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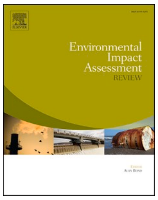

Environmental and social life cycle assessments of an industrial LED lighting product

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ABSTRACT

It is necessary to assess a product's sustainability from both environmental and social perspectives. However, combined environmental and social performance assessments have not been given enough attention. This paper presents a combined Environmental Life Cycle Assessment (*E*-LCA) and Social Life Cycle Assessment (S-LCA) of an industrial LED luminaire through its life cycle. The LCA screening studies were conducted in line with ISO 14044 and United Nations Guidelines for *E*-LCA and S-LCA with Ecoinvent and PSILCA databases. The study analysed the key potential risks as well as the interrelation between *E*-LCA and S-LCA results, in which the production of LED driver, LED panel, and electricity consumption were identified as the hotspot processes to both environmental and social impacts. Four social issues were identified, namely 'association and bargaining rights', 'sanitation coverage', 'public sector corruption' and 'pollution'. LED driver and panels are responsible for 78% and 20% of the environmental impacts respectively in the production phase. Electricity accounts for an average of 51% of environmental impacts. The process also made the key contribution to the 'social responsibility along the supply chain' (52%), 'industrial water depletion' (84%) and 'contribution to environmental load' (63%) risks. Meanwhile, in the category 'contribution to economic development', 18% positive social impacts were identified. Based on the results obtained, recommendations were derived for the development of sustainable LED lighting products and services with a trade-off between the environmental impact and the socio-economic benefits. According to the literature review, this research is the first attempt to assess a combined environmental and social performance in industrial LED lighting products and provides a valuable contribution to knowledge for future research in this area.

1. Introduction

Lighting is responsible for about 15% of global electricity consumption and 4.6% of greenhouse gas emissions (UNEP, 2017). Light-emitting diodes (LEDs) have been developed to a level of performance and light quality that enable the replacement of the most conventional light sources (GLA, 2020). Global LED use has increased substantially, rising from a market share of 5% in 2013 to more than half of global lighting sales in 2020 LEDs (IEA, 2021). The energy and environmental benefits of LED technologies are proven, but the development of sustainable luminaires remains critical to reducing emissions and increasing energy efficiency, particularly examining its performance throughout life cycle perspective.

Environmental and social aspects are important in evaluating the overall sustainability performances of products and services. Life cycle Assessment (LCA) methodology, including the Environmental Life Cycle Assessment (*E*-LCA) and Social Life Cycle Assessment (S-LCA), is constantly used to evaluate sustainability performance and how well the chosen sustainability requirements were fulfilled (Kravchenko et al., 2019). However, sustainability issues are often addressed from the environmental aspect while the social aspect is not addressed sufficiently (Santillo, 2007; Onat et al., 2017). A recent review study (Kravchenko et al., 2019) shows that merely 16% (46 out of 279) sustainability-related indicators address social performance whereas 61% (170 out of 279) measure environmental performance. Although this may be due to the 'intangible' and 'complex' nature of S-LCA (Chou et al., 2015; Costa et al., 2015), more attention needs to be paid to S-LCA.

E-LCA and S-LCA should be conducted together to understand the rationale behind and to identify improvement opportunities in

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advancing sustainability. Franze and Ciroth (2011) and Ciroth and Franze (2011) identified both environmental and social hotspots through a notebook's life cycle and rose production processes, which are pioneering studies showing early efforts in the combination of *E*-LCA and S-LCA. 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 examined in the S-LCA study. 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 they reported that mechanical harvesting shows better environmental and social performance. In a most recent case study, Khorassani et al. (2019) developed an S-LCA operational model based on UNEP/SETAC's guideline and a standard *E*-LCA to identify the environmental and social hotspots in cultural heritage restoration. Król-Badziak et al. (2021) evaluated three tillage systems (no tillage, reduced tillage and conventional tillage) in Poland based on environmental and socio-economic criteria using LCA and Fuzzy Analytic Hierarchy Process. The comparative results differ between the tree systems in terms of environmental and socio-economic performances. These studies show that the *E*-LCA and S-LCA results can be interlinked or completely different, so both dimensions need to be assessed to holistically understand sustainability.

However, in the current combined studies of *E*- LCA and S- LCA, most of the studies were performed according to the standard procedure of E-LCA and the LCIA methods, whereas the S-LCAs were less harmonised because of the complex nature and methodological aspects. In addition, the connections, and opportunities between the results of *E*- LCA and S-LCA are rarely discussed in these studies. There are a number of studies regarding E-LCA of lighting products, most of which are comparative studies of LED products, such as examination of energy efficiency and environmental sustainability among different lighting technologies (Tähkämö et al., 2012; Principi and Fioretti, 2014), and *E*-LCA based investigation which addresses eco-design of LED lighting products (Wang et al., 2020). The literature review revealed that very limited research has been conducted on the social performance of lighting products. Moreover, the derivation of guidelines for further implementation of sustainable LED lighting products/services is also limited.

To address these shortcomings, this paper presents a combined E-LCA and S-LCA study of an industrial LED lighting luminaire with well-recognised databases and Life Cycle Impact Assessment (LCIA) methods. This study is the first attempt to assess both the environmental and socio-economic performance of the LED lighting products through their whole life cycle. This paper also has identified the interrelationships between environmental and social assessment results and derived strategic recommendations to serve the sustainable implementation of lighting products/services, which are novel contributions to knowledge in this area.

2. Research method

The research method is outlined in Fig. 1. This study consists of *E*-LCA and S-LCA of a low bay industrial LED luminaire in the market. The E-LCA considers environmental impacts through life cycle stages. The S-LCA aims to assess the social and socio-economic aspects of the product and the potential positive and negative impacts along its supply chains (UNEP/SETAC, 2009). According to the international standards ISO 14044 (ISO, 2006) and UNEP Guidelines for social life cycle assessment (UNEP, 2020; UNEP, 2021), goals and scope definition, life cycle inventory (LCI), Life cycle impact assessment (LCIA) and interpretation are conducted, and LCA software tools are utilised to calculate both performances (detailed in section 3.5 and 4.3).

The *E*-LCA and the S-LCA shares the same goal and scope, which aims to identify the environmental and social hotspots of the LED lighting product throughout the life cycle of the product and seek opportunities to derive sustainable recommendations and implications. In the data collection step, a collaborative investigation with the manufacturer was conducted to obtain case-specific data of the LED luminaire. There are three types of data: *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 the company social performance regarding different stakeholders through life cycle stages. Data collection forms for E-LCA and S-LCA are designed and used for engineers to provide the corresponding information. Interviews with engineers, employee representatives, and company directors were also carried out to obtain the company's social condition related information.

During LCIA, the key life cycle stages, key assembly components, and opportunities for performance improvement are identified on environmental and social aspects. In addition, the potential environmental issues, potential social risk to the stakeholders, namely workers, society, local community, consumer, value chain actors, and potential social benefits are also obtained and analysed (detailed in section 4).

Finally, the *E*-LCA and S-LCA results obtained from the second step are analysed. The interrelation between the *E*-LCA and S-LCA results is

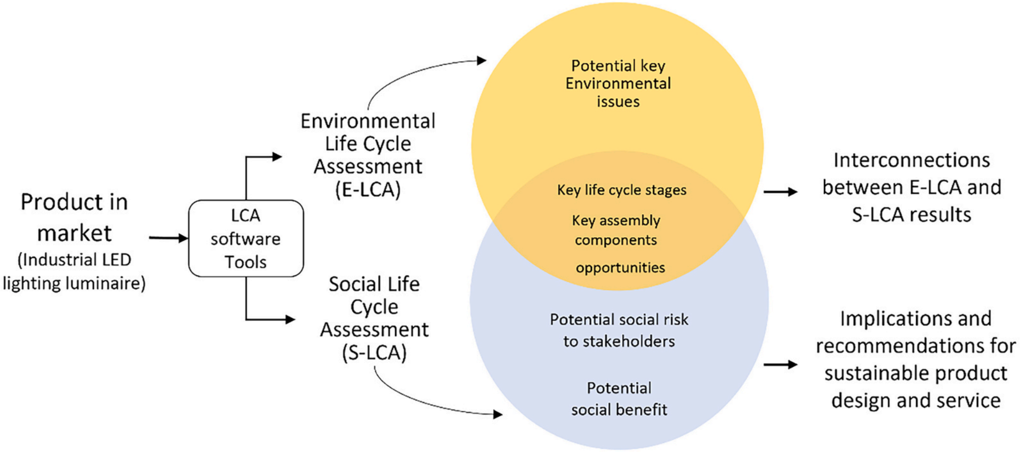

Fig. 1. The research method.

analysed. The insights and findings from the analyses are derived and transformed into applicable sustainable design recommendations and implications, subsequently guiding sustainable product development and business service implementation.

3. Environmental life cycle assessment

E-LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO, 2006). The procedure of conducting an E-LCA consists of four steps (ISO, 2006): 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, ecotoxicity, etc.); interpretation.

The LCA of an industrial LED lighting product in the market (Fig. 2) was conducted. The LCA covers all life cycle stages in accordance with the international standards ISO 14044 (ISO, 2006), as detailed below.

3.1. Goal

The goal is to evaluate the environmental impacts and to identify the hotspots 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 product's overall environmental performance.

3.2. Functional unit

The functional unit is one unit of the 100 W LED Low Bay luminaire (KMSD100LLBE) with 40,000 h operating time at 11500 lm. The luminaire is an energy-saving, high-performance product that is usually applied in general industrial areas, such as manufacturing workshops, warehouses, leisure facilities, and retail environments. KMSD100LLBE consists of three parts: housing, electronic device, and fastening

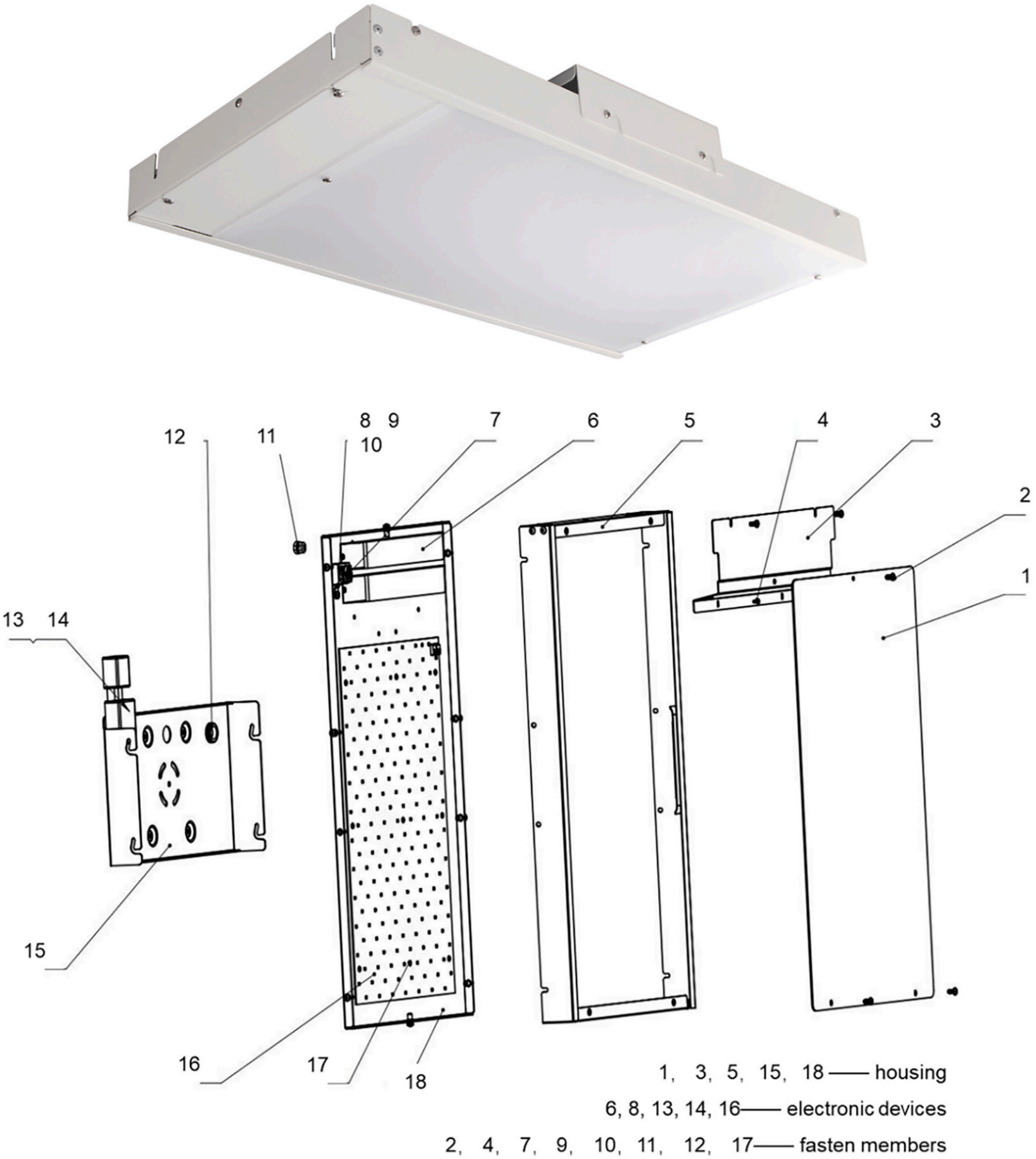

Fig. 2. The 100 W LED low bay luminaire (KMSD100LLBE) under assessment.

members (Fig. 2). 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 manufacturer is Kosnic Lighting LTD (UK), and the technical specifications of the product investigated in this research are listed in Table 1.

3.3. System boundary

All life cycle stages are considered in the system boundary, includes raw material extraction, production of basic materials, production of the components, LED lighting assembly, packaging, distribution (transportation) and end-of-life (EoL) treatment. The life cycle process flowchart of the product is illustrated in Fig. 3.

In the manufacturing stage, components and basic materials production and assembly processes are considered, including raw material acquisition, production, energy consumption, waste/emissions generation, and disposal during manufacturing. The packaging and transportation activities are within the boundary as well. The LED lighting product is manufactured in China (Hangzhou) and then shipped to the UK for wholesaling. Electricity demand 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 (40,000 h).

3.4. Life cycle inventory

The data of material use, energy consumption, waste is provided by the lighting company through the data collection process (see section 2). 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 2.

3.5. Life cycle impact assessment

The *E*-LCA product system model was developed with openLCA software, in line with the Ecoinvent 3.5 database (Ecoinvent, 2018). The ReCiPe (2014) Hierarchist method is selected for the E-LCA. 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., 2017).

Sensitivity analyses were also carried out regarding three EoL options and different lifetime use scenarios to validate the obtained results (see section 5.1). In addition to the default EoL scenario (S1), two alternative EoL scenarios (S2, S3) were considered and assessed to investigate whether performance varies with separate disposal and separate treatment of electrical devices and whether the use of post-consumer materials for reprocessing affects overall performance. The three EoL scenarios are assumed as follows:

- Scenario 1 (S1, default): It assumed that the functional unit after service time is processed in compliance with the 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 of as general solid waste. Packaging waste is separated from the general waste bin, then is incinerated.
- Scenario 2 (S2): It assumes that the entire EoL LED lighting product is directly sent to a waste bin as solid waste and treated 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 manufacturer 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 checked for reusability, and the selected electrical devices (assumed 60% reuse efficiency by the manufacturer) will be repaired and refurbished for producing new LED lighting products. Similarly,

Table 1
Technical Specifications of KMSD100LLBE.

Product Code	KMSD100LLBE-W65-WHT
Power (W)	100
Voltage	220-240Vac 50-60 Hz
Current (mA)	448
Protection	Class I, IP20
Power Factor	0.97
Luminous Flux (lm)	11,500
Beam Angle (°)	120
Lifetime (h)	40,000
Dimmable	No
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

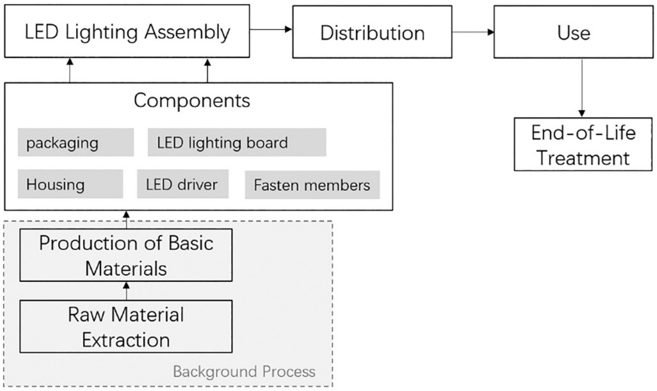

Fig. 3. Life cycle process flowchart.

Table 2
Inventory data of KMSD100LLBE.

Assembly Component	Material	Amount	Unit
Housing	PC plastic	0.29	kg
	Carbon steel	2.199	kg
	Aluminium	1.1	kg
LED driver	PC plastic	0.172	kg
	Printed circuit board	0.688	kg
LED lighting board	LED	0.32	kg
	Aluminium	0.012	m2
Junction Box	PC plastic	0.02	kg
Press button	PC plastic	0.007	kg
Fasten members	Carbon steel	0.07838	kg
	PVC lastic	0.0016	kg
Packaging	Printed board box	1.17	kg
	PE plastic	0.0003	kg
	Paper	0.0004	kg
	Plastic form	0.066	kg
Electricity		4000	kWh
Transportation by sea		56,451.96	kg*km
Transportation by road		1429.68	kg*km
waste aluminium		1.1	kg
waste steel		1.854	kg
Solid waste		1.7667	kg
Electronic waste		0.86	kg
Waste paperboard		1.8537	kg

the qualified materials in housing, such as aluminium and steel, will be repaint (assumed with 70% reuse efficiency) for new products. The remaining wastes from the used lighting product are treated as same as S1.

In addition, to determine the relationship between lifetime and environmental impact and to derive recommendations, two lifetime scenarios were assessed, namely 40,000 h and 50,000 h. In this analysis, a new functional unit, i.e., the performance of 1 h output of a 100w LED luminaire, was adopted, with the inventory data divided by 40000/ 50000 to obtain the numerical value for the calculation.

4. Social impact 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, 2013), which explains the rationale regarding social impacts for the product and provides a solid social impact evaluation framework. The guideline was updated in 2020 which added additional social impact subcategories and social organizational LCA (UNEP, 2020).

Social Life Cycle Assessment (S-LCA) is a methodology to assess the social impacts of products and services across their life cycle (supply chain, including use phase and waste treatment). The stakeholder categories, i.e., workers, local community, society, consumers, and value chain actors, are at the basis of an S-LCA assessment because they are the items on which the justification of inclusion or exclusion in the scope needs to be provided. Linked to the stakeholder categories, are the impact subcategories that comprise socially significant themes or attributes UNEP, 2020).

S-LCA shares the same procedure with *E*-LCA: goal and scope, social life cycle inventory (S-LCI), social life cycle impact assessment (S-LCIA) and interpretation. In the first phase, goal and scope, such as the stakeholders, subcategories and system boundaries, are determined. S-LCI regards collecting data for all unit processes within the system boundaries, which includes site specific (primary) and generic (secondary) data for unit processes and activity variables (the most common activity variable currently is worker hours). An activity variable is a measure of process activity related to processing output to reflect the share of a given activity associated with each unit process, i.e., inventory indicators may be defined as simple variables. Characterization models, which convert inventory indicators into social impact indicators that are to be developed for conducting S-LCIA (UNEP and Social LC Alliance, 2020).

4.1. Stakeholders and subcategories

Identification of suitable subcategories from the UNEP defined subcategories (UNEP/SEAC, 2009, 2013) was carried out for this S-LCA study. The selection of stakeholders and subcategories was based on criteria of relevance to the case company (manufacturer), 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 Lighting Ltd., then were verified if data is available for all the subcategories. Finally, S-LCA related literature was consulted to validate those subcategories (Jørgensen et al., 2008; Siebert et al., 2018; Mancini et al., 2018) which provide a total of 24 S-LCA cases serving to identify the most relevant social indicators by their use frequency. The selected subcategories and indicators (for foreground system) are listed in Table 3.

Table 3
Stakeholders and subcategories selection.

Stakeholder	Relevance	Data availability	Bibliography validation	Subcategory	Indicator
Workers	YES	YES	20	Fair salary	Living wage, per month Minimum wage, per month Sector average wage, per month
	YES	YES	15	Working time	Hours of work per employee, per week
	YES	YES	20	Discrimination	Women in the labour force Men in the labour force Gender wage gap
	YES	YES	20	Health and Safety	Accident rate at workplace Fatal accidents at workplace Presence of sufficient safety measures Workers affected by natural disasters
	YES	YES	18	Freedom of association and bargaining	Trade union density as a % of paid employment total Right of Association Right of Collective bargaining Right to Strike
Value Chain Actors	YES	YES	0	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation
Society	YES	YES	13	Contribution to economic development	Contribution of the sector to economic development Public expenditure on education Illiteracy rate, male Youth illiteracy rate, male Illiteracy rate, female Youth illiteracy rate, female Illiteracy rate, total Youth illiteracy rate, total
Local Community	YES	YES	0	Access to material resources	Level of industrial water use, out of total withdrawal Presence of certified environmental management systems
	YES	YES	6	Safe and healthy living conditions	Pollution level of the country Contribution of the sector to environmental load Drinking water coverage Sanitation coverage
	YES	YES	5	Local employment	Unemployment rate in the country
Consumers	YES	YES	0	Transparency	Presence of business practices deceptive or unfair to consumers

All the five types of stakeholders, namely ‘workers’, ‘local community’, ‘society’, ‘consumers’ and ‘value chain actors’ were taken into consideration. 11 subcategories, as indicated in Table 3, were selected to assess the social sustainability of the LED lighting product’s supply chain: ‘fair salary’, ‘working time’, ‘discrimination’, ‘health and safety’, ‘Freedom of association and bargaining, ‘fair competition’, ‘contribution to economic development’, ‘Access to material resources’, ‘Safe and healthy living conditions’, ‘Local employment’, ‘Safe and healthy living conditions’, ‘Transparency’.

4.2. Social life cycle inventory data

The generic data for unit processes can be collected through a literature review, web search, and existing databases with data for different purposes and levels of detail (UNEP and Social LC Alliance, 2020). In this study, the well-established S-LCA database PSILCA 2.0 (GreenDeLTa, 2018) was used for the generic data selection, as it’s the most updated available data source (when the analysis was conducted) 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. 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.

Site-specific data were collected (see section 2), and all reference costs were estimated by the final product company. The background process data (Fig. 3) were retrieved from the PSILCA database. The social life cycle inventory data of the final product is presented in Table 4.

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 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).

Table 4
Social life cycle inventory data of the final product.

Assembly component	Supplier company	Supply country	Material	Price per functional 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 plastic form	2.701
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 manufacturing factory is based in Suzhou, China where the lighting product KMSD100LLBE is produced and comprises research and design, production, and quality testing departments. There are 53 employees (15 males and 38 females) in the factory. The majority of female employees work in the assembly line, while male employees mainly work in design or technical positions.

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 approximately 1.5 times higher than that of females in the factory. They use a 13-month payment system with an additional bonus scheme. All employees receive paid annual leave, and national holidays are also guaranteed. The average working time is 40-48 h per week, and overtime pay is provided. In addition, there are open and transparent channels for employees to pursue promotions and salary raises.

There are no fatal or serious accidents involved in the production process as the main production activities 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 average electricity bill is approximately 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 (40,000 h) is 643.2 USD, which is obtained by the UK national statics (Statista, 2019).

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 costs. The time frame of the 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.

4.3. Social life cycle impact assessment

PSILCA uses money flows to link processes, inputs are expressed in monetary terms (USD), while outputs are measured by risk levels of the related subcategory indicators through worker hours. Based on the selection of the stakeholders and inventory development (section 4.1 and 4.3), the social life cycle assessment of the reference products was conducted. The site-specific social data collected from the company were used to assess the level of risk for each selected indicator, i.e., low, medium and high-risk levels. For example, for the ‘fair salary’ subcategory, the average salary of the case company is approximately 6% higher than the local average salary, which is determined as a very low-risk level for this social impact subcategory. ‘Worker hours’ has been utilised as the ‘Activity variable’ in PSILCA, which is calculated as follows (Eisfeldt, 2017):

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

Subsequently, life cycle characterization models for social assessment were constructed in the software tool openLCA. The product system model is made based on self-construct processes supported by the commodity data within the database of the country, e.g., ‘electronic element and device-CN’. The social LCIA method (GreenDelta, 2020) was utilised to calculate social performance.

5. Results and interpretation

5.1. Environmental aspects

The environmental impacts of life cycle stages in percentages for eighteen impacts categories are presented in Fig. 4. The production stage contributes 49% (on average) of the environmental impacts per function unit as it is the input-output intensive stage where the main consumption of materials and energy takes place. Further analysis of the production stage suggests that the manufacturing of the electric devices, including the LED driver and LED light panel, which respectively accounts for 78% and 20% impacts in the production stage and are identified as significant contributors to the impact of production/assembly stage.

It is identified that the 'wire printed board production' and 'light emitting diode production', which contribute to the LED driver and LED lighting board respectively, as well as the 'electricity production' are the hotspot processes to the functional unit (see Fig. 5). Further analysis regarding the background results of the LED driver and lighting board process flows implied that the extraction of raw materials, especially precious materials, such as gold and silver, transportation, fabrication, and the production processes for the wire printed board and light-emitting diode are the major ascriptions. In addition, the emissions and processed water involved in these processes contain hazardous heavy metals, and consequently cause potential damages directly or indirectly to the 'marine ecotoxicity', 'freshwater ecotoxicity', 'human toxicity' and 'freshwater eutrophication'. To identify the opportunities for impact reduction behind this process, an alternative production scenario using the post-consumer materials was also assessed and reported within EoL scenario S3. Productions of other assembly members, such as housing, fastening members and packaging, account for a very small percentage of impact for each environmental category.

The use stage presents a predominant environmental impact (51% on average) to the functional unit. 'Electricity production' is the main ascription (see Fig. 5) to 63% of 'marine ecotoxicity', 64% of 'freshwater ecotoxicity', and 26% of 'human toxicity. It is noticed that different energy sources of producing electricity significantly affect the environmental impact of the product, previous LCA studies on lighting products (Longo et al., 2014) have proven that the environmental impacts are sensitive to the choice of the use scenario, and to the energy source (Zhang et al., 2017), the lifespan of LED lighting product (Principi and Fioretti, 2014). This study assumes that the energy source in the use phase is from the UK according to the target market, which might cause uncertainties on the results, for example on 'marine ecotoxicity' that is linked to metal emissions. However, the results are unlikely to change drastically as the reported results are in agreement with the findings of existing similar studies for the top three impact categories identified in this study (Tan et al., 2015; Tähkämö et al., 2014); in addition, as mentioned in 3.1, the goal of this study is to identify opportunities to derive recommendations for new sustainable innovation to improve the environmental performance.

Furthermore, another lifetime scenario (50,000 h) was assessed to compare the difference in the environmental performance results. The results (Fig. 6) show a 20% impact reduction on average. This means that prolonging the product serve time is an effective opportunity in improving environmental performance. Another opportunity in the use phase is to increase the efficiency of the luminaires so that the illuminance is improved and thus the number of lighting installations for an area with given illumination requirements can be reduced, thus reducing the associated environmental impacts.

The EoL results show a small percentage of positive effects (Fig. 4) under the default EoL scenario. The analysis results (Fig. 7) of the three EoL scenarios show that among the relative impact category results, the impact of S3 drops dramatically due to the reuse of the recovered materials. S2 and S1 have very small differences in each corresponding subcategory per unit process. This indicates that there is no evident change on the environmental impact regardless the electronic devices are independently disposed of or not. The results only show a dramatic

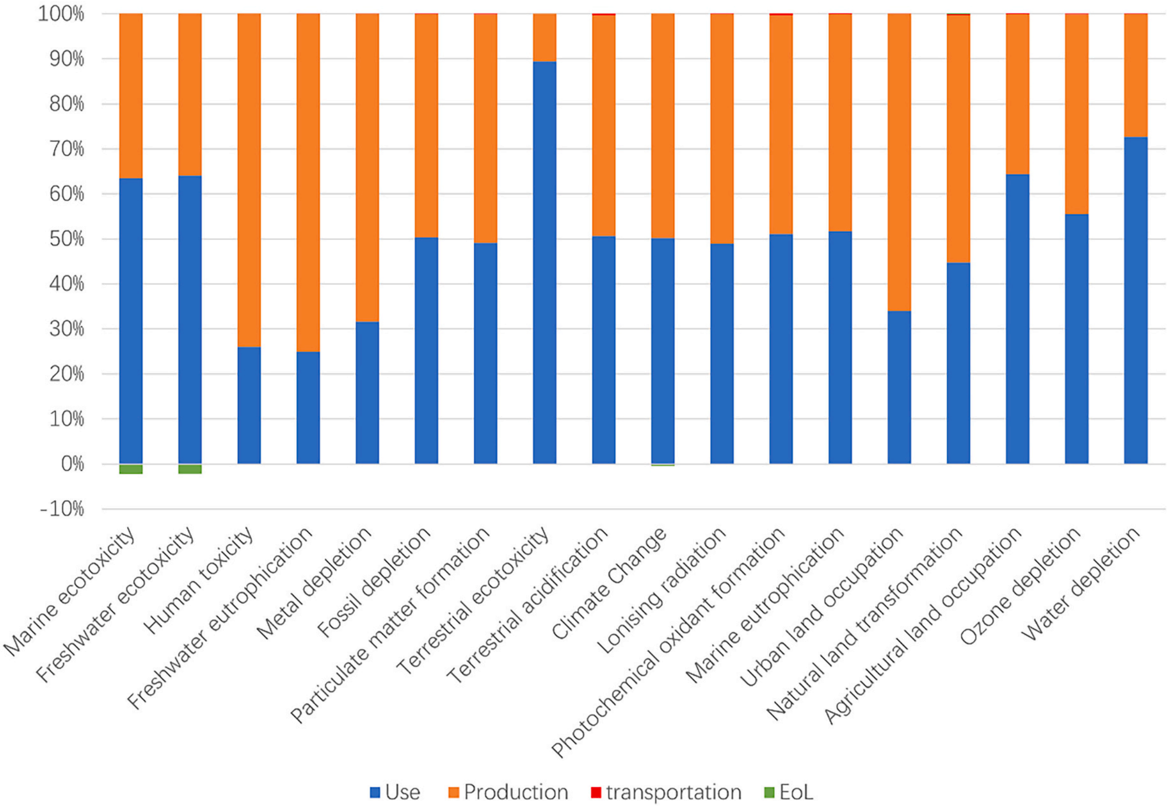

Fig. 4. Contribution percentages of each life cycle stage on midpoint impact categories.

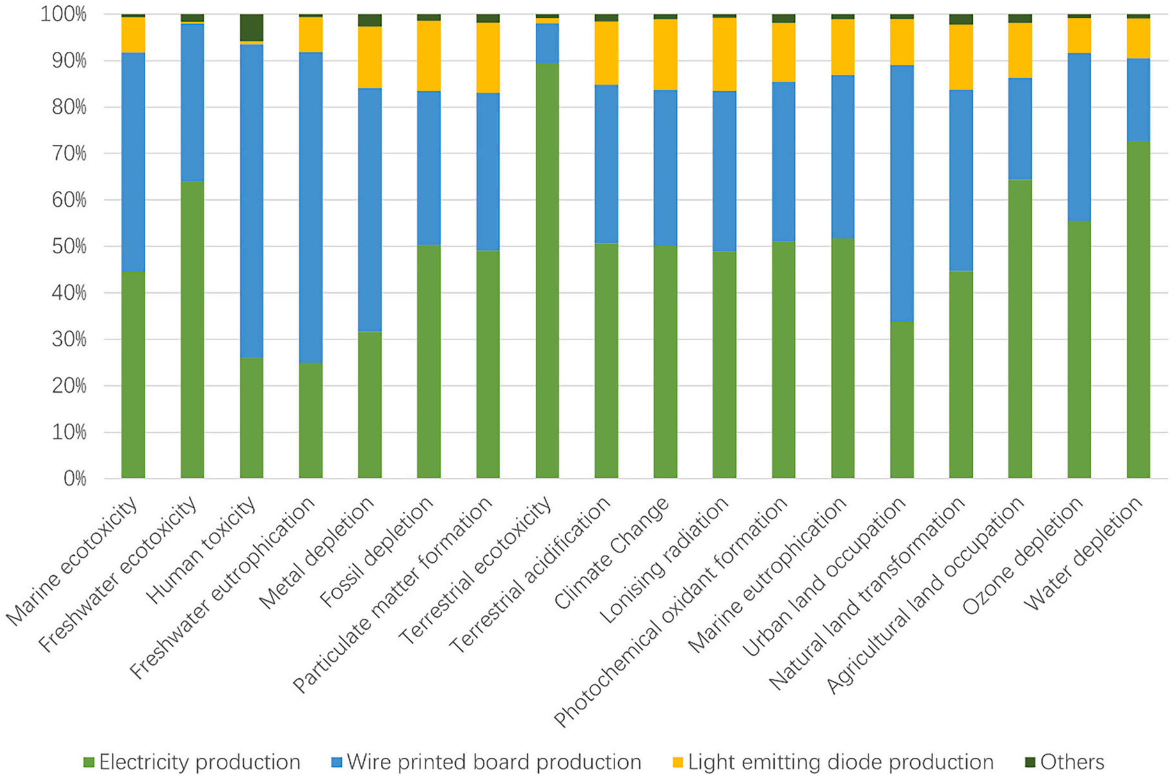

Fig. 5. Contribution tree in midpoint categories.

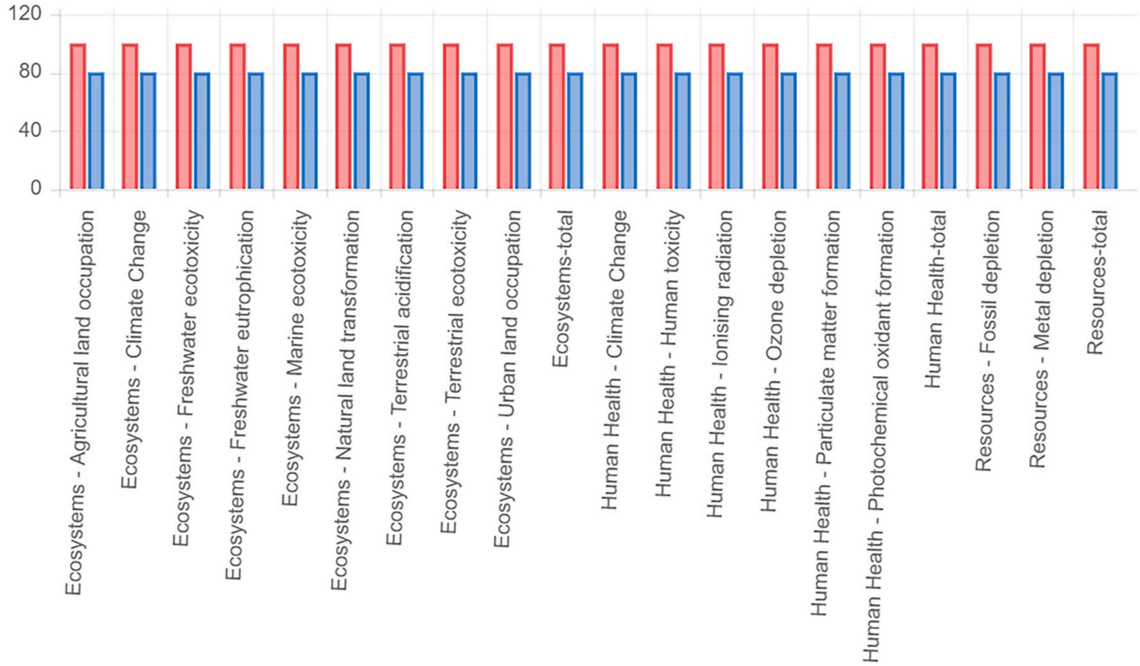

Fig. 6. Relative results under different lifetime settings.

improvement on the environmental performance if the post-consumer materials/components are reused, i.e., the electronic devices are repaired and reused as an assembly part in new products.

5.2. Social aspects

The social life cycle impacts were obtained and compared to the electronic appliance industry in China as the production plant is in China as well as its components. Table 5 shows the results of the comparison S-LCA between the production of a 1 USD reference product and the production of an equivalent value of electronic appliance product in China (see supplementary material for the absolute results per functional unit of the reference product). As shown in Table 5, the comparison results show that the reference product overall presents a better

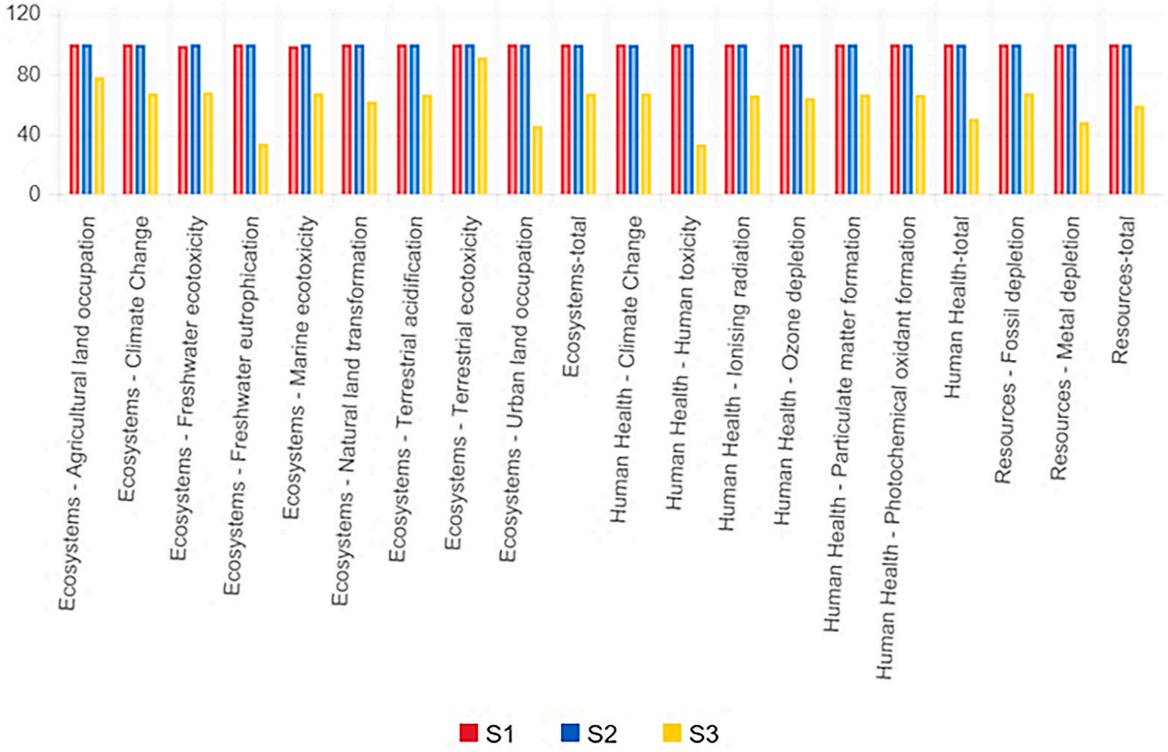

Fig. 7. Relative results of the three EoL scenarios.

social performance all impact categories (only the selected subcategories are included). However, common key issues are identified, namely 'association and bargaining rights', 'sanitation coverage', 'certified environmental management system', and 'pollution'. A high risk linked to sanitation and polluting problems (i.e., 'sanitation coverage'), during the extraction and manufacturing processes were identified, which is also the ascriptions of the environmental burden ('pollution') in the local communities. Worker right issue 'Association and bargaining rights' was identified as a risk in the material supply country. However, this may be caused by 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 important issue in the local community is the 'certified environmental management system'. It is a nationwide issue in the industry and mainly results from the production of metal components and electricity usage for the reference product.

Further analysis of the spotted social issues revealed 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 dominants the risks to the important social issues. In addition, the production of LED driver, LED panel and electricity, are the main contributors that are identified as the key opportunities to improve the social performance of the reference product. Production of plastic components and distribution activities have minor impacts on the impact of social issues. China is the main country affected by the potential social risk because all the main production stages take place there.

The electricity supply chain during the use phase is identified as the main contribution of 'social responsibility along the supply chain' (52%), 'industrial water depletion' (84%), and 'contribution to environmental load' (63%) risks. As the same as *E*-LCA, it is assumed the use stage takes place in the UK. The results suggest that during the production of the electricity, the background processes related to 'electricity, gas, steam and hot water supply', which supplied by Austria and Netherland, are the main contributors to the risks on the above social impact categories. Additional attention should be paid to ease the risks generated during electricity production processes on the stakeholder local communities and value chain actors.

There is no outstanding social issue in stakeholder allocated to the impact category 'society' or 'consumers'. On the contrary, a 3.5% more positive social effect was detected under the category 'contribution to economic development' in comparison with the results of the referenced industry in China. It's the only indicator assessing positive social impact through PSILCA database (when the assessment was conducted), the result presents a '-' to differentiate the positive effect between other impacts. As shown in Fig. 8, manufacturing activities account for the most positive effects, production of LED driver (37%), housing (31%), and LED panel (22%) are the main contributors that link to the economic contribution. China benefits the most positive effects since the main manufacturing processes have taken place there.

6. Interrelation between *E*-LCA and S-LCA results and sustainability improvement opportunities

The E-LCA and S-LCA results inform the challenges and opportunities in improving sustainability performance from different perspectives. Fig. 9 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 are responsible for the major potential environmental and social risks. In terms of the overall processes, the production of LED driver, LED panel, and electricity are revealed identified 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 and are directly applied to construct

Table 5
Comparison S-LCA impact result with reference to the electriconic industry of China.

Impact category	China electronic appliance industry	Reference product	Unit
Anti-competitive behaviour or violation of anti-trust and monopoly legislation	0.0156	0.0065	AC med risk hours
Association and bargaining rights	9.0726	1.8746	ACB med risk hours
Certified environmental management system	3.3660	2.5212	CMS med risk hours
Contribution to economic development	−0.5421	−0.5611	CE med risk hours
Contribution to environmental load	1.1786	0.2575	CS med risk hours
Drinking water coverage	0.0085	0.0045	DW med risk hours
Education	0.8363	0.1717	E med risk hours
Fair Salary	1.0258	0.4375	FS med risk hours
Fatal accidents	0.0106	0.0022	FA med risk hours
Gender wage gap	0.0804	0.0076	GW med risk hours
Illiteracy, female	0.0826	0.0432	I med risk hours
Illiteracy, male	0.0083	0.0044	I med risk hours
Illiteracy, total	0.0084	0.0044	I med risk hours
Industrial water depletion	0.1817	0.0947	WU med risk hours
Men in the sectoral labour force	0.0008	0.0002	M med risk hours
Non-fatal accidents	0.0122	0.0025	NFA med risk hours
Pollution	8.2452	1.7032	P med risk hours
Presence of business practices deceptive or unfair to consumers	0.0260	0.0045	CONS med risk hours
Safety measures	0.1571	0.1409	SM med risk hours
Sanitation coverage	8.2837	1.7329	SC med risk hours
Trade unionism	0.1930	0.0563	TU med risk hours
Unemployment	0.0084	0.0017	U med risk hours
Violations of employment laws and regulations	0.1708	0.0399	VL med risk hours
Women in the sectoral labour force	0.0012	0.0006	W med risk hours
Weekly hours of work per employee	0.0342	0.0032	WH med risk hours
Workers affected by natural disasters	0.8469	0.1716	ND med risk hours
Youth illiteracy, female	0.0009	0.0004	YI med risk hours
Youth illiteracy, male	0.0017	0.0005	YI med risk hours
Youth illiteracy, total	0.0009	0.0004	YI med risk hours

sustainable product and service concepts.

Furthermore, the sensitivity analysis results of EoL and lifetime scenarios (detailed in section 5.1) complement and validate the opportunities, which support the formulation of the design recommendations. The comparison results of the three EoL scenarios indicate that dramatic impact reduction occurs only if the post-consumer materials/components can be reused for reproduction. Meanwhile, the lifetime scenario analysis results show an average of 20% impact reduction (see section 5.1) with an additional 10,000 h lifetime on the total impact. These results reveal that prolonging the product serve time, improving EoL treatment towards remanufacturing are effective opportunities in improving environmental performance. Other opportunities relate to electricity could be achieved by increasing the luminaire efficiency.

It is noticed from S-LCA results that, apart from the overlapped key processes (LED driver, panel and electricity), production of housing is the main ascriptions to the majority of the important social issues, especially to the common social issues (between the product and the referenced sector in China, see section 5.2).

Nevertheless, these activities (linked with yellow lines) are also detected as the main contributors to the positive effect in boosting the regional economy. In this case, finding the mitigating solution to reduce the environmental impact and social impact whilst facilitating the positive socio-economic effect (boosting the regional economy) are essential. However, the S-LCA results are not directly integrated into the design practices, and the social improvement requires comparison assessment to be detected which is due to the intangible and semi-quantitative nature of S-LCA. Thus, S-LCA findings are preferable on guiding life cycle thinking for product-service design. Potential business models based on sustainable design are proposed in the later section to trade off the environmental impact with the socioeconomic benefit.

7. Discussion

7.1. Recommendation for sustainable industrial LED lighting product design

Based on both assessment results and analyses, the recommendation has been developed aiming at industrial lighting product innovation with longevity and energy reduction features. In addition, adaptability of related product service is also considered, which are all stated as follows:

- Design of the LED driver. An LED driver is the most important and problematic component of an LED lighting product. It is suggested to re-design the circus board, reduce precious metal inputs within the component by substituting with other materials. A more compact and efficient driver design is suggested, and modular design is encouraged to enable the change of damaged module(s) without affecting other functional modules thereby reducing the maintenance time and costs.
- Improve energy efficiency. High efficiency is considered crucial for industrial LED lighting products, improving energy efficiency means the lighting product provides more brightness by consuming the same amount of electricity, which can reduce the impacts caused by the energy consumption, and reduce energy cost at the same time. This can be achieved by replacing the light-emitting diode with a higher luminous efficiency product, and refining the arrangement of the LED optics; improving the power control system and design with a high-efficiency lampshade, e.g., change diffuser to the lens, etc.
- Prolong the lifetime. Prolonging the lifetime has been proven to cause less impact on the environment (section 5.1). A lighting product with a longer lifetime requires high reliability and upgradability, especially under an industrial application circumstance. It is suggested to implement a modular design to facilitate easy access to electronic components to change/upgrade while keeping the housing construction to prolong the lifetime.
- Reduce housing material and refine the product's dimensions.
- Use recycled packaging material (e.g., 80% post-consumer cardboard and 50% recycled plastic materials).
- Design for easy assembly and disassembly for all the components.
- Use recycled plastic material, ensuring chlorine content in the plastic parts is less than 50%.

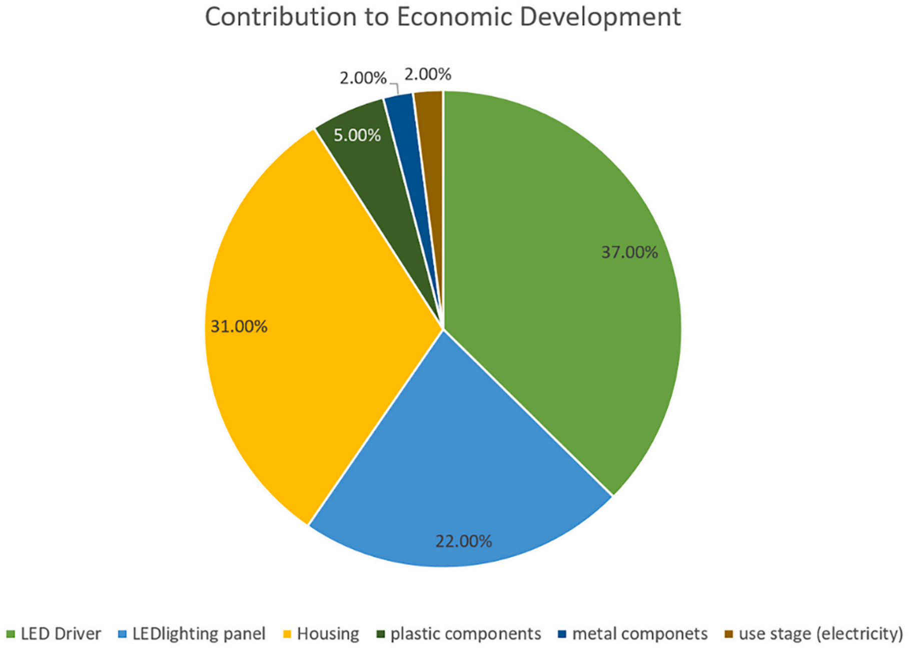

Fig. 8. Process contribution to positive social impact.

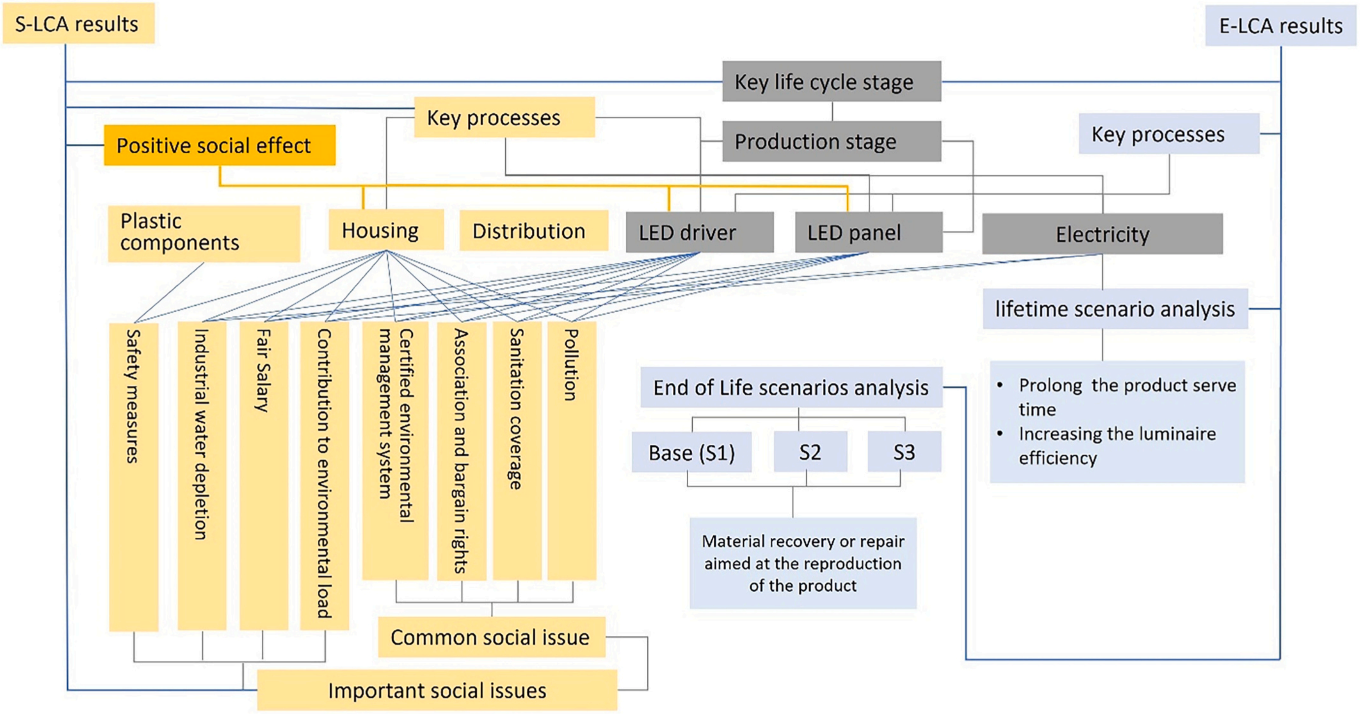

Fig. 9. *E*-LCA and S-LCA results and interrelations in brief.

7.2. Recommendation for service based on sustainable lighting products

Based on the implementation of the proposed sustainable innovation of the industrial LED lighting product, product services following circular economy principles are also recommended:

- Establish a take-back scheme (to collect end of service products from consumers and reintroduce them to the original processing and manufacturing cycle). The Major environmental and social risks are detected in relation to the 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 (see section 6). Therefore, a take-back scheme could mitigate the negative environmental and social risks in mining for new materials, i.e., by means such as using the post-consumer recycled materials to remanufacture, as well as sustain the economic effect. The results of the EoL scenario (S3) also proved the environmental improvement of initiating the 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. The service also includes the maintenance and collection of the lighting products. By providing the energy-efficient luminaire with a 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. The proposed services enable a relatively more predictable material flow from a stewardship perspective. By creating value from the waste, the manufacturer will need to pay more attention to reusability, EoL options in the product design stage, thereby minimising waste disposal. Moreover, the collaboration of all supply chain partners under the proposed services aims for the best user experience, a wide range of stakeholders are benefited along the supply chain (e.g., new job roles are needed), and a healthy recurring profit stream.

7.3. Limitations and future work

The interrelationships between the *E*-LCA and S-LCA results may vary due to the characteristics of different products, which need to be further investigated. Besides, the existing studies have proven that the environmental impacts are sensitive to the choice of the use scenario, especially to the energy source (Zhang, Burr and Zhao, 2017). This study assumes that the use scenario of E-LCA is in the UK, and how the electricity mix in the UK affects E-LCA results has not been fully investigated, which should be considered in the future study.

In addition, assumptions were made to the EoL scenarios, such as the recycle and remanufacturing efficiencies, which may cause uncertainties. The logistics of the three EoL scenarios were excluded since the transportation information is out of reach, and standard processing data from ecoinvent was utilised due to the lack of on-site LCI data.

Although positive socio-economic effect, i.e., ‘contribution to economic development’ was identified in the S-LCA study, the positive impact was not particularly addressed since the study was conducted before the launch of the Guideline for Social Life Cycle Assessment of Products and Organisations 2020 (UNEP and Social LC Alliance, 2020). However, there are still challenges in assessing the positive impacts such as the aggregation with the negative impacts, which is to be addressed in future studies.

The recommendations derived from this study should be subsequently applied to the practice of industrial lighting product development and services, through the product life cycles, to prove the applicability and suitability of the recommendation. In particular, a holistic approach for sustainable product development and service is expected to be further developed based on the sustainability study present in this paper.

8. Conclusion

This paper presented the research in the environmental and social assessments of an industrial LED lighting product along its supply chain. The key issues and opportunities from both environmental and social perspectives are identified, analysed, and subsequently applied to the recommendations for sustainable implementations.

This research has made several novel contributions. According to the literature review, it is the first study to conduct a combined *E*-LCA and S-LCA of LED lighting products. The research discovered the interconnection between E-LCA and S-LCA results and demonstrated how the findings inform and formulate attainable recommendations. These derived recommendations can be directly applied to the development of new sustainable products and services. The recommendations are also tailored for the enterprise with evidence-based (i.e., environmental and social performance results) systemic solutions, which include technical and environmental beneficial requirements for the new product and the requirements to address social issues in the service. By integrating the recommendations into sustainable product and service conceptualisation, the negative impact can be reduced in the development stage to improve the overall sustainability of the product.

Finally, this study concludes that it is necessary to assess a product’s supply chain from both environmental and social perspectives, not only to identify the issues and risks but also to have a holistic understanding of the product’s life cycle so that opportunities can be detected. The demonstration of the proposed method and case study is also helpful for further sustainable studies. The integration of the E-LCA and S-LCA into the lighting product sustainability assessment and its outcomes are novel contributions to the sustainable LED lighting product and service innovation.

Author statement

This paper is part of the PhD project of Dr. Shuyi Wang, who produced the first draft of the paper. The paper is further revised by Dr. Shuyi Wang, Professor Daizhong Su and Dr. You Wu. The PhD project is supervised by Professor Daizhong Su. The research was part of the European Commission’s H2020 CIRC4Life project, of which Professor Daizhong Su is the grant holder and project coordinator.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2022.106804.

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