance in new product and service development. The sustainable recommendations are to be given based on the assessment results so that they can be applied to the PDS construction. The approach includes three steps: data collection, conducting sustainable assessment, and deriving recommendations and implications to product and service design. A data collection method (first step) also has been developed and demonstrated in case studies, as well as the other two steps. The conceptualisation approach proved to be effective to inform strategic PDS for addressing variant sustainable innovation goals/needs.

- A sustainable concept selection method during product development stages is brought out. This concept selection method aims to guarantee environmental, the ability of service, and cost-effective features in design concept decision-makings. Threshold and comparative criteria are initiated, and the principles of structuring the criteria, as well the weighting method are proposed and applied in case studies.

- A simulation-test confirmation method is presented. The method is applicable in the detailed design stage, before the product prototype is ready to predict the experimental test with strength requirements. The simulation of the experimental test with FEA techniques is confirmed with the physical experimental test which indicates the method is effective in simulating and, which is a time-effective and cost reduction method to apply in product development.

- It is novel to integrate sustainability assessment (E-LCA and S-LCA) in the product/service development stage. E-LCA and S-LCA assessment models are developed and assessed. The research demonstrates those techniques applications step by step in different industrial cases, especially providing an important example for further S-LCA studies, which has been identified as lack of practice in the product development stage (see literature review). Furthermore, it is a important contribution and exploration to integrate the sustainability assessment in the early product development stage for deriving the sustainable opportunities and implications, and for the identification of the interrelationships between both environmental and social assessment results that are subsequently transformed into strategic recommendations for addressing TBL sustainability issues in the early product and service development stage.

- A sustainable industrial LED lighting product and service are developed by utilising the proposed approach. The sustainable lighting product has an innovative modular design and ultra-high efficiency and longevity, which is designed for its service. There is no such product in the market, which is unique. The sustainability performances of the sustainable LED lighting product and service are assessed. The environmental assessment results indicate that the sustainable LED lighting product developed with the proposed approach (ARCUS-II) presents a 46% lower environmental impact. The sustainable service based on the sustainable LED lighting product is evaluated as environmentally friendly and socioeconomically beneficial. The proposed product and service has the capacity of benefiting multiple stakeholders, such as promoting workers' welfare, cutting costs for manufacturer and customers (end users) with prominent services and, benefiting all stakeholders with a healthy recurring profit stream.

- A domestic eco-lighting product is developed by utilising the approach. Several eco-features were demonstrated in the lamp, especially on reducing the use of materials in design and manufacturing: 0.8 kg in weight and made from only one kind of material; using post-consumer or manufacturing remnants as material and a simplified manufacturing technique which reduces resources on a large scale; a modular design which advances the recyclability, etc. Comparative LCA results indicated that the eco-designed Lamp presented a better environmental performance by resulting in the lowest impact scores (16.4 Pt) which are 27% to 58% less than the existing products in service. The eco-lighting product is aiming to demonstrate the approach when the alternative sustainable goal is identified, i.e. environmentally sustainability is the paramount goal for the case company. It can be concluded that it is valid in improving LED lighting product's environmental performance by utilising the proposed approach, specifically, by integrating LCA results as a reference into product design, in developing PDS and decision-making processes.

- An eco-friendly and cost-effective raised flooring product is developed by utilising the proposed approach. The eco-flooring product is an all-in-one structure that is made from composite material (glass fibre reinforced PU) only, thus there are no additional floor finish/cover or floor layers. The floor sample meets British Standard BSEN 12825:2001 (BSI, 2001), PSA MOB PF2 PS and fire resistance standard UL 94 (MOB,1992). In addition, the product embraces several prominent features: lightweight, ease of assembly and disassembly, ease of manufacturing, cost-effectiveness, etc. The flooring product proved to have an approximately 75%-76% environmental impact reduction in comparison with the equivalent product in market, which indicates the holistic approach is applicable to the development of a static product with a strict technical requirement as well.

- Key factors to the environmental profile of the three case products, focusing on lighting and furniture/construction products, are detected. Those factors can be integrated generally in the sustainable development under those product categories, in defining the eco-product specifications and eco-design decision-making processes. Furthermore, the sustainable products/services developed in the thesis also provides a benchmark for further sustainable research.

This thesis presents a sustainable product development and service approach that covers products' whole life cycle as well as TBL of sustainability. The approach is illustrated with the applications of three industrial products. The sustainable products and services developed by utilising this approach proved to have prominent environmental, social and economic benefits. Thus, it can be concluded that the SPDS approach is effective in developing product and service that advances the TBL of sustainability, which is novel in the subject area.

8.2 Limitations and future work

The sustainability assessment of the proposed sustainable PSS hasn’t been explored. It was due to the limitation of time and resources, as well as no universal agreed methods to conduct the full-scale E-LCA and S-LCA of the PSS. Future work related to this study is to explore the sustainability evaluation of PSS and the integration of evaluation results to inform decision making and sustainable consumption. In addition, sustainability benchmarking, such as how to integrate environmental performance and social performance together, to scale the holistic sustainability of product and service, is also a direction for future studies.

TBL of sustainability is addressed in this SPDS approach, however, the economic aspects mainly focus on the cost of the products, cost reduction for consumers, and the profit of the providers since the research is within the product development subject. Professional economic assessment, such as life cycle cost (LCC) is not conducted due to the complexity of the methodology and the limitation of time and resource.

In addition, as mentioned in each case study, the eco-features of products and services can't be fully reflected in sustainability assessments, which is a barrier in evaluating and identifying the potential sustainable product, especially in eco-labelling schemes. Furthermore, social aspects of sustainability are currently independently considered by sustainability awarding parties. On one hand, from the policy level, initiatives are needed to combine the environmental and socio-economic aspects jointly in scaling products'/services' sustainability performance. On the other hand, from an academic perspective, agreed mechanisms and approach upon weighting and scoring the two aspects from existing assessment tools, such as E-LCA and S-LCA, are still needed.

In this research, the SPDS approach has been applied in various products with individual sustainable development goals to demonstrate the general applicability, including an industrial LED lighting product and services towards TBL of sustainability, an eco-friendly domestic lighting product as well as eco-friendly and a cost-effective flooring product. These products represent energy-consuming products and static products; in terms of the sustainable goals, TBL of sustainability, environmental sustainability, as well as economical sustainability, are covered within the case products. However, a wider range of products should be explored using the SPDS approach in the future to illustrate the suitability and effectiveness of the approach.

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