Master's Thesis - Master Sustainable Business and Innovation

Utrecht University
Internship at Copper8

University supervisor:
Vivian Tunn

Internship supervisor:
Stefan Favrin

Second reader:
Matthijs Jansen

Conditions a Circular Business Model should meet to contribute to lowering environmental impact

Submitted by:
Laurien van Houten
November 4th, 2023

Abstract

Globally, 54 million tonnes of e-waste are produced each year. This amount is rapidly growing, as global access to digital technology is expanding. The disposal of e-waste contributes to a range of environmental impacts, such as globally increasing amounts of greenhouse gases, extraction of rare metals and minerals and leaching of toxic substances.

Transitioning towards a Circular Economy (CE) has been put forward as a solution to these increasing global pressures. A shift towards the CE can be operationalized through Circular Business Models (CBMs). CBMs that involve refurbishment and leasing are commonly employed within the IT sector. However, the effective sustainability advantages that occur as a result of the CE and CBMs remain ambiguous in academic literature. Therefore, this research explores the conditions that allow CBMs offering a laptop to have a lower environmental impact than a Linear Business Model(LBM).

This was evaluated based on case studies of three different CBM implementations and one LBM Life Cycle Assessments (LCAs) were performed to determine the environmental impact of each case study.

The results showed that a CBM can have a lower environmental impact than a LBM under the right conditions. Furthermore, the production phase of a laptop was determined to be an environmental impact hot spot within its life cycle. The production phase was also the sole lifecycle phase that showed results, in terms of changes in environmental impacts, that were different in practice to the expected outcome based on CBM Theory.

This research established that to ensure that a refurbishing and leasing CBM has a lower environmental impact than a LBM, the decrease in environmental impacts that result from the CBMs' production phase should offset the additional environmental impacts that occur due to extra services and transport that are integral to the CBM. This can be achieved through the implementation of measures that facilitate lifetime extension, such as an increased lease contract duration or refurbishment rate. Additionally, interventions to keep environmental impacts of the service and transport phases to a minimum were formulated.

Executive summary

Globally, the shift towards a more Circular Economy is acknowledged as a way to mitigate environmental impacts. Circular business models (CBMs) are frequently recognized as an important driver towards the CE. However, ambiguity persists regarding the reductions in environmental impact resulting from implementing a CBM in practice. To help Copper8 investigate conditions that allow CBMs to have a lower environmental impact than Linear Business Models (LBMs), this research was executed.

More specifically, this thesis investigated the conditions under which a laptop offered within a CBM that encompasses leasing and refurbishing has a lower environmental impact than a laptop provided in a LBM.

Using Life Cycle Assessments (LCA), this research conducted analyses on three CBM implementations involving the refurbishment and leasing of laptops, and compared them with a LBM. The LCAs compared the overall environmental impacts of laptops within the LBM and the different CBM implementations included. Furthermore, an environmental impact hot spot was identified based on the distribution of the laptops' impacts throughout the lifecycle. To understand the environmental impacts of each case study in greater detail, the environmental impacts in each life cycle phase were evaluated and compared to anticipated environmental impacts according to CBM theory. Subsequently, the impact of lifetime extension was explored in sensitivity analyses targeting prolonged contract durations and an increased refurbishment rate after the first lifecycle.

Finally, conditions were formulated that a CBM incorporating leasing and refurbishment should satisfy to have a lower environmental impact than a LBM. Furthermore, recommended measures were included for companies to adhere to these conditions.

Introducing, the case studies

The CBM case studies included all had their own implementation of a CBM that incorporated leasing and refurbishing. Three of Bocken et al.'s (2016) Circular Business Model strategies were recognized in all of the case studies: Access and Performance, Extended Product Value and Extended Resource Value.

Table 1. Three selected CBM strategies by Bocken et al. (2016)

Access & Performance	**Extended Product Value**	**Extended Resource Value**
Providing the capability or services to satisfy user needs without actually having to own the product. This strategy translated into a leasing business model and offering services, in the included case studies.	*Exploiting residual value of products – from manufacture to consumer, and back to manufacturing -or collection of products between distinct business entities.* This strategy translated into refurbishment performed at the laptops' first End-of-Life, in the included case studies.	*Exploiting the residual value of resources: collection and sourcing of 'otherwise wasted' materials or resources to turn these into new forms of value.* This strategy translated into component reusage in the service- and refurbishment phases, in the included case studies.

The biggest differences between the CBM implementations will be discussed here. These differences need to be acknowledged as these variables eventually determine whether a CBM can have a lower environmental impact than a LBM.

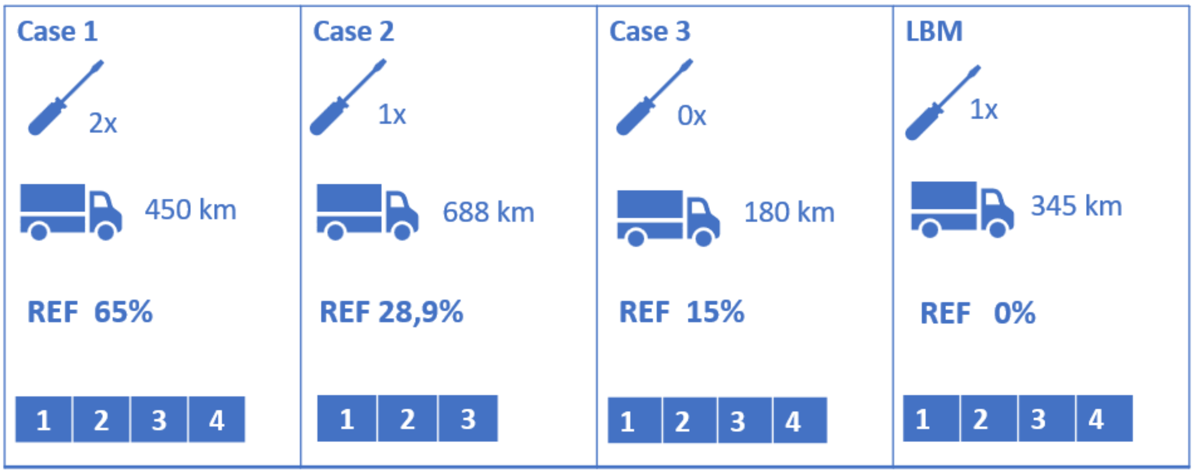


Fig. 1 service frequency, transport kilometres, refurbishment rate and lease contract duration summarized for all case studies

In terms of the lease contract duration, two of the case studies offered the laptop for a fixed duration of four years. Case 2 was the exception to this rule, by offering the laptop for a fixed duration of three years.

All case studies refurbished some of their laptops after the first lifecycle. However, the amount of laptops refurbished after being used differed: see fig. 1. Additionally, some of the case studies offered service for the laptops. Case 3 did not offer service. The last variable that impacts the environmental impacts of a laptop in a CBM is the transportation phase. Case 2 reported the highest impacts for this phase, which can be attributed to their geographical distance to the customer and their usage of a car instead of a van for the last mile.

The functional unit of the LCA was the same among all case studies: a functioning laptop for the duration of eight years that is used for five and a half hours a day, two hours on standby and the remaining sixteen and a half hours turned off.

Comparison of the environmental impacts of a laptop offered in CBMs and an LBM

The results of the LCA study showed differences in terms of overall environmental impact when comparing the CBM case studies with the LBM. The average amount of environmental impacts was always lower for the CBM case studies, albeit the amount of difference between LBM and CBMs differed in magnitude per impact category.

In the category of Climate Change (CC), expressed in kilogrammes of CO_2 equivalent, a 0,44 % difference between the CBMs and the LBM was reported. Larger differences between LBM and CBMs were reported for the categories of Human Toxicity (HT), expressed in kilogrammes of dichlorobenzene equivalent and Metal Depletion (MD), which was expressed in kilogrammes of iron equivalent: a 7 and 5 % difference respectively.

The reason for the first category to have a smaller difference between LBM and CBM is that the category of Climate Change has a relatively high impact in the use phase, 23 % on average across all case, whereas not a lot of impacts were registered for the use phase in the other impact categories. The use phase was assumed to be equal across both CBMs and LBM, as it was assumed that user behaviour did not differ. As a result, the difference between the CBMs and the LBM is smaller for the category of Climate Change.

The distribution of environmental impacts throughout a laptops lifetime

The production phase was determined to be a hot-spot in terms of environmental impacts across all impact categories. This phase was responsible for 69% of all Climate Change impacts in the lifecycle of a laptop, 82% of Human Toxicity and 87% of Metal Depletion, when taking the averages of all case studies included.
Due to the production phase being an environmental impact hot-spot, it was expected that lifetime extension of the laptop would lead to a decreased environmental impact in the production phase. This was examined in the sensitivity analysis with the hypothetical introduction of two different measures that lead to a prolonged lifetime: extending the lease contract duration and increasing the refurbishment rate. Both of these interventions had a decrease in environmental impacts across all CBM case studies, across all environmental impact categories as their outcome.

The environmental impact of the CBM strategies by Bocken et al., reviewed in practice

This part of the research served as a way to compare environmental impacts that were observed in the case studies in practice, with the changes in environmental impacts that were expected according to the CBM Strategies applied by the case studies.
The expected environmental impacts according to the CBM strategies were reported in all phases, except for the production phase. It was expected that all CBM strategies would have a lowering effect on the environmental impacts caused in the production phase. However, lifetime extension was expected to result from the Access and Performance strategy, but this was hindered by fixed lease contract durations and low refurbishment rates. As a result, environmental impacts were not lower in the production phase for all cases. Moreover, it was expected that the Extending Resource Value strategy would also have a lowering effect on this phase due to the implementation of reused components. However, component reuse only occurred in the service and refurbishment phase. Therefore, this expectation was not met.

Conditions and recommendations for a lower environmental impact in a CBM

Exploring the environmental impacts of a laptop on a business model, lifecycle and lifecycle phase level allowed an insight into the drivers underlying the potential for a lowered environmental impact in a CBM in comparison to an LBM. As a result, the following condition that enables an IT sector CBM, that incorporates refurbishment and leasing, to have a lower environmental impact than a LBM was formulated: The additional environmental impacts that occur as a result from services and transports integral to the CBM should be compensated with a decrease in environmental impacts in the production phase, in comparison to the LBM. This can be achieved by simultaneously extending the lifetime of the laptop to lower impacts in the productions phase and by ensuring minimum environmental impacts for the service and transport phases.
Multiple recommendations were formulated for companies opting for a CBM to prolong the lifetime of their electronic devices.

- Improving device design

Companies can collaborate on negotiating with their manufacturers to implement increased repairability, longevity and upgradeability into the design of their products.

- Retention or extending the use duration of the product.

This can be achieved by the introduction of dynamic lease durations and discounts on lease pricing in case of extended product usage. Moreover, user attachment can be heightened through personalization of devices.

- Recirculation

Increasing the refurbishment rate leads to an increase in overall product lifetime. Alongside an increased refurbishment rate, it is recommended that companies actively promote their refurbished products to their customers to decrease apprehension in regards to using refurbished electronic devices. Sometimes, used electronic devices do not meet the functionality requirements of the Dutch market at their End-of-Life. In this instance, it is recommended that companies donate their devices to countries that currently employ a lower functionality standard for their electronics. Lastly, previously used components can be implemented within the production phase of 'new' electronic devices. Thereby decreasing the amount of product components that have to be produced from scratch.

The following measures are meant to minimize the environmental impacts of additional services and transports as a part of the CBM strategies implemented by the case studies.

- Transportation

It is recommended that companies avoid excessive transports by offering online services, keeping storage of spare parts and products on-site, and sourcing their suppliers based on their geographical proximity. Transitioning to an electronic transport fleet can also lower transport emissions.

- Service

Companies can provide online service instead on in-person whenever feasible and stimulate users to repair their devices themselves by providing clear manuals and repair kits. Furthermore, companies can lobby or negotiate for changes in product design that lead to a diminished need for service.

In sum, this research aimed to answer the question: '*Under what conditions does a refurbishing and leasing Circular Business Model (CBM) in the IT sector contribute to a lower environmental impact compared to a Linear Business Model (LBM)*?' One condition was constructed according to the outcomes of this research. According to this condition, the decrease in environmental impacts occurring in a CBMs' production phase should be sufficiently lowered to offset additional environmental impacts that occur in the CBMs transport and service phases. Consequently, when this condition is met CBMs can be considered an suitable tool to help mitigating environmental impacts.

Abbreviations

A&P – Access and Performance

CBM – Circular Business Model

CBS – Centraal Bureau voor de Statistiek

CC – Climate Change

CE – Circular Economy

CEAP – Circular Economy Action Plan

CLLM – Classic Long Life Model

CO2 – Carbon Dioxide

DCB – dichlorobenzene

EC- European Commission

EoL – End of Life

EPV – Extended Producer Value

ERV – Extended Resource Value

ES- Encourage Sufficiency

EU- European Union

Fe – Iron (Ferrum)

GHG – Greenhouse gas

HT – Human Toxicity

IS - Industrial Symbiosis

LBM – Linear Business Model

LCA – Life Cycle Assessment

LC-Life Cycle

LCI – Life Cycle Inventory

MD – Metal Depletion

NDA – Non Disclosure Agreement

PaaS – Product as a Service

PSS- Product Service System

WEEE Directive - Waste Electrical and Electronic Equipment Directive

List of tables

List of figures

INDEX

1. Introduction

Every year, an approximate 53.6 million tonnes of electrical and electronic waste are produced on a global scale, of which only 17% is formally recycled (Forti et al., 2020). As access to electronics and digital technology is expanding at a rapid pace, the amount of e-waste is expected to have doubled by 2050. Due to rapid advancements in the IT sector, product upgrade cycles have been shortened which leads to a decreased overall lifespan of products. As a consequence, a growing proportion of electronic devices is being disposed of within a shortened amount of time (World Economic Forum, 2019).

Due to its quick expansion, the IT sector has an increasing 'carbon footprint', which results from greenhouse gases (GHG's) being emitted throughout all its life cycle stages. It is estimated that this sector's global GHG emissions make up between 2.1 and 3.9% of total global emissions (Freitag et al., 2021). Furthermore, IT hardware frequently contains rare metals. When hardware is inadequately recycled, these metal's potential value as vital urban resource remains untapped (André et al., 2019). Besides containing valuable materials, many electronic devices also encompass toxic substances such as mercury, arsenic and lead that might be leached or otherwise be emitted if subjected to improper recycling methods and pose serious threats to human health (Williams et al., 2008).

In 2019, the European Commission (EC) brought forward the concept of transitioning to a Circular Economy as a 'prerequisite' for lowering global environmental pressures. This is particularly evident in the significant role played by the Circular Economy Action Plan (CEAP) within the European Green Deal. Within this context, it is stated that CE will *"help avoid the irreversible damages caused by using up resources at a rate that exceeds the Earth's capacity to renew them [...]"* (European Commission, 2020, pp. 2). With regards to the IT sector specifically, the Circular Electronics Initiative is a part of the CEAP that will require manufacturers of electronic devices to implement circularity principles such as extending use times, sustainability certification, creating durable electronics, and recycling and refurbishment of electronic devices (European Commission, 2020). As a result, the incorporation of CE principles has become an obligation for many companies working in or with IT.

The circular economy (CE) forms an alternative to the linear economy, in which resources are collected as raw materials, made into products, used by customers and then accumulated as waste. Alternatively, the CE aims at retaining the value embedded in materials by slowing down, narrowing and closing resource loops (Bocken et al., 2019).

Conceptually, the CE was built upon an understanding that the environment has limited capacity to carry pressures caused by economic activity (Boulding, 1966). CE theory proposes that an increase in the efficiency of resource use and slowing or closing material loops will lead to decreased extraction of materials, disposal of waste and ultimately environmental pressures (Pearce and Turner, 1989; Ghisellini et al., 2016; Helander et al., 2019; Bocken et al., 2016).

Whilst the CE was originally introduced as a promising response to global environmental pressures, it has now become apparent that increased circularity performance does not necessarily lead to increased performance in terms of lowering environmental impact (Korhonen et al., 2018; Harris et al., 2020). In fact, the CE can even have adverse consequences concerning environmental impacts. Many strategies that are adopted within the context of the CE revolve around enhancing material efficiency. This contributes to a decline in pollution levels and the volume of waste generated. However, overall environmental impacts might not be lowered in a corresponding fashion. For instance, while products can undergo remanufacturing and recycling with remarkable efficiency, these processes may demand a higher energy input and involve intensified transportation. Hereby, the burden of environmental impact is shifting from one process in the product system to the other (Van Meeteren, 2021). Another example of such an adverse implication is the emergence of rebound effects (Ibid). Rebound effects occur, for example, when the substitution of new products with reused or remanufactured equivalents leads to an overall higher consumption of the product and the environmental impact of increased consumption outweighs the savings that occurred due to the discontinued use of new products (Van Loon et al., 2021). Collectively, these adverse outcomes make scholars question the CE's potential to contribute to environmental sustainability (Harris et al., 2021; Van Loon, et al., 2021; Manninen et al., 2018).

In practice, the transition towards the CE can be realized through the implementation of circular business models (CBMs), in which circularity principles are incorporated to align value creation and business practices with the CE (Bocken et al., 2016; Manninen et al., 2018; Geissdoerfer et al., 2020). Examples of what a CBM could entail in practice are business models centred around lease, subscription, rental and remanufactured, refurbished or reused (second-hand) products (Das et al., 2022).

CBMs are often seen as a promising strategy to reduce the environmental impact of product systems. They aim to decouple economic growth from resource use, which could ultimately result in lowered overall resource usage and subsequent environmental impact (Kjaer et al., 2018; Hoffman et al., 2022).

Stimulated by the EC's Circular Electronic Initiative, the IT sector is also experimenting with the implementation of CBMs. In this research, the focus is on CBMs in the IT sector that involve refurbishment and a leasing component. Refurbishment could potentially lower environmental impacts as it prolongs the life cycle of a product and thereby leads to a delayed need to produce new electronic products (Bocken et al., 2016) By transitioning from conventional ownership-based approaches to implementing 'as a service' business models, manufacturers are economically incentivized to provide their clientele with products that last for a longer lifespan, as ownership of these products still resides with the manufacturer. As a result manufacturers benefit from a prolonged user period, thereby reducing their need to generate new products (Bocken et al., 2016).

Verifying the potential environmental benefits of CBMs is challenging due to a lack of data, the complexity of value chains and challenges in regard to defining a reference system to assess environmental product improvements (Manninen et al., 2018; Harris et al., 2020). Moreover, aforementioned adverse implications such as burden shifting and rebound effects also occur in CBMs, which in some cases generate a negative influence on the environment (Pieroni et al., 2019; Kravchenko et al., 2020). The essential question that arises is therefore:

Under what conditions does a refurbishing and leasing Circular Business Model (CBM) in the IT sector contribute to a lower environmental impact compared to a Linear Business Model (LBM)?

This will be the research question around which this report is centred. To create a comprehensive understanding of how CBMs affect the environmental impact of businesses, the environmental impact of the business model itself should be measured. The preferred method for quantifying the environmental impact of CBMs the application of a Life Cycle Assessment (LCA), which stands as the most commonly used approach for this purpose (Haupt & Zschokke, 2017).

To allow for the comparison between business models, a product level perspective was taken for the LCA. The product selected for this comparative analysis is a laptop, which was deemed relevant as laptops are a commonly used product that is subject to rapid technological advancements. This leads to the continual emergence of newer models, which potentially has a short operational lifetime and premature obsolescence of laptops as a result (André et al., 2019; Proske et al., 2016). The environmental impact of a laptop in several different implementations of a refurbishing and leasing CBM was compared to the environmental impact of a laptop in a linear 'take-make-use-waste' business model to answer the question:

'What is the environmental impact of a laptop in different implementations of a refurbishing and leasing CBM compared to a LBM?'.

Subsequently differences in environmental impact between the multiple implementations of the CBM and the LBM are compared at the life cycle phase level. This investigation aims to unveil the distribution of environmental impacts throughout a laptops' lifecycle, facilitating the identification of environmental impact hot-spots. Through this analysis, insights will be gained into the following question:

'How is the environmental impact of a laptop distributed in different implementations of refurbishing and leasing CBMs and which phase(s) can consequently be considered environmental impact hot-spots?'

Multiple frameworks to classify different kinds of CBMs exist. In this research, the CBM strategy framework by Bocken et al. (2016) was selected to fulfil this purpose. This allowed for conducting a comparative analysis between the anticipated changes in environmental impacts throughout various life cycle phases according to the CBM strategies and the actual environmental impacts that were observed in the CBM case studies. This analysis provided an insight into the practical effectiveness of CBM strategies in lowering environmental impacts, answering the following sub question:

'How do anticipated changes in environmental impact according to CBM strategies materialize in practice in a refurbishing and leasing CBM offering a laptop?'

Examining these sub questions allows for understanding how different implementations of a refurbishing and leasing CBM relate to a product's overall environmental impact throughout its life cycle, including its effects on individual phases of that cycle. Moreover, this research delves into an examination of the influence of CBM strategies derived from literature on the environmental impacts of the CBMs in practice. Ultimately, this will provide an overview of the practical conditions that enable a refurbishing and leasing CBM, specifically within the realm of the IT sector, to contribute to increased environmental sustainability when compared to its linear equivalent.

This thesis contributes to existing research on the sustainability potential of CBMs by providing a practical illustration of the environmental impacts of a products' life cycle in multiple case studies that provided input on several different implementations of a refurbishing and leasing CBM. In doing so, it builds on existing research in the fields of (circular) business model innovation for sustainability (i.a. Das et al., 2022; Pieroni et al., 2019) and measuring the environmental impact of the CE (i.a. Cooper & Gutowski, 2017; Haupt & Hellweg, 2019; Junnila et al., 2018; Whalen, 2019) and measuring the environmental impact of remanufactured or reused electronic devices (André et al., 2019). Furthermore, no research currently exists in which the environmental impact of different CBMs in the IT sector is compared through case studies, which demarcates the literature gap for this research.

Considering its societal relevance, this overview of required conditions for this type of CBMs to contribute to lowering environmental impacts offers valuable guidance for businesses in the IT sector contemplating the transition to a CBM. It helps them make decisions that prioritize reduced environmental impact. Furthermore, having an overview of these conditions will be helpful for companies that have already adopted a CBM to optimize their business model to increase its contribution to lowering environmental impact. Also, the validation of the environmental sustainability advantage of certain aspects of CBMs can serve as a justification for companies that are in the initiation phase of a potential transition towards a CBM.

2. Theoretical Framework

2.1 Defining Circular Business Models

The current global economic model centres around linear flows of materials and energy (Korhonen et al., 2018). This linear economy results in the exhaustion of natural resources, waste accumulation and pollution (Geissdoerfer et al., 2017). The transition to a circular economy (CE), in which global economic development is decoupled from the consumption of finite resources is considered a way to progress towards a more sustainable society (Ellen McArthur Foundation, 2013).

To operationalize the CE, a transition should be made from linear to circular business models (Nußholz, 2017; Pieroni et al., 2020). CBMs integrate CE principles, such as replacing the end-of-life stage with reducing, reusing, recycling and recovering materials, into their value propositions and throughout their value chains. They are considered to be necessary to promote and support the transition towards the CE, as the agglomeration of businesses is of great influence on how an economy behaves (Bocken et al., 2019; Manninen et al., 2018).

The currently prevailing LBM is defined in this research as "*a business model with a production that involves the phases of take-make-use-and dispose*". The core goal of most conventional LBMs is to generate profit by maximising product sales (Bocken et al., 2016; Bakker et al., 2014). Alternatively, the definition used for Circular Business Models (CBMs) is ''*CBMs are business models that are cycling, extending, intensifying, and/or dematerialising material and energy loops to reduce the resource inputs into and the waste and emission leakage out of an organisational system*.' (Geissdoerfer et al., 2020, pp. 7). Therefore, in a circular approach the central objective is to make profits through the ongoing circulation of materials and products over time (Bocken et al., 2016).)

2.2 Conceptual Framework

Referring to one CBM framework is deemed useful for this research as it provides a common language and understanding of the concepts used. The selected framework of CBMs by Bocken et al. (2016) is a resource-focused conceptual framework that describes CBM strategies, pairing them with product design strategies that align with CE principles. This framework is considered a fitting tool in this research for the following reasons:

1. This framework categorizes CBMs on the basis of their material and energy flows (Bocken et al., 2016). As these resource flows have an impact on the environment, anticipated environmental impacts or changes resulting from each strategy are made explicit within the used framework.
2. Due to its focus on material- and energy flows, this CBM framework was deemed suitable to apply to case studies with a business model centred around a physical product.
3. The fact that the CBM framework by Bocken et al. (2016) is resource-focused allows for connecting it to the chosen method to quantify environmental impacts: Life Cycle Assessment.

In the following sections this framework will be described on the basis of the distinction it makes into two groups of circular resource flows: slowing and closing resource flows. Furthermore, the CBM strategies attributed by Bocken et al. (2016) to each group of resource flows are elaborated upon, and an emphasis is placed on those strategies that could be applied to the case studies. Moreover, it was described why some CBM strategies could not be fully applied to the included case studies.

Table 2. CBM framework. Retrieved from Bocken et al., 2016.

Slowing resource loops	
Access and Performance	Providing the capability or services to satisfy user needs without actually having to own the product.
Extending Product Value	Exploiting residual value of products – from manufacture to consumer, and back to manufacturing -or collection of products between distinct business entities.
Classic long-life Model	Business model focused on delivering long product life, supported by design for durability or repair for instance.
Encourage sufficiency	Solutions that actively seek to reduce end-user consumption, through principles such as durability, upgradability, service, warrantees and reparability, and a non-consumerist approach to marketing and sales (e.g. no sales commissions).
Closing resource loops	
Extending resource value	Exploiting the residual value of resources: collection and sourcing of 'otherwise wasted' materials or resources to turn these into new forms of value.
Industrial Symbiosis	A process oriented solution concerned with using residual outputs from one process as feedstock for another process, which benefits from geographical proximity of businesses.

Building on work by Braungart et al. (2007), Mcdonough & Braungart (2010) and Stahel (2010), Bocken et al. (2016) introduced two strategies for the cycling of resources and one for reducing resource flows respectively: Slowing resource flows, closing resource flows and narrowing resource flows.

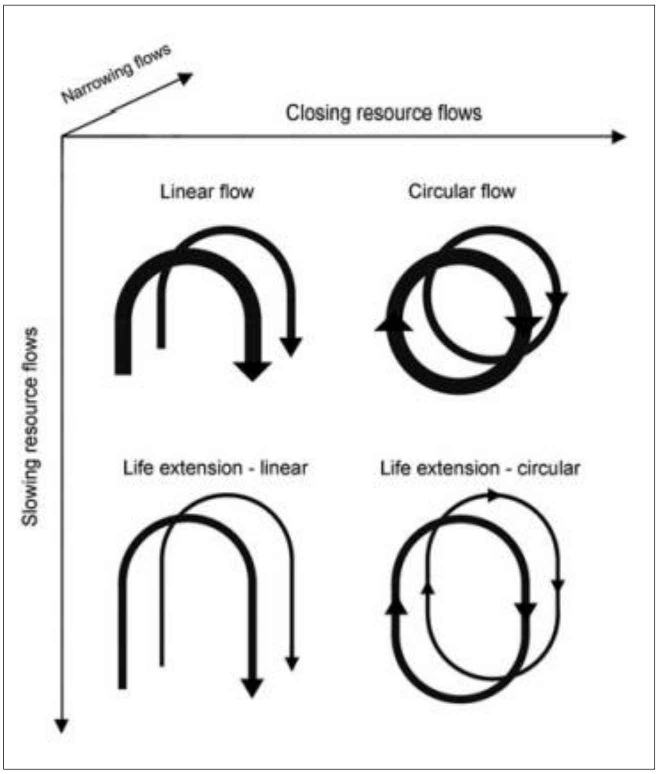


Fig. 2 Slowing, closing and narrowing flows. Retrieved from Bocken et al., 2016.

Slowing resource flows use long life design and product life extension to establish the extended use and reuse of resources and products over time. The group of closing resource flows employs recycling as a way to reuse materials. Lastly, the category of narrowing resource flows aims to use a smaller amount of resources per production process or product (Bocken et al., 2016). This latter strategy already somewhat prevails in many LBMs, as more effective resource use can also lead to cost savings. However, Geissdoerfer et al. (2020) describe that no definitions exist that classify business models as being 'circular' when solely 'narrowing' strategies are incorporated. They note that this strategy can be considered an extension of other strategies rather than a CBM strategy in its own right.

When considering the strategy of narrowing resource flows in the context of this research and its case studies on companies offering laptops-as-a-service, it can be expected that any narrowing measures are either applied by all case studies or none of the case studies as none of them preferred any specific laptop brand or type due to their environmental impact. This assumption will be further explained in section 6.2, LCI production phase. As a consequence of this assumption, the strategy of narrowing is not a differentiating factor between the companies that were included in this case study. Thus this strategy will not be discussed as thoroughly as the closing and slowing strategies, nor will it be applied to any of the case studies.

2.2.1 Circular Business Model Strategies

For slowing and closing material flows, Bocken et al. (2016) developed circular business model strategies (CBM strategies) that differentiate between different streams of materials within those flow patterns. These strategies serve as a way to classify different kinds of CBMs. Consequently, the concepts of CBM strategies and different kinds of CBMs are used interchangeably in this research. Furthermore, each of these CBM strategies have their own way to contribute to lowering environmental impact. Therefore, the distinction between these strategies is useful in this research as the environmental impact of each strategy can be evaluated and compared.

Slowing resource flows

The slowing resources group consists of four CBM strategies: Access and performance; Extending product value; Classic Long Life Model and Encouraging Sufficiency (Bocken et al., 2016).

Access and Performance

The Access and Performance strategy aims at fulfilling the needs of users through the supply of capabilities and services, without transferring product ownership. This business model category can contribute to slowing resource loops by increasing the utilisation factor and decreasing the customers' need for product ownership and thus the production of physical goods. As product ownership remains with the company applying the A&P strategy, this company is incentivized to extend usage of the same product for the longest possible extent as this lowers costs (Bocken et al., 2016). The lifetime of products can be extended with this strategy through alterations in product design that increase longevity, upgradeability and repairability (Bieser et al., 2021).
The decreased production of physical goods and a resulting lower resource and energy usage are the potential contribution of this CBM strategy to lowering environmental impacts.
To illustrate, the ability to use a car-sharing service, such as Greenwheels, gives users access to the utilities associated with private car ownership, whilst avoiding actual ownership (Greenwheels, 2023). Given that this sharing service is distributed between multiple users, a smaller demand for the production of new cars potentially arises, which could lead to a lowered environmental impact.

Extending Product Value

Extending product value aims at taking back used products to exploit their residual value, most commonly through remanufacturing or repair. Making use of the residual value of a product allows for the product to be used for an extended period of time, which eventually leads to a lower number of products and resources to be produced and extracted respectively. As a result, the environmental impact of this business model can be lower than the environmental impact of a LBM.
To exemplify, certain chain clothing retailers offer their customers a discount coupon for their next purchase when they return their pre-owned garments to the store . Subsequently, the clothing retailer uses the parts of clothing that are still useful to reuse, repurpose or recycle, thereby potentially avoiding a part of their new clothing production (H&M Group, 2023). As a result, environmental impact might be lowered.

Classic Long Life Model

The Classic Long Life Model aims at a long product life by designing durable products and offering high-quality service. Using products for a longer time leads to a decreased amount of products that need to be produced overall. Consequently, this CBM strategy can lead to a lower environmental impact than a LBM.

For instance, certain watch manufacturers offer their customers watches that are promised to last ‘beyond a lifetime’ (Rolex, 2023). This approach negates the need for frequent watch replacements throughout an individuals’ lifetime, consequently implying the potential for a diminished volume of new watch production. This could lead to lower environmental impacts in comparison to the impact of a watch manufacturer that produces watches that need replacement every few years.

Encourage Sufficiency
Encouraging Sufficiency as a strategy is similar to the previous strategy due to its focus on durable products and a high level of service. Additionally, this strategy incorporates a ‘non-consumerist’ approach to promotion and sales, thereby contributing to the reduction of resource consumption.
An in-practice illustration of this CBM strategy is observable in advertisements of outdoor sports brand Patagonia. Within this campaign, Patagonia urges customers to refrain from acquiring new items, as can be seen in their slogan ‘Don’t buy this jacket’. Hereby, the brand stimulates the usage of pre-existing items of clothing (Patagonia, 2011). This marketing strategy might result in the prolonged use of garments and a reduced demand for new clothing production. However, it should be noted that Patagonia was also criticized for the paradox of this marketing strategy, as even though they fight against a consumerist society, this advertisement also allowed their business to grow amongst ‘sustainability-minded’ consumers (The Correspondent, 2019).

Closing resource flows
For the second group, closing resource flows, Bocken et al. (2016) identified two CBM strategies: Extending Resource Value and Industrial Symbiosis.

Extending Resource Value
Extending resource value aims at collecting materials that would otherwise be wasted and turning them into new forms of value. By employing materials that would go to waste in a LBM, this CBM strategy has the potential to lower environmental impact. Environmental impacts are potentially lower because making use of resources multiple times leads to a lower rate of ‘new’ resources that need to be extracted.
To illustrate, certain clothing brands employ used plastic bottles as a means to create polyester fibres for clothing. Accordingly, a smaller amount of virgin resources has to be extracted for the creation of said polyester fibres, resulting in a smaller environmental impact (Patagonia, 2023).

Industrial Symbiosis
Industrial symbiosis aims to use residual products from one process as a resource in another processes within the same or another company that is located within the geographical proximity of the waste creating company. The potential for lowering environmental impact of this strategy is similar to that of the latter strategy: as residual resources of one process can function as feedstock for a process nearby it can be expected that a lower amount of ‘new’ resources is required and as a result environmental impact can be lowered.
A concrete example of industrial symbiosis is the scenario wherein food waste from a restaurant is utilised as fodder for livestock on a nearby farm (Symbiosis Project, 2018). Consequently, the necessity for fodder production diminishes and environmental impacts are potentially lowered.

2.3 The application of this framework

Fully circular business models are currently scarce. This can be attributed to the difficulty of altering a value chain that exists within a linear system to align with CBM principles (Geissdoerfer et al., 2017; Ritala et al., 2021). Therefore, this research views circularity as a spectrum rather than only having a binary view of traditional- and circular business models. This approach aligns with the view of Urbinati et al. (2017), describing how often, CBMs are described as a variety on a Boolean on/off adaption in which companies that adopt any circular elements in their internal activities are considered to have a CBM. Rather, Urbinati et al. (2017) speak of the degree of circularity to describe the extent to which a business model has adopted circular elements.

To illustrate the aforementioned, one could imagine a business model that incorporates a landlord renting out houses (Copper8, 2019). This is a CBM strategy that can be classified under the Access and Performance category by Bocken et al. (2016) as it aims to *'fulfil the needs of users without having to incorporate product ownership'*. However, if the landlord does not do any maintenance on the house and fails to ensure that the house or its materials will be reused at the 'end of their life', the loop is not entirely closed and thus the business model does not reach all of its potential circular impact (Copper8, 2019).

This research encompasses business models that do not strictly conform to the binary classification of circular versus traditional business models. Consequently, all business models under consideration for this research are those that incorporate CBM strategies as they were defined by Bocken et al. (2016), that were deemed to have 'circular intentions'. Circular intentions were defined by Copper8 (2019) as a company not only striving for commercial goals but also aiming to operate within the Earth's planetary boundaries, whilst ensuring social values. The operationalization for selecting CBMs to be involved as a case study in this research are elaborated upon in section 3, Methods.

2.4 Life Cycle Assessment

In line with the research question, the main objective of this research is to identify the conditions that need to be met for a CBM to have a lower environmental impact than a LBM. Life Cycle Assessment is an analysis method that is used to determine environmental impact throughout a products' lifecycle, covering all lifecycle phases from the extraction of raw materials to end-of-life (Finnveden et al., 2009). The word 'product' here can refer to both goods and services. Owing to its systemic and comprehensive approach, LCA is a widely used tool to provide insight into the environmental impact of products and processes and potential environmental trade-offs that can arise in product and process selection (Scientific Applications International Corporation et al., 2006).

Due to its comprehensive lifecycle viewpoint, problem shifting from either one lifecycle phase to another or from one category of environmental impact to another can largely be avoided when using LCAs (Finnveden et al., 2009).

In this research, Life Cycle Assessments were executed as a means to establish the environmental impact of the CBMs in a quantitative manner. Subsequently, the environmental impacts of the CBMs were compared, both to each other and to the impact of a LBM. Furthermore, hot-spots in terms of environmental impact along the lifecycle of the product could be determined. As all of the lifecycle phases present in each CBM were classified according to the CBM strategies by Bocken et al. (2016) an evaluation of the effectiveness of the CBM strategies in lowering environmental impact, when compared to their linear equivalents and to each other could, be executed. Eventually, this led to the identification of conditions that should be met in a CBM to allow it to contribute to lowering environmental impact in comparison to a LBM.

2.5 Analytical framework

The analytical framework of this research consists of the integration of LCA lifecycle steps with the CBM strategies by Bocken et al. (2016). For each lifecycle step, the expected environmental impact that could occur as a result of each CBM strategy was determined. These potential environmental impacts were compared to the environmental impacts that were identified in the LCAs.

Dividing the lifecycle of a laptop into separate lifecycle stages allows for determining how impacts are distributed across its lifecycle. Furthermore, partitioning each life cycle step facilitates the identification of those aspects of the business model that caused a change in environmental impact in comparison to a LBM. In the LCA that was performed in this research, the product system investigated was divided into six lifecycle steps: Production, Transportation, Use, Refurbishment; Service and Disposal. The first five steps were included in this research. The lifecycle steps were subsequently coupled with those CBM strategies that apply to the refurbishing and leasing CBMs included in this research. Thereafter, the potential environmental impact is described for the CBM strategies in each lifecycle step and juxtaposed with the environmental impacts for the same step in a LBM. In section 4.2 Introducing the case studies, the business model implementation of each case study was introduced and the CBM strategies were applied to the CBM implementations as they were found in the case studies.

2.5.1 Coupling the life cycle phases and the CBM strategies

The life cycle steps that are included in this research are coupled to three CBM strategies that are deemed relevant to a refurbishing and leasing CBM in the IT sector. Moreover, the environmental impact that potentially occurs as a result of each CBM strategy is divided into three categories:

Table 3. Description of the effect coupled with each symbol included in the table

Expected effect according to theory	Explanation
-	The amount of environmental impact due to this CBM strategy in this phase is expected to be less than the environmental impact in a LBM.
+	The amount of environmental impact due to this CBM strategy in this phase is expected to be more than the environmental impact in a LBM.
equal	The amount of environmental impact due to this CBM strategy in this phase is expected to be equal to the environmental impact in a LBM.

The CBM strategies that are considered to be present within a refurbishing and leasing CBM are Access & Performance, Extending Production Value and Extending Resource Value. More details on the application of the CBM strategies on the case studies was included in paragraph 4.2 Coupling the CBM strategies with the case studies.

2.5.2 Access & Performance

In this CBM strategy, the manufacturer enjoys increased profits if they can provide durable, energy efficient, reusable and repairable products, as these can be used for a longer time against a lower expense (Bocken et al., 2016). This has an effect on multiple phases in the laptops' lifetime:

- Production phase: Extending the lifetime of a laptop results in a decreased amount of laptops that has to be produced per time interval. As a consequence, overall environmental impact should be lower in this phase, unless added design elements to increase the lifetime have a larger negative effect than the savings on environmental impact resulting from a slowed production rate.
- Use phase: A prolonged use phase due to lifetime extension leads to an extended use period per laptop and as a result, a higher aggregated environmental impact in the use phase. However, on a yearly basis, the environmental impact of the use phase in a CBM will be equal to the use phases' environmental impact of a laptop in a LBM, unless significant changes are made in the design that have an impact on energy usage.
- Service and transportation phases: Taking over the 'hassle' of maintenance is the responsibility of the manufacturer in this business model (Bocken et al., 2016). Therefore, it can be expected that the environmental impact of the service and transportation phase, the latter being often required to facilitate service on-site, is expected to increase in comparison to a LBM.
- Refurbishment phase: In the refurbishment phase, extra parts need to be produced to extend the lifetime of a laptop. However, refurbishment is not an inherent part of the A&P strategy. Therefore, environmental impacts within this phase are not expected to be altered due to this CBM strategy.
- Disposal phase: Due to lifetime extension it will take longer before a product is disposed. Upon disposal, positive impacts may result from an enhanced design for repairability. This could translate to simplified disassembly of laptops, leading to decreased emissions and heightened residual value of disposed materials. Consequently, this could contribute to reduced emissions in the subsequent production phase by providing valuable materials from the previous disposal phase.

2.5.3 Extending Product Value

This CBM strategy allows for leveraging the residual value of a product (Bocken et al., 2016). Combined with the intention to slow down resource loops, the following environmental impact of this CBM strategy would be expected in a laptop-centred business model:

- Production phase: Exploiting the remaining value of a laptop allows for extending its overall operational longevity in comparison to a laptop in a LBM. As a result, the pace by which new laptops need to be produced slows down, which manifests into an overall lower environmental impact during the production phase.
- Use phase: As this strategy leads to a longer use phase per laptop due to lifetime extension, the environmental impact of the use phase in total will be higher.
- Refurbishment phase: Extending Product Value might take place by refurbishing laptops as a way to utilize value that is still present in them after their first lifecycle. As LBM's do

not have a refurbishment phase it is expected that the environmental impact of refurbishing will be higher in comparison.

- Service and transportation phases: The strategy of Extending Product Value mainly applies to the residual value that is still present in a product at the moment in which it would typically reach its end of life in a LBM. Therefore, this strategy does not influence the environmental impact of the service and transport phases.

- Disposal phase: Due to lifetime extension it will take longer before a product is disposed. Upon disposal, positive impacts may result from an enhanced design for repairability. This could translate to simplified disassembly of laptops, leading to decreased emissions and heightened residual value of disposed materials. Consequently, this could contribute to reduced emissions in the subsequent production phase by providing valuable materials from the previous disposal phase.

2.5.4 Extending Resource Value

This CBM strategy focuses on the collection and use of materials that would otherwise be discarded. As a result of using resources that would otherwise be disposed of, it is expected that a smaller amount of resources needs to be extracted overall. When resources can be repurposed repetitively, this eventually leads to the closure of a resource loop. If this CBM strategy would be applied to a laptop-centred business model with the intention of closing resource loops, the following environmental impacts could be expected.

- Production phase: The ability to make use of otherwise discarded resources allows for a diminished imperative to extract resources in the production phase, which could lead to a lower environmental impact.

- Service phase: The application of this CBM strategy includes reusing laptop components during the service phase. This would avoid the need for producing new laptop components, leading to a lower environmental impact in this phase in comparison to the service phase in a LBM.

- Refurbishment phase: Previously used components can also be employed during the refurbishment phase, instead of having to produce new components as replacements for old ones for the sake of refurbishing the laptop. Consequently, it is expected that the environmental impact of this phase would be lower when the strategy of Extending Resource value is applied.

- Use and transport phase: The environmental impact of the use and transport phase in an Extending Resource Value business model would be equal to that of the use and transport phase in an LBM, as this CBM strategy has no further expected effect on these phases.

- Disposal phase: The disposal phase is expected to have a lower environmental impact when Extending Resource Value due to parts of the used laptop still being suitable for reuse at the end of a laptop's lifecycle. As a result, a smaller amount of material needs to be disposed of at the end of life, leading to a smaller environmental impact.

Table 4. Expected environmental impact of three CBM strategies by Bocken et al. (2016) on each lifecycle phase in comparison to a LBM

CBM strategy/life cycle phase	Production	Use	Service	Transport	Refurbishment	Disposal
Access and Performance	-	Equal to LBM	+	+	Equal to LBM	-
Extending Product Value	-	Equal to LBM	Equal to LBM	Equal to LBM	+	-
Extending Resource Value	-	Equal to LBM	-	Equal to LBM	-	-

3. Methodology

3.1 Research Design

Relevant themes regarding leasing and refurbishing CBMs, LBMs and their potential environmental impact were identified within the theoretical framework. On the basis of these themes, a conceptual framework was constructed, encapsulating those concepts that are most relevant for this research. Moreover, in the analytical framework the concepts of LCA life cycle steps and a selection of Bocken et al.'s (2016) CBM strategies were coupled. This integration aims to predict potential changes in environmental impact that result from applying each CBM strategy, in comparison to the environmental impact of a LBM.

To measure the environmental impacts of these different CBM strategies in practice, an Excel-based LCA model was generated. This model compared the environmental impact of a laptop in three different case study implementations of a refurbishing and leasing CBM, contrasted both amongst themselves and in relation to the outcomes of an LCA that was conducted on a laptop integrated in a LBM scenario.

Input data for the LCAs was collected through a combination of semi-structured interviews, reviewed literature and utilization of the EcoInvent v.3.8. database. Once the goal and scope of the LCAs were clearly defined, the inventory and impact assessment outcomes were generated. This was done by clearly delineating each relevant in- and output process and subsequently connecting these processes to environmental impacts in the categories of Climate Change, Human Toxicity and Metal Depletion. Finally, in the concluding step of the LCA process the qualitative, contextual insights that were obtained in the semi-structured interviews facilitated an accurate interpretation of the quantitative results that were derived from the LCAs first three steps. The last step of the LCA is integrated with all previous phases, as iterative reviewing is considered to be an important part of conducting an LCA.

The environmental impacts that resulted from the conducted LCAs were linked to each individual CBM strategy and compared to the environmental impact that they were expected to cause, based on the analytical framework. This facilitated an examination of the environmental outcomes that can arise as the result of different implementations of a refurbishing and leasing CBM, in comparison to the environmental impacts of a LBM. Furthermore, measures that companies can take to lower their environmental impacts in comparison to an LBM according to the LCA outcomes were sourced from academic literature. In sum, this allowed for answering the research questions. The research methods that were used will be explained in more detail in the following sections.

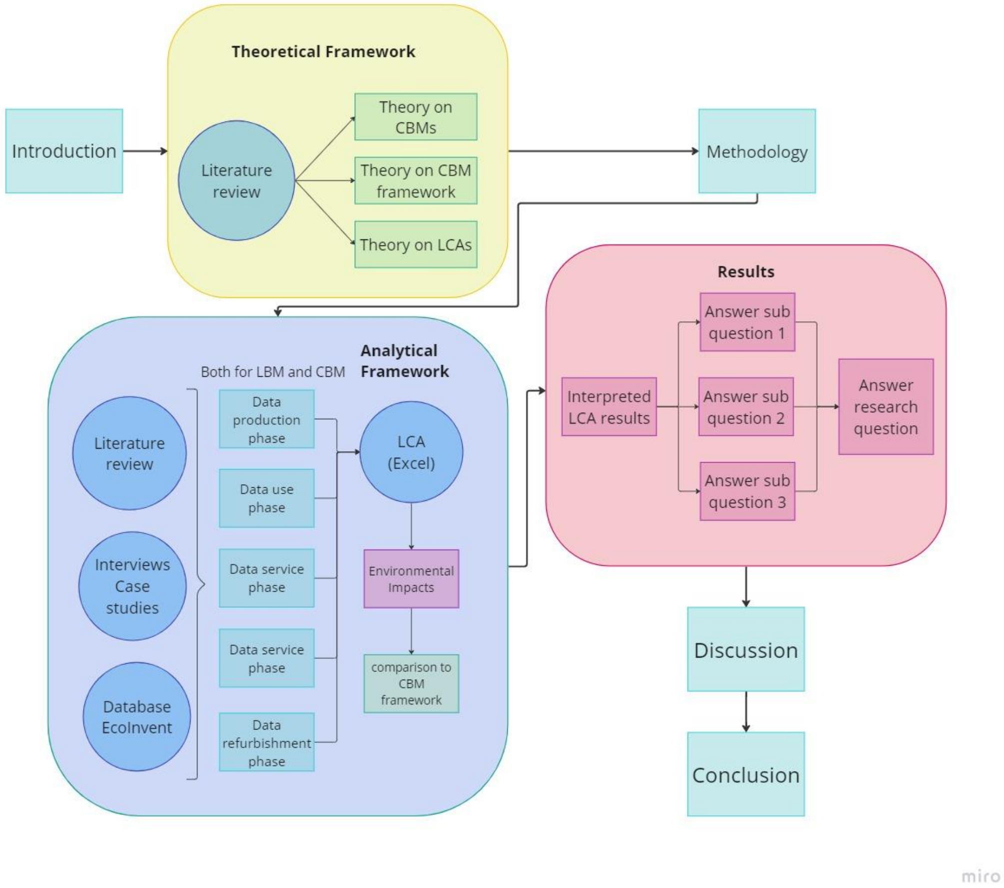


Fig. 3 Summary of research design

3.2 Semi Structured Interviews

Companies that provide a laptop as a service or a laptop for lease, whilst also including a refurbishment aspect to their business model, were approached to be included in this research as case study participants. Interviews were held with all case study participants. Their purpose was twofold: firstly the interviews were used as a way to get acquianted with the case studies and their business models. This way, the context in which the business models currently exist could be comprehended. The second aim of these interviews was to retrieve quantitative data about the cases' business models that could serve as input for the LCAs.

3.2.1 Selection of cases

The companies approached to serve as a case study had to fulfil multiple requirements to be included in the sample. Firstly, they had to be companies with 'Circular Intentions'. Circular intentions are defined by Copper8 as 'A motivation to contribute to the Circular Economy, with the eventual goal of operating within the natural limits of our planet, while preserving social foundations'. Alongside these circular intentions a company can still have the objective to reach commercial targets (Copper8, 2019).

Ensuring that each company included as a case study had circular intentions avoided companies to be included that merely applied circularity principles to their business model without actually wanting to contribute to a more circular system. The presence of circular intentions of each company was determined by reviewing their company websites for their approach to

sustainability and circularity. Herein it was ascertained whether their circularity principles were actually also related to a bigger goal instead of merely being a marketing tool. Companies that did not include any information on their website regarding sustainability or the Circular Economy in a broader sense were excluded from the sample.
The second requirement that the case study companies had to fulfil was that they had to offer their laptops to the users ‘as a service’ or under a lease contract instead of selling them to the customer. Lastly, each company included in the sample had to perform refurbishment on their laptops.
The criteria that a company had to meet before being included in this sample were established by the researcher before commencing with the interviews. Furthermore, these criteria were based upon the research question and general area of interest of this research. Therefore, this sampling approach falls under the category of generic purposive sampling (Bryman, 2012, pp. 412-415).
All companies included in the case studies were approached through phone call or email.

3.2.2 Interview approach

One interview, lasting between 90 and 120 minutes, was conducted with each company. All interviews were held at the main location of each case study and were followed up with a tour of the premise. To ensure the ethical handling of the interviewees and the data they provided, a Non Disclosure Agreement (NDA) was signed both by the researcher and interviewees. Furthermore, a summary of each interview was sent to the interviewee for verification to ensure the correct interpretation of retrieved data.
The interviews were of a semi-structured nature, which allows for covering a set range of subjects that are present in the interview guide, whilst also leaving room for additional insights that might potentially enrich the theory of this research (Bryman, 2012, pp. 212). For each case study a separate interview guide was compiled. The interview guides were tailored in such a way that they would align with the business model implementation in question, whilst also ensuring that similar questions were asked to each case study participant to safeguard comparability of interview data between case studies.
The representatives selected for interviews all held a position in the company that is related to the company’s business model or value chain. This was done to ensure the interviewees’ expertise on the subject matter. In all three cases clarifications and further questions were needed after the first interview. Therefore, additional questions were answered through email or phone conversation.

3.2.3 Analysis of interview data

The quantitative data that was gathered served as input for a LCA that was conducted to indicate the environmental impact of the company's business model. For the LCA input, the most recent available data on process and products in the business model was requested, as the aim is to get an understanding of the current impact of the company. After the interview, retrieved data that would later on serve as input for the LCA was reviewed and follow up questions to clarify certain information that was needed to execute the LCAs were sent to each case study participant. Accurate data was unavailable for some aspects of the LCA. Therefore, some assumptions had to be made regarding the input for the LCAs. All assumptions were made in agreement with the interviewees. These assumptions are included in section 13, Appendix.

The qualitative data obtained from the interviews was used to provide transparency regarding the provided input data for the LCA and to get a deeper understanding of the intended objectives of the company's business model. This data was not coded, instead themes that were deemed relevant on the basis of the theoretical framework were used to sketch an image of all cases studies included and to interpret the results that came out of the LCAs.

4. LCA Methodology

4.1 Goal and scope definition

In the first stage of the LCA, the intended application, the reason for carrying out the study and its intended audience are specified. Furthermore, in the scope definition, it is described what was analysed and how this was done (Hausschild et al., 2018, pp. 75-76).
The goal of this study is to analyse the environmental impact of a laptop in different implementations of a leasing and refurbishing CBM. These environmental impacts will be compared among the different implementations of the CBMs as well as the environmental impact of a laptop in a LBM.
The reason for carrying out this study is the existing ambiguity surrounding the potential decrease in environmental impacts resulting from leasing and refurbishing CBMs. The results of this study will provide conditions that need to be met to ensure a lowered environmental impact in a refurbishing and leasing CBM in comparison to a LBM, in the context of the IT sector.
The intended audience for this LCA consists of scholars in the field of CBMs that are interested in the environmental impacts of CBMs studied through an LCA lens, as well as business owners that aim to integrate CBM strategies into their business model whilst simultaneously lowering their environmental impact.
The geographical scope for the production phase of this study comprised of laptops produced in Shenzen, China, as this is considered the electronics producing capital of the world (World Economic Forum, 2019). Consequently, transports of the laptop from its production location towards the Netherlands, where it would be used, were all considered to be between Shenzen, China and Rotterdam Harbour, the Netherlands.
The geographical scope for the use phase was considered to be the Netherlands. Several of the case study companies that were included mentioned that they also transport laptops to customers abroad. However, this was considered to be outside of the scope of this research.
The temporal scope of the system was set up to be indicative of the current time, given that primary data was used. Nonetheless, secondary data sourced from the EcoInvent v.3.8.1 was also included. This data was 15 years old at most, which lowers the temporal adequacy of this research.

4.1.1 Functional Unit

The functional unit is a functioning laptop for the duration of eight years that is used for five and a half hours a day, two hours on standby and the remaining sixteen and a half hours turned off. The laptops included in the case studies are laptops that businesses acquire for their employees, therefore the laptops are assumed to be solely used for office work purposes. Assuming that the user is working on their laptop for five and a half hours a day, participates in a meeting or other activities for two hours a day and does not use their laptop at all for the remaining hours aligns with data that Centraal Bureau voor de Statistiek (CBS) provided on average laptop usage among Dutch employees that received higher education in 2022 (CBS, 2022).

4.2 Life cycle inventory analysis

In the Life Cycle Inventory, information about elementary flows (i.e. emissions or resource use of a product system) is collected and connected to the functional unit (Hausschild et al., 2018, pp. 118-119, 168). For the CBMs, data describing these flows was derived from the interviews conducted with representatives of each company included in the sample. For the LBM, standardized data obtained from database EcoInvent v.3.8. was used to describe the elementary flows.

As the LCAs of different business model implementations were compared, transparancy on assumptions and uncertancies that are involved in the LCAs was included. Furthermore, the functions provided by the business models, their functional units, were defined in such a way that their properties are suitable for comparison (Hausschild et al., 2018, pp. 84, 114).

To establish a baseline of environmental impacts for a laptop in a LBM, data on its environmental impact was derived from life cycle inventory database EcoInvent (version 3.8). Since a case study for a LBM was not included, the entire LBM business model was based on EcoInvent data. Assumptions that are part of the EcoInvent database were addressed to provide transparency and clarity regarding the data that wil be used (see 13, Appendix).

4.3 Life Cycle Impact Assessment

The ReCiPE Midpoint 2016 method is used to transform the list of life cycle inventory results to a comprehensive number of impact scores (Pré Consultants, 2018). This method is a commonly used way to establish the environmental impacts of processes and products. It was built upon three principles: Relevance (considering only relevant impacts), Completeness (covering all environmental effects that are deemed significant) and Parsimony (keeping the assessment simple and straightforward) (Huijbregts et al., 2016; Hausschild et al., 2013). The eighteen indicators that that this method employed at Midpoint level focus on single environmental problems, e.g. Human Toxicity and freshwater depletion (Rijksinstituut voor Volksgezondheid en Milieu, 2011). The ReCiPe method was chosen as the method for LCIA in this research due to its relatively low level of uncertainty and because it is the midpoint framework containing the broadest range of impact categories (Pré Consultants, 2018)

Not all eighteen impact categories that are part of the ReCiPe methodology can be considered equally relevant for CBM's in the IT sector. Therefore, the impact categories that were deemed most relevant to include are Climate Change (Pachauri et al., 2014 ; Hoang et al., 2009), Metal Depletion (Andre et al., 2019) and Human Ecotoxicity (Rosenbaum et al., 2008). These impact categories were selected based on their recent inclusion in LCAs that were performed on laptops (Andre et al., 2019). Following, when discussing environmental impact and its association with CBM's within the context of this report, the focus is strictly on the influence pertaining to these three defined impact categories. Other environmental impact categories are outside of the scope of this report.

Table 5. Impact categories according to ReCiPe Midpoint and impact units. Retrieved from Huijbregts et al., 2016.

Impact category	Midpoint Characterisation Factor	Unit	Abbreviation
Climate Change	Global Warming Potential (GWP)	Kilogram Carbon dioxide equivalent	Kg CO_2 eq.
Metal Depletion	Metal Depletion Potential	Kilogram Iron equivalent	Kg Fe eq.
Human Toxicity	Toxicity potential (TP)	Kilogram 1,4-dichlorobenzene equivalent	Kg DCB eq.

4.4 Interpretation

The research's interpretation phase involved an iterative cycle of validating results, fine-tuning data inputs, assessing the comprehensiveness and coherence of the system model, performing sensitivity analyses, and ultimately pinpointing areas of significant environmental impact within each business model implementation.

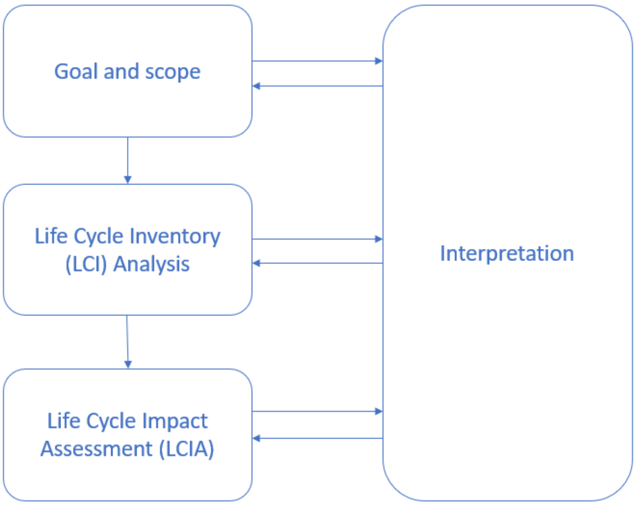


Fig. 4 The four steps of conducting an LCA. Retrieved from Hausschild et al., 2018.

4.5 Sensitivity analyses

A sensitivity analysis was performed to assess the robustness of the results as they were presented in section 7, LCA Impact Assessment and Interpretation. According to the ILCD handbook, 'The consideration and communication of uncertainties related to results obtained via modelling and/or measurements is vital for their correct interpretation' (2018, pp. 273). After applying this sensitivity analysis the results were evaluated again to see the change in impact due to applying this analysis.

Two sensitivity analyses were executed: one on the influence of extending the laptops' lease contract lifetime and one on the influence of the refurbishment rate on the environmental impact of the CBM implementation.

4.6 Allocation methods

Addressing multifunctionality is a crucial element for all LCAs that involve multiple in- or outputs (Nicholson et al., 2009). In this study, life cycle assessments (LCAs) were conducted to facilitate a comparative analysis of results. To ensure a fair comparison, consistent allocation methods were employed across all cases, as suggested by the ILCD Handbook (2018, pp. 113). In this research, the 50/50 method was employed for the included allocation processes. This method distributes burdens based on the number of uses (Nicholson et al., 2009). However, to get a sense of the timing when environmental impacts occur, the environmental impacts were modelled as closely as possible to the moment in which they were assumed to occur. In case of this research the 50/50 method was applied on two processes that involve multifunctionality:

1. The environmental impacts of a laptop being cut off before ending its intended lifespan.

2. The environmental impact of components that only enter the product system after their first life cycle.

4.6.1 Cut off

In Case 2, where laptops had a three-year lifespan within an eight-year functional unit, the final life cycle encompassed only two out of the three years (years 7 and 8). Consequently, all burdens associated with the complete life cycle of the laptop were multiplied by two-thirds, representing the proportion completed. Furthermore, these environmental impacts were still modelled approximately when they were assumed to occur in the lifecycle of the product.

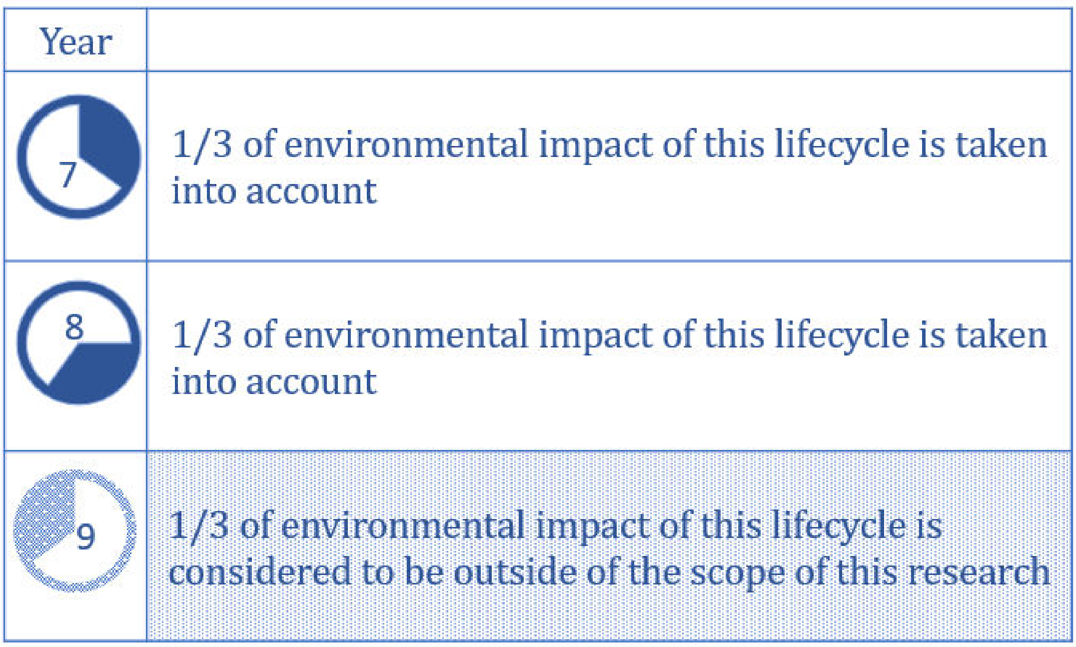


Fig. 5 Allocation of environmental impacts in case of a cut off at 2/3 of a lifecycle

4.6.2 Component reuse

Lastly, the 50/50 allocation method was applied to situations involving component reuse. In all cases, data regarding the previous use of components stored was unavailable, except for the knowledge that these components had been used not more than once before. Therefore, half of the production impact of these components was allocated to their first life cycle, assuming a that the component completed a full life cycle based on the business model of the respective case. The remaining half of the production impact was allocated to their second and final life cycle, which was included in the product system.

5. Case Studies

The following section is dedicated to providing background information on the three cases used in this research. These cases all implemented a different version of a refurbishing and leasing CBM, and it was reported that they differ in terms of refurbishment rates, transport, production and service.

5.1 Case 1

5.1.1 General information

Case 1 is piloting a 'Device as a Service' model for electronic devices. Therefore, some of the data they provided is derived from expectations associated with their future business model that has not come to fruition yet.

Case 1 receives previously used products after their first lifecycle. In the case of laptops, this would typically occur after four years of use. To enable a just comparison between the laptops' life cycles of Case 1 and those in the other cases, the 'first' life cycle of the laptop is also considered. However, it must be acknowledged that it takes place outside of Case 1s ownership or accountability. Data pertaining to the first life cycle of a laptop in Case 1 is therefore based on assumptions provided by Case Study 1s representative.

Case 1 only works on a business-to-business basis and did not specify the type or brand of laptop that they tend to work with. They also reported that they can refurbish 65 % of laptops after their first life cycle. These laptops will still be used for another four years after refurbishment on average, which is the duration for a contract Case 1 has in mind for their future Device-as-a-Service model. A contract duration of two times four years is assumed for this LCA, to meet the functional unit of eight years in total.

Case 1s representative stated that:

"In our business model, a laptop can be used for eight years in total. By aligning a laptops' technological capabilities with the functionalities required for the user, we avoid overburdening our laptops, which leads to a longer life expectancy. Furthermore, we notice that taking good care of also laptop aids in prolonging its functional lifetime."

The remaining 35 % consists of laptops that are Beyond Economical Repair, i.e. laptops that could technically be repaired still, but that would cost more than they would yield, and laptops that are considered to be unsuited for future usage overall. The 35% of laptops considered to be Beyond Economic Repair or technically irreparable also contains laptop components that can be used in the service and refurbishment phases. However, tracing these components was not feasible for this thesis as components derived from a single laptop could be used in multiple serviced or refurbished laptops. Also, Case 1 did not have data available yet to track these previously used components. As a result, an informed estimate was made that pre-used components were used in the service and refurbishment phases in 50% of times (see 6.4, LCI, Refurbishment phase).

Table 6. Categories for future applications laptops after first lifetime Case 1

Categories future applications laptop Case 1	Percentages after four years
Refurbishment	65%
Beyond Economic Repair or technically irreparable	35%

5.1.2 Use Phase

During the use phase, on-site service is offered two times on average to ensure that the laptops stay in the best possible condition. The representative of Case 1 stated that:

"Especially when the laptop is used frequently and without the best of care, we always advise the provision of service once every two years. The same advice would be applicable to laptops that are used in particularly dusty and humid spaces. This way, we can ensure that the laptop can be used for eight years in total."

Concerning refurbished laptops, they added: "*For our refurbished laptops, we expect that service on a biannual basis would also be sufficient as it is expected that their functioning is compatible with a new laptop."*

5.1.3 End of Life

At the end of life, Case 1 collects and transports these laptops and takes components that are still usable into their storage for potential use when performing reparations during service. Laptops and separate components that are not suitable for reuse on component level will be disposed of according to WEEE regulations (Directive 2002/96). Case 1s representative stated that the company ensures to execute recycling:

"*As locally and efficiently as possible, taking both cost and benefit into consideration."*

Looking ahead, they expressed a desire for their company to transition towards a model that enables tracking the quantities of resources obtained through recycling as well as the monetary returns they generate. This move is aimed to enhance their understanding of the company's contributions to sustainable disposal and its potential profitability. A more in-depth description of each step of Case 1s life cycle is provided in Section 6, LCI.

5.2 Case 2

5.2.1 General Information

Case study 2 offers a variety of products for lease, among which are laptops. Besides laptops they also lease out beds, washing machines and bikes. Their laptops are both offered business-to-business and to individual customers. For this research, only Case 2s business-to-business (B2B) branch is considered, facilitating a comparative analysis with the other included case studies that similarly adopted a B2B business model. Case study 2 has been operating their leasing business model for 50 years.

Case 2 offers their customers a contract with a duration of three years for laptops. Case 2s representative shared that their contract duration is based upon research by Nibud, in which a three-year lifetime expectancy was estimated for laptops. Before, Case 2 also ran laptops on a five-year contract duration, but they ceased to do so due to the altered lifetime expectancy by Nibud. It is important for Case 2 that they only offer the best functionality to their customers, which they say they can solely guarantee by offering a lease contract of three years maximum. Another note made by Case 2s representative was that:

"Technological development is rapid for consumer electronics; we cannot offer a laptop that is eight years old for instance. No one would be interested in that as it has simply become too slow to keep up with the level of functioning that is required nowadays."

5.2.2 Refurbishment

After a first lease round of three years, 35 % of laptops can be refurbished to be used for another three years. 45 % of the other laptops will be used as a temporary laptop that the customer can use when service is provided on their 'own' laptop, 10% will be bought by the customer after the first life cycle and 10% will go to disposal directly. Case 2s representative:

"We only refurbish laptops of which we know for sure that they will last for another three years. Laptops that might only function on the level we expect it to for another year or two will be used as a temporary laptop."

After the second three-year life cycle, again 35 % of the laptops will be refurbished (65% * 35% = 22.75). And the remaining 77.25 % of laptops will have to be newly produced.

Only laptops that fall into the categories of 'new' and 'refurbished' are considered to be part of the scope of this research for the second life cycle. At Case 2, laptops can only be refurbished once. Therefore, it is assumed that all refurbished laptops go to disposal after being used for three years, on top of their initial lifetime of three years. Case 2s representative stated that:

"Case 2 aims to procure 'A level brands' with high levels of repairability. Doing so ensures that our customers have the best user experience and allows for better chances at refurbishment after the first life cycle. A challenge that we experience is that suppliers aim for a high turnover of products to gain more profits, whereas we would like to be able to facilitate our customers to use their laptops for the longest possible time."

Case 2 offers their customers on-site service on average once every three years, on each laptop. Additionally, Case 2 offers their customers online support whenever they encounter software problems. Case 2s representative stated that providing service can help ensure that the laptop lasts for its entire contract duration. Other measures implemented by Case 2 that contribute to this goal involve sharing guidance on laptop maintenance through blogposts and supplying all customers with a laptop sleave, which is meant to negate the risk of damage in daily transports.

Table 7. Future applications after first and second lifetime laptops Case 2

Categories future applications laptop Case 2	Percentages after three years	Percentage after six years
Refurbished laptop	35%	22.75%
Temporary laptop used during service	45%	57.25%
Purchased by customer	10%	10%
Disposal	10%	10%
Total	100%	100%

5.2.3 End of Life

At the end of their functional life, Case 2 undertakes the collection and transportation of these laptops and transports them to their designated warehouse for a comprehensive assessment aimed at identifying potential future applications. In cases where a laptop is ensured to have exhausted its functional utility, Case Study 2 adheres to the Waste Electrical and Electronic Equipment (WEEE) regulations to ensure appropriate disposal (Directive 2002/96). Case study 2 aims to only procure A-level brands, offering customers high quality products and ensuring the laptop’s repairability after initial use. A more in-depth description of each step of Case 2s life cycle is provided in section 6, LCI.

5.3 Case 3

5.3.1 General Information

Case study 3 offers laptops and other electronic devices 'as a service' to their customers. They only offer products on a business-to-business basis. When Case 3 initially starts working with a customer, it is their standard procedure to offer them a new laptop. Case 3s representative expressed:

"It is our experience that employees that just start working on a new job generally anticipate the provision of a brand-new laptop, which is why companies we work with tend to include the provision of new laptops as a part of their on-boarding protocol. They say it serves to project their image of professionalism and creates a welcoming environment for the employee."

5.3.2 Refurbishment

Case 3s representative remarked that companies are slowly becoming more interested in including refurbished laptops. Nonetheless, especially when an employee starts working at a new company, mainly new laptops are provided.
Case 3 states that refurbished laptops are compatible with new ones in terms of their functionalities and that they try to stimulate refurbished laptop usage to the most possible extent. However, Case 3s representative also foresees certain challenges pertaining to refurbished laptops:

"Companies want laptops they use across all departments of their business standardized as much as possible, as this simplifies management. Since we tend to work with large companies that need to equip many employees, sourcing a refurbished laptop that adheres to these standardized requirements can be a challenge."

Another challenge that was addressed is that multiple large companies were unwilling to introduce refurbished laptops due to a perceived risk concerning data safety.
At Case 3, whenever a user needs service on their laptop, the laptop will immediately be swapped for a brand new one that Case 3 ensured to have in storage on-site of the users' working space. The laptop that requires service will go to reparations and will be stored to be employed for the next time a service requiring laptop needs to be swapped out. On average, 15% of all laptops that are used by Case 3s customers are 'redeployed'. Case study 3 does not classify these laptops as being refurbished, but instead calls them 'redeployed laptops.'
For the sake of clarity and to enable comparison between the cases, second chance laptops that Case 3 puts in the category of 'redeployment' will be classified as 'refurbished laptops' in this research. This is deemed to be a reasonable classification as the actions that Case 3 performs in their 'redeployment' are very similar to those performed by the other case studies in the refurbishment phase.

Table 8. Future applications laptops after first lifetime Case 3

Categories for future applications laptops Case 3	Percentage after four years
Refurbishment *(called 'Redeployment' by Case 3)*	15%
Offered at disposal market (what happens with the laptop is outside of the influence of Case 3)	85%

At Case 3, an online portal is used for laptop registration, offering valuable insights into user behaviour. This portal aids communication between Case 3 and the customer and offers the opportunity to assess and optimize equipment provided to the user. For instance, when a user needs additional or fewer functionalities, their laptop can be exchanged for a more suitable alternative. Doing so prevents laptops from being unnecessarily overloaded or having functionalities that exceed user requirements.
Moreover, Case 3 is exploring methods to determine when a laptop might still be suitable for use past the proposed end of its lease contract, which potentially allows for extending the laptops' operational lifespan. Conversely, this approach might also lead to the withdrawal of a laptop from operation prior to the proposed end of its lease contract in the instance of suboptimal performance. Data concerning alternative durations of lease contracts due to insights derived from the portal was not available. Therefore, these instances were considered outside of the scope of this research.

5.3.3 End of Life

At the End-of-Life of the laptops after four years, Case 3 transports laptops back to their warehouse location to wipe them of all data. Due to the online portal, all laptops are registered which ensures that they will all be returned to Case 3 at their EoL. According to Case 3s representative this is an advantageous aspect of their business model, as in other companies that provide electronics to their employees, items frequently go missing and fail to be returned. Case 3 subsequently transports the laptops to the disposal market, where they are often bought by parties that either refurbish them on product- or component level. As the laptops that are bought to subsequently be refurbished are outside of Case 3s ownership, these are considered to be outside of the scope of this research.
Alternatively, products and components that are not fit to be reused are bought by market actors to be disposed and where possible recycled according to WEEE Regulations (Directive 2002/96).
A more in-depth description of each step of Case 3s life cycle is provided in section 6, LCI.

5.4 Coupling the case studies with the CBM strategies

This research focuses on the environmental impact of companies offering their customers a Device as a Service. The business models of the case studies included can be classified into on the basis of three main CBM strategies: Access and performance, Extending Product Value and Extending Resource Value. It is also discussed in this section why the remaining CBM strategies do not apply to the case studies in this research to the same extent as the former three. Categorizing the CBM strategies and deciding which ones apply to the case studies allows for scrutinizing the influence of the selected CBM strategies on the environmental impact in each practical example that was provided.

Table 9. CBM strategies applied to the case studies

	Case 1	Case 2	Case 3
Slowing resource flows			
Access and Performance (A&P)	All case studies fall into this CBM strategy, as they offer essential services to users (such as laptop access, usage, repair, and end-of-life disposal) without the need for product ownership by the user.	All case studies fall into this CBM strategy, as they offer essential services to users (such as laptop access, usage, repair, and end-of-life disposal) without the need for product ownership by the user.	All case studies fall into this CBM strategy, as they offer essential services to users (such as laptop access, usage, repair, and end-of-life disposal) without the need for product ownership by the user.
Extended Product Value (EPV)	All case studies incorporate refurbishment in their business models, effectively extending the functional lifespan of laptops compared to non-refurbished equivalents. This aligns with Bocken et al.'s (2016) EPV strategy.	All case studies incorporate refurbishment in their business models, effectively extending the functional lifespan of laptops compared to non-refurbished equivalents. This aligns with Bocken et al.'s (2016) EPV strategy.	All case studies incorporate refurbishment in their business models, effectively extending the functional lifespan of laptops compared to non-refurbished equivalents. This aligns with Bocken et al.'s (2016) EPV strategy.
Classic Long Life model (CLLM)	All case studies offer laptop installation, regular servicing, and repairs to users during the product's lifetime, which are assumed to positively impact product longevity. Extending product life aligns with the CLLM strategy. However, the case studies do not fully adhere to this strategy since they have predetermined product lifetimes in their business models, limiting the potential for maximum product lifespan extension. Case 1 provides service on the laptops, which potentially increases the duration of the laptop's life time. However, as Case 2 has a 'set' duration for their device-as-a-service contracts, a CLLM strategy does not fully apply.	All case studies offer laptop installation, regular servicing, and repairs to users during the product's lifetime, which are assumed to positively impact product longevity. Extending product life aligns with the CLLM strategy. However, the case studies do not fully adhere to this strategy since they have predetermined product lifetimes in their business models, limiting the potential for maximum product lifespan extension. Case 2 offers laptop services, user care instructions, and blogs on laptop lifespan extension. While these measures can enhance laptop durability, a predetermined lease duration limits the full impact of this strategy.	All case studies offer laptop installation, regular servicing, and repairs to users during the product's lifetime, which are assumed to positively impact product longevity. Extending product life aligns with the CLLM strategy. However, the case studies do not fully adhere to this strategy since they have predetermined product lifetimes in their business models, limiting the potential for maximum product lifespan extension. Case 3 employs an online portal to identify laptops with extended potential lifespans, but lacks data on such extended durations. Consequently, the CLLM strategy could not be applied in Case 3.

Encourage Sufficiency (ES)	Case 1 did not report activities that align with the ES strategy.	Case 2 offers laptop services, user care instructions, and blogs promoting laptop lifespan extension. This aligns with sufficiency by discouraging new purchases. However, Case 2s fixed lease duration prevents classification under this strategy.	Case 3 utilizes a portal to identify laptops with extended potential lifespans and optimize employee-specific functionalities. These measures potentially result in the encouragement to refrain from acquiring a new laptop or choosing a more simple laptop model according to the functionalities that are required. However, due to a lack of available data provided on these measures, this strategy was not implemented in Case 3.
Closing resource flows			
Extended Resource Value (ERV)	All case study companies engage in component-level refurbishment, repurposing viable old laptop components that would be discarded in a LBM. These components are used to replace faulty parts in refurbished laptops, aligning with the ERV strategy."	All case study companies engage in component-level refurbishment, repurposing viable old laptop components that would be discarded in a LBM. These components are used to replace faulty parts in refurbished laptops, aligning with the ERV strategy.	All case study companies engage in component-level refurbishment, repurposing viable old laptop components that would be discarded in a LBM. These components are used to replace faulty parts in refurbished laptops, aligning with the ERV strategy.
Industrial Symbiosis (IS)	The IS strategy could not be applied to any of the cases as this strategy requires residual resources of one process to be feedstock for a nearby different process, which was not reported by any of the case studies.	The IS strategy could not be applied to any of the cases as this strategy requires residual resources of one process to be feedstock for a nearby different process, which was not reported by any of the included case studies.	The IS strategy could not be applied to any of the cases as this strategy requires residual resources of one process to be feedstock for a nearby different process, which was not reported by any of the included case studies.

6. Life Cycle Inventorisation

6.1 LCI: System description and system boundaries

This section describes the system and its boundaries as well as the way in which data was obtained for each process. The life time of laptops was divided into six steps for each business model implementation: Production, Transport, Use, Service, Refurbishment and Disposal. Although all CBMs included in this research can be considered relatively similar due to all incorporating refurbishment and a lease business model, their implementation of this business model differed. For example, Case 1 offers service once every two years whereas Case 2 only offers on-site service once every three years. Or transportation distances may differ between case studies. The most notable differences between case studies were highlighted in section 4.1 Case study descriptions. Furthermore, a LBM was included for comparison. The LBM followed similar life cycle steps to the CBMs, except for refurbishment.

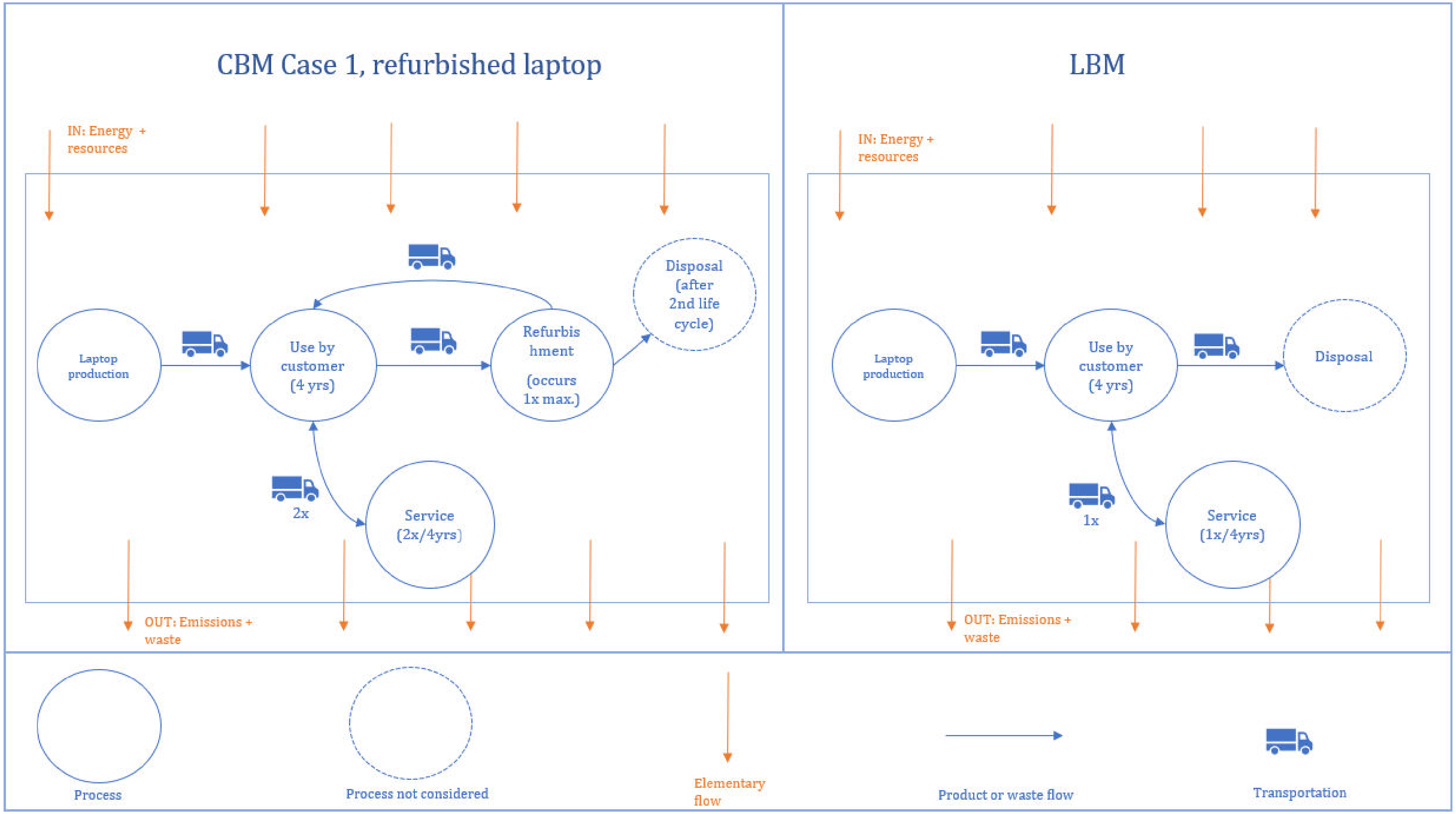


Fig. 6 visualization product system with system boundaries Case 1 and LBM

6.2 LCI Production phase

All businesses participating in the case studies acquire laptops from an external source. Therefore, primary data on the production of these laptops was not available. Moreover, there was a significant overlap in the types of laptops offered by the case study participants to their customers, which led to the assumption that the same laptop was offered in all cases, including the LBM.

In order to ensure a fair comparison across the various business models and business model implementations, the same impact for the production process of the laptops was assigned to all cases. The dataset used to describe this process was derived from EcoInvent v.3.8. and it 'includes materials (mainly metals and plastics) with their respective manufacturing processes (e.g. sheet rolling, press moulding). Further inventoried is the infrastructure (factory), the electricity for the assembly of the laptop computer, the water consumption and industrial waste water (EcoInvent, 2023). Included in this step are the extraction of raw materials, manufacturing of components and the final product as included in the EcoInvent dataset. Furthermore, transportation of the final product (transport from Shenzen, China to Rotterdam Port, the Netherlands by both sea container and truck, see section 13, Appendix for assumptions that were employed in the production phase) was considered to be a part of the production phase.

All three cases reported that they do not dispose of all laptops at their EoL within the business model implementation that was included in this research. Some of these laptops still serve a function as a temporary replacement laptop when the primary laptop is undergoing service or will be donated to another user. However, this was considered to be outside of the scope of this LCA.

It should be noted that for Case 3, a new laptop is provided instantly for the customer when service is provided. This occurs in 5% of cases, once every four years. Case 3 also mentioned that some users may receive refurbished laptops instead of brand new ones when they need service. However, there is no available data to specify the frequency of this occurrence. Consequently, this occurrence was excluded from the LCA.

New or refurbished replacement laptops are assumed to have the same contract lifetime of four years. Consequently, the five % of laptops that were introduced into the product system half way of the first life cycle need replacement half way of the second life cycle.

Moreover, Case 3 did report that 15% of laptops was refurbished after their first life cycle of four years. As 5% of laptops were introduced into the product system in the middle of the first life cycle, only 95% of laptops needs replacement after the first four year lifecycle. As a result, 15% of laptops that is introduced into the product system in year 5 is refurbished and 85% (of which 5% is introduced halfway LC 1 and 80% at the start of LC2) is assumed to be new.

Details on the EcoInvent dataset used for the production phase are included in Appendix (13).

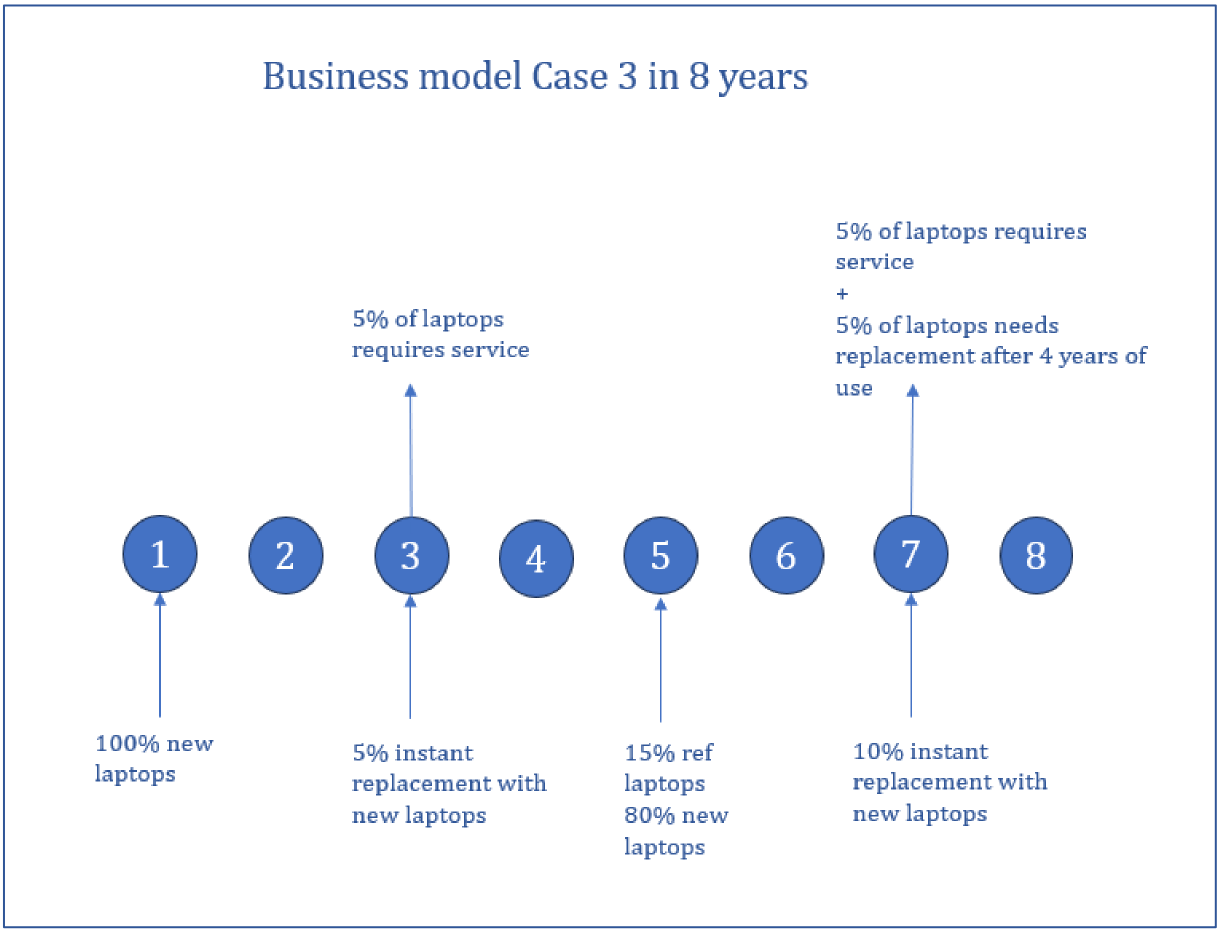


Fig. 7 visualization of the in- and outflow of laptops for Case 3 during eight years

6.3 LCI Use phase

The impact that is included for the use phase is impact that occurs as a result of the energy provision that the laptop needs for charging its battery. It was assumed that users in the various cases had comparable usage patterns. As a result, the average times that the laptop is deemed to be operational (5.5 hours per day), in standby mode (2 hours per day), and turned off (16.5 hours per day) were assumed to be identical for all case studies, including the LBM. These numbers are based on data on average laptop usage for Dutch employees at an office job that was published by the CBS in 2022 (CBS, 2022).

A year has 229 working days per year. Employees call in ill for 8 days per year on average and there is a minimum requirement of 20 days of paid leave per year (CBS, 2022). Therefore, there are 201 days the laptop will be used per year.

By including refurbished laptops in their business models, the case study companies take away the users need to acquire a new laptop that could presumedly have state-of-the-art technological features such as higher energy efficiency. However, although new laptops are more energy efficient per computational power, they also tend to consume more energy overall (Boyd, 2012). This offsets the potential increase in energy efficiency that is gained by purchasing a new laptop versus using a refurbished laptop (Boyd 2012, pp. 109-112; Prakash et al., 2016; André et al., 2016). Consequently, energy usage is assumed to be uniform across refurbished and new laptops in this research.

Data on contract lifetime of the products in years was obtained through interviews and varied across the case studies. A newly acquired laptop from Case 1 is used for four years, after which it will be operational for an additional four years following refurbishment. On the other hand, a new laptop obtained from Case 2 is in use for three years and will be operational for an additional three years following refurbishment. For Case 3, a newly acquired laptop is used for four years and will be operational for an additional four years following refurbishment. It is noteworthy that, as Case 1 has not executed their CBM implementation in practice they do not have a set user period as part of their business model. Therefore, the laptops' contract lifetime for this firm is an estimated average value that was proposed by the company's representative. Details on the dataset employed for the use phase are included in section 13, Appendix.

Table 10. Use duration; service frequency; replaced components; second hand components; refurbishment rate; refurbished components; total km transportation by van and total km transportation by passenger car

Case	Duration of lease contract	Service frequency	Components that are most frequently replaced in service	(average) Amount of previously used components used in service + refurbishment	Refurbishment rate	(average) Amount of previously used components used in refurbishment	Components that are most frequently replaced in refurbishment	Total km by Light vehicle (van) in eight years	Total km by passenger car in eight years
1	4 years	Once every two years	Keyboard and adapter	50%	65% is refurbished after first life cycle	50%	Screen and HDD	900 km	n.a.
2	3 years	Once every 3 years	Keyboard and adapter	50%	35% is refurbished after first life cycle, 22.75% after second life cycle	50%	Screen and HDD	1003 km	372 km
3	4 years	No service (laptop instantly gets refurbished instead)	n.a.	50%	15% is refurbished after first life cycle	50%	Keyboard and battery	360 km	n.a.
LBM	4 years	Once every 4 years	Keyboard and adapter	n.a.	n.a.	n.a.	n.a.	691 km	n.a.

6.4 LCI Refurbishment phase:

Table 10 demonstrated that the proportion of laptops considered suitable for refurbishment after their initial life cycle varied among the different business model implementations. However, the refurbishment process reported in all case studies was found to be similar. It involved e.g. the complete erasure of all data, cleaning the laptop, and repairing or replacing any visually or functionally damaged components. The objective of the refurbishment process was similar in all cases: to provide the customer with a laptop that is functionally and visually equivalent to a new one.

In this LCA, only the replacement of visually or functionally damaged components is considered as a part of the refurbishment phase. This choice stems from the unavailability of accurate data on other refurbishment-related impacts such as the environmental impact of cleaning the laptop and data wiping. Furthermore, the potential impact of these steps was estimated to be negligible in comparison to the impact of component level replacements.

None of the case studies could provide primary data on the most frequent repairs or replacements performed during refurbishment. Instead, they provided an informed estimate of the top two components that are commonly replaced in refurbishment.

All cases studies reported that they reuse components that are still suitable for usage after their first employment. It was assumed that this occurred in 50% of cases on the basis of estimates that were provided by the interviewees.

The LBM did not have a refurbishment phase.

Datasets used for the refurbishment phase are visible in section 13, Appendix.

6.5 LCI Service phase

All of the analysed case studies included provision of services during the product's lifetime, such as repairing laptop components during the use period to enable continued use of the same device after a malfunction, rather than disposal and replacement with a new one. As with the refurbishment step, primary exact data on the most frequently occurring repairs was not available. However, case study participants could provide estimations of what they thought were the most frequently occurring reparations on average. Therefore, an informed estimate based on interview data of the average top two repairs per case study was included in the analysis. Notably, the components that were mentioned needing replacement in service most often were the same among case studies providing service: Keyboards and adapter were most frequently replaced.

For the LBM, it is assumed that one repairment occurs in the total operational life span of the laptop. This is an assumption based on EU law mandating warranties for electronic products in cases of malfunction, excluding user- induced faults, within a two year timeframe. As the most frequently occurring components needing repairment was consistent across CBM case studies, it was assumed that these same replacements were applicable in case of the LBM.

Outside of components replacements, no service activities were included in the LCA. Companies did mention other service activities such as cleaning hardware, software services and repair on component level, but no accurate data was available on these activities and the environmental impact of these activities can be considered negligible in comparison to replacing used components for new ones.

All CBM case studies reported that they have components in storage from laptops that were not suitable for use on product level anymore, but that did have value on component level. None of the case studies had exact data available on the frequency with which they were able to use previously used components. However, the estimated frequency with which all companies

reported to have components in storage was an average of '50% of cases'. Therefore, for 50% of the replaced components the impact of new components was added. For the other 50% of replaced components, only half of the impact of new components was allocated. Adding to a total of 75% of the impact of new components. The service frequency differs per case study as can be seen in table 10. For the LBM it was assumed that no previously used components were kept in storage. As a result, replacement was modelled to take place with new components only for the LBM.
Datasets that were used for the service phase are included in Appendix (13).

6.6 LCI Transportation phase

This step includes all transportation activities involved in the transportation of the laptop from the moment it arrives at the company's premises, to the point of its final transportation to the waste incineration and recycling facilities. To ensure a uniform comparison across cases, it was assumed that the same type of vehicle was utilized when case study participants declared the use of a 'truck' or 'lorry' (i.e., a lorry with a carrying capacity exceeding 32 metric tons using EURO5 fuel), when they reported making use of a 'van' (i.e. light commercial vehicle in EcoInvent v.3.8.) or when they reported the use of a 'passenger vehicle' (i.e. a passenger car using EURO5 fuel in EcoInvent v.3.8.). For all vehicles, a 'market' dataset in EcoInvent V.3.8. was used. Market datasets include the consumption mix for a product according to the region in which it is located, also including the potential product losses that occur during a transaction between producer and consumer (EcoInvent, 2022).
The impact of the transportation phase differed between the different business models due to variance in geographical proximity to the customer and variance in terms of vehicle usage. A summary of this phase is provided per business model. To account for the distance between the case study's warehouse and the customer, an average distance to customer as provided by the interviewees was included.
The exact datasets used for the transport phase are included in Appendix (13).

6.6.1 LBM

As the LBM is a fictional case, the transport distances included were based on the average distances of all three other cases (table 11).

Table. 11 Assumptions made for transport in the LBM

Transport	Assumption
Delivery of laptop from distribution centre to customer	The average distance of all case studies between distribution centre and customer is used: 78.33 km
To- and from the customer to the service location	The distance between customer and service location is assumed to be equal to the distance between customer and distribution centre: 78.33 km
Transport from customer to distribution centre at EoL	It is assumed that this transport occurs at every EoL and that the distance is the average distance of all case studies between distribution centre and customer: 78.33
Transport from distribution centre to recycling facility at EoL	The average distance between distribution centre and recycling facility of all case studies is used: 32.33 km

As illustrated in table 12, the business model entails delivering the laptop to the customer, transporting it for servicing, transporting it back to the warehouse/distribution centre and then the recycling facility at its end-of-life (EoL). Assumptions that were employed and more detailed calculations that led to the averages included for the transportation phase in the LBM can be found under section 13, Appendix .

Table 12. Transport distances in the LBM

Year	Distance	Reason for transport	Vehicle
1	78.33 km	Delivery to customer	Light commercial vehicle
2	156.66 km	Service	Light commercial vehicle
3	-	-	-
4	110,66 km	EoL transport (customer to distribution centre and distribution centre to recycling)	Light commercial vehicle
5	78,33 km	Delivery to customer	Light commercial vehicle
6	156,66 km	Service	Light commercial vehicle
7	-	-	-
8	110,66 km	EoL transport (customer to distribution centre and distribution centre to recycling)	Light commercial vehicle

6.6.2 Case 1

As illustrated in table 13, the business model entails delivering the laptop to the customer, transporting it for servicing, transporting it at its end-of-life (EoL), and delivering it to the recycling facility. Since the Case 1s recycling facility is located 100 meters away from their main location it is assumed that no additional trip needs to be made from the main location to the recycling facility. The total distance covered by each vehicle during the study's temporal scope amounts can be found in table 10.

Table 13. transport distances for Case 1

Year	Distance	Reason for transport	Vehicle
1	75 km	Delivery to customer	Light commercial vehicle
2	150 km	Service	Light commercial vehicle
3	-	-	-
4	150 km	Service	Light commercial vehicle
4	75 km	EoL transport	Light commercial vehicle
5	75 km	Delivery to customer	Light commercial vehicle
6	150 km	Service	Light commercial vehicle
7	-	-	-
8	150 km	Service	Light commercial vehicle
8	75 km	EoL transport	Light commercial vehicle

6.6.3 Case 2

As illustrated in table 14, Case 2s business model implementation entails delivering the laptop to the customer, transporting it for servicing, transporting it at its end-of-life (EoL), and delivering it to the recycling facility. The total distance covered by each vehicle during the study's temporal scope is included in table 10. Transports occurring in year 7 and 8 are multiplied by 0.67 as only 0.67 or two thirds of the life time of the laptop of 3 three years is 'utilized'.

Table 14. Transport distances Case 2

Year	Distance	Reason for transport	Vehicle
1	85 km	Delivery to hub	Light commercial vehicle
1	35 km	Delivery to customer	Passenger car
2	170 km	Service	Light commercial vehicle
2	70 km	Service	Passenger car
3	122 km	EoL transport + recycling	Light commercial vehicle
3	35 km	EoL Transport customer - hub	Passenger car
4	85 km	Delivery to hub	Light commercial vehicle
4	35 km	Delivery to customer	Passenger car
5	170 km	Service	Light commercial vehicle
5	70 km	Service	Passenger car
6	122 km	EoL transport + recycling	Light commercial vehicle
6	35 km	EoL transport customer -hub	Passenger car
7	(85) * 0.67 = 57 km	Delivery to hub	Light commercial vehicle
7	(35)*0.67 = 23.45 km	Delivery to customer	Passenger car
8	(170)*0.67 = 114 km	Service	Light Commercial Vehicle
8	(70)*0.67 = 47 km	Service	Passenger car
8	(122) * 0.67 = 81,74 km	EoL transport + recycling	Light commercial vehicle
8	(35)* 0.67 = 23.45 km	EoL transport customer - hub	Passenger car

6.6.4 Case 3

Case 3: As illustrated in table 15 the business model entails delivering the laptop to the customer, transporting it at its end-of-life (EoL), and delivering it to the recycling facility. Remarkably, Case 3 has a customer base located in closer proximity relative to the other cases and does not have additional service transports to take into account. The latter is caused by extra laptops that are brought to the customers' location along with the initial delivery of laptops, to have in storage to replace laptops needing service. Only transportation from the customer location back to the warehouse for laptops needing refurbishment/reparation is taken into account. As a result, Case 3s overall transportation kilometres are lower than those of the other case studies. The total distance covered by each vehicle during the study's temporal scope is included in table 10.

Table 15. Transport distances for Case 3

Year	Distance	Reason for transport	Vehicle
1	40 km	Delivery to customer	Light commercial vehicle
2	-	-	-
3	40 km	Transport laptop to warehouse for refurbishment/reparations	Light commercial vehicle
4	100km	EoL and recycling transport	Light commercial vehicle
5	40 km	Delivery to customer	Light commercial vehicle
6	-	-	-
7	40 km	Transport laptop to warehouse for refurbishment/reparations	Light commercial vehicle
8	100 km	EoL and recycling transport	Light commercial vehicle

6.6.5 Disposal phase

The disposal phase will be excluded from the LCA since the disposal of electrical and electronic equipment in the European Union is governed under the Waste from Electrical and Electronic equipment (WEEE) directive and is thus subject to standardized treatment (Directive 2002/96). Consequently, including this phase for comparison across all case studies would not provide valuable insights into the distinguishing aspects of each business model implementation and the LBM. Furthermore, as some of the case studies give their products to a third party for handling their disposal, accurate data on disposal activities was frequently unavailable. This lack of accurate data would introduce potentially inaccurate estimations into the LCAs.

7. Life Cycle Impact Assessment and Interpretation

In this section, the results of the environmental impact scores will be presented and interpreted. First, environmental impacts will be compared between the CBM implementations and the LBM. Furthermore, the distribution of environmental impacts across a laptops' lifecycle phases is examined, to eventually identify potential environmental impact hot spots. Last, the environmental impact scores will be described on the basis of expected environmental impacts that derived from coupling the CBM strategies by Bocken et al. (2016) with each individual life cycle phase.

7.1 Coupling impact with the overall cases

7.1.1 Climate change

The impact category climate change is expressed through kilogrammes of CO_2 equivalent emitted. The total amount of CO_2 impact that was emitted by the case studies in eight years varied between 388 and 533 kg CO_2 equivalents, Case 2 being responsible for the highest amount and Case 1 for the lowest.
The CO_2 impact of the LBM was second to highest with a total of 453 kg CO_2 eq. in eight years. The difference between the CO_2 emissions of the highest, Case 2, and lowest emitting case, Case 1, was 12.4% in total. This variation in total amounts of CO_2 emissions during eight years sparks interest with regards to the factors that led to its occurrence, which will be further explored in section 7.2 The distribution of environmental impacts throughout the life cycle phases.
The LBM reported 453 kg of CO_2 emissions in total, whereas the average value for CO_2 emissions of all case studies combined was 451. This is a 0.44% difference only. However, between the LBM and Case 1, the case study that reported the lowest impact in this category, there was a 14.35% difference.

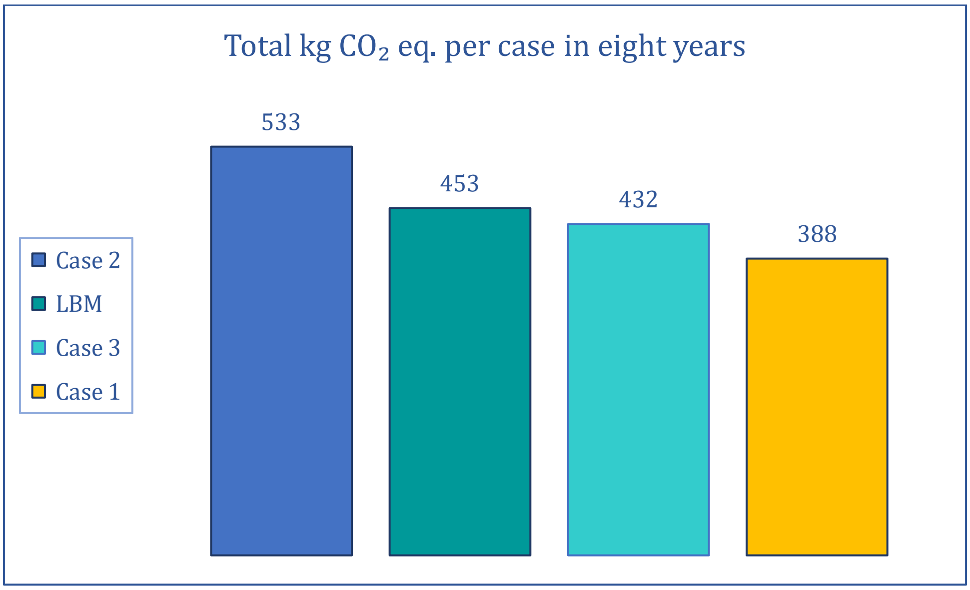


Fig. 8 Total environmental impacts in the category of Climate Change for all included cases.

7.1.2 Human Toxicity

The total amount of Human Toxicity ranged between 430 and 582 kg DCB eq. in eight years of laptop usage, a difference of 35% between the company with the highest and the company with the lowest amount of Human Toxicity. Similar to the previously discussed impact category of CO_2 emissions, for this impact category, Case 2 is also responsible for the highest amount. In contrast, Case 1 reported the lowest number of emissions here again.

The LBM was responsible for emitting 501 kg DCB eq. during the eight years that make up the functional unit. The average value for Human Toxicity for al CBMs combined was 489, a 7% difference. When considering the largest value that was reported for Human Toxicity, 430 kg DCB eq. by Case 1, and comparing it to the LBM the difference amounts to 14.17%.

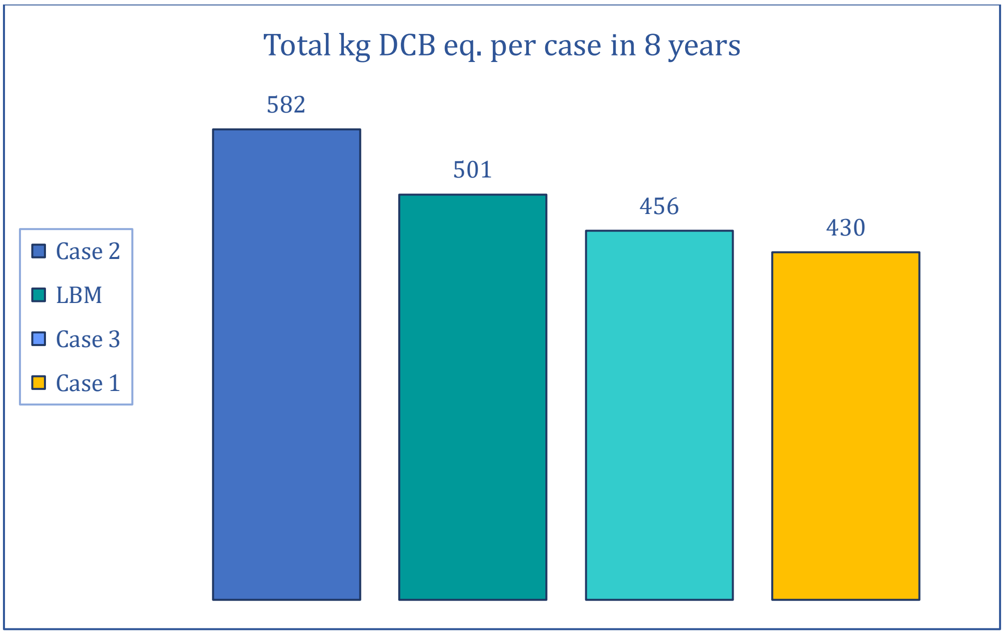


Fig. 9 Total environmental impacts in the category of Human Toxicity for all included cases.

7.1.3 Metal Depletion

The total amount of Metal Depletion ranged between 129 kg Fe eq. (Case 1) and 183 kg Fe eq. (Case 2). The discrepancy between the emissions of Case 1 and 2 adds up to a total of 41%. Similar to the formerly mentioned impact categories, it should be noted that the same cases take the first and last place in terms of environmental impact scores: Case 2 has the highest score for Metal Depletion and Case 1 has the lowest score. Again, in this impact category, the LBM has an impact score that is second to highest of all cases studied here.
The average MD for all CBM cases is 152 kg Fe eq. In comparison, the LBM reported an MD impact score of 159 Fe eq. A 4.6% difference. Nonetheless, between the case study with the lowest score in this impact category, Case 1, and the LBM, the difference was 18.87% in total.

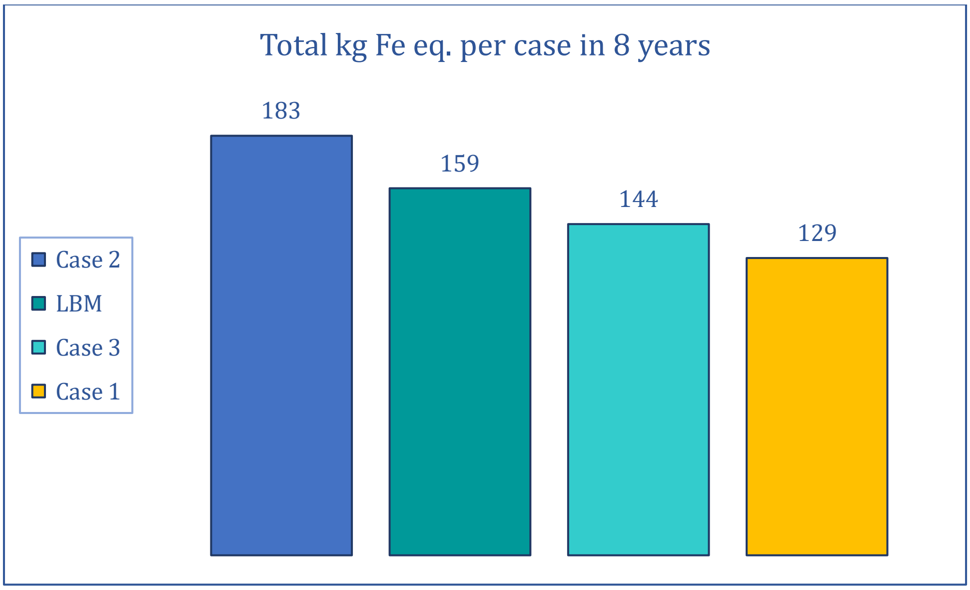


Fig. 10 Total environmental impacts for the category of Metal Depletion for all included cases.

Overall, the results show a consistency between cases with the highest and lowest scores among the environmental impact categories. Notably, there is one CBM implementation wherein reported environmental impact scores exceeded those associated with the LBM: Case 2. However, the LBM does consistently secure the second highest ranking across all environmental impact categories. The factors contributing to these overall differences will be further investigated in the next section.

7.2 The distribution of environmental impacts across the lifecycle phases

7.2.1 Production phase

In the following section the environmental impact of the production phase of the case studies will be disclosed. All results are visible in table 16, and those results that stand out most will be discussed in this section.

Across all case studies, Case 1 demonstrated the lowest CO_2 impact during its production phase (227 kg CO_2 eq.). This can be attributed to the fact that Case 1 combines a contract life time of four years with a high refurbishment rate (65%). Due to their strategy of refurbishing 65% of laptops after their initial four functional years, the lifetime of Case 1s laptops is extended by another four years. In contrast, Case 2s shorter product life and lower refurbishment rate result in a 60% higher impact in this phase (364 kg CO_2 eq.). And while Case 3 shares Case 1s four year contract lifetime, its smaller 15% refurbishment rate leads to a higher overall CO_2 impact in the production phase.

The LBM has the second to highest CO_2-eq. impact in the production phase: 336 kg CO_2 eq. in eight years of laptop usage. In the LBM it is assumed that a new laptop needs to be purchased after four years of using the first laptop, effectively doubling the production impact of a new laptop. This leads to a higher overall CO_2 impact in the LBMs production phase. However, due to the assumption of a lifetime of four years in the LBM, the impact for this phase is still lower for the LBM than for Case 2s production phase as this was based on a contract lifetime of three years. Consequently, new laptops need to be produced for Case 2 more frequently within the same time interval of eight years.

Similar results were reported for the categories of Human Toxicity and Metal Depletion. This can mainly be ascribed to factors that determined differences in the impact category of CO_2 too: a difference in contract life time of the laptop and a difference in refurbishment rate.

Table 16. Environmental impacts production phase, all impact categories and all cases.

CO_2 impact production phase	
Business model	CO_2 impact in kg CO_2 eq.
LBM	336
Case 1	227
Case 2	364
Case 3	319
Human Toxicity production phase	
Business model	HT in kg DCB eq.
LBM	439
Case 1	296
Case 2	475
Case 3	417
Metal Depletion production phase	
Business model	MD in kg Fe eq.
LBM	149
Case 1	101
Case 2	162
Case 3	142

7.2.2 Use phase

In this section the environmental impact of the use phase of laptops in the four cases will be disclosed. Table 17 shows a comparison between the four cases within three environmental impact categories: Climate Change, Human Toxicity and Metal Depletion.
The CO_2-eq. impact for the use phase is consistent between all cases due to the assumption of uniform user behaviour and due to the assumption that the same model of laptops is used across all case studies, including the LBM. In all cases, the total CO_2 impact in the use phase accumulated over eight years amounted to 104 kg CO_2 eq. Notably, this is the only life cycle phase in which no difference was reported between the CO_2 impact of the LBM and the CBMs. Likewise, this assumption of consistent user behaviour across case studies also led to equal values being reported for the impact categories of Human Toxicity and Metal Depletion.

Table 17. Environmental impacts in the use phase for all impact categories, for all cases.

CO_2 impact in the use phase	
Business model	CO_2 Impact in kg CO_2
LBM	104
Case 1	104
Case 2	104
Case 3	104
Human Toxicity in the use phase	
Business model	HT in kg DCB eq.
LBM	41
Case 1	41
Case 2	41
Case 3	41
Metal Depletion in the use phase	
Business model	MD in kg Fe eq.
LBM	2
Case 1	2
Case 2	2
Case 3	2

7.2.3 Service phase:

This section compares the environmental impact of the service phase in all cases. In table 18 the four cases and their environmental impact across three impact categories are visible.
Case 1 has the highest CO_2 impact for this phase, which can be traced back to their servicing occurring every two years. On the other hand, Case 3 is an outlier among the case studies as they adopted a different strategy. Case 3 does not perform service reparations, but instead sends laptops that need repairment directly to refurbishment.
After Case 3, the LBM reported the lowest numbers for Climate Change in comparison, which can be attributed to the fact that it was assumed that service was performed once every four years in the LBM. However, this result is notable as in case of the LBM, components that need replacement were always new components, whereas the CBMs were able to use second hand components in 50% of replacements. Nonetheless, the environmental impact of this phase was higher for Case 1 and 2 than it was for the LBM.
The results for Human Toxicity and Metal Depletion in the service phase were similar to the results in the category of CO_2 impact. Here too, a higher service frequency was more impactful than employing second hand components in this phase.
Lastly, it should be recognized that proper service and instructions for laptop use might contribute to lowering CO_2 emissions in the long run due to potentially extending product life.

Note the emphasis on potentially here, as all case studies now have a ‘set’ duration for their lease contracts.

Table 18. Environmental impacts in the service phase, for all environmental impact categories, for all cases.

CO_2 impact in the service phase	
Business model	CO_2 Impact in kg CO_2
LBM	12
Case 1	29
Case 2	19
Case 3	0
Human Toxicity in the service phase	
Business model	HT in kg DCB eq.
LBM	22
Case 1	74
Case 2	49
Case 3	0
Metal Depletion in the service phase	
Business model	MD in kg Fe eq.
LBM	8
Case 1	23
Case 2	15
Case 3	0

7.2.4 Refurbishment phase:

The environmental impacts of the refurbishment phase are visible in table 19. Since, the LBM does not do any refurbishing, its environmental impact scores are zero in this phase.
Case 1 has a higher CO_2 impact than the other cases in the refurbishment phase due to having a significantly higher refurbishing rate than the other case study companies (Case 1. 65% vs Case 2. 35% and 22.75 vs Case 3. 15%).
A similar result was observed for the impact categories of Metal Depletion and Human Toxicity, which can also be attributed to differences in refurbishment rate.

Table 19 Environmental impacts in the refurbishment phase, in all impact categories, for all cases

CO_2 impact in the refurbishment phase	
Business model	CO_2 impact in kg CO_2 eq.
LBM	0
Case 1	25
Case 2	19
Case 3	0,2
Human Toxicity in the refurbishment phase	
Business model	HT in kg DCB eq.
LBM	0
Case 1	19
Case 2	13
Case 3	0,5
Metal Depletion in the refurbishment phase	
Business model	MD in kg Fe eq.
LBM	0
Case 1	3
Case 2	2
Case 3	0,2

7.2.5 Transport phase:

In this section, the environmental impacts related to the transport phase are described for all cases, per impact category, based on the numbers provided in table 20.
Due to an increased service and refurbishment frequency in the CBM case studies in comparison to their LBM counterpart, additional transport movements were reported.
A relatively higher CO_2 impact in the transport phase, which we see in Case 2, can be explained by a larger average distance to the customer, a larger number of transports due to a high service frequency and the usage of a passenger car for the last mile (which can transport a lower number of laptops than a lorry or light commercial vehicle). However, the passenger car for the last mile and high frequency of transport for service do contribute to customer service and better customer reviews.
Similar to the CO_2 impact, in the impact categories of Metal Depletion and Human Toxicity the highest numbers were reported for Case 2.
Remarkable in this lifecycle phase is that the LBM has the second to lowest score on all impact categories. This contrasts with its performance within the other phases, where the LBM reported among the highest impact scores. This can potentially be explained by the fact that the CBMs offer more service, which requires transport. Moreover, some cases reported a larger distance to customer than the average distance that was assumed for the LBM. Also, in the LBM a passenger car was not employed for the last mile. And the usage of a passenger car for the last mile contributes more to environmental impact per laptop than transport by lorry or van. Finally, it should be noted that transportation of the laptop from the factory in which it was produced to the warehouse from which it was sold, is included in the production phase instead of the transportation phase. Would the production transports be included within the transport phase, it could be anticipated that the LBM would rank higher for environmental impacts in this phase.

Table 20. Environmental impact in the transport phase, for all impact categories, for all cases.

CO_2 impact in the transportation phase	
Business model	CO_2 impact in kg CO_2 eq.
LBM	2
Case 1	3
Case 2	30
Case 3	1
Human Toxicity in the transportation phase	
Business model	HT in kg DCB eq.
LBM	0,5
Case 1	0,9
Case 2	8
Case 3	0,3
Metal Depletion in the transportation phase	
Business model	MD in kg Fe eq.
LBM	0,1
Case 1	0,2
Case 2	2
Case 3	0,1

7.2.6 Environmental impact hotspot(s)

Table 21 shows that, among all impact categories reviewed, most environmental impacts were caused in the production phase. Therefore, this phase is considered an environmental impact hot-spot as it is responsible for an average of 69% of all impacts for Climate Change, 82% for Human Toxicity and 87% for Metal Depletion, when the numbers for offering a laptop during eight years for all business model implementations are combined.
It is remarkable that the CO_2 impact category has the lowest percentual share of CO_2 emissions in the production phase when compared to the other impact categories (Human Toxicity and Metal Depletion). This can be attributed to the fact that 23.5% of total CO_2 emissions are emitted during the use phase of the laptop, whereas the average percentual impacts in the use phase for HT (8%) and MD (3.3%) are much lower. In short, a higher impact in the use phase for Climate Change leads to a lower percentage of impacts that are caused in the production phase.
Amid the case studies, the highest proportion of environmental impacts in the production phase was reported by Case 3. However, in absolute values Case 2 and the LBM reported higher numbers. Case 3 having the highest percentual impacts in the production phase amongst all cases can be attributed to the relatively lower impacts it reported for the lifecycle phases Transport, Refurbishment and Service.
Drivers for high environmental impacts in the Production phase are the amounts of CO_2 (167 kg CO_2 eq.), HT (219 kg DCB eq.) and MD (75 kg Fe eq.) that are emitted or depleted during the manufacturing process of a laptop, as well as CO_2 emissions (0.62 kg CO_2 eq.), HT levels (0.107 kg DCB eq.) and MD (0.014 Fe eq.) during overseas transportation of the laptop, which was also considered to be a part of the production phase in this research.

Table 21. Percentage of impacts per lifecycle phase in the categories of Climate Change, Human Toxicity and Metal Depletion.

Percentage of impacts in category of Climate Change, per phase						
Business model	Production phase	Use phase	Refurbishment phase	Transport phase	Service phase	Total
LBM	74%	23%	0%	0%	3%	100%
Case 1	59%	27%	6%	1%	7%	100%
Case 2	68%	19%	4%	5%	4%	100%
Case 3	76%	24%	0%	0%	0%	100%
Percentage of environmental impacts in category of Human Toxicity, per phase						
LBM	87%	8%	0%	0%	4%	100%
Case 1	69%	9%	4%	0%	17%	100%
Case 2	81%	7%	2%	1%	8%	100%
Case 3	91%	9%	0%	0%	0%	100%
Percentage of environmental impacts in category of Metal Depletion, per phase						
LBM	94%	1%	0%	0%	5%	100%
Case 1	69%	9%	4%	0%	17%	100%
Case 2	88%	1%	1%	1%	8%	100%
Case 3	98%	2%	0%	0%	0%	100%

A notable observation is that the environmental impact of the service phase is a lot higher for Case 1 than it is for the other examined case studies. Especially when considering the differences in Table 21. This higher service impact also has a lower percentual impact for Case 1s production phase as a consequence. The discrepancy between Case 1 and the other cases in terms of proportions environmental impacts caused in the Production and Service phase is particularly pronounced in the impact categories of HT and MD.

The underlying factor causing higher environmental impacts in Case 1s service phase is the heightened frequency of service interventions once every two years for Case 1, as opposed to once every three years (Case 2), once every four years (LBM) or a complete absence of service (Case 3).
Alternatively, Case 2 reported a slightly lower service frequency than Case 1. Nonetheless, the environmental impacts of service constitute between 4 and 8% of Case 2s total impacts only. This can be attributed to the fact that Case 2 reports the highest numbers of environmental impact for the transportation phase among the included cases. As a result, Case 2s proportional impacts that are caused in the service phase are significantly lower than those reported for Case 1 in this phase.

Table 22. Impacts per lifecycle phase, per case, in the categories of Climate Change, Human Toxicity and Metal Depletion.

Impacts in kg CO_2 eq. in category of Climate Change per phase						
Business model	Production phase	Use phase	Refurbishment phase	Transport phase	Service phase	Total
LBM	336	104	0	2	12	453
Case 1	227	104	25	3	29	388
Case 2	363	104	19	28	19	533
Case 3	328	104	0,2	1	0	432
Impacts in kg DCB eq. in category of Human Toxicity per phase						
LBM	439	41	0	0,5	22	501
Case 1	296	41	19	1	74	430
Case 2	474	41	13	7	49	584
Case 3	428	41	0,5	0,3	0	469
Impacts in kg Fe eq. in category of Metal Depletion per phase						
LBM	149	2	0	0,1	8	159
Case 1	101	2	3	0,2	23	129
Case 2	161	2	2	2	15	183
Case 3	145	2	0,2	0,1	0	148

In summary, merely one environmental impact hot spot could be identified among the lifecycle phases of a laptop in different CBM implementations. This hot spot is the production phase.
For the impact category Climate Change, the production phase is followed by the use phase among all case studies. This impact category is responsible for 23.5 % of environmental impacts across the lifecycle of the laptop on average. For the other impact categories, proportional impacts in the use phase were much lower: between 8 (HT) and 3 (MD) percent on average and thus cannot be considered a hot spot.
An exception was observed for the environmental impacts in Service phase in Case 1: 17% of environmental impacts for both the categories of HT and MD were attributed to this phase and 7% of CC impacts.

7.3 The environmental impact of CBM strategies in practice

7.3.1 The influence of CBM strategies on the production phase

Considering the CBM strategies by Bocken et al. (2016), it was expected in this research that the case studies that adopted a leasing and refurbishing CBM would have a lower environmental impact than the LBM in the production phase. This hypothesis was not validated, as the LBM does not have the highest environmental impact for the production phase across all selected impact categories.

In terms of Access and Performance, it would be expected that the lifetime for which a laptop is operationalized by one user would be extended in comparison to LBMs. This was expected because extended use of the same laptop by one user leads to an extended service or lease contract and consequential financial gains for the company offering the laptop. According to the A&P strategy, lifetime of a product can be prolonged through changes in product design increasing longevity and repairability or through increased product retention by the user (Bieser et al., 2021; Ertz et al., 2018). This expectation was not met, as the contract lifetime of all included case studies was equivalent to or lower than the assumed lifetime for the LBM.

For the strategy Extending Product Value it was expected that value that still resided in the laptops at their end-of life-as it conforms to a LBM, would be exploited. This would lead to a lower environmental impact in the production phase as fewer new laptops would have to be produced per time interval. This expectation was fulfilled as all case studies refurbished laptops after their first life time. However, the extent to which the environmental impact in the production phase was lowered differed among the case studies, which can be attributed to differences in refurbishment rate. A case study that refurbishes only 15 % of its laptops, still works with the original contract lifetime for the remaining 85 %. Consequently, for the remaining 85 % of laptops lifetime extension was not achieved.

According to CBM strategy Extending Product Value, it would be expected that environmental impact in the production phase would be lower in comparison to a LBM. Whilst the environmental impact was lower than the LBM in this phase for all case studies excluding Case 2, this decrease in environmental impact cannot be attributed to the incorporation of second-hand components in the production phase: all case studies reported that they employ previously used components solely in the service and refurbishment phase.

Table 23. The CBM strategies and their environmental impact on production phase in comparison to LBM

CBM Strategy	In theory	In practice
Access and Performance	-	Equal to LBM
Extending Product Value	-	-
Extending Resource Value	-	Equal to LBM

.

7.3.2 The influence of CBM strategies on the use phase

Whilst the CBM strategy Extending Product Value led to life time extension of the laptops, the environmental impact of using the laptops per time unit does not change. This is due to the assumption that the user will spend a similar amount of time on their laptops across all cases. Moreover, the CBM strategy Extended Resource Value was not expected to alter the environmental impact of this phase.

Therefore, the environmental impact that was established in the use phase, throughout the case studies, confirms the theory that application of these three CBM strategies does not lead to environmental wins in the use phase. However, manufacturers can stimulate users to handle their laptops more carefully which could potentially lead to life time extension. Thereby, behaviour in the use phase that aligns with the CBM strategies can indirectly lead to a decrease in environmental impacts.

Table 24. The CBM strategies and impacts on use phase in comparison to LBM in theory and practice

CBM Strategy	In theory	In practice
Access and Performance	Equal to LBM	Equal to LBM
Extending Product Value	Equal to LBM	Equal to LBM
Extending Resource Value	Equal to LBM	Equal to LBM

7.3.3 The influence of CBM strategies on the service phase

A higher frequency of service and more extensive service in comparison to a LBM can be a part of the Access and Performance strategy. Consequently, a higher environmental impact was expected here. This expectation was met in theory: The cases that offered service with a higher frequency turned out to have a higher environmental impact in this phase.

The fact that the remaining value of laptops at their 'Linear End of Life' was exploited for the Extending Product Value strategy did not have any influence on the environmental impact in this phase, as was expected according to theory. However, it could be argued that the higher frequency and larger extent of service aligns with this strategy as these measures do have an indirect effect on the remaining value at the laptops' End of Life: By providing more and better service, the remaining value of the laptop could be higher i.e., there is a higher chance that the case study is able to refurbish the laptop and employ it for an additional life cycle. This could apply to Case 1, as this is the Case with both the highest service frequency and the highest refurbishment rate out of all cases examined. However, the determination of cause and effect between increased service and refurbishment rates fell outside of the scope of this research. Furthermore, this is not a part of the Extending Product Value strategy explicitly, therefore the expectation of the environmental impact of this strategy remaining equal in the service phase is considered to be met.

The strategy Extending Resource Value was applied by all case studies in 50% of components. A second-hand component only carries 50% of the environmental impact of a new component, as 50% of the environmental impact is allocated with its first use cycle. As a result, the environmental impact of the service phase is lowered due to employing this strategy. Nevertheless, the case studies did perform service more often than the LBM, which led to a higher environmental impact. This impact could not be offset by the lowered impact that resulted from Extending Resource Value, leading to a higher overall environmental impact for the CBMs than for the LBM.

Table 25. The CBM strategies and their environmental impacts on use phase in comparison to LBM in theory and practice

CBM Strategy	In theory	In practice
Access and Performance	+	+
Extending Product Value	Equal to LBM	Equal to LBM
Extending Resource Value	-	-

7.3.4 The influence of CBM strategies on the refurbishment phase

In the Access and Performance strategy it is expected that manufacturers try to prolong the lifetime of their products. However, this strategy focuses on prolonging usage by the same user. Therefore it was not expected that this strategy changed the environmental impact of CBMs within this lifecycle phase.

As a part of the Extending Product Value strategy, it was expected that residual value at the end of the products life was exploited. Within the case studies, this was established through refurbishment of laptops after their first lifecycle. It should be noted however, that only 65% (Case 1), 35% and 22.75% (Case 2) and 15% (Case 3) of laptops was refurbished after its first lifecycle. The LBM did not have a refurbishment phase and therefore the expected higher environmental impact for the CBM studies was met in practice. Nevertheless, it should be emphasized that the total environmental impact of the refurbishment phase is much lower on average than the environmental impact of the production phase for a new laptop that needs to be produced in a LBM (see Table 22).

Resource Value was extended in the Refurbishment phase by employing second hand components to refurbish laptops. Consequently, the environmental impact of the refurbishment phase was lower than it would have been without the strategy of Extending Resource Value. However, as the LBM does not have a refurbishment phase at all, the environmental impact of the CBM case studies was higher for this phase in comparison.

Table 26. The CBM strategies and impacts on the ref. phase in comparison to LBM in theory and practice

CBM strategy	In theory	In practice
Access and Performance	Equal to LBM	Equal to LBM
Extending Product Value	+	+
Extending Resource Value	-	-

7.3.5 The influence of CBM strategies on the transportation phase

It can be expected that the environmental impact of transport will be increased when an Access and Performance strategy is applied, because this strategy includes delivering the laptop to the users' door, transporting the laptop for service, picking up the laptop and ensuring that it is recycled properly at its End-of-Life. In comparison a LBM, which only delivers the laptop when it is purchased. As a result a higher impact is expected for this CBM strategy. This expectation was met.

For the CBM strategies Extending Product and Resource Value it was expected that they did not have any impact on the transport phase. This expectation as also met in practice.

Table 27. The CBM strategies and impacts on transport phase in comparison to LBM in theory and practice

CBM Strategy	In theory	In practice
Access and Performance	+	+
Extending Product Value	Equal to LBM	Equal to LBM
Extending Resource Value	Equal to LBM	Equal to LBM

Overall, the expectations in terms of environmental impacts according to Bockens' (2016) CBM strategies were met for all lifecycle phases except for the Production Phase. The A&P strategy was expected to lower environmental impacts in this phase by extending product lifetime. However, this expectation could not be met due to fixed lease contract durations within all included case studies.

Lower environmental impacts were expected as a result of the EPV strategy, which was confirmed by two out of three cases. However, Case 2 reported a higher environmental impact than the LBM, owing to its three year laptop lifetime and relatively low refurbishment rate. Therefore, this expectation was only partially met.

Lastly, it was envisioned that the ERV strategy would lower environmental impacts. However, the results made evident that this strategy was only active in other lifecycle phases than the productive phase in the case studies included.

For the remaining lifecycle phases, expectations of environmental impacts resulting from CBM strategies were all met: It was anticipated that the three CBM strategies included would not have any impact on the Use phase, which was correct in practice.

For the service phase, higher impacts were expected as a result of the A&P strategy, which was confirmed by the results. It was predicted that the EPV strategy would not make any changes to environmental impacts in the service phase, this expectation was met in practice. However, the EPV strategy might cause a long term decrease in overall environmental impacts due to increased servicing targeting lifetime extension, but this connection could not be confirmed within this research. Lastly, it was expected that utilizing second-hand components would lower environmental impacts in the service phase, this expectation was met, even though overall impacts in the service phase were higher than in the LBM.

In the refurbishment phase equal impacts were expected for the A&P strategy. This expectation was fulfilled by the case studies in practice. Furthermore, increased impacts were anticipated for the CBM strategy EPV, as the LBM does not have a refurbishment phase and therefore no environmental impacts in this phase. This prediction was validated by the results. Furthermore, it was envisioned that ERV would have a decreasing effect on environmental impacts in this phase due to usage of second hand components, which was also confirmed.

In the transport phase, higher impacts were anticipated as a result of increased service transport as a part of the A&P strategy. This expectation was validated by the results. The remaining two strategies were expected not to have any influence on the transport phase, which was also confirmed by the results.

8. Sensitivity Analyses

8.1 Sensitivity Analysis: The impact of extending contract lifetime

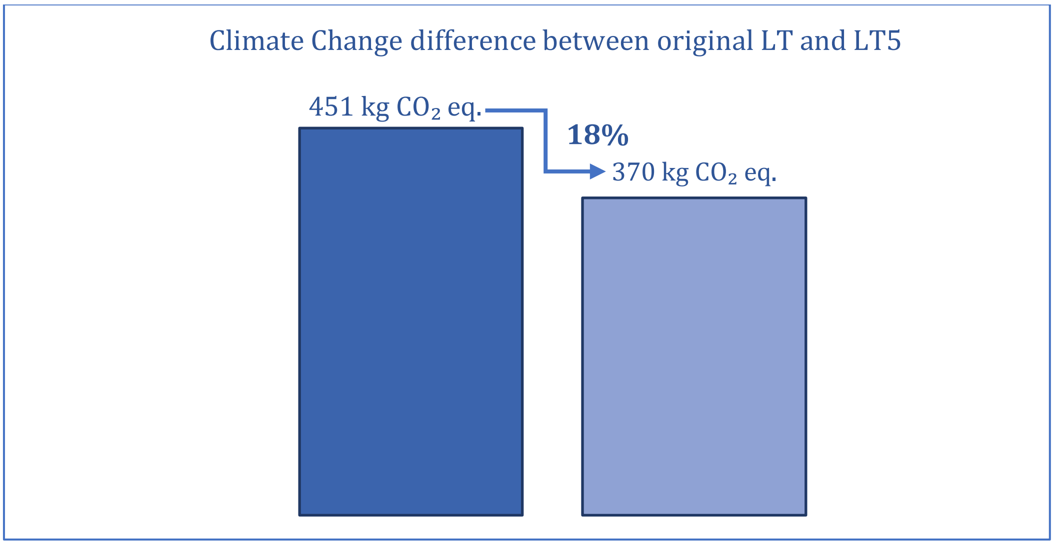
The first sensitivity analysis performed was used to determine the influence of the duration of a laptops' lifespan on its total environmental impact. For all cases, a sensitivity analysis was performed, in which the contract lifetime of the laptop was prolonged to five years. For the sake of simplicity, the duration of the contract lifetime will be referred to in the following manner:

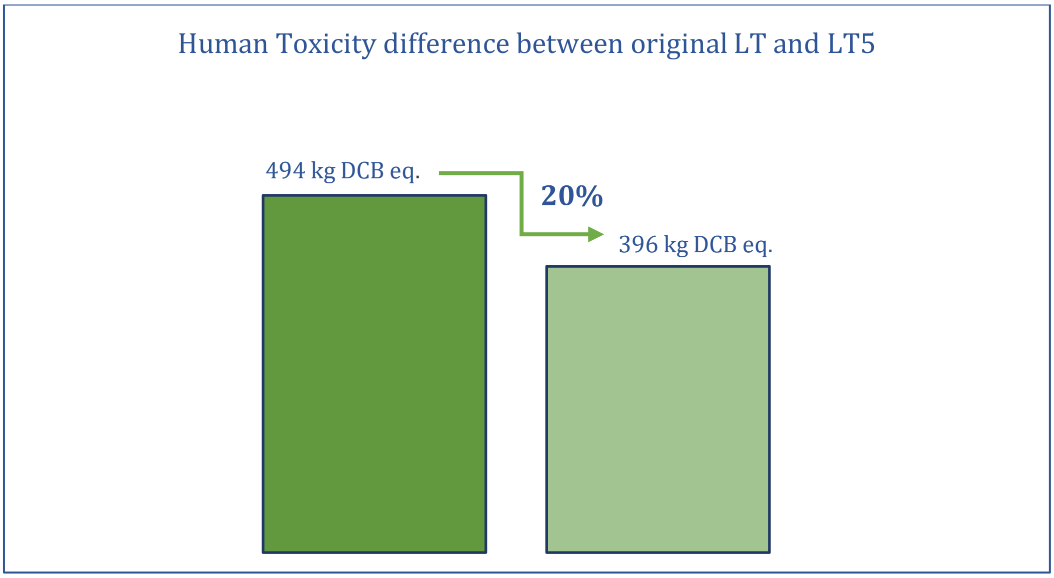
LT3 – a laptop with a contract lifetime of 3 years
LT4 – a laptop with a contract lifetime of 4 years
LT5 – a laptop with a contract lifetime of 5 years

As the cases included in this research vary in lifespan, it should be noted that in Case 2, another two years were added to the original contract duration to reach a lifespan of five years (LT5). For Case 1 and 3, only one year had to be added to the original lease contract duration of four years (LT4) to get to a lease contract duration of five years (LT5).
To illustrate, in the original scenario of LT3, Case 2 produces 2.6 laptops in eight years. In the sensitivity analysis of LT5 only 1.6 laptops need to be produced. For the other cases, 2 laptops were produced in eight years in the original scenario of LT4, versus also 1.6 in the sensitivity analysis lifetime LT5. A significantly smaller difference.
It is assumed that all other variables remained the same in terms of their frequency per time interval. For example, Case 1 performs service once every two years. In a sensitivity analysis assuming a five-year lease contract duration, it was therefore assumed that service occurred two and a half times.

8.1.1 Difference in average environmental impacts between the original lifetime and LT5

The sensitivity analysis shows that across case studies, 18% less CO_2 emissions occur due to prolonging the lifetime of a laptop up towards five years, 20% less Human Toxicity occurs, and Metal Depletion decreases with 21 %. This is visible in fig. 11, 12 and 13 Overall, it can be concluded that environmental impacts are lowered due to increasing the lifetime of a laptop in a CBM to five years in total.





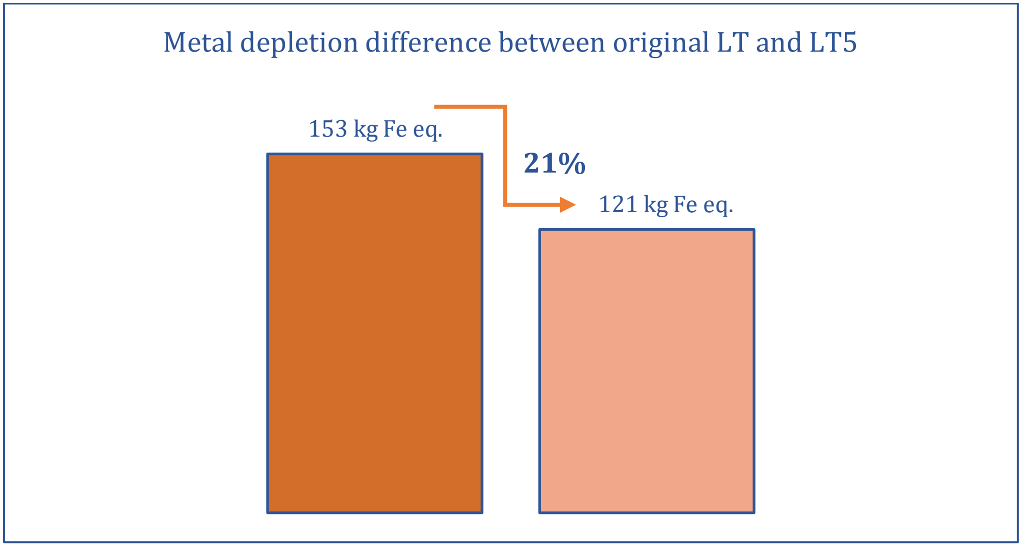


Fig. 11, 12 and 13. Fig. 11 representing the difference in CO_2 impact between the original lifetime and a laptop lifetime of 5 years. In fig. 12 this difference is visualised for HT and in 13 for Metal Depletion.

8.1.2 Individual differences per case, per impact category

Figures 11, 12 and 13 are made up of average numbers that result from combining all case studies included in this research. When considering the difference between the original lifetime and LT5 for each case individually, it became clear that the environmental impact of each case study reacts differently to an alteration of the original lifetime of the laptop. The most remarkable discrepancies between case studies and the underlying variables that contributed to this will be discussed below.

Out of all case studies, Case 2 reported the highest overall impacts and the highest differences between its original lifetime and LT5. The height of this proportional difference between the original lifetime and LT can be ascribed to Case 2s original contract lifetime of three years, whereas the other cases have an original contract lifetime of four years. To illustrate this effect, the total decrease in terms of CO_2 impact resulting from adding one extra year to the laptops' lifetime is 28% divided by two years is 14%, which is similar to the difference in CO_2 impact reported for Case 3.

Alternatively, Case 1 reported the lowest differences in environmental impacts between its original lifetime and LT5. Case 1 reported the lowest impacts across all impact categories and the lowest difference between impacts in the original lifetime and LT5.

Case 1s smaller difference in terms of environmental impacts can be attributed to its relatively lower amount of impact derived from the production phase (66% on average, see table 21) and its absolute amounts of environmental impacts occurring in the production phase also being the lowest of all case studies. The reason for Case 1 to have the lowest production impact is the fact that this case reported the highest refurbishment rate (65%), which leads to a relatively lower rate of new laptops that need to be produced. Altering the CO_2 impact of the production phase by extending the laptops' contract lifetime did not make as much of a difference as it did in the other case studies due to Case 1 having the lowest amount of production impacts already.

Table 28. Environmental impacts resulting from sensitivity analysis 1

Impact category	Case 1	Case 2	Case 3
CO_2 impact in kg CO_2 eq. original LT	388	533	432
CO_2 impact in kg CO_2 eq. LT = 5 yrs	354	385	371
% difference in kg CO_2	-9%	-28%	-14%
HT in kg DCB eq. original LT	430	584	469
HT in kg DCB LT = 5 yrs	392	407	389
% difference HT	-9%	-30%	-17%
MD in kg Fe eq. original LT	129	183	148
MD in kg Fe eq. LT = 5 yrs	118	124	121
% difference MD	-9%	-32%	-18%

8.2 Sensitivity Analysis 2: The environmental impact of an increased refurbishment rate

In the second sensitivity analysis, the influence of different refurbishment rates on the environmental impact of the case studies is explored. The lowest refurbishment rate that was found among the case studies was 15% of all laptops being refurbished after their first lifecycle by Case 3. For Case 2, a refurbishment rate of 35% after the first lifecycle and 22.75% after the second lifecycle was found and Case 1 reported a refurbishment rate of 65%.
Intuitively, it would seem that increasing the refurbishment rate would decrease the amount of new laptops that need to be produced. Consequently, it is expected that environmental impacts would be lowered due to an increase in refurbishment rate. In this sensitivity analysis the effect on environmental impacts of a 10 % increase of the refurbishment rate on each of the case studies will be determined.
This entailed that for Case 1, a refurbishment rate of 75% was employed, 45% in the second and 33% in the third lifecycle for Case 2 and 25% for Case 3. Due to increasing the refurbishment rate with 10%, a lower number of new laptops have to be produced after the first lifecycle. Therefore, production rates decrease by 10%.
It is assumed that all other variables remained the same in terms of their frequency per time interval.

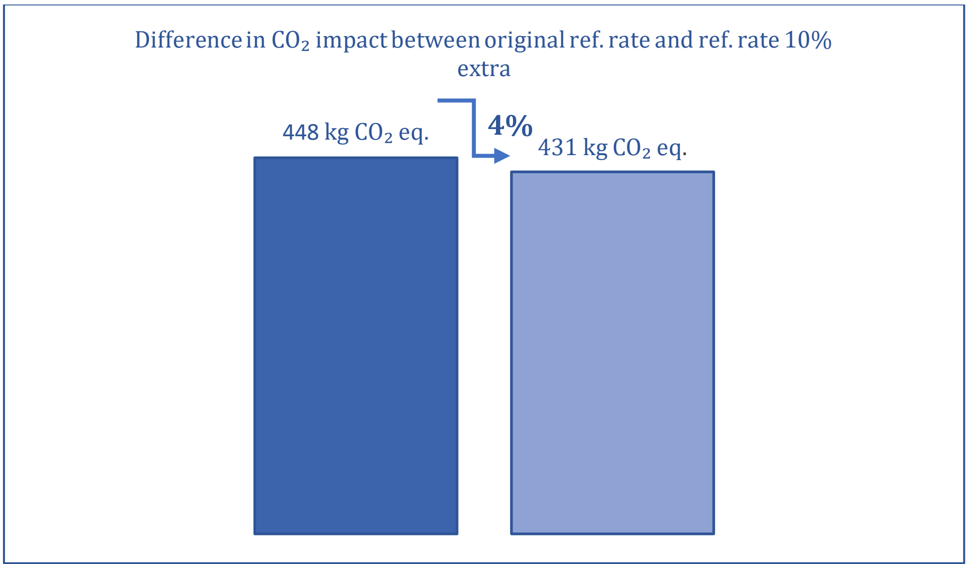
Table 29. Refurbishment and production rates sensitivity analysis 2

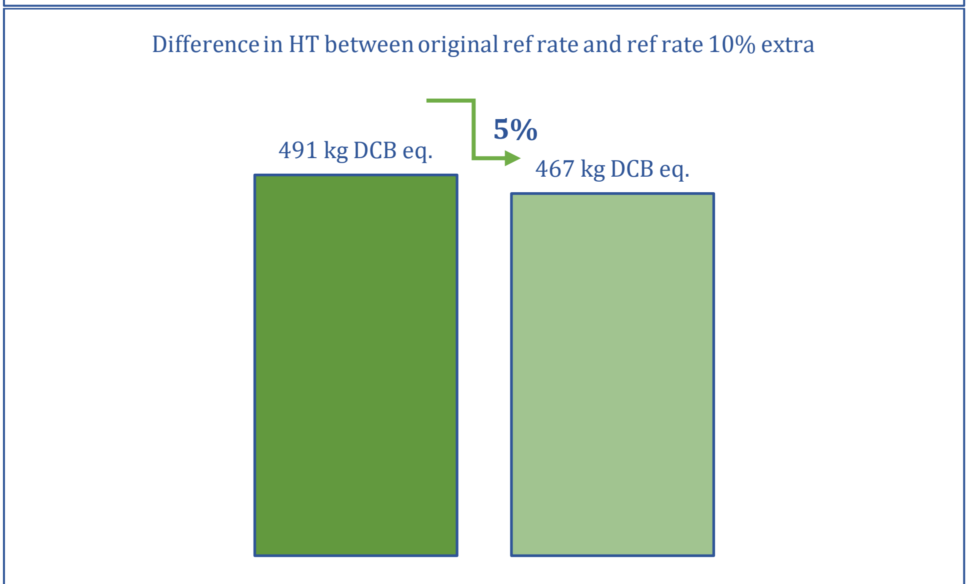
Case	Original ref. rate	Original production rate after first LC	10% extra ref. rate	10% less production rate after first LC
1	65%	35%	75%	25%
2, first lifecycle	35%	65%	45%	55%
2, second lifecycle	22.75%	75.25%	32.75%	65.25%
3	15%	85%	25%	75%

8.2.1 Average difference in overall impacts as a result of a 10 % increase in refurbishment rate

Increasing the refurbishment rate leads to a lower number of new laptops that need to be produced in comparison to the amount that had to be produced with the original refurbishment rate. Therefore, an increased refurbishment rate has a lower environmental impact as a result for all environmental impact categories included.

For the category of Climate Change, an average decrease of 4% was reported due to increasing refurbishment rates with 10%. For Human Toxicity, environmental impacts decreased with 5% on average. The highest average decrease was reported for Metal Depletion: 6%.





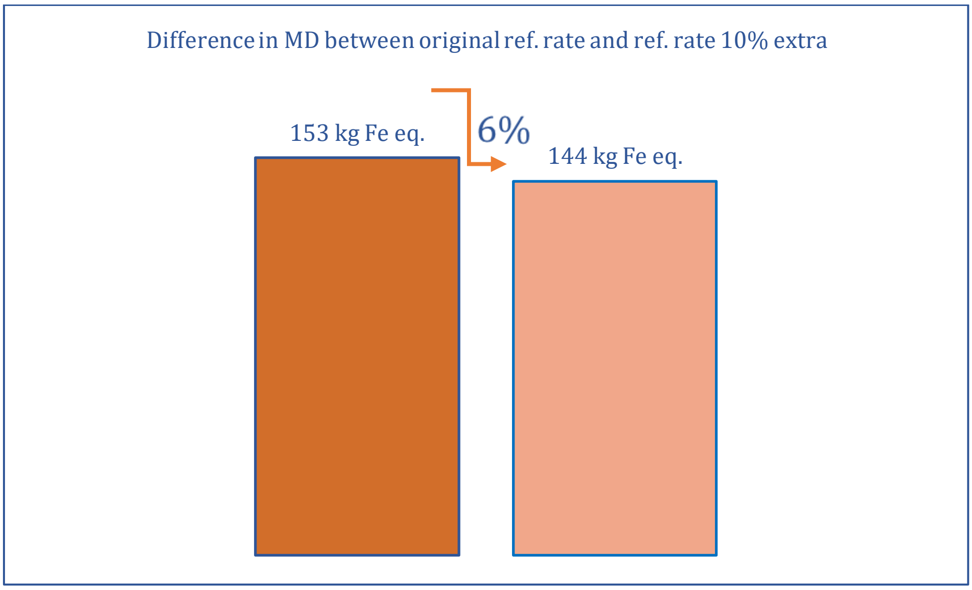


Fig. 14, 15 and 16. Visualising the average difference between the original refurbishment rate and a 10% increased refurbishment rate for the impact categories of Climate Change, Human Toxicity and Metal Depletion.

8.2.2 Individual differences between cases and impact categories

Fig 14, 15 and 16 represent average numbers, that are derived from combining results from all three CBM cases. When also considering the individual results, it becomes evident that a 10% increase in refurbishment rate has a unique effect on the environmental impact of each case study.

The largest decrease in terms of environmental impacts between the original refurbishment rate and 10% extra was reported for Case 2. This can be ascribed to Case 2 having the shortest contract lifetime out of all included cases. Consequently, laptops need replacement more frequently in Case 2 than for the other cases. Therefore, an increase in refurbishment rate and a resulting decrease in production impacts, has the largest effect on this Case 2 in terms of lowering its environmental impacts.

Table 30. Increasing the ref. rate by 10%, all cases and all impact categories

Impact category	Case 1	Case 2	Case 3
CO_2 impact in kg CO_2 eq. original ref. rate	388	536	421
CO_2 impact in kg CO_2 eq. 10% extra ref. rate	375	512	405
% difference in CO_2 impact	-3%	-5%	-4%
HT in kg DCB eq. original ref. rate	430	586	457
HT in kg DCB ref. rate 10% extra	411	552	435
% difference HT	-4%	-6%	-5%
MD in kg Fe eq. original ref. rate	129	183	145
MD in kg Fe eq. ref. rate 10% extra	122	171	137
% difference MD	-5%	-7%	-5%

8.3 The minimum required lifetime

Among all case studies and across the three studied environmental impact categories, environmental impacts were lowered due to increasing the lifetime of the laptop up to five years in Sensitivity Analysis 1. Furthermore, whilst there are differences in the range with which the environmental impact of a laptop changed due to increasing the refurbishment rate with 10%, overall impacts are lowered within all categories. The main reason for this is that production emissions are responsible for the largest contribution to environmental impact. Thus, for every year added to the lifetime of a laptop, both through lease contract prolongation or refurbishment, the initial production impact is spread out over more years. At the same time, the production of a new laptop is postponed. The reduced impact from a prolonged lifetime usually comes at the cost of more transportation, service and refurbishment impact, which can be integral to the implementation of a refurbishing and leasing CBM.

This prompts the question: what is the minimum lease contract lifetime or refurbishment rate of a laptop that a CBM must ensure to generate a lower environmental footprint than a LBM?

To establish this lifetime and refurbishment rate, it was determined how much reduction in the production phase was required for the CBM to offset additional impacts that might occur in the CBMs transport and service phases.

8.3.1 The formula

A formula was articulated to calculate the lowest contract lifetime or refurbishment rate of a laptop that still generates a lower environmental impact than a laptop offered in a LBM. This formula is partly case study dependant because variables such as transport, refurbishment and service impacts differ. This discrepancy can be attributed to a variety within refurbishment, transportation and service plans in the business model, which affects variables such as distance to customer and the amount of services that companies offer to their customers. However, all CBMs offering laptops that encompass a refurbishing and leasing aspect, can fill in the variables mentioned in this formula according to their own business set-up.

In sum, to get an overall lower environmental impact in the CBM in comparison to the LBM, the additional impacts that tend to occur in a CBM as a result of additional services and transports should be offset by the decrease in impacts within the production phase of the laptop. Therefore, the difference between the CBMs total production impact, refurbishment impacts included and the LBM production impact plus the difference between the CBM and LBM transport and service impacts should be zero, or below zero within the formula.

A decrease in production impacts can be established by setting a certain minimum lifetime or contract duration for one laptop used or by increasing the refurbishment rate. To achieve the minimum lifetime or refurbishment rate required, the following formula can be used.

$$((Prod_{CBM})/(((1\text{-}Refrate)*LT)+(LT_{ref}*Refrate)))* IP = ((Prod_{LBM})/LT_{LBM}) * IP)+((TR_{CBM} + Serv_{CBM})-(TR_{LBM}+Serv_{LBM}))$$

Where:

$Prod_{LBM/CBM}$ = 168 kg CO_2-eq.
LT = Contract lifetime of CBM/LBM in years
LTref = Total lifetime of a refurbished laptop in years
Refrate = refurbishment rate in percentages
TR = transport emissions in kg CO_2-eq.
Serv = service emissions in kg CO_2-eq.
IP = Impact Period in years

It should be noted that these calculations were based on lowered environmental impacts in comparison to an LBM within the impact category of Climate Change. The prevalence of kilogrammes of CO_2 impacts in similar LCAs calculating a laptops' environmental impact guided this decision. Comparable calculations can be conducted for alternative impact categories. It is anticipated that the minimum refurbishment rates presented would show similarities to those derived from the Climate Change category, albeit varying slightly

8.3.2 Minimum requirement for contract lifetime and refurbishment rate applied to the case studies

To illustrate potential outcomes of formula for calculating the minimum required contract lifetime of a laptop, the formula was applied to the case studies included within this research. It should be noted that minimum lifetimes are calculated by applying the original variables (such as refurbishment rate) of each case study to this formula. A different value in one of the variables, would result in another minimum lifetime for each case study. Therefore, the resulting minimum lifetimes cannot be applied generally. However, they do give an insight in the minimum required contract lifetime for each case study individually, to generate lower environmental impacts than a LBM.
Using the formula, the following results are derived:

Minimum lifetime Case 1 :2.8 years

Minimum lifetime Case 2: 3.6 years

Minimum lifetime Case 3: 3.4 years

Similar to the minimum lifetime that was established to enable each case study to have a lower environmental impact than the LBM, certain reservations about the generalizability of the minimum refurbishment rate should be expressed. The minimum refurbishment rates are based upon the individual variables of each included case study. The required height of the refurbishment rate depends on the case studies' original lifetime, environmental impacts made in the transport and service phase and refurbishment impacts relative to the refurbishment rate. Therefore, a case study with high impacts in the transport and service phases needs a higher refurbishment rate in order to offset these impacts by avoiding the production of new laptops. The minimum refurbishment rate based on a combination of data from all CBM implementations combined is 37.2%.
However, all original refurbishment rates and CBM implementations as a whole differed across case studies. Therefore, the minimum refurbishment rate that allows for a lower environmental impact in a CBM than in a LBM differed between the cases.

Minimum refurbishment rate Case 1: 6.7%
Minimum refurbishment rate Case 2: 81%
Minimum refurbishment rate Case 3: -4%

The results indicate that multiple factors can lead to a higher minimum lifetime or refurbishment rate:

- High initial production emissions, relative to the LBM. This was seen in Case 2, which had the highest environmental impact in its production phase out of all included case studies.
- High transport emissions in comparison to the LBM. In Case 2, this was applicable due to both having a relatively high distance to customer and due to the modes of transportation that were employed.

- High service impacts, relative to service impacts in the LBM. High service impacts were reported for Case 1. However, high service impacts were offset by low scores in terms of production and transport emissions. As a result, Case 1 required the lowest minimum lifetime of all included case studies despite reporting the highest impacts of all case studies in the service phase.

Notably, Case 2 is the only case that requires a longer lifetime beyond its current practice to generate lower impacts than the LBM. This corresponds to Case 2 reporting higher overall impacts for its business model than the environmental impacts that were calculated for the LBM.

8.4 Measures to extend the laptops' lifetime

It was evident from the results that lifetime extension and a lowered environmental impact were not always sufficiently achieved in companies that applying these strategies, as was observed in the case studies. In those cases, the decrease in environmental impact that occurred in the CBMs due to lifetime extension was insufficient to counterbalance the additional environmental impacts that occurred either in the service, transportation or refurbishment phase or a combination. To address this, measures that could further extend the lifetime of the product are deemed beneficial to further decrease the CBMs' environmental impact.
Therefore, the following section will present practical measures that companies in the IT sector can take to prolong the lifetime of their products. These practical measures are structured according to Bocken et al.'s (2016) CBM strategies and the segment of the laptops' lifetime on which they exert an influence. The CBM strategies and their influence on the laptops' lifetime are visualised in fig. 17.

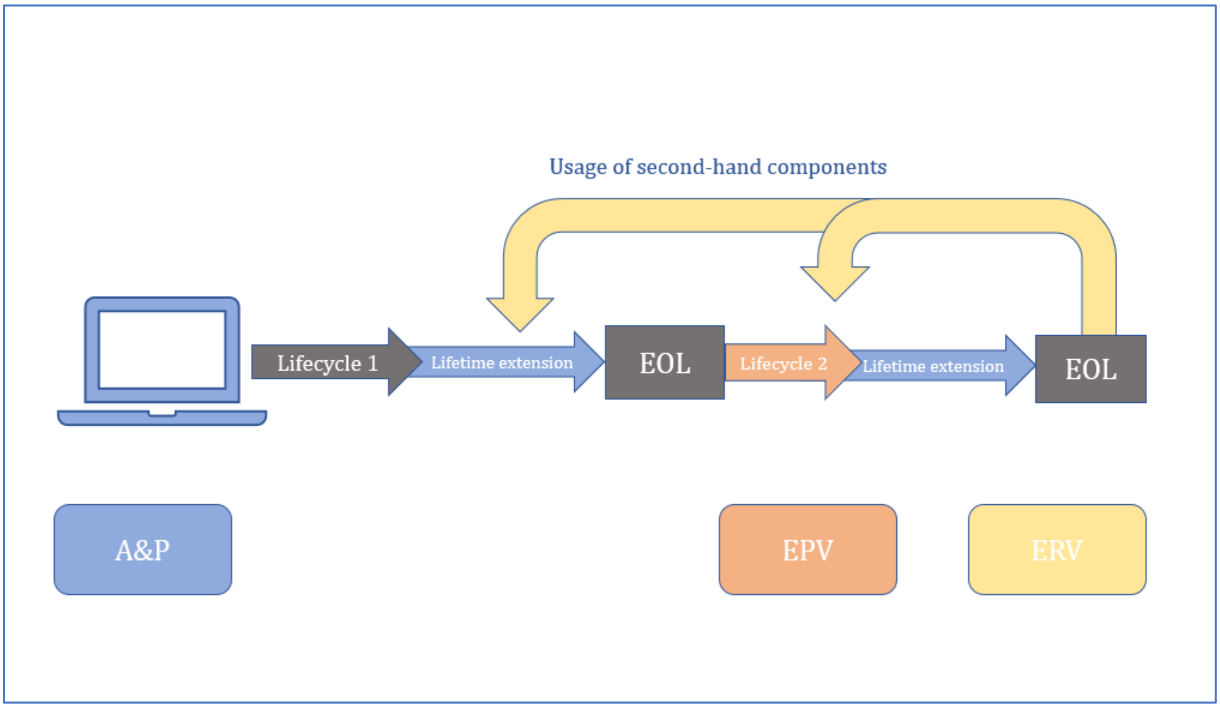


Fig. 17 The CBM strategies by Bocken et al. (2016) and their influence on parts of the laptop lifecycle.

8.4.1. Access and performance

The A&P strategy can contribute to lifetime extension in two overarching ways: by improving the research design of the product and by increasing a products' functional use time (Bieser et al., 2021).

All case studies included in this research articulated that they have little influence on the design of laptops that are produced by large multinational manufacturers. However, as improving the design of a device is considered to be an important measure to prolong the functional lifetime of a product it was deemed worthwhile to mention it here (ibid).

The included case studies may not directly influence the design processes of multinational manufacturers they procure from. Nonetheless, they might collectively advocate or lobby for differences in device design through institutions that uphold international standards for procurement in the IT sector. Examples of such entities include the IT Buyer Group, mainly active on the national level or through the Circular and Fair ICT Pact, which 'accelerates circularity, fairness and sustainability in the IT sector' on an international scale (PIANOO, 2023; Circular & Fair ICT Pact, 2023).

Furthermore, international regulations might also compel manufacturing companies to abide to certain measures stimulating product lifetime extension. An example can be found in the forthcoming requirement for eco-design and energy labelling for computers and computer servers. This initiative, scheduled to be implemented in 2024, constitutes a part of the European Unions' Ecodesign Directive and Energy Labelling Regulation (Directive, 2009/125; Regulation, 2017/1369; Nickel, 2023).

To enhance device longevity, several actions could be undertaken by the manufacturing company. Firstly, software induced obsolescence should be avoided or users should be informed about the consequences of possible software updates. Addressing hardware induced obsolescence involves adopting universally used interface standards and the implementation of durable materials (Schiske et al., 2016; Proske et al., 2016).

Psychological obsolescence, which arises from products being incompatible with current trends, can be mitigated be increasing user attachment (Proske, 2016; Sung, 2015; Komejani, 2015). Furthermore, adherence to design principles for repairability and upgradeability, combined with the availability of spare components and clear repair guidelines facilitates the extension of functional product life (Wilhelm, 2012; Bieser et al., 2021).

The other measure that could be taken to extend the products' lifetime in the light of the Access and Performance strategy is to encourage the user to use its device for a prolonged period of time. This can also be called 'retention' (Bieser et al., 2021).

Within the case studies that were included, service was often provided, which has the potential to increase the duration of product usage by the same user (Bieser et al., 2021). However, this potential did not come to fruition due to the fixed lease contract durations that were employed by all case studies. To increase the potential of this measure, it is recommended that the case studies discard their fixed lease contract durations. Instead, they could even work with a discount rate for a longer lease duration to stimulate users to maintain their laptop well. An example of this was found in Fairphones 'Keep Club', which is a rewards program for users that keep their device for the longest time possible (Fairphone, 2023).

Furthermore, Bieser et al. (2021) mention that offering users the option to repair their own devices can also increase retention. For instance, Fairphone offers their users the option to purchase spare parts for their phone themselves (Fairphone, 2023). Furthermore, the Dutch phone manufacturer collaborated with IFixit, an online community platform focussed on increasing the repairability of electronic devices, to design a screwdriver that is specifically made to repair Fairphones (ibid).

Another measure that could increase retention of electronic products is increasing user attachment. User attachment could be stimulated by upcycling or personalization which can be achieved through buttons, stickers or personal engravings (Sung et al., 2015, pp. 2). This is an intervention that the included case studies could actually include as a part of their Access and Performance CBM strategy. This strategy aims to offer customers the functionalities of a product through a service instead the of ownership of said product and personal engravings could be included within the service offered.

8.4.2. Extended Product Value and Extended Resource Value

The strategies of EPV and ERV can further prolong a products lifetime by ensuring that a device or part of a device is used by an additional user and/or in a different use context after its first lifetime. Thereby, the product or product components are recirculating (Bieser et al., 2021). This intervention was present in all of the business models of the case studies included, as all of them incorporated refurbishment as a part of their Extending Product Value strategy. However, the rate at which refurbishment was offered after the first life cycle differed between 15 and 65% across case studies. For all case studies, an increase in refurbishment rate is recommended, as Sensitivity Analysis 2 confirmed that this lowered environmental impacts considerably.

Refurbishment also comes with its potential challenges. One case study participant stated that their customers preferred using newly produced laptops as opposed to refurbished one due to quality or data safety concerns. Scepticism with regards to previously used electronic devices was confirmed by Wieser & Tröger (2018) and Axelsson (2020). A potential way to mitigate scepticism with regards to second-hand products was addressed by Gavertsson et al. (2020). They underscore that actively promoting the equivalent-to-new quality of second-hand products is an essential measure for companies offering them. Therefore, to decrease the environmental impact of their CBM, it is recommended that the case studies actively encourage their customers to choose second hand products by convincing them of their benefits. This would allow them to increase their refurbishment rate, which in turn could lead to more recirculation and a lower environmental impact.

As a part of the Extending Resource Value strategy, all case studies reported that second-hand components that were taken off of no longer functional devices were reused in the service and refurbishment phase. Hereby, they were also contributing to the recirculation of parts of their products. To extend the potential of second-hand components, they could also be employed for manufacturing new laptops (André et al., 2019). Even though the included case studies are not personally responsible for the manufacturing process of their laptops, it is recommended that they collectively negotiate with laptop manufacturers to establish the implementation of second-hand components in the production of new laptops.

Table 31. Recommended measures to extend product lifetime in a refurbishing and leasing CBM

Measure	Recommendation for companies
Improving device design (Access and Performance)	Collectively 'demand' or lobby for improvements in product design with regards to repairability, longevity and upgradeability.
Retention (Access and Performance)	Discard fixed lease contract duration. Incentivise users to prolong their use duration by offering a discount in case of prolonged usage.
	Increase user attachment through personalization.
Recirculation (Extended Product Value & Extended Resource Value)	Increase refurbishment rate after the first lifecycle.
	Actively promote refurbished products to ensure customers of their quality.
	Collectively demand usage of second hand components in production phase from manufacturers.

9. Discussion

9.1 Comparison of results with previous literature

The results of this study have shown that, under certain circumstances, refurbishing and leasing CBMs in the IT sector can contribute to lowering environmental impacts. As the environmental impact of three different CBM strategies was considered in this research: Access & Performance, Extending Product Value and Extending Resource value, previous academic findings will be organised along the lines of these concepts.

9.1.1. Access & Performance

Business models that incorporate an A&P strategy often offer their product to the user in the shape of a service, rather than selling it (Bocken et al., 2016). Business models such as Product-as-a-Service (PaaS) or a Product Service Systems (PSS) can be considered a part of this strategy.

Both Bocken et al. (2016) and Ertz et al. (2019) consider business models that applied the A&P strategy suitable for extending product lifetime. Whilst laptop lifetimes were extended through refurbishment in all case studies this was considered to be a part of the CBM strategy Extending Product Value. In the A&P strategy, a products' lifetime is solely extended before it has reached its original EoL (Bocken et al., 2016). Therefore, this research established that an A&P strategy did not stimulate the extension of the lifetime of laptops, as all included case studies had a fixed duration for their lease contracts. This can be considered a missed opportunity, because a company can financially benefit when the product lasts for an extended period of time without needing replacement, which in turn leads to lowered environmental impacts.

Nevertheless, it should be acknowledged that an A&P business model also potentially facilitates the return of devices to case studies upon reaching their End of Life. This prevents that devices that could still potentially be reused or refurbished are neglected in storage, which often occurs in an LBM (Glöser-Chahoud et al. 2019). This aspect of the A&P strategy was also observed in all included case studies, as they all reported that customers hand in their devices at the end of their lease contract.

In other research conducted on PSS and PaaS' contribution to lowering environmental impacts, slightly differing results were found. Hankammer & Steiner (2015), in their research on the sustainability potential of electronic devices within a PSS, emphasize an increased responsibility along the entire product lifetime in a PSS, shared by both consumer and manufacturer. This shared responsibility generates an incentive to prolong the products' lifetime whilst it is functional. Furthermore, increased responsibility is considered to be a potential catalyst for enhanced reparability, durability and modularity of implemented in the design phase of electronic devices (Hankammer & Steiner, 2015). This, along with higher recycling rates at EoL, leads to decreased environmental impacts. This result differs from the outcomes derived from this research as lifetime extension due to an increased sense of responsibility or changes in device design were not reported here.

9.1.2. Extending Product Value

Within this CBM strategy, the residual value of a used product is exploited. For the case studies included within this research, this entailed that they refurbished their laptops to ensure that they could be used for a longer period of time. This research found that refurbishment can allow for lowering environmental impacts in a CBM in comparison to an LBM due to prolonging the functional lifetime of the laptop. Moreover, a formula to calculate the minimum lease contract lifetime and refurbishment rate to ensure a lower environmental impact than was found in the LBM was established.

The general consensus in all academic sources found was that refurbishing of electronic devices has great potential for lowering environmental impacts. Hischier and Boni (2020) found that for electronic devices in which the production phase is most dominant, such as a smartphones or

laptops, reusing, lowers environmental impacts. This is the case because refurbishment prolongs the functional lifetime of the product and consequently prevents the production impact for new laptops. Nonetheless, they do warn for rebound effects that might occur when second hand devices are acquired additionally to new ones instead of replacing them.
And Bieser et al. (2021) established that recirculation, of which refurbishment is considered to be a part, can contribute to prolonging the lifetime of Mobile Internet Enabled Devices, such as laptops. As a result, environmental impacts can be lowered.
Furthermore, in a study by Nunes et al. (2021), reusing electronic devices in a PSS is heralded as a sustainable alternative for the End of Life phase of electronics. Nunes et al. (2021) based this finding on their LCA study on an LCD screen. This is confirmed by this research, as in section 8.1 it is shown that an increased lifetime is the most beneficial intervention to lower the environmental impact of a laptop. As direct reuse requires even less handlings that might potentially introduce additional environmental impact than refurbishment, it is expected that these CBMs perform even better.
Lastly, André et al. (2019) performed an LCA study on second hand laptops for commercial reuse. Besides establishing the environmental benefits of this practice as opposed to usage of new laptops, this study found that the impacts of transportation and other activities required to enable the reuse of laptops were negligible in comparison to the environmental advantages. The latter result is in line with this research in which the transportation and service phase made up 0.7 and 6.3 % of average environmental impacts respectively.
Additionally, they found that the impact categories Human Toxicity and Metal Depletion benefitted the most from laptop reuse. A similar result was found in this research, in which a 2% difference in impacts was found between the CBMs and LBM for HT, 4% for MD and a lower percentage of 0.4 % for Climate Change. However, the LCA by André et al. (2019) considered all ReCiPe Midpoints' eighteen impact categories. It remains uncertain whether the result would be the same for this research if all impact categories were to be included.

9.1.3. Extending Resource Value

This strategy aims to extend the value present in resources at their End of Life, which was done in all case studies included by using second hand components in their refurbishment and service phases. According to the results of this research, reusing second hand components can lower the environmental impacts of a CBM.
Several examples of previous literature agreeing with this finding were found. Marconi et al. (2017, pp. 171) stated that the reuse of components 'always leads to a benefit'. They explain that the avoidance of the production impact for new components is general higher than the impact of energy consumed in processes that enable reuse of components, such as disassembly. Griesse and Poetter already had similar outcomes for their research in 2004, in which they state that reparation of computers with second hand components comes with a short ecological payback period. They also addressed that the strategy of ERV should be combined with an appropriately organized take-back system as well as quality assurance measures to assure that sufficient, quality compliant components are available for repairments.

9.2. The production phase as an environmental impact hot spot

The production phase was considered to be an environmental impact hot spot in this research. The production phase being the dominant phase when it comes to the environmental impacts of a laptop was confirmed by an LCA performed by Dell in 2019, in which 88% of CO_2 impacts was caused by the production phase. Additionally, in an LCA performed by Ciroth and Franze in 2011, it was stated that that 90% of Human Toxicity and 80% of Metal Depletion impacts of a laptop can be traced back to the production phase. Consequently, product lifetime extension is widely considered to be an effective measure to lower the environmental impact of consumer electronics (Bieser et al., 2021; André et al., 2019; Prakash et al., 2016).

9.3 CBMs as a driver for the CE

This research indicates that certain implementations of CBMs have lower environmental impacts than a LBM. However, CBM does not exist in isolation. Business models, and CBMs especially, are reliant on other supply chain actors functioning within the boundaries of the linear economy (Geissdoerfer et al., 2018). The reliance on linear actors within the supply chain was mentioned as a barrier in the transition to a more circular approach to their business model by representatives of all included case studies. Furthermore, this reliance on a linear supply chain potentially hinders CBMs in their role to operationalize the transition to the CE on a system level (Harris et al., 2020).

The environmental impacts of CBMs on the level of the sector (meso level) or the city, nation or world (macro) they exist in have not been determined within this research. Moreover, they could also not be verified through existing academic sources (Harris et al., 2020). Further research is needed to determine the potential of lowering environmental impacts through CBMs on a system level to explore whether CBMs successfully contribute to a circular economy that contributes to a more sustainable future.

9.4 Limitations

As is the case in any LCA study, methodological choices come with limitations. Generally, LCA uses a simplified model that is based on assumptions and scenarios to represent the complex reality of the environmental impacts of product systems occurring in the real world (Curran, 2014). All methods and data inputs used in the LCAs were documented in a transparent manner, to ensure replicability of the research.

In this research, as much primary data as possible was gathered through semi structured interviews. The interpretation of information gathered in the interviews was verified by each case study's representative to ensure its validity. However, secondary data was also used in this research, as not all primary data could be obtained due to time and scope restrictions. Secondary data that was utilized was obtained from EcoInvent v.3.8.1. Especially the LBM case study was based on secondary data only, as this case study was hypothetical and based on estimated averages found in EcoInvent and literature. Inaccuracy for the secondary data was reduced by validating with other literature sources.

Also, due to challenges concerning data availability on multiple processes relevant for this LCA, assumptions had to be made in various instances. These assumptions potentially led to inaccuracy in terms of the environmental impacts that resulted from the LCA. To ensure that the assumptions approximated the actual process to the highest possible extent, they were validated by the case study representatives. An example of such an assumption is that none of the case study participants could specify one model of laptop that they sell most frequently. Therefore, a standard laptop dataset from EcoInvent was employed for all case studies equally. However, differences in the design of laptops that are sold or leased out could have an influence on the lifetime and repairability of the product. Both lifetime and repairability, variables that can vary depending on a laptops' design, were determined in this research to be important factors with respect to the

environmental impact of business models offering a laptop. Therefore, some nuance might have been lost with regards to differences between the environmental impact of the offered laptops.
Also, not all processes potentially influencing the environmental impact of a laptop in each case study could be captured within the LCA. This can be attributed to its limited scope and a lack of available data. For instance, Case 3 mentioned that their online portal facilitates the assessment of whether users possess laptops exceeding the required processing capacity for the functionalities required of them for their job. Consequently, in such cases, the laptop may be substituted for one having lower processing capacities, potentially leading to lower energy consumption of the laptop and avoiding the usage of a laptop with high specifications by a user not requiring such functionalities.
Another example is Case 1, which occasionally donates laptops that have reached their functional End of Life according to Dutch standards, to individuals in countries were standards for laptop functionality are lower. This practice potentially mitigates the production impact of laptops with lower functionality grades. However, this was not represented in the provided data on Case 1s refurbishment rate. Therefore, this was considered to be outside of the scope of this research.
Several examples of processes mentioned were outside of the scope of the LCA by case study representatives that potentially exert both positive and negative environmental impacts. However, it should be acknowledged that while LCA is a method that aims to approximate environmental impact to the fullest possible extent it is more useful for the identification of patterns or trends than for providing an exact replication of reality. As discerning patterns of conditions that allowed for an overall lower environmental impact in a CBM in comparison to an LBM was the aim of this research, LCA was considered a valuable approach, despite its inherent limitations.

9.5 Areas for future research

A shortcoming of the LCA method is that it mainly captures environmental impacts, as opposed to also including the social and economic domains that are also a part of sustainability (Roos Lindgreen et al., 2021; Geissdoerfer et al., 2017). These domains of sustainability were also underrepresented within this research. For instance, whilst some of the case study representatives mentioned their concerns regarding the financial viability of refurbishing their laptops, this concern cannot directly be related to the LCAs that were performed.
In terms of the social aspect of sustainability, many issues have been raised regarding dangerous labouring conditions in the manufacturing process of electronics (Sandoval & Bjurling, 2013; Bieler & Chun-Yi Lee, 2018). Whilst there is a good chance that these unsafe circumstances also affected the production process of the laptops included in this research, this was not reflected in the LCA studies. Future research in which the social and financial pillar of sustainability are accurately represented is recommended. This could give an indication of the overall sustainability potential of CBMs, rather than solely CBMs potential to contribute to environmental sustainability.
Moreover, the exclusion of the disposal phase in the LCAs should be acknowledged. The motivation for this omission was that all companies included have to abide to the same WEEE regulations (Directive, 2002/96). Therefore, little variation in terms of environmental impact was anticipated in this phase. However, the significance of the disposal phase of electronic devices such as laptops should be acknowledged. Employing an as Product-as-a-Service model enhances the likelihood of retrieving laptops post usage (Glöser-Chahoud, 2019). This allows for redirecting flows of previously used laptops into WEEE recycling, thereby contributing to an overall reduction in environmental impacts (André et al., 2019).
In contrast, within a LBM, laptops might be lost out of sight at their EoL, given that users are not obligated to return the laptops to the original selling company. Furthermore, whilst all case studies had to abide to WEEE regulations, their execution of these regulations can exert influence on the environmental impacts that arise in the disposal phase. For instance, interview respondents mentioned their autonomy in selecting a recycling location. Variability in proximity to a recycling

location has a determining effect on environmental impacts that occur in relation to the disposal phase due to transport impacts. Therefore, it is recommended that future research on a similar topic does include the disposal phase to determine whether this affects the difference in environmental impact between CBM and LBM.
Finally, the outcomes presented in this research result from three case studies with different implementations of a CBM and a hypothetical fourth case representing the LBM. While the outcomes drawn from this research might provide insights into the potential environmental impact of other CBMs in the IT sector, the results of this research can only be generalised with great care. This caution is particularly relevant considering the substantial influence that the context surrounding a business model can have on its environmental impact, a factor that is linked to business' dependencies on various down- and upstream supply chain actors (Geissdoerfer et al., 2018). To determine the potential of alternative CBM implementations to contribute to lowering environmental impacts, additional research should be executed, in which variables pertaining to the alternative CBM and its value chain are included.

10. Conclusion

This thesis investigated under which conditions a laptop offered in a refurbishing and leasing CBM generates a lower environmental impact than a laptop offered in a LBM.
To establish the environmental impact of CBMs, LCAs were performed on case studies of three distinct CBM implementations, alongside an LBM, for comparative analysis. Each CBM case study involved refurbishment and leasing.
Furthermore, the identification of environmental impact hotspots was based on the distribution of environmental impacts throughout different life cycle phases. Through sensitivity analyses the influence of lifetime extension of the laptops through prolonging contract duration and through increasing the refurbishment rate were explored. This provided an answer to the second sub question of this research.
To answer the last sub question, comparisons between LCA results and expected environmental impacts according to CBM theory facilitated the determination of the practical manifestation of environmental benefits found in the case studies. Moreover, measures to potentially increase the effectiveness of CBM theory in practice were formulated according to literature research.
By providing an answer to sub questions included in this research, the main research question: *'Under what conditions does a refurbishing and leasing Circular Business Model (CBM) in the IT sector contribute to a lower environmental impact compared to a LBM (LBM)*?' could be answered by formulating conditions that a CBM, encompassing leasing and refurbishment, must fulfil to outperform and LBM in terms of environmental impacts

First, the environmental impacts of the CBM implementations were determined. For the environmental impact category Climate Change, this impact was on average 451 kg CO_2 eq. in the CBM case studies and 453 kg CO_2 eq. in the LBM. A 0.44% difference. A larger difference was reported between the CBM implementation with the lowest environmental impact for Climate Change and the LBM: a difference of 14%. For the environmental impact category Human Toxicity, this impact was on average 466 kg DCB eq. in the CBM implementations and 501 kg DCB eq. in the LBM. A difference of 7%. However, between the case with the lowest values for Human Toxicity and the LBM a 14.17% difference was reported. For the impact category of Metal Depletion this impact was on average 152 kg CO_2 eq. in the CBM implementations and 159 kg CO_2 eq. in the LBM, differing by 5%. For this category too, the difference between Case 1 and the LBM amounted to a higher difference of 18.87%.
One of the CBM case studies reported an overall impact for all impact categories that was higher than that of the LBM. This can be attributed to this case having a shorter contract lifetime than

the assumed lifetime for the LBM. Additionally, this case reported the highest environmental impacts out of all cases studies for the transport and service phase.
However, besides this one exception, the average environmental impact of the CBM case studies show a lower environmental impact than was calculated for the LBM.

Next, one significant environmental impact hot-spot could be identified within the lifecycle of a laptop. This hot-spot of environmental impacts prevailed in the production phase of the laptop, in which an average of 68% of environmental impacts for Climate Change was emitted, an average 81% of HT and an average of 86% of Metal Depletion, combining the results of both the CBM and LBM case studies.
In the impact category of Climate Change, the use phase had a combined average impact of 24 %. This can be attributed to electricity usage causing a relatively high amount of impact for this category. Less than ten % of impacts were caused in the use phase for the other impact categories.
As a consequence of the production phase being an environmental impact hot spot, the main variables that contribute to lowering environmental impacts are contract lifetime and refurbishment rate. This was indicated by the sensitivity analysis, in which a decrease in environmental impacts was reported both as a result of increasing contract lifetime and refurbishment rate.

Last, the effectiveness of the CBM strategies by Bocken et al. (2016) in terms of lowering the environmental impact of a laptop in different life cycle phases was determined. For the A&P strategy, it was anticipated that the lifetime of the product would be extended through changes in product design or retention by the customer. However, due to fixed lease contract durations in all case studies, this expectation was not met in practice. Alternatively, the EPV strategy influenced the environmental impact of the production phase by extending the laptops' lifetime through refurbishment in all case studies. Furthermore, the potential to reuse components as a part of the ERV strategy did not come to fruition within this phase.
For all the other lifecycle phases, the expected influence of the CBM strategies on the environmental impact of the case studies was met in practice.

Notably, this research established that a CBM does not always generate a lower environmental impact than a LBM. Therefore, it can be stated that a CBM is not always the better option than an LBM in terms of its environmental sustainability performance. Nonetheless, a CBM that incorporates leasing and refurbishment in the IT sector can contribute to a reduced environmental impact compared to an LBM. However, this contribution only occurs under the condition that the additional environmental impacts resulting from supplementary services and transportation integral to the CBM strategies are offset with a reduction in environmental impacts during the production phase. Whether the environmental impact in the production phase decreased sufficiently to service and transportation impacts largely depends on the lifetime and contract duration of laptops offered for lease and the rate of refurbishment after the first lifecycle. Moreover, when a CBM can establish relatively low environmental impacts for the additional services and transports it provides, a smaller amount of impacts needs to be offset by savings in the production phase.
A general minimum lease contract lifetime to enable refurbishing and leasing CBMs to establish a lower environmental impact than a LBM cannot be produced, as this minimum lifetime is affected by variables that are unique to each CBM implementation. However, based on the condition that companies should meet to generate lower environmental impacts with their CBM than with an LBM, a formula was generated for companies to calculate the minimum required

contract lifetime based on the variables that align with their CBM. This allows companies to adjust their lifetime both through an altered contract duration and an altered refurbishment rate, thereby allowing their CBM to have a lower environmental impact than an LBM.

$$((Prod_{CBM})/(((1\text{-}Refrate)*LT)+(LT_{ref}*Refrate)))*IP = ((Prod_{LBM})/LT_{LBM}) * IP) + ((TR_{CBM} + Serv_{CBM})\text{-}(TR_{LBM}+Serv_{LBM}))$$

Where:

$Prod_{LBM/CBM}$ = 168 kg CO_2 eq.

LT = Contract lifetime of CBM/LBM in years

LTref = Total lifetime of a refurbished laptop in years

Refrate = Refurbishment rate in percentages

TR = Transport emissions in kg CO_2 eq.

Serv = Service emissions in kg CO_2 eq.

IP = Impact period in years

Fig. 18 Formula to calculate minimum LT and ref. rate required for lower environmental impact than LBM

10.1 Recommendations

For companies offering electronic devices through a CBM that encompasses refurbishment and leasing, the following recommendations were formulated to ensure a lower environmental impact than an equivalent product offered through an LBM. All recommendations align with the three CBM strategies that were deemed relevant for a refurbishing and leasing CBM and are therefore structured accordingly.

First, recommendations targeting lifetime extension that can be achieved as a part of the A&P strategy. Companies can improve device design by collectively demanding enhancements in terms of longevity, repairability and upgradeability. To establish product retention by users, companies can start offering lease contracts with a dynamic duration. Lastly, user attachment to the product can be increased through personalization, which could become integral to the services offered as a part of the A&P strategy.

Furthermore, multiple measures that companies could take to increase the recirculation of their electronic devices as a part of the EPV and ERP strategies resulted from this research. It is recommended that companies increase their refurbishment rate to allow a larger proportion of their products to recirculate. This should go hand in hand with the active promotion of refurbished products to take away any reservations that customers might have with regards to the quality of second-hand electronic devices. Lastly, it is recommended that CBM companies reuse second-hand components in their service and refurbishment phases to avoid the production of new components and consequently lower environmental impacts. Furthermore, refurbishing and leasing CBMs in the IT sector could collectively demand the implementation of used components in the production process of 'new' laptops, which could also lower environmental impacts.

In addition to lowering environmental impacts during the production phase through lifetime extension, it is also recommended for companies to keep the environmental impacts of the additional services and transports they offer as an integral part of their CBM, as low as possible. This can be established by the implementation of interventions aimed at lowering excessive transports and switching to electronic transport modes for the transportation phase. In the service phase, impacts can be minimized by providing online service whenever feasible, promoting repairment by the user and repairing laptops with second-hand components. Lastly, improvements in device design can also contribute to lowering environmental impacts in the service phase due to increased repairability and longevity.

Finally, the take home message that arises from this research is that CBMs providing a laptop through the CBM strategies that enable leasing and refurbishment can lead to a lower environmental impact than a LBM providing an equivalent laptop. However, for a refurbishing and leasing CBM to contribute to lower environmental impacts in comparison to a LBM, one condition should be met. The additional environmental impacts that occur as a result from services and transports integral to the CBM should be compensated with a decrease in environmental impacts in the production phase in comparison to the LBM. This can be achieved by simultaneously extending the lifetime of the laptop to lower impacts in the production phase and by ensuring minimum environmental impacts for the service and transport phases.

11. Acknowledgements

Writing this thesis has been a challenging and transformative journey for me. Yet, today marks the culmination of this process, as I submit the final version of my thesis. I feel very content for finally reaching this stage and want to acknowledge that I could not have done this without the assistance of a few people.

First of all, I would like to thank Stefan Favrin, for being an amazing internship supervisor at Copper8. Stefan was always there to answer my, seemingly endless, stream of questions and to get me out of a rut whenever my head was overflowing. Furthermore, I had the honour to have multiple stand-in supervisors at Copper8 whenever Stefan was unavailable. Therefore I would also like to say a special thanks to Cécile van Oppen and Noor Huitema. Besides my supervisors, all the colleagues at Copper8 made me feel very welcome at their organization and always offered me a helpful hand any time I needed one, for which I am grateful.

At the University of Utrecht, I would like to say a massive thank you to my supervisor Vivian Tünn. Vivians' enthusiasm regarding my research topic had a contagious effect on me and talking about my research to Vivian, I always felt very encouraged about the next steps I had to take in my research process. Moreover, I would like to thank Blanca Corona, for improving my understanding of the LCA process. And finally, I would like to thank my second reader Matthijs Jansen for providing me feedback on my research proposal.

Last, I would like to thank the representatives of the three case studies for their information and openness about their business model, which allowed me to perform my LCAs.

12.References

André, H., Söderman, M. L., & Tillman, A. M. (2016, September). Circular economy as a means to efficient use of scarce metals?. In 2016 Electronics Goes Green 2016+(EGG) (pp. 1-8). IEEE.

André, H., Söderman, M. L., & Nordelöf, A. (2019). Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. Waste Management, 88, 268-279.

Axelsson, M. (2020). The dependence on staying updated.

Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: exploring product life extension through design. Journal of cleaner Production, 69, 10-16.

Bieler, A., & Lee, C. Y. (2018). Exploitation and resistance: a comparative analysis of the Chinese cheap labour electronics and high-value added IT sectors. In Chinese Labour in the Global Economy (pp. 24-37). Routledge.

Bieser, J., Burkhalter, L., Hilty, L. M., Fuchs, B., & Blumer, Y. (2021). Lifetime extension of mobile internet-enabled devices: measures, challenges and environmental implications. In 4th Conference on Product Lifetimes and the Environment (PLATE), Virtual Conference, Limerick, 26-28 May 2021. University of Limerick.

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of industrial and production engineering, 33(5), 308-320.

Bocken, N., Strupeit, L., Whalen, K., & Nußholz, J. (2019). A review and evaluation of circular business model innovation tools. Sustainability, 11(8), 2210.

Boulding, K. E. (1966). The economics of the coming spaceship earth. New York, 1-17.

Boyd, S. B. (2011). Life-cycle assessment of semiconductors. Springer Science & Business Media.

Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions–a strategy for eco-effective product and system design. Journal of cleaner production, 15(13-14), 1337-1348.

Bryman, A. (2012). Social research methods. Oxford university press.

Centraal Bureau voor de Statistiek. (2022, October 17). ICT-Gebruik Bij bedrijven. CBS. https://longreads.cbs.nl/ict-kennis-en-economie-2022/ict-gebruik-bij-bedrijven/.

Ciroth, A., & Franze, J. (2011). LCA of an ecolabeled notebook: consideration of social and environmental impacts along the entire life cycle.

Cooper, D. R., & Gutowski, T. G. (2017). The environmental impacts of reuse: a review. Journal of Industrial Ecology, 21(1), 38-56.

Curran, M. A. (2014). Strengths and limitations of life cycle assessment. Background and future prospects in life cycle assessment, 189-206.

Copper8. (2019, September 25). Circulaire Verdienmodellen.

Das, A., Konietzko, J., & Bocken, N. (2022). How do companies measure and forecast environmental impacts when experimenting with circular business models?. Sustainable Production and Consumption, 29, 273-285.

Dell. (2019, August). Latitude 7410 2-in-1 chromebook enterprise PCF datasheet. https://corporate.delltechnologies.com/content/dam/digitalassets/active/en/unauth/data-sheets/products/laptops/latitude-7410-2-in-1-chromebook-enterprise-word-pcf-datasheet.pdf

Directive 2003/96/EC Directive (EC) 2002/96 of the European Parliament and of the Council on 27 January 2003 on waste electrical and electronic equipment (WEEE). https://faolex.fao.org/docs/pdf/eur54059.pdf

Directive 2009/124. Directive (EU) 2019/904 of the European Parliament and of the Council of 21st October 2009 on establishing a framework for the setting of ecodesign requirements for energy-related production. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:285:0010:0035:en:PDF

EcoInvent. (2022, June 28). Market activities. EcoInvent. https://EcoInvent.org/the-EcoInvent-database/market-activities/.

EcoInvent. (2023). Computer Production, laptop. Ecoquery.EcoInvent.org. https://ecoquery.EcoInvent.org/3.8/cutoff/dataset/2077/impact_assessment.

Ellen McArthur Foundation. (2013). Towards the Circular Economy Vol. 1: an economic and business rationale for an accelerated transition. Ellen McArthur.

Ertz, M., Leblanc-Proulx, S., Sarigöllü, E., & Morin, V. (2019). Made to break? A taxonomy of business models on product lifetime extension. Journal of Cleaner Production, 234, 867-880.

European Commission. (2012.). Waste from electrical and electronic equipment (WEEE). Environment. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

European Commission. (2020, March 11). A new Circular Economy Action Plan.

Fairphone. (2023). Reserveonderdelen voor je fairphone, Vindt Ze Hier. Fairphone BV. https://shop.fairphone.com/nl/shop/category/spare-parts-4?ci=1

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., ... & Suh, S. (2009). Recent developments in life cycle assessment. Journal of environmental management, 91(1), 1-21.

Forti, V., Baldé, C., Kuehr, R., & Garam Bel. (2020). The Global E-Waste Monitor.

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G., & Friday, A. (2021). The climate impact of ICT: A review of estimates, trends and regulations. arXiv preprint arXiv:2102.02622.

Gåvertsson, I., Milios, L., & Dalhammar, C. (2020). Quality labelling for re-used ICT equipment to support consumer choice in the circular economy. Journal of Consumer Policy, 43, 353-377.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm?. Journal of cleaner production, 143, 757-768.

Geissdoerfer, M., Morioka, S. N., de Carvalho, M. M., & Evans, S. (2018). Business models and supply chains for the circular economy. Journal of cleaner production, 190, 712-721.

Geissdoerfer, M., Pieroni, M. P., Pigosso, D. C., & Soufani, K. (2020). Circular business models: A review. Journal of cleaner production, 277, 123741.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner production, 114, 11-32.

Glöser-Chahoud, S., Pfaff, M., Walz, R., & Schultmann, F. (2019). Simulating the service lifetimes and storage phases of consumer electronics in Europe with a cascade stock and flow model. Journal of Cleaner Production, 213, 1313-1321.

Greenwheels. (2023). How carsharing works. How it works. https://www.greenwheels.nl/en-us/how-it-works.

Griese, H., Poetter, H., Schischke, K., Ness, O., & Reichl, H. (2004, May). Reuse and lifetime extension strategies in the context of technology innovations, global markets, and environmental legislation [electronics]. In IEEE International Symposium on Electronics and the Environment, 2004. Conference Record. 2004 (pp. 173-178). IEEE.

H&M Group. (2023, August 23). Collect, recirculate and Recycle. H&M Group. https://hmgroup.com/sustainability/circularity-and-climate/recycling/.

Harris, S., Martin, M., & Diener, D. (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption, 26, 172-186.

Haupt, M., & Hellweg, S. (2019). Measuring the environmental sustainability of a circular economy. Environmental and Sustainability Indicators, 1, 100005.

Haupt, M., & Zschokke, M. (2017). How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. The International Journal of Life Cycle Assessment, 22, 832-837.

Hauschild, M. Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., ... & Pant, R. (2013). Identifying best existing practice for characterization modeling in life cycle impact assessment. The International Journal of Life Cycle Assessment, 18, 683-697.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment. Springer International Publishing, Cham. https://doi. org/10.1007/978-3-319-56475-3 Book.

Hankammer, S., & Steiner, F. (2015). Leveraging the sustainability potential of mass customization through product service systems in the consumer electronics industry. Procedia CIRP, 30, 504-509.

Helander, H., Petit-Boix, A., Leipold, S., & Bringezu, S. (2019). How to monitor environmental pressures of a circular economy: An assessment of indicators. Journal of Industrial Ecology, 23(5), 1278-1291.

Hischier, R., & Böni, H. W. (2021). Combining environmental and economic factors to evaluate the reuse of electrical and electronic equipment–a Swiss case study. Resources, Conservation and Recycling, 166, 105307.

Hoang, A., Tseng, W., Viswanathan, S., & Evans, H. (2009). Life cycle assessment of a laptop computer and its contribution to greenhouse gas emissions (Doctoral dissertation, National University, San Diego).

Hoffman, M., Schenck, C. J., & Herbst, F. (2022). Exploring the Intersection Where Business Models, a Circular Economy and Sustainability Meet in the Waste Economy: A Scoping Review. Sustainability, 14(6), 3687.

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M. D., ... & van Zelm, R. (2016). ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report I: characterization.

Junnila, S., Ottelin, J., & Leinikka, L. (2018). Influence of reduced ownership on the environmental benefits of the circular economy. Sustainability, 10(11), 4077.

Kjaer, L. L., Pigosso, D. C., McAloone, T. C., & Birkved, M. (2018). Guidelines for evaluating the environmental performance of Product/Service-Systems through life cycle assessment. Journal of Cleaner Production, 190, 666-678.

Komeijani, M., Ryen, E. G., & Babbitt, C. W. (2016). Bridging the gap between eco-design and the human thinking system. Challenges, 7(1), 5.

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: the concept and its limitations. Ecological economics, 143, 37-46.

Kravchenko, M., McAloone, T. C., & Pigosso, D. C. (2020). To what extent do circular economy indicators capture sustainability?. Procedia CIRP, 90, 31-36.

Manninen, K., Koskela, S., Antikainen, R., Bocken, N., Dahlbo, H., & Aminoff, A. (2018). Do circular economy business models capture intended environmental value propositions?. Journal of Cleaner Production, 171, 413-422.

Marconi, M., Favi, C., Germani, M., Mandolini, M., & Mengarelli, M. (2017). A collaborative End of Life platform to favour the reuse of electronic components. Procedia CIRP, 61, 166-171.

McDonough, W., & Braungart, M. (2010). Cradle to cradle: Remaking the way we make things. North point press.

Nicholson, A. L., Olivetti, E. A., Gregory, J. R., Field, F. R., & Kirchain, R. E. (2009, May). End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions. In 2009 IEEE international symposium on sustainable systems and technology (pp. 1-6). IEEE.

Nickel, L. (2023, August 23). Ecodesign Directive for Sustainable Products (ESPR): 2023 overview. Ecochain. https://ecochain.com/blog/espr-2023-overview/#:~:text=)%3A%202023%20Overview-,Ecodesign%20Directive%20for%20Sustainable%20Products%20(ESPR)%3A%202023%20Overview,norm%20on%20the%20EU%20market

Nunes, I. C., Kohlbeck, E., Beuren, F. H., Fagundes, A. B., & Pereira, D. (2021). Life cycle analysis of electronic products for a product-service system. Journal of Cleaner Production, 314, 127926.

Nußholz, J. L. (2017). Circular business models: Defining a concept and framing an emerging research field. Sustainability, 9(10), 1810.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC.

Patagonia. (2011, November 22). Don't buy this jacket, Black Friday and the New York Times. Patagonia Stories. https://www.patagonia.com/stories/dont-buy-this-jacket-black-friday-and-the-new-york-times/story-18615.html.

Patagonia. (2023). Recycled polyester. Patagonia. https://eu.patagonia.com/nl/en/our-footprint/recycled-polyester.html.

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001: 2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resources, Conservation and Recycling, 129, 81-92.

Pearce, D. W., & Turner, R. K. (1989). Economics of natural resources and the environment. Johns Hopkins University Press.

PIANOo. (2023). Buyer group ICT hardware: Pianoo - Expertisecentrum Aanbesteden. PIANOo. https://www.pianoo.nl/nl/themas/maatschappelijk-verantwoord-inkopen/buyer-groups/bedrijfsvoering/buyer-group-ict-hardware

Pieroni, M. P., McAloone, T. C., & Pigosso, D. C. (2019). Business model innovation for circular economy and sustainability: A review of approaches. Journal of cleaner production, 215, 198-216.

Pieroni, M. P., McAloone, T. C., & Pigosso, D. C. (2020). From theory to practice: systematising and testing business model archetypes for circular economy. Resources, conservation and recycling, 162, 105029.

Prakash, S., Kohler, A., Liu, R., Stobbe, L., Proske, M., Schischke, K., IEEE, 2016. Paradigm Shift in Green IT – Extending the Life-Times of Computers in the Public Authorities in Germany. 2016 Electronics Goes Green 2016+ (Egg), 7

PRé Consultants. (2018). SimaPro Database Manual - Methods Library. https://doi.org/10.1017/CBO9781107415324.00

Proske, M., Winzer, J., Marwede, M., Nissen, N. F., & Lang, K. D. (2016, September). Obsolescence of electronics-the example of smartphones. In 2016 Electronics Goes Green 2016+(EGG) (pp. 1-8). IEEE.

Regulation 2017/1369 Regulation (EU) 2017/1369 of the European Parliament and of the Council of 04 July 2017 on setting a framework for energy labelling and repealing https://eur-lex.europa.eu/eli/reg/2017/1369/oj

Ritala, P., Albareda, L., & Bocken, N. (2021). Value creation and appropriation in economic, social, and environmental domains: Recognizing and resolving the institutionalized asymmetries. Journal of Cleaner Production, 290, 125796.

Rijksinstituut voor Volksgezondheid en Milieu (2011). Life cycle assessment (LCA) | RIVM. https://www.rivm.nl/en/life-cycle-assessment-lca

Rolex. (2023). Rolex guarantee. Buying a Rolex - The Rolex Guarantee | Rolex®. https://www.rolex.com/buying-a-rolex/the-rolex-guarantee.

Roos Lindgreen, E., Salomone, R., & Reyes, T. (2020). A critical review of academic approaches, methods and tools to assess circular economy at the micro level. Sustainability, 12(12), 4973.

Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A., Jolliet, O., Juraske, R., ... & Hauschild, M. Z. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. The International Journal of Life Cycle Assessment, 13, 532-546.

Sandoval, M., & Bjurling, K. (2013). Challenging Labour-Working Conditions in the Electronics Industry.

Schischke, K., Proske, M., Nissen, N. F., & Lang, K. D. (2016, September). Modular products: Smartphone design from a circular economy perspective. In 2016 Electronics Goes Green 2016+(EGG) (pp. 1-8). IEEE.

Scientific Applications International Corporation (SAIC), Curran, M. A., National Risk Management Research Laboratory (US), & Office of Research and Development, Environmental Protection Agency, United States. (2006). Life-cycle assessment: principles and practice.

Sinha, R., Laurenti, R., Singh, J., Malmström, M. E., & Frostell, B. (2016). Identifying ways of closing the metal flow loop in the global mobile phone product system: A system dynamics modeling approach. Resources, Conservation and Recycling, 113, 65-76.

Stahel, W. (2010). The performance economy. Springer.

Sung, K., Cooper, T., & Kettley, S. (2015). An exploratory study on the links between individual upcycling, product attachment and product longevity.

Symbiosis Project. (2018, December 11). The project. Symbiotic Networks of Bio-Waste Sustainable Management. https://symbiosisproject.eu/the-project/

The Correspondent (2019, June 27). Hoe Feller Patagonia Zich Verzet Tegen de Consumptiemaatschappij, Hoe Groter Het Kledingmerk Wordt.

Tukker, A. (2004). Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. Business strategy and the environment, 13(4), 246-260.

Tukker, A. (2015). Product services for a resource-efficient and circular economy–a review. Journal of cleaner production, 97, 76-91.

Urbinati, A., Chiaroni, D., & Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. Journal of cleaner production, 168, 487-498.

Van Loon, P., Diener, D., & Harris, S. (2021). Circular products and business models and environmental impact reductions: Current knowledge and knowledge gaps. Journal of Cleaner Production, 288, 125627.

Van Meeteren, O. (2021, July 9). Why your circular business may not be as sustainable as you think. Circle Economy - Practical, scalable implementation of the circular economy. https://www.circle-economy.com/blogs/why-your-circular-business-may-not-be-as-sustainable-as-you-think.

Wieser, H., & Tröger, N. (2018). Exploring the inner loops of the circular economy: Replacement, repair, and reuse of mobile phones in Austria. Journal of Cleaner Production, 172, 3042-3055.

Wilhelm, W. B. (2012). Encouraging sustainable consumption through product lifetime extension: The case of mobile phones. International Journal of Business and Social Science, 3(3).

Williams, E., Kahhat, R., Allenby, B., Kavazanjian, E., Kim, J., & Xu, M. (2008). Environmental, social, and economic implications of global reuse and recycling of personal computers. Environmental science & technology, 42(17), 6446-6454.

Whalen, K. A. (2019). Three circular business models that extend product value and their contribution to resource efficiency. Journal of cleaner production, 226, 1128-1137.

World Economic Forum. (2019, January). A New Circular Vision for Electronics.

World Economic Forum. (2019, November 9). The astonishing rise of Shenzhen, China's Gadget Capital. World Economic Forum. https://www.weforum.org/agenda/2017/11/inside-shenzhen-china-s-gadget-capital/

13. Appendix

13.1 EcoInvent datasets

13. 1.1. Production phase

For the production of the laptop, it should be noted that the EcoInvent dataset 'Computer production, laptop, GLO' included disposal of the laptop. As this lifecycle phase was outside of the scope of this research, this part of the dataset was excluded from the LCA.

Table 32. Data inputs production phase

Product/process	**Material and product input**	**Used average quantity per laptop**	**Unit in dataset**	**Dataset**	**Source of data**
Laptop production	• materials (mainly metals and plastics) • manufacturing processes (e.g. sheet rolling, press moulding). • infrastructure (factory), • electricity for the assembly of the laptop computer • the water consumption and industrial waste water • the dataset includes the exchange "used laptop computer" to take into account the disposal.*	1 (minus dataset 'used laptop computer' as disposal is outside of scope)	1	'computer production, laptop - GLO'	EcoInvent v.3.8.1.

*This material input was excluded from the dataset as this process was outside of the scope of this research.

13.1.2. Transports production phase

Table 33. Data inputs transport production phase

Product/process	Dataset description	Used average quantity per laptop	Unit in dataset	Dataset	Source of data
Transport overseas	• Delivering the service of transportation of 1 metric ton across the distance of 1 km. • Ship operates with heavy fuel oil and has a mass of 18,165,000 kg. • The DWT (load capacity) of the container ship is 43,000 tonnes.	(2,04*18234 km)/1000 = 37,2 ton km per laptop (Routescanner, 2023)	1 metric ton * km	'market for transport, freight, sea, container ship - GLO - transport, freight, sea, container ship'	EcoInvent v.3.8.1.
Transport lorry in China	• Delivering the service of transportation of 1 metric ton across the distance of 1 km. • Vehicle operates with diesel, its emission standard is classified as EURO5 and it falls under the lorry size class of >32 metric tons. • Average freight load factor is 15.96 tonnes.	(2,04*1408)/1000 = 2.9 ton km per laptop (Routescanner, 2023).	Metric ton * km	'market for transport, freight, lorry >32 metric ton, EURO5 - RoW - transport, freight, lorry >32 metric ton, EURO5'	EcoInvent v.3.8.1.
Transport lorry Rotterdam Harbour – distribution centres	• Delivering the service of transportation of 1 metric ton across the distance of 1 km. • Vehicle operates with diesel, its emission standard is classified as EURO5 and it falls under the lorry size class of >32 metric tons. • Average freight load factor is 15.96 tonnes.	Distance differs per case study: Case 1: 0,13 ton km Case 2: 0,104 ton km Case 3: 0,13 ton km LBM: 0,2 ton km	Metric ton * km	'market for transport, freight, lorry >32 metric ton, EURO5 - RoW - transport, freight, lorry >32 metric ton, EURO5'	EcoInvent v.3.8.1.

13.1.3. Use phase

Table 34 Data inputs use phase

Product/process	Material and product input	Used average quantity per FU	Unit in dataset	Dataset	Source of data
Laptop use	• Electricity active mode: 0.229 hour • Electricity off mode: 0.688 hour • Electricity standby mode: 0.0833 hour	38588 hours	1 hour	'operation, computer, laptop, 23% active work - GLO'	EcoInvent v.3.8.1.
Electricity active mode	• computer, laptop 2.85e-05 unit • electricity, low voltage 0.019 kWh	(5.5 * 201 =) 1105 hrs/year 8840 hours/FU	1 hour	'Operation, computer, laptop, active mode'	EcoInvent v.3.8.1.
Electricity off mode	No dataset was used, as the impact was assumed to be zero	(16.5 * 201 =) 3316.5 hrs/year 26532 hours/FU	n.a.	n.a.	n.a.
Electricity standby mode	• computer, laptop 2.85e-05 unit • electricity, low voltage 0.004 kWh	(2 * 201 =) 402 hrs/year 3216 hours/FU	1 hour	'Operation, computer, laptop, standby mode'	EcoInvent v.3.8.1.

13.1.4. Refurbishment phase

Table 35. Data input refurbishment phase

Product/process	Material and product input	Used average quantity per FU	Unit in dataset	Name Dataset	Source of data
Battery production	• battery cell, Li-ion 0.799 kg cable • data cable in infrastructure 0.373 m cable • three-conductor cable 0.025 m • electricity, low voltage 0.108 kWh • metal working factory 4.58e-10 unit • printed wiring board, surface mounted, unspecified, Pb containing 0.00102 kg • printed wiring board, surface mounted, unspecified, Pb free 0.00237 kg • reinforcing steel 0.145 kg • sheet rolling, steel 0.145 kg	0,333 kg (EcoInvent, 2023)	kg	'Battery production, Li-ion, rechargeable, prismatic'	EcoInvent v.3.8.1.
Hard Disk Drive production	• acrylonitrile-butadiene-styrene copolymer 0.00051 kg • aluminium, cast alloy 0.0293 kg • aluminium, wrought alloy 0.0622 kg • electricity, medium voltage 1.71 kWh • hot rolling, steel 0.0024 kg • powder coat, aluminium sheet 0.00633 m2 • printed wiring board mounting facility 3.33e-08 • unit printed wiring board, surface mounted, unspecified, Pb containing 0.00125 kg • printed wiring board, surface mounted, unspecified, Pb free 0.00291 kg • printed wiring board, through-hole mounted, unspecified, Pb containing 0.00125 kg 4 • printed wiring board, through-hole mounted, unspecified, Pb free 0.00291 kg • section bar extrusion, aluminium 0.0874 kg • sheet rolling, aluminium 0.00408 kg • sheet rolling, steel 0.0151 kg • steel, chromium steel 18/8, hot rolled 0.0024 kg • steel, low-alloyed, hot rolled 0.0151 kg • stretch blow moulding 0.00051 kg • transport, freight train 0.0023 metric ton*km	1	unit	'Market for Hard Disk drive, for laptop computer, GLO'	EcoInvent v.3.8.1.

	• transport, freight, lorry, unspecified 0.0023 metric ton*km				
Screen production	• electricity, medium voltage 94.6 kWh • glass, for liquid crystal display 0.743 kg • injection moulding 0.113 kg • integrated circuit, logic type 0.000261 kg • light emitting diode 0.00899 kg • liquid crystal display, minor components, auxilliaries and assembly effort 1 kg • polycarbonate 0.0148 kg • printed wiring board, surface mounted, unspecified, Pb free 0.00594 kg • sheet rolling, chromium steel 0.214 kg • sputtering, indium tin oxide, for liquid crystal display 8.02e-08 m3 steel, chromium steel 18/8 0.214 kg	0,428 kg (EcoInvent, 2023).	kg	'Liquid crystal display production, unmounted, mobile device. GLO'	EcoInvent v.3.8.1.
Keyboard production	• acrylonitrile-butadiene-styrene copolymer 0.77 kg • copper, cathode 0.0329 kg • electricity, medium voltage 1.11 kWh • extrusion, plastic pipes 0.0371 kg • injection moulding 0.77 kg • polyvinylchloride, suspension polymerised 0.00413 kg • printed wiring board mounting facility 2.45e-07 unit • printed wiring board, surface mounted, unspecified, Pb containing 0.018 kg • printed wiring board, surface mounted, unspecified, Pb free 0.042 kg • steel, chromium steel 18/8, hot rolled 0.28 kg • wire drawing, copper 0.0329 kg • 4 zinc coat, pieces 0.0698 m2 • transport, freight train 0.0301 metric ton*km • transport, freight, light commercial vehicle 0.0189 metric ton*km • transport, freight, lorry, unspecified 0.609 metric ton*km • transport, freight, sea, container ship 1.31 metric ton*km	1	Unit	'Market for keyboard, GLO'	EcoInvent v.3.8.1.

13.1.5. Service phase

Table 36. Data input service phase

Product/process	Material and product input	Used average quantity per FU	Unit in dataset	Name Dataset	Source of data
Adapter production	• cable, connector for computer, without plugs 1.8 m • copper, cathode 0.0536 kg • electricity, medium voltage 0.278 kWh • extrusion, plastic pipes 0.125 kg • plug, inlet and outlet, for computer cable 1 unit • polystyrene, high impact 0.0892 kg • polyvinylchloride, emulsion polymerised 0.00456 kg • polyvinylchloride, suspension polymerised 0.0311 kg • printed wiring board mounting facility 7.43e-08 unit • sheet rolling, steel 0.178 kg • steel, chromium steel 18/8, hot rolled 0.178 kg • 4 wire drawing, copper 0.0536 kg • transport, freight train 0.00812 metric ton*km • transport, freight, lorry, unspecified 0.17 metric ton*km • transport, freight, sea, container ship 0.59 metric ton*km	1	Unit	'Market for power adapter, for laptop, GLO'	EcoInvent v.3.8.1.
Keyboard production	• acrylonitrile-butadiene-styrene copolymer 0.77 kg • copper, cathode 0.0329 kg • electricity, medium voltage 1.11 kWh • extrusion, plastic pipes 0.0371 kg • injection moulding 0.77 kg • polyvinylchloride, suspension polymerised 0.00413 kg • printed wiring board mounting facility 2.45e-07 unit • printed wiring board, surface mounted, unspecified, Pb containing 0.018 kg • printed wiring board, surface mounted, unspecified, Pb free 0.042 kg • steel, chromium steel 18/8, hot rolled 0.28 kg • wire drawing, copper 0.0329 kg zinc coat, pieces 0.0698 m2 • transport, freight train 0.0301 metric ton*km • transport, freight, light commercial vehicle 0.0189 metric ton*km • transport, freight, lorry, unspecified 0.609 metric ton*km • transport, freight, sea, container ship 1.31 metric ton*km	1	Unit	'Market for keyboard, GLO'	EcoInvent v.3.8.1.

13.1.6. Transportation phase

Table 37. Data inputs transport phase

Product/process	Dataset description	Unit in dataset	Name Dataset	Source of data
Transport by passenger car	• average transportation of passenger/s across one km • only considers the transportation of passengers. • considers different car classes (EURO 3, EURO 4 and EURO 5). • Vehicle is an average of car sizes (small, medium and large) and fuel types (petrol, diesel and natural gas) for each EURO category.	1 km	'market for transport, passenger car with internal combustion engine - RER'	EcoInvent v.3.8.1.
Transport by Van	• Transportation of 1 metric ton across the distance of 1 km • only considers the transportation of goods. • operates with diesel or petrol • production is based off the Golf A4	1 ton * km	'market for transport, freight, light commercial vehicle - GLO'	EcoInvent v.3.8.1.
Transport by Lorry*	• transportation of 1 metric ton across the distance of 1 km. • only considers the transportation of goods. • operates with diesel, emission standard EURO5 • lorry size class > 32 metric tons	1 ton * km	market for transport, freight, lorry >32 metric ton, EURO5 - GLO'	EcoInvent v.3.8.1.

* note: this vehicle was only used in international transports and thus is attributed to the production phase

13.2 Distribution of impacts across lifecycle original lifetime and LT=5

13.2.1 Case 1

Case 1 performs service once every 2 years. With a lifetime of five years in the SA this comes down to 2.5 times service.
Year 6, 7 and 8 are 3/5 or 60% of the five year LT. Hence, 60% of impacts are allocated.

Table 38. Distribution of impacts new laptops Case 1

Year	**LT = 4 yrs**	**Sensitivity analysis LT = 5 yrs**
Year 1	Production batch 1	Production batch 1
Year 2	Service	Service
Year 3		
Year 4	EoL batch 1; Service	Service
Year 5	Production batch 2	EoL batch 1; Service *0.5
Year 6	Service	Production batch 2 35%*0,6; Service 35%*0,6
Year 7		Service 35%*0,6
Year 8	EoL batch 2; Service	EoL batch 2 35%*0,6; Service 35%* 0,3

Table 39. Distribution of impact refurbished laptops Case 1

Year	**LT= 4 yrs**	**Sensitivity analysis LT = 5 yrs**
Year 1		
Year 2		
Year 3		
Year 4		
Year 5	Refurbishment 65%	
Year 6	Service 65%	Refurbishment 65% * 0,6; Service 65% *0,6
Year 7		Service 65% *0,6
Year 8	EoL 65%; Service 65%	EoL 65% *0,6; Service 65%*0,3

13.2.2. SA Case 2

Explanation for service: In 3 years Case 2 performs service 1x

That means that in 5 years Case 2 performs service 1 times + 0,66 times. When there is a cut off at 3 years even though the LT = 5, this comes down at 1 time full service in total in those 3 years

Table 40. Distribution of impacts new laptops Case 2

Year	**LT = 3 yrs**	**Sensitivity analysis LT= 5 yrs**
Year 1	Production batch 1	Production batch 1
Year 2	Service	Service
Year 3	EoL batch 1	
Year 4	Production batch 2	
Year 5	Service	Service*0,67 EoL batch 1
Year 6	EoL batch 2	Production batch 2 65%*0,6
Year 7	Production batch 3 *0,67	Service 65%
Year 8	Service batch 3*0,67 EoL batch 3* 0,67	EoL batch 2 65%*0,6;

Table 41. Distribution of impacts refurbished laptops Case 2

	LT = 3 yrs	**Sensitivity analysis LT = 5 yrs**
Year 1		
Year 2		
Year 3		
Year 4	Refurbishment 35%	
Year 5	Service 35%	
Year 6		Refurbishment 35% * 0,6
Year 7	Refurbishment 35%*0,67	Service 35%
Year 8	Service 35%*0,67 EoL 35%*0,67	EoL 35% *0,6;

13.2.3. Case 3

Table 42. Distribution of impacts new laptop Case 3

Year	LT = 4 yrs	Sensitivity analysis LT= 5 yrs
Year 1	Production batch 1	Production batch 1
Year 2		
Year 3	Production 5% extra	Production 5% extra
Year 4	EoL batch 1	
Year 5	Production batch 2	EoL batch 1
Year 6	EoL 5% extra	Production batch 2*0,6
Year 7	Production 10% extra (because of EoL)	EoL 5% extra
Year 8	EoL batch 2 + EoL 10% extra *0,5	Production 10% extra*0,2 + EoL batch 2 *0,6 + EoL 10% extra*0,2

Table 43. Distribution of impacts refurbished laptops Case 3

Year	LT= 4 yrs	Sensitivity analysis LT= 5 yrs
Year 1		
Year 2		
Year 3		
Year 4		
Year 5	Refurbishment 15%	
Year 6		Refurbishment 15% * 0,6
Year 7		
Year 8	EoL 15%	EoL 15% *0,6

13.3 Interview guide

The same interview guide was employed for all three cases. As the interviews were of a semi-structured nature there was room to adjust questions during the interview to better fit the case studies' business model. The interviews were conducted in Dutch, therefore the provided interview guides are also in Dutch. As the interviews were of a semi-structured nature the interviewer deviated from the questions included in the interview guide whenever this was deemed relevant.

Table 44. Interview guide

Onderwerp	Vragen
Bedrijf en business model algemeen	Kan u mij kort vertellen wat jullie bij Case X verstaan onder circulaire IT? *Sub: welke elementen van jullie business model dragen bij aan circulaire IT* ? Hoeveel mensen zijn er werkzaam bij jullie bedrijf? Waar kopen jullie je laptops in? Hoeveel laptops gaan er gemiddeld per maand nieuw naar een klant? Wie zijn jullie klanten? Bedrijven? Hoe veel medewerkers? Hoeveel laptops hebben jullie gemiddeld in opslag? Kan je mij de stappen uitleggen die een laptop doorloopt in jullie business model? Hebben jullie een standaard model laptop of een model dat het meest verkoopt? Zijn er bepaalde criteria waaraan een laptop moet voldoen voordat jullie deze opnemen in jullie assortiment?
Transport	Met wat voor vervoersmiddel worden jullie laptops vervoerd naar de klant? Doen jullie het transport zelf of wordt dit uitbesteed? Hebben jullie data over gemiddelde afstand van jullie opslagplaats tot de klant?
Refurbishen	Waar refurbishen jullie? Is dit op dezelfde plek als waar de laptops binnen komen?

	Zijn er bepaalde refurbish-handelingen die het vaakste voorkomen/ die jullie altijd moeten doen ? Hebben jullie hier kwantitatieve data over? Vervangen jullie ook onderdelen? Waar halen jullie die onderdelen vandaan? Zijn alle laptops die jullie binnen krijgen met als doel om te refurbishen uiteindelijk ook bruikbaar om te refurbishen? Hoeveel procent? Zijn er naast impacts door het vervangen van onderdelen en het gebruik van elektriciteit nog andere impacts op het milieu door het refurbishen? Bijvoorbeeld door te ontvetten of te lakken?
Service	Bieden jullie ook een reparatieservice aan aan de klant? Zijn er cijfers over hoe vaak er per laptop service wordt verleend? En per tijdsperiode? Wordt de laptop opgestuurd? Faciliteren jullie het transport? Zijn er bepaalde service handelingen die het meest voorkomen? Welke zijn dat? Vervangen jullie bij service ook onderdelen? Waar komen die vandaan?
Gebruik	Hoe lang wordt een laptop van Case X gemiddeld gebruikt? Sturen jullie aan op het verlengen van de levensduur van de laptop? Geven jullie de klant tips over hoe ze het beste met hun laptop kunnen omgaan?
End of Life	Nemen jullie de laptops terug ? Als jullie de laptops niet terug nemen, wat gebeurt er dan met de laptops? Hoe zit het met het transport bij de EoL? Wat gebeurt er met de gebruikte laptops? Worden ze soms gebruikt voor een tweede

	levenscyclus? In hoeveel procent van de gevallen? Worden deze laptops gerefurbished? Ziet deze refurbish ronde er anders uit dan de 'eerste' refurbish ronde: i.e. zijn er andere handelingen die het vaakst voorkomen? Wat gebeurt er met de laptops die niet gerefurbished worden? Hoe ziet het transport naar de afvalverwerking/recycling locatie er uit?