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Business model life cycle inventory analysis of Factorylux modular office lighting fixture

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ABSTRACT

The substantial material consumption and greenhouse gas emissions attributed to lighting underscore the urgency for energy-efficient, resource-conscious manufacturing approaches and business models. This research investigates the potential for reducing material usage and carbon emissions by transitioning to a circular business model (BM) within the context of modular office lighting fixtures, designed and assembled by Factorylux. One fixture unit produces 8850 lumens. This study focuses on material usage during the production and assembly stages. It utilizes primary data from Factorylux and secondary data from the Idemat 2023 database to calculate the embodied carbon from cradle-to-gate. A life cycle inventory analysis (LCIA) was conducted using Microsoft Excel for data analysis. The circular BM parameters were defined through discussions with Factorylux and existing literature. Results highlight the composition of one fixture unit, weighing 23.58 kg with an associated embodied carbon of 152.85 kg. A sensitivity analysis reveals potential material and embodied carbon savings of 27–45 % through circular BM adoption, contingent upon material reusability rates. Aluminium, steel, and copper emerge as key contributors to both material usage and carbon footprint, with aluminium particularly dominant. The research supports the adoption of a Lighting-as-a-Service (LaaS) BM by Factorylux, promoting product reuse and aligning with circular design principles, offering ecological and economic benefits. It also suggests exploring alternative materials and increasing recycled content for aluminium, steel, and copper. Furthermore, it recommends comprehensive life cycle analysis (LCA) combined with cost analysis to inform circular strategies and marketing approaches. Despite limitations, this study emphasizes the significance of LCIA within LCA, particularly in assessing the environmental impact of manufacturing processes in luminaire studies. Its novel contribution lies in defining circular BM parameters and comparing material usage and embodied carbon between linear and circular BM for a specific luminaire manufacturer, offering insights into the evolving circular business landscape.

1. Introduction

Lighting is responsible for 15 % of worldwide electricity usage and 5 % of global greenhouse gas emissions, making the rapid adoption of energy-efficient lighting a potentially impactful near-term strategy for enhancing both economic and climate conditions on a global scale (ECEEE, 2017). Notable advancements have been made in the adoption of light-emitting diodes (LEDs) and the improvement of lighting efficiency. The global sales of LEDs have experienced remarkable growth in recent years, surging from a mere 5 % market share in 2013 to over 50 % of global lighting sales in 2021. Additionally, the integration of LED luminaires has played an increasingly significant role in this upward trend. Developed markets such as the United States and Europe have played a pivotal role in the rapid expansion of the luminaire market segment, while China has established a substantial manufacturing base both domestically and globally (IEA, 2022).

Humanity's utilization of materials is vast and continually expanding and the energy required for material production and the associated carbon emissions account for 15 % of the overall global primary energy consumption annually (Ashby, 2021). A handful of material categories,

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including steel, aluminium, and combined plastics (key materials used in making lighting fixtures) predominantly contribute to the global energy demand for material production. Researchers further predict a surge in demand for these materials between 2005 and 2050 (Gutowski et al., 2013). Priarone et al. (2017) argue that it is therefore evident that globally, there's a pressing need for energy-efficient and resource-conscious manufacturing approaches, necessitating focused research efforts in this field.

In light of these challenges, this paper focuses on material usage during the product manufacture and assembly stage and the material carbon footprint of a lighting fixture using LED technology. Life cycle assessment (LCA) is a well-established approach for comprehending and reducing the environmental impacts of products. The LCA approach involves tracking a product's entire journey from resource extraction and production to use and disposal – i.e., "cradle-to-grave" (ISO, 2006; Baumann and Tillman, 2004). Since LCA can be very data-intensive, it is important to define a clear scope and focus (Henriksen et al., 2017; Curran, 2016; Clift et al., 2000). This study concentrates on the life cycle inventory analysis (LCIA) phase, acknowledging the key role of data collection in any LCA (Saavedra-Rubio et al., 2022).

Existing LCA studies on lighting consistently find that the use phase has the highest environmental impact followed by the manufacturing phase, and that LEDs are environmentally favourable (Wang et al., 2022; Casamayor et al., 2017; Tähkämö et al., 2012; Welz et al., 2011). Aluminium is identified as the main material used in LED lamps (Albu et al., 2023; Hendrickson et al., 2010). Recent research confirms the advantages of LED-based luminaires. However, most of these studies conducted for different lamp types focus on generic or use-phase impacts. In contrast, our study provides a novel contribution by examining raw material usage and embodied carbon at the inventory level for a specific luminaire design from a particular manufacturer. This individualized approach offers detailed inventory data that adds value to the existing body of LCA research on lighting fixtures.

In parallel, industry and policymakers are encouraging a shift from the traditional linear "take-make-dispose" business model to circular business models (BMs) that emphasize resource efficiency. Darsy (2021) critiques the linear BM as leading to excessive resource consumption. Bakker et al. (2014) suggest that rising costs, competition, and environmental concerns are driving industries toward circular models. Likewise, European Union policies support servitization (prioritizing function over ownership) in the context of a circular economy (Plepys et al., 2015). The lighting industry has begun adopting service-oriented models; for instance, companies are moving from selling luminaires and control systems to offering "lighting as a service" or pay-per-lux arrangements, incorporating circularity in product design and production (Beu et al., 2018). Philips is identified as a pioneer in embracing this combined approach of service and circular design (Fleming and Zils, 2014). These trends underline the importance of developing circular BMs in lighting.

1.1. Research question and objectives

This study addresses the research question "To what extent can Factorylux reduce material usage and material carbon footprint associated with its modular office lighting fixture by transitioning to a circular BM?". A single fixture unit generates 8850 lumens of output. Below is a breakdown of the study and the research question into specific objectives:

A. To perform an LCIA of one unit of the Factorylux modular office lighting fixture, focusing on material usage during the product manufacture and assembly stage and the embodied carbon of materials using cradle-to-gate data. This work serves as an initial step for Factorylux towards a comprehensive LCA of the fixture.
B. Define the circular BM parameters in order to calculate and compare savings in material usage and embodied carbon data between the existing linear BM and the circular BM for the Factorylux modular office lighting fixture.
C. The findings will contribute to product and process improvements for Factorylux and facilitate the development of marketing strategies to showcase enhanced environmental performance. It provides a starting point for defining an effective circular BM.

2. Methodology

2.1. Goal and scope

As illustrated in Fig. 1, this study aims to perform an LCIA of one unit of Factorylux modular office lighting fixture, focusing on material usage during the production and assembly stage. Primary inventory data was collected from the factory for this analysis. Additionally, the research aims to determine the embodied carbon of materials for one unit of the lighting fixture using secondary data, considering its entire life cycle from cradle-to-gate (i.e. from raw material extraction, processing and transport from suppliers to Factorylux, up to manufacture of final product. It excludes transport of final product to customer, use and disposal). For broader context, a cradle-to-grave assessment considers the entire linear life cycle from raw material extraction to disposal. In contrast, a cradle-to-cradle approach is based on a circular model, where materials are continually reused or recycled, minimizing waste. The database Idemat 2023 (SSIM, 2023), comprising practical data from carefully selected life cycle inventories sourced from peer-reviewed papers and scientific databases at universities, was used for the assessment. Microsoft Excel software was employed to conduct the evaluation.

Furthermore, the study aims to define parameters for a circular BM and compare material usage and embodied carbon data between the linear and circular BMs. By doing so, it seeks to identify whether and to what extent adopting a circular model can lead to savings in material usage and carbon emissions during the selected stages of the lighting fixture's life cycle.

a. Stages 1, 2, 3, 4.1, 4.2, 5, 6, 8 represent a full Cradle-to-Grave life cycle.
b. Stages 7.1 and 7.2 are specific to Circular BM scenario (Cradle-to-Cradle).

System boundary for this study:

i. **Material usage**= Stage 4.1 (Final product Manufacture and Assembly
excluding Final product Packaging)
ii. **Embodied carbon of materials**= Stages 1, 2, 3 and 4.1(Cradle-to-Gate)

The findings from this research will provide a starting point for Factorylux to conduct a comprehensive LCA of one unit of the modular office lighting fixture. Moreover, it will help the company in defining a circular BM, enabling them to enhance their existing products and processes and develop marketing strategies that showcase improved environmental performance. Ultimately, the study aims to provide valuable insights into sustainable practices for the lighting industry.

2.2. Life cycle inventory analysis (LCIA): Data collection

Curran (2016) and Clift et al. (2000) point out that LCIA is data-intensive, so a useful distinction is made between Foreground and Background operations in the analysis. Foreground operations involve specific processes analysed using primary inventory data (material usage data in this study), while Background operations include all other processes that exchange energy and materials with the Foreground, represented by generic inventory data from reliable databases based on average industry data (data related to embodied carbon of raw materials

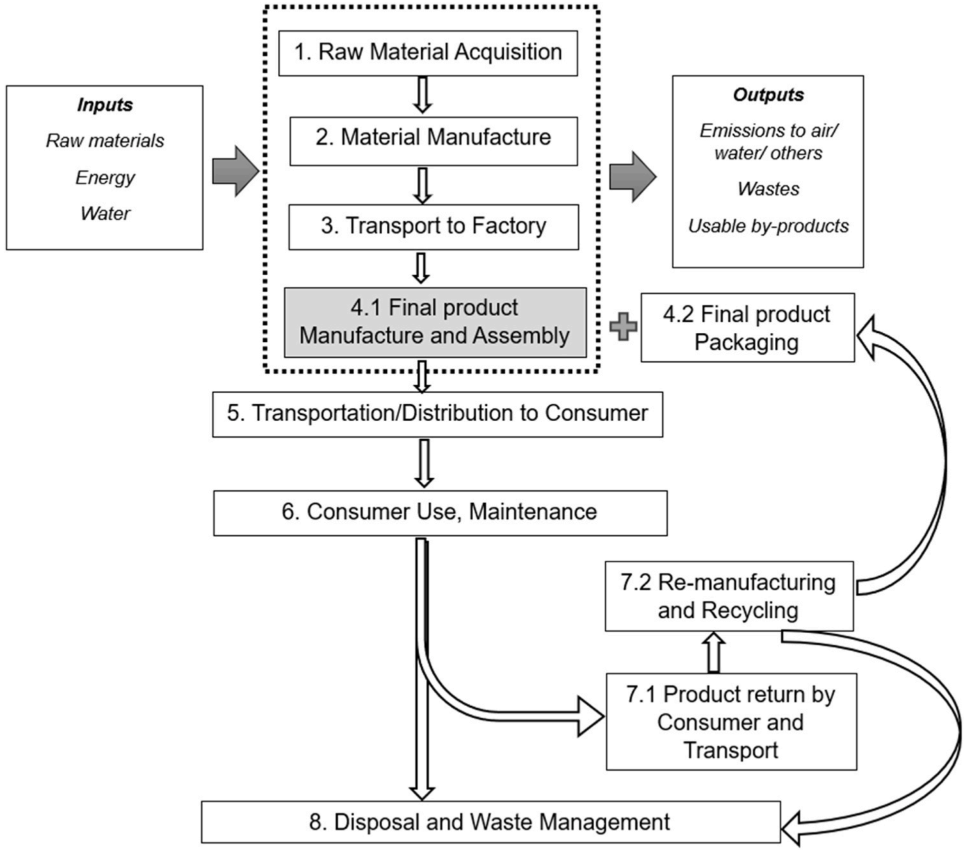

Fig. 1. Outline of life cycle stages of the Factorylux modular office lighting fixture (Author's own).

in this study).

2.2.1. Material usage

Factorylux supplied a Google sheet containing a list of 73 components required to assemble one unit of the modular office lighting. The sheet included information about the quantity of each component and the name of the supplier. To gather additional information about the principal raw materials used in each component, part descriptions and their reusability, data was collected from Factorylux and supplier websites. The 73 components were weighed, and their individual masses were recorded in the sheet. 67 components consist of a single material, six of them have composite materials combining metals and plastics. Due to resource limitations, it was not possible to break down the composite components and weight each material individually for this study. Therefore, it is assumed that plastic comprises 20 % and metal makes up 80 % of weight in these components, due to the lightweight nature of plastics, being significantly less dense than metals (Todor and Kiss, 2016; Mathijsen, 2016) contributes to this assumption.

2.2.2. Material carbon footprint

Data for embodied carbon (cradle-to-gate greenhouse gas emissions) per unit mass for each material was sourced from the Idemat 2023 database. These emission factors are expressed in kg of carbon dioxide equivalent per kg of material (kg CO_2e/kg). This study employed trade mix data for metals, combining primary production with virgin material and secondary production from recycled materials. Table 1 provides an overview of the material composition and embodied carbon of the fixture's components. The complete inventory data used in this study is provided in Appendix 1.

Table 1
Component wise material composition, reusability, weight and carbon footprint (cradle-to-gate) of one unit of Factorylux modular office lighting fixture. Note: IC=Integrated circuit, PBT=Polybutylene terephthalate, PCB=Printed circuit board, PLA=Polylactic acid, PMMA=Polymethyl methacrylate, SSTL=Stainless Steel.

Component	Material	Reusability	Weight (kg)	Embodied CO_2e (kg)
Housing	Aluminium, Steel, Stainless Steel	100.00 %	7.15	49.05
Heat Sink	Aluminium	100.00 %	6.58	50.18
Cable	Brass, Copper, Polyethylene, Silicone	100.00 %	4.02	10.57
Fastener	Aluminium, Brass, Copper, Nylon, PBT, PLA, Steel, Stainless Steel, Zinc	96.84 %	3.87	25.99
Optical	Aluminium, PMMA, Stainless Steel	31.05 %	1.19	5.72
DC/DC Converter	Copper, Epoxy, Polycarbonate	0.00 %	0.56	1.53
Electrical connector	Copper, Nylon, PLA	70.52 %	0.20	0.68
LED	PCB including ICs, Epoxy	0.00 %	0.02	9.13
Electrical Insulator	Polyethylene	0.00 %	< 0.01	< 0.01

2.3. Sensitivity analysis

Sensitivity analysis can assist in the interpretation phase of LCA by evaluating how different assumptions and models affect the results (Rigamonti et al., 2016). In this study, two sensitivity analyses were conducted. The first assessed how changes in the reusability proportion of reusable materials affected the savings in material and its embodied carbon by adopting circular vs. linear BM. The second analysis explored how variations in the proportion of plastics and metals within composite components of the fixture influenced the savings results.

3. Case study

3.1. Product description

The study conducted in this paper involves the examination of a lighting fixture designed and assembled by Factorylux in Yorkshire, United Kingdom. The luminaire is specifically designed to prioritize technical performance and adhere to principles of the circular economy (Factorylux website, n.d.).

The product under investigation is a recently developed 'modular office lighting' solution (illustrated in Fig. 2) that combines two existing products from Factorylux, namely Track Pipe and Ninety-Nine, utilizing LED light source. This lighting fixture comprises a 3-meter-long 'Track-Pipe,' six 'Ninety-Nine' spotlights, one 'Live Feed', one 'End Cap', and two 'Wire Suspensions' for ceiling fixation points.

Ninety-Nine is a minimalist spotlight created from sturdy, extruded aluminium. It offers various options for remote or integrated power supply units and drivers. The light engine can be customized for high performance. The spotlight is offered in stone rumbled finish (selected for this study) or environmentally friendly, free from volatile organic compounds (VOC) eco paint finishes (see Section 3.2), promoting the principles of the circular economy. Track-pipe also prioritizes the principles of the circular economy and is manufactured using high-quality stainless steel. It is designed to be durable, long-lasting and can be repurposed at the end of its life cycle. It can be easily disassembled and sorted into its constituent materials. It can be easily relocated and the LED light source, as well as other components, can be detached and replaced with ease.

Additionally, the fixture is compatible with the Digital Addressable Lighting Interface (DALI) system. As per Duine (n.d.) to facilitate efficient control and management of lighting systems, the sensor-ready interface builds upon the DALI architecture, enabling digital control, configuration, and querying of ballasts. DALI lighting control systems provide various advantages, including advanced dimming capabilities, daylight sensing, and cost savings in terms of energy consumption and maintenance. They offer exceptional flexibility as the lighting systems can be reconfigured through software reprogramming without the need to modify the wiring. Different lighting functions and moods can be achieved in different areas or rooms of a building and easily adjusted and optimized (Meyer and Yunk, 2007; DiiA, n.d.).

3.2. Existing linear business model (BM) with circular design

Factorylux is currently operating under a linear BM where all the necessary components of their products are procured from various suppliers, assembled in their factory, transported to customers, used, and eventually discarded by the customers. However, when it comes to product design, assembly and packaging, Factorylux follows a four-module circular economy process:

Fig. 2. Visual representation of the Factorylux modular office lighting fixture already installed in a client's office (Factorylux website, n.d.).

1. *Make/Unmake*: It acknowledges that the individuals involved in creating a product have the best understanding of how to dismantle it. Therefore, they prioritize the ease of disassembly. For instance, they previously used glue to attach the radiator to the circular metal outer layer tube, but now they have developed a circular ring that simplifies the disassembly process.
2. *Stone Rumbling*: It recognizes that applying paint or additive finishes hinders the circular economy as it becomes challenging to recover the original materials. To address this, they employ component surface finishing, a subtractive finish technique using stones made of ceramic and plastic. This approach ensures better material recovery and reuse.
3. *Magic Paint*: It offers additional colour options such as matt white/black besides stone rumbled finish which utilize natural clay and chalk-based paints that are VOC free. These environmentally friendly paints contribute to a more sustainable product design and reduce harmful emissions.
4. *Magic Packaging*: Factorylux employs 100 % recycled cardboard for their packaging materials. They ensure that the packaging is specifically tailored to fit the product, minimizing waste. Additionally, they use water-based glue or adhesive alternatives on paper-based packaging, eliminating the need for traditional glue or cello tape.

The company aims to shift away from the linear BM and embrace a more sustainable and environmentally conscious circular BM.

3.3. Circular business model (BM)

Factorylux aspires to adopt a BM wherein, after the luminaire reaches its estimated lifespan, customers would return the product to the company. Subsequently, the company would refurbish the product for resale.

As listed in Table 2, the circular BM is founded on various assumptions derived from discussions with the company's co-investigators,

Table 2
Circular BM parameters derived from primary and various secondary data sources.

Circular BM parameters	Value	Unit	Sources
Useful life of LED luminaire, light source	50000	Hours	Benali et al. (2022); Team (2021); Nistler (2018); Schratz et al. (2016); Tähkämö and Halonen (2015); Jenkins and Bhargava (2015); Bessho and Shimizu (2012); Philips (2010); Dmlights (n.d.); WAC Lighting (n.d.); Factorylux co-investigators
Office hours (Europe)	10	Hours	Yanatma (2023); Statista_EU (2023); Statista_UK (2023); ONS (2023); Eurostat (2022)
No. of working days	260	Days/ Year	
Useful life of LED luminaire, light source	19	Years	
Luminaire fixture lifetime	25	Years	Benali et al. (2022); Tähkämö and Halonen (2015); Jiang et al. (2015); Jägerbrand (2015); Factorylux co-investigators
Timeframe of calculation	50	Years	

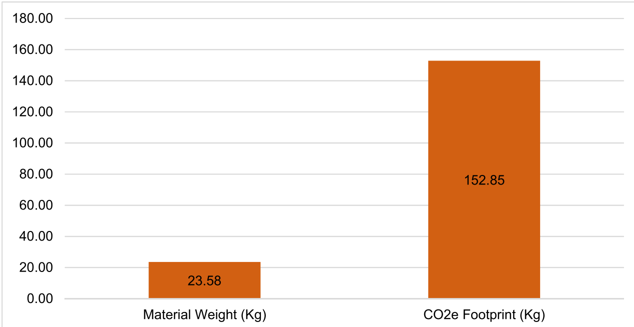

Fig. 3. Total material weight and embodied carbon of raw materials (in kg) used in one unit of Factorylux modular office lighting fixture.

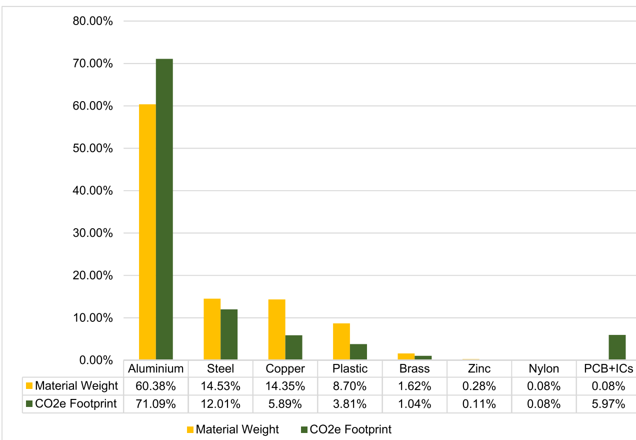

Fig. 4. Weight and embodied carbon of raw materials used in one unit of Factorylux modular office lighting fixture. Note: Silicone is not illustrated in the graph as its proportion in total weight and embodied carbon is < 0.01 %.

existing academic literature on LCA of lighting products, luminaire vendors' websites, statistical and market research websites and reports and business case studies.

The lifespan of an LED lighting fixture consists of two distinct aspects: the useful life and fixture lifetime. The useful life refers to the number of hours the fixture delivers sufficient light for a specific application. Fixture lifetime encompasses the overall reliability of the fixture as a system, including its components and construction. LED fixture manufacturers calculate the useful life based on specific physical and operational characteristics of their lighting fixtures (Philips, 2010).

Factorylux modular office lighting fixture benefits from good availability of parts and support. With a historical significance in lighting technology transitions and upcoming regulations on energy efficiency, it is well-suited for retrofitting with more efficient LED modules. Its utilitarian look aligns with enduring elements of building services which have remained relatively unchanged for decades. Therefore, its estimated lifespan is around 25 years.

LED luminaire (light source) typically has a useful life ranging from 40,000 to 100,000 h, with 50,000 h being the most commonly considered value. Based on an average workweek of 40 h (8 h per day) in Europe, and accounting for a 2-hour buffer, the number of working days per year is calculated as 260 (52 weeks x 5 days). Office buildings usually keep lights on for 2600 hours per year (260 days x 10 h). Therefore, the useful life in years is determined to be approximately 19 years (50,000 h / 2600 hours). While there was no specific information available for the fixture lifetime in office buildings in secondary sources as listed in Table 2, data related to public and street lighting suggests a range of 20–40 years. Considering this information along with primary data collected from Factorylux, a reasonable estimate of 25 years for the fixture lifetime in office buildings is selected. Hence, a calculation period of 50 years is selected, implying that within the circular BM, once the fixture lifetime is reached, the luminaire will be refurbished and resold. This translates to the equivalent of two units of the product being sold in the linear BM.

3.4. *Reusability of components*

73 components are used to assemble one unit of the modular office lighting (see Section 2.2.1). This study operates under the assumption that each component is either entirely reusable or not reusable at all. The Modular Office Lighting product is designed and assembled by Factorylux using principles of make and unmake, enabling swift assembly and disassembly into basic components. The Stone Rumbling technique, a subtractive finishing method, is used on applicable components that slightly removes surface material which restores them to the exact original look. The product design and process ensure better material recovery and reuse of existing components. According to Factorylux, 28 % of total components require stone rumbling method to be reused.

4. Results

Fig. 3 illustrates that a single Factorylux modular office lighting unit

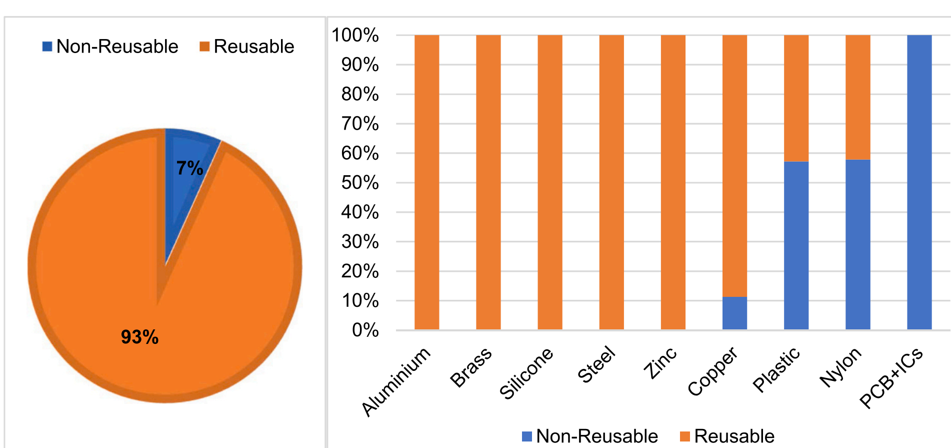

Fig. 5. Reusability and non-reusability of total components (pie-chart) and individual raw materials (stacked column chart) used in one unit of Factorylux modular office lighting fixture.

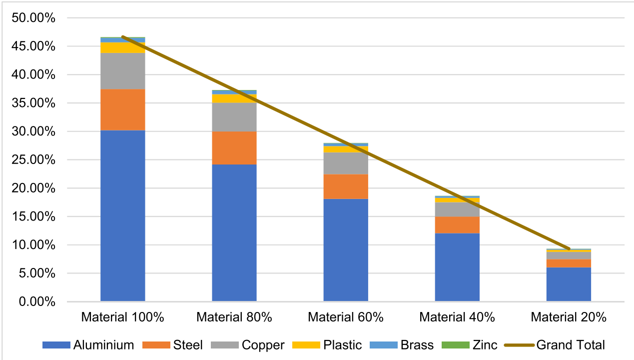

Fig. 6. Adoption of Circular vs. Linear BM resulting into Savings in Material Usage with different reusability scenarios (100 %, 80 %, 60 %, 40 % and 20 %) of reusable materials used in Factorylux modular office lighting fixture. Note: Nylon, Silicone and PCB+ICs have not been individually illustrated in the stacked columns as their proportion is < 0.1 % each in every scenario. The grand total includes all materials.

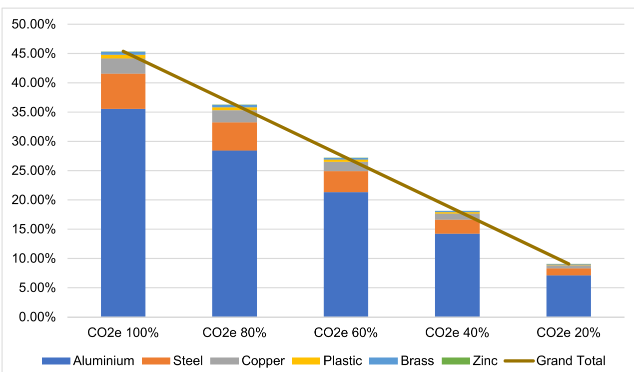

Fig. 7. Adoption of Circular vs. Linear BM resulting into Savings in Carbon Footprint of materials with different reusability scenarios (100 %, 80 %, 60 %, 40 % and 20 %) of reusable materials used in Factorylux modular office lighting fixture. Note: Nylon, Silicone and PCB+ICs have not been individually illustrated in the stacked columns as their proportion is < 0.1 % each in every scenario. The grand total includes all materials.

is made up of materials weighing 23.58 kg, with an associated embodied carbon of 152.85 kg. This result establishes the baseline resource consumption and carbon emissions for one unit which helps identify the savings between linear and circular BM.

4.1. Weight and embodied carbon of materials

Fig. 4 helps identify weight and carbon footprint of each material used in one fixture unit. Aluminium alone accounted for 60 % of total material weight and 71 % of material carbon footprint followed by steel and copper. The carbon footprint is directly linked to material weight, decrease in weight is accompanied by reduced CO_2e emissions. Also, PCB+ICs and aluminium are the only two materials exhibiting higher carbon footprint proportion in comparison to their weight. Whereas, copper, plastic and zinc are materials with lower embodied carbon.

4.2. Reusability of components and materials

In the existing linear BM, each new product requires 100 % virgin materials. In contrast, the circular model allows for component refurbishment and reuse from returned units, reducing the need for new inputs. Fig. 5 reveals that 93 % of total components can be reused with metals demonstrating very high reusability.

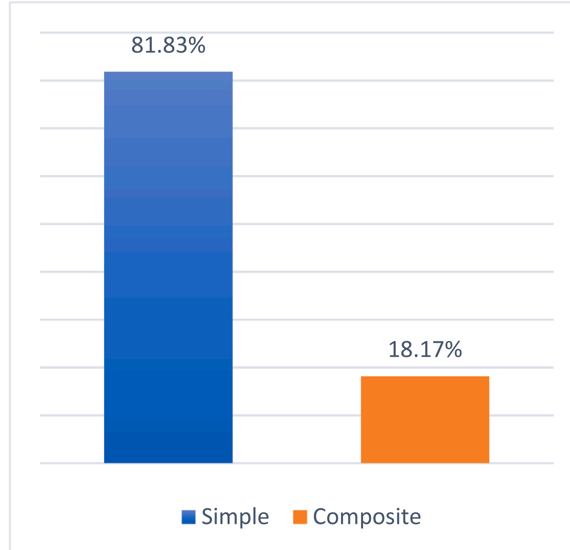

Fig. 8. Material weight of Simple vs. Composite components used in one unit of Factorylux modular office lighting fixture. Simple component comprises single material while composite component comprises mix of metals and plastics.

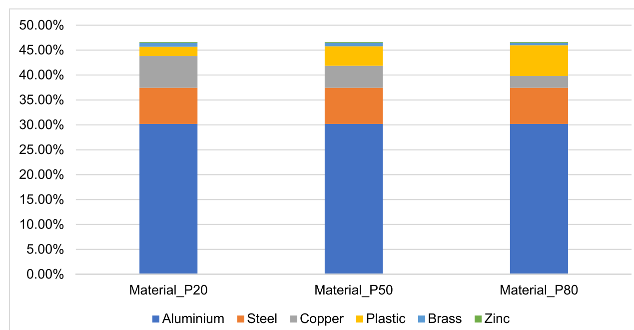

Fig. 9. Adoption of Circular vs. Linear BM resulting into Savings in Material Usage with different composition scenarios (in terms of weight of plastics and metals) of composite components used in Factorylux modular office lighting fixture. Note 1: P20: 20 % Plastic and 80 % Metal, P50: 50 % Plastic and 50 % Metal, P80: 80 % Plastic and 20 % Metal. Note 2: Nylon, Silicone and PCB+ICs have not been individually illustrated in the stacked columns as their proportion is < 0.1 % each in every scenario. The grand total includes all materials.

4.3. Sensitivity analysis

4.3.1. Savings in material use and emissions with different reusability scenarios

In the reusability scenario, five levels of component reuse were considered: 100 %, 80 %, 60 %, 40 %, and 20 %, with the reduction applied uniformly across all components. These levels represent the percentage of material reused in a circular BM instead of being replaced. Decrements of 20 % were chosen to cover a range from the ideal case (100 % reuse) to the most conservative case (only 20 % reuse). This range was used to assess how the benefits of the circular model scale with the success of reuse efforts, in the absence of industry reuse benchmarks. For each level, the reduction in new materials and their carbon footprint was calculated relative to the linear BM.

With adoption of circular BM vs. linear BM, the graphs presented in Figs. 6 and 7 show similar savings proportion and steady decline in savings of material usage and its embodied carbon with a decrease in reusability proportion of reusable materials. Savings of around 45 % at 100 % scenario, 36 % at 80 % scenario, 27 % at 60 % scenario, 18 % at 40 % scenario and 9 % at 20 % reusability scenario is attained. Also,

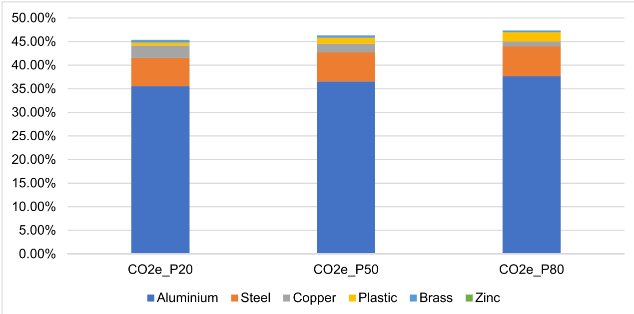

Fig. 10. Adoption of Circular vs. Linear BM resulting into Savings in Carbon Footprint of materials with different composition scenarios (in terms of weight of plastics and metals) of composite components used in Factorylux modular office lighting fixture. Note 1: P20: 20 % Plastic and 80 % Metal, P50: 50 % Plastic and 50 % Metal, P80: 80 % Plastic and 20 % Metal. Note 2: Nylon, Silicone and PCB+ICs have not been individually illustrated in the stacked columns as their proportion is < 0.1 % each in every scenario. The grand total includes all materials.

aluminium alone accounts for 65 % of material savings and 78 % of savings in material carbon footprint in all the scenarios.

4.3.2. Savings in material use and emissions with different composition scenarios

As can be seen in Fig. 8, one unit of the lighting fixture comprises 18 % components which are composite.

With adoption of circular BM vs. linear BM, the three scenarios presented in Fig. 9 show that despite the gradual increase in plastic vs. decrease in metal proportion in composite components, the total material savings remains the same as the total material weight remains unchanged. However, the share of copper decreases from 6 % in P20 to 2 % in P80. Fig. 10 indicates slight increase in savings of material carbon footprint by around 1 % in each scenario with gradual decrease in metal proportion indicating higher carbon footprint of plastics per unit mass vs. metals.

5. Discussion

5.1. Key findings in relation to research question and objectives

The main question in this study sought to estimate the potential savings in material use and its embodied carbon, through the adoption of a circular BM vs. linear BM, linked to the Factorylux modular office lighting fixture. One fixture produces 8850 lumens of output. To address this inquiry, it was important to establish parameters for a circular BM. The study involved carrying out an LCIA of one fixture unit, computing material usage during the product manufacture and assembly stage, along with the embodied carbon of materials, utilizing cradle-to-gate data. To summarise:

- Section 5.1.1 addresses research question 1.1 (A),
- Sections 3.3, 5.1.2 and 5.1.3 address research question 1.1 (B) and
- Section 5.1.4 addresses research question 1.1 (C).

5.1.1. Material weight and embodied carbon

The results of this study revealed that one unit of the fixture consists of materials that have a total weight of 23.58 kg and an associated embodied carbon of 152.85 kg. The material embodied carbon per lumen translates to 17.27 g. Aluminium, steel and copper together constitute 89 % of the total material utilised and 89 % of the total material carbon footprint associated with a single unit. The significant impact of aluminium on the luminaire's weight aligns with findings discussed in the literature review (Albu et al., 2023; Hendrickson et al., 2010). Moreover, there exists a direct correlation between the carbon footprint and the weight of materials, a reduction in weight leading to lower CO_2e emissions. This is consistent with general LCA findings that lighter products often have lower manufacturing impacts, a principle also noted in other sectors (e.g., automotive materials selection for lightweighting (Gonçalves et al., 2022; Todor and Kiss, 2016).

Table 3
Evaluation of Component reusability (top four components by weight): using Stone Rumbling technique and Component Lifespan.

Component, % weight	Reusability via Stone Rumbling	Lifetime (Years)	Sources
Housing, 30.30 %	62.56 % of total housing components	> 50	Toko Tech (2023); USI (2023); Nickel Institute (n.d.); SDO (n.d.); Factorylux co-investigators
Heat Sink, 27.88 %		> 50	Telephonic discussion with manufacturers of aluminium heatsinks Padmawati extrusion (n.d.); S.K. Enterprises heatsink (n. d.); Mayur metals (n.d.)
Cable, 17.04 %		25–50	Scherer Electric (2020); Voltimum (2010); Eland Cables (n.d.)
Fastener, 16.41 %	53.02 % of total fastener components	~50	Fleck (2021); InterNACHI (2020); Radix (n.d.); Factorylux co-investigators
Total	27.66 % of total components		Factorylux co-investigators

Table 4
Savings achieved in material usage and material carbon footprint of the Factorylux modular office lighting fixture by adopting Circular vs Linear BM under different reusability scenarios. One unit of fixture is composed of materials weighing 23.58 kg with an associated embodied carbon of 152.85 kg. The material embodied carbon per lumen is 17.27 g.

Reusability Scenario	Material and CO_2e Savings (%)	CO_2e Savings (kg)	CO_2e Savings (g) per lumen
100 %	~45	138.72	15.67
80 %	~36	110.97	12.54
60 %	~27	83.23	9.40
40 %	~18	55.49	6.27
20 %	~9	27.74	3.13

5.1.2. Reusability of components

Additional findings of this study indicated that 93 % of total components can be reused with metal intensive components demonstrating high reusability. The components contributing to 92 % of weight and responsible for 89 % of the carbon emissions of one fixture unit are Housing components, Heat Sink, Cables, and Fasteners demonstrating very long lifespan as described in Table 3. Ahmed et al. (2024) and Cooper and Allwood (2012) reveal that within metal-intensive products, if the component is in good condition, it can often be easily transferred to another product with minimal refurbishment requirements, like simple cleaning or repairs/adjustments.

5.1.3. Sensitivity analysis

In the sensitivity analysis linked to reusability scenarios, adopting a circular BM vs. linear BM demonstrated equal levels of savings in both total material usage and its embodied carbon as shown in Table 4. Also, aluminium, steel and copper together accounted for 94 % of material savings and 97 % of savings in material carbon footprint in all the reusability scenarios. Adjusting the composition of plastic and metal within composite components, which constitute 18 % of the total

Table 5
Real world example demonstrating the LaaS model implemented by Signify and its benefits (Ellen MacArthur Foundation, 2022; Laubscher and Marinelli, 2014).

LaaS model	Signify retains ownership of lighting systems and offers performance contracts based on light levels, uptime, and energy savings. At the contract's end, clients can renew or return equipment for reuse/recycling. The LaaS model drives Signify to create durable, modular, and high-quality equipment, promoting resource conservation. Managed with artificial intelligence and Internet of things, the system boosts efficiency, resulting in substantial energy savings.
LaaS implementation with National Union of Students (NUS) in the UK	NUS rents lighting equipment from Philips, paying a set rate for agreed energy usage. If energy consumption surpasses the agreed limit, NUS receives cashback. This arrangement encourages Philips to deliver highly energy-efficient services, offering stability through a fixed price for fifteen years. Philips aims to sustain installation value, uphold technology standards, and extend the contract, preventing the loss of value seen in complete lighting replacements.
Key Benefits	1. Each square meter needed only 5.9 W of electricity for lighting, which is less than the usual 8–12 W. This helped save energy and reduce emissions significantly. 2. Reduced material usage/ higher material recovery due to circular product design and sales model. 3. Reduced capital expenditure for customers as they did not have to purchase the lighting equipment upfront. Also, reduced costs related to energy usage due to energy savings.

components, led to minimal changes in material carbon footprint savings. While the overall savings in material usage remained unaffected, a higher concentration of copper relative to other metals was observed within the composite components.

These findings along with the existing product design, assembly and components reusability approach employed, as described in case study (see Section 3), advocate and support adoption of a circular BM by Factorylux.

5.1.4. Business model (BM) recommendation

This study supports evidence from previous observations (e.g. Darsy, 2021; Bakker et al., 2014; Fleming and Zils, 2014) that having product design flexibility, along with easy disassembly and replaceability of components, is essential for embracing service-based BMs like LaaS. These models, in turn, can significantly contribute to establishing efficient product return processes for consumers. Given the existing circular product design and compatibility with DALI technology, adoption of the LaaS model by Factorylux emerges as a potentially effective solution to unlock the ecological and economic advantages associated with the circular BM. Laubscher and Marinelli (2014) claim that creating direct financial value involves material recovery and asset recuperation. Material recovery saves costs through material reuse and sales of reclaimed materials. Asset recovery boosts profitability by selling refurbished equipment and components. Innovative designs aid refurbishment, extend product life, lower non-quality costs by enabling repair and curb material carbon footprint. Table 5 presents how implementation of LaaS model by Signify (Philips Lighting) influences its sales approach while incentivizing product returns by customers following initial use and the derived benefits.

5.2. Limitations and recommendations on future research

The study found that aluminium, steel, and copper, together, constitute 89 % of both the total material used and its associated carbon footprint in a single fixture unit. Therefore, further studies are suggested on one hand, to explore alternate materials with reduced weight, cost, and embodied carbon, with potential for reuse and recycling. To determine their suitability for replacing aluminium and stainless steel in components like housing and heat sinks can be useful, considering the direct relationship between material weight and carbon footprint. On the other hand, incorporating a higher proportion of recycled metals in the production of fixture components has the potential to significantly decrease the embodied carbon of these materials. This would necessitate discussions with suppliers to facilitate such a transition. Notably, aluminium and steel boast recovery rates of 96 % and 88 % respectively from recycling (Lotrič et al., 2021). Around 84 % of globally produced steel is still in use, showcasing durability and recycling success (Harder, 2021). Copper, similarly, is 100 % recyclable and both copper and aluminium can be recycled without any loss in quality (ICA, 2022; TIAI, 2018).

The current study is limited to inventory analysis based on material weight that fails to account for material volume. For instance, although plastic might be used more extensively than aluminium, the higher weight of aluminium may give a different representation. Therefore, further investigation to find an approach that considers both material volume and weight to offer a more accurate representation is recommended.

The research revealed that within a single lighting fixture unit, 18 % of the components are composite. Due to resource constraints, the study assumed that plastics constitute 20 % of the composite components' weight, while metals account for 80 %. Therefore, it is advisable for future investigations to break down these composite components and individually assess the weight of each constituent material.

There is abundant room for further progress in conducting a complete LCA combined with Life Cycle Cost Assessment (LCCA) offering a comprehensive approach to understand challenges in closed-loop material systems helping to assess cost-emission trade-offs in end-of-life strategies. LCCA evaluates costs incurred, contrasting with LCA's emissions focus (Dzombak et al., 2020). This would facilitate in determining the terms, conditions and feasibility of a circular rental or service-based BM, allowing for product return and refurbishment. However, non-willingness to use refurbished items could be a challenge which can be overcome by educating customers about the advantages of circular economy principles (Fleming and Zils, 2014). Utilising results of a combined LCA and LCCA of the fixture can help in devising marketing strategies highlighting improved environmental performance and justifying product costs.

Key next steps in conducting a fuller LCA will include assessing energy and resource consumption during reuse and refurbishment of the fixture which primarily involves component surface finishing using stone rumbling process. Further research in determining the useful life and cost of the stones can also be considered.

Future work is needed to ascertain a practical reuse and recovery rate for fixture components and to identify alternative end-of-life approaches for components that cannot be remanufactured using existing parts. Cooper and Allwood's (2012) study on the potential reuse of steel and aluminium components in metal-intensive products revealed a global technical potential for component reuse of 27 % for steel and 33 % for aluminium. The circular product design and process employed by Factorylux seem promising for achieving higher reuse rates for steel and aluminium components of its fixture, which can however be validated only through additional research.

6. Conclusions

The study examined potential of Factorylux to reduce material usage and carbon footprint in its modular office lighting fixture through a circular BM. Utilizing primary and secondary data, the LCIA revealed significant material and embodied carbon savings achievable through circular BM adoption, particularly in reusability scenarios of aluminium, steel, and copper. The findings endorsed the adoption of LaaS by Factorylux, emphasizing ecological and economic benefits. However, limitations such as a sole focus on material weight and assumptions about composite components' composition were acknowledged, suggesting a need for more comprehensive investigation.

This research establishes the critical role of LCIA within LCA and the significant environmental impact of the manufacturing phase in existing LCA studies of luminaires. What sets this research apart is the individualised examination of material usage and embodied carbon of a lighting fixture, specific to a luminaire manufacturer. Given the evolving market landscape and sustainability pressures, the study's exploration of circular business practices becomes pivotal, establishing a foundational step in defining parameters of a circular BM and comparing material usage and embodied carbon across linear and circular BM.

CRediT authorship contribution statement

Dr Simon Mair: Writing – review & editing, Supervision. **Neha Lakdawala:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Appendix 1: Component wise material usage and embodied carbon data for one unit of Factorylux modular office lighting fixture is provided in below sheet (password: universityofyork).

https://docs.google.com/spreadsheets/d/1Gj3cIxuGQbeWMm_rMEsCWwBGc7ZsOawQ/edit?usp=drive_link&ouid=114395760597761233741&rtpof=true&sd=true

Data availability

I have shared link to my data file in the research paper appendix section

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