Environmental impacts of ICT and the opportunities of circular economy solutions

Case study of the City of Helsinki's ICT procurements

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Elektroniikkajäte on maailman nopeimmin kasvava jätevirta, mikä johtuu yhteiskunnan kiihtyvästä digitalisaatiokehityksestä. Tehokkaampia laitteita tulee markkinoille jatkuvasti, minkä seurauksena käytössä olevat laitteet vanhentuvat kiihtyvällä tahdilla. Kiihtyvän digitalisaation ja kasvavien jätevirtojen ympäristövaikutuksista merkittävimpiä ovat kasvihuonekaasupäästöt sekä luonnonvarojen kulutus. Ratkaisuksi näihin ympäristöhaasteisiin on esitetty kiertotaloutta, jossa tuotteiden arvo pyritään säilyttämään mahdollisimman tehokkaasti ja tavoitteena on luoda suljettu materiaalien kierto.

Tässä tutkielmassa tarkastellaan kiertotalouden periaatteisiin pohjautuvan tuote palveluna -mallin ja laitteiden omistajuuteen pohjautuvan mallin eroja kannettavien tietokoneiden ja tablettien hankinnasta aiheutuvien ympäristövaikutusten osalta. Tutkielman tuloksia hyödynnetään Helsingin kaupungin Kierto- ja jakamistalouden tiekartan toimenpideohjelman tavoitteiden toteutuksessa. Tutkielma toteutettiin yksinkertaistettuna elinkaariarviointina, jossa hyödynnettiin systemaattista kirjallisuuskatsausta laitteiden elinkaaren vaiheisiin ja komponentteihin liittyvien ympäristövaikutusten kartoituksessa. Lisäksi edellä mainittuja liiketoimintamalleja edustavien yritysten uudelleenkäyttö ja kierrätyskäytänteistä kerättiin tietoa haastattelemalla kumpaakin hankintamallia toteuttavan yrityksen edustajia. Lopuksi systemaattisen kirjallisuuskatsauksen ja asiantuntijahaastattelujen avulla kerättyjen tietojen pohjalta arvioitiin laitteiden kasvihuonekaasupäästöihin ja materiaalihukkaan liittyviä eroja näissä hankintavaihtoehdoissa. Tarkastelussa käytettiin Helsingin kaupungin vuosittaisia laitteiden hankintamääriä.

Tutkielman tulosten perusteella kasvihuonekaasupäästöjen kannalta laitteiden merkittävimmät elinkaaren vaiheet ovat tuotanto ja käyttö. Ympäristövaikutuksiltaan merkittävimpiä komponentteja ovat piirilevyt, virtapiirit, näytöt ja kotelot. Tulosten perusteella laitteiden elinkaaren pidentäminen tarjoaa mahdollisuuksia vähentää merkittävästi laitteiden ympäristövaikutuksia kummassakin tarkastelukategoriassa, mikäli laitteet kierrätetään asianmukaisesti pidennetyn elinkaaren päätteeksi.

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Tiivistelmä - Referat - Abstract

Electronic waste is the fastest growing type of waste stream in the world, and this development results from the rapidly accelerating digitalization. Electronic devices become obsolete on an accelerating speed, as there are constantly more powerful devices coming to the market. The most significant environmental impacts of this development are greenhouse gas emissions and natural resource consumption. Circular economy has been proposed as a solution to these environmental challenges, and the goal of this approach is to preserve the value of the materials in the circulation as efficiently as possible. One way of implementing the principles of circular economy is the product-as-a-service-based business model.

This research examines the differences between the product-as-a-service-based model and ownership-based model in terms of the environmental impacts that are related to the laptop and tablet procurements. The results of this thesis will be utilized in implementing the actions of the City of Helsinki's Roadmap for Circular and Sharing Economy. This research was conducted as streamlined life cycle assessment, in which the systematic literature review was used for tracking the environmental impacts of the products' life cycle stages and components. In addition, expert interviews were carried out in order to collect information about the reuse and recycling practices of the supplier companies that follow these previously mentioned business models. Finally, based on the results of the systematic literature review and the interviews, the company specific differences were assessed in terms of the greenhouse gas emissions and material waste that result from the procurements. The City of Helsinki's annual procurement volumes were used in this assessment.

Based on the results of this research, production and use are the most significant life cycle stages in terms of the devices' greenhouse gas emissions. Printed circuit boards/printed wiring boards, integrated circuits, displays, and casings are the components with the most significant impact. The results suggest that increasing the lifespan of the devices provides opportunities for significantly lowering impacts in both impact categories, if the devices are efficiently recycled after this.

Keywords
circular economy, ICT, environmental impacts, product-as-a-service

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List of abbreviations and concepts

3R framework	Circular economy related framework, which consists of the practices of reducing, reusing, and recycling the products (Kirchherr, Reike & Hekkert 2017, 221)
CO_2 emissions	Carbon dioxide emissions
CO_{2e} emissions	Carbon dioxide equivalent emissions, which describe the total impacts of CO_2 and other GHG emissions (Clément et al. 2020, 1)
Direct effects	Emissions and resource usage that stem from production, use, and disposal (Bieser & Hilty 2018, 1.)
E-waste	Electronic waste (Kahhat 2012, 5)
Flowchart	Documentation of the activities and the flows between these activities in the analyzed system (Baumann & Tillman 2004, 26)
Functional unit	Quantified performance of a product system that can be used as a reference unit (ISO 14040 2006, 16-17)
GHG emissions	Greenhouse gas emissions (Bieser & Hilty 2018, 11)
GWP	Global warming potential (Clément et al. 2020, 1)
IC	Integrated circuit (Clément et al. 2020, 3)
ICT	Information and communication technology (Bieser & Hilty 2018, 1)
Indirect effects	ICT-induced changes in consumption and production patterns in other domains than ICT. (Bieser & Hilty 2018, 1)
LCA	Life cycle assessment is a methodological approach, in which the products' environmental impacts are mapped from raw material extraction to disposal phase (Baumann & Tillman 2004, 19)
LCI	Life cycle inventory analysis is a stage of LCA where the data is collected and the relevant inputs and outputs of the product system are calculated (ISO 14040 2006, 32–33)
LCIA	Life cycle impact assessment is a stage of LCA, where the magnitude of environmental impacts is evaluated (ISO 14044 2006, 14-15)
LCD	Liquid-crystal display (André et al. 2019, 270)

LED	Light-emitting diode (André et al. 2019, 270)
PaaS	Product-as-a-service is a procurement model where the supplier retains the product’s ownership and the customer procures them as a service (Vermunt et al. 2018, 893)
PC-ABS	Polycarbonate/acrylonitrile butadiene styrene plastic (Meyer & Katz 2015, 372)
PCB	Printed circuit boards (Clément et al. 2020, 5)
PCR	Post-consumer recycled materials (Meyer & Katz 2015, 381)
PWB	Printed wiring board (Kasulaitis et al. 2015, 2)
sLCA	Streamlined life cycle assessment refers to qualitative or semi-quantitative form of LCA, or a quantitative LCA that is based on already existing data (Pesonen & Horn 2013, 1782)
SLR	Systematic literature review is used for finding, picking out, evaluating, and combining all relevant research that is related to the research question (Bettany-Saltikov 2012, 5)
WEEE	Waste electrical and electronic equipment (Kahhat 2012, 5)

Table of content

1 Introduction

Electronic waste is the fastest growing type of waste stream in the world. This development is related to rapidly accelerating digitalization, which causes the electronic devices to become obsolete on an accelerating speed. Growing waste volumes and rapid manufacturing of new and more powerful devices cause significant stress for the environment, for example in terms of carbon dioxide equivalent (CO_{2e}) emissions and material consumption. (Ojala, Mettälä, Heinonen & Oksanen 2020, 24, 75.) The significance of these impacts is extensively associated with the end-of-life disposal options (see subsection 5.1.3). It is important to find solutions for a more comprehensive utilization of this waste, as it is likely that the acceleration of the digitalization continues in the future (e.g. Schwab 2016, 12).

Circular economy has been proposed as a measure for redesigning the linear consumption patterns. It is a systematic approach, in which the aim is to preserve the value of the materials in the circulation as efficiently as possible. In contrast to a so-called linear economic model, in which the raw materials are collected in order to make a product, which is then used, and finally disposed as a waste, in circular economy the goal is to form closed material cycles. (e.g. Ellen MacArthur Foundation 2013.) The problem with the concept of circular economy is its ambiguous nature, but very often it is associated with a so-called 3R framework, which consists of the practices of reducing, reusing, and recycling the products (Kirchherr, Reike & Hekkert 2017, 221). One form of implementing circular economy is the so-called product-as-a-service (PaaS) business model, in which the supplier retains the ownership of the products, and the customer procures them as a service (Vermunt et al. 2018, 980). This has been argued to extend the useful life of products due to the product take-back programs (Kerdlap, Gheewala & Ramakrishna 2020, 331). Circular economy has been proposed as a solution to the overconsumption of natural resources and to CO_{2e} emissions that exert pressure on biodiversity (Ellen MacArthur Foundation 2019B, 9, 26). Thus, it is important to study the potential of this approach in reducing the environmental impacts of ICT devices.

In order to comprehend the total impacts of ICT devices, it is necessary to understand the impacts that occur at every different life cycle stage. Life cycle assessment (LCA) is a methodological approach, in which the products' environmental impacts are mapped from raw material extraction to disposal phase (Baumann & Tillman 2004, 19), and by utilizing this approach it is possible to assess the ICT devices' most relevant components, life cycle phases, and environmental impacts. Several researchers also argue that there is a research gap in the studies considering environmental impacts of implementing circular economy, due to the lack of real-world business-related case studies (André, Söderman & Nordelöf 2019, 269). This study aims to advance the filling of this gap by providing information about the environmental savings potential of circular economy utilization in ICT procurements, focusing on opportunities that exist in the real-world business context.

Cities have been identified as especially important actors for advancing the transition from linear economy to circular economy (Häikiö & The ORSI consortium 2020), and large shares of natural resource consumption, greenhouse gas emissions production, and global waste generation take place in cities (Ellen MacArthur Foundation 2019A, 3). Therefore, studying the environmental saving potential of the product-as-a-service solutions in the context of cities' procurement operations is highly relevant. In this thesis, the object is to study the environmental savings potential of these solutions in the context of the City of Helsinki's ICT procurements. Finland is one of the world's leading countries in digitalization (Ojala et al. 2020, 13) and the City of Helsinki is the largest public procurement operator in Finland (Helsinki 2020, 5). Thus, studying the City of Helsinki's procurement alternatives provides an excellent target for a case study, in which the aim is to understand the environmental impacts of these procurement model options.

This thesis is conducted as a commission work for the City of Helsinki, and the objective of this study is to provide support for procurement related actions that are declared in The City of Helsinki's (2020) *Roadmap for Circular and Sharing Economy*. These actions include transition to service-based procurement model for those product groups that it is sensible and increasing understanding of procurement models that are smart in terms of life cycle impacts. (City of Helsinki Urban Environment Division 2020, 13.) The focus of this study is on the environmental impacts of laptops and tablets, and on the most significant life cycle stages and components of these devices, in terms of the most relevant impact categories. The differences between the life cycle impacts of these devices are assessed in the case of ownership-based procurement model and product-as-a-service-based procurement model.

In this study, two alternative ICT supplier companies' operations and environmental impacts are assessed. One of these companies states to follow the principles of circular economy, and to operate as a platform for service-based product procurements. Since the principles of a circular economy can mean many different things, this study also compares the company's operations to the most common definitions of the circular economy. This thesis is carried out as streamlined life cycle assessment case study, which is based on the ISO 14040 (2006) and ISO 14044 (2006) -standards, which provide a systematic approach for conducting the life cycle assessment. The data that is used for carrying out the LCA is collected by conducting a systematic literature review of the already existing studies, and by interviewing the representatives of the supplier companies.

The goal is to provide an answer to the following research questions:

RQ1. What are the most important stages and components in laptops' and tablets' life cycles, in terms of CO_{2e} emissions and material consumption?
RQ2. How are these stages and their impacts different in ownership-based procurement model and service-based procurement model?

The need for a shift from linear to circular economy has also been recognized in the City of Helsinki's strategy papers. In the *Helsinki City Strategy for 2017–2021*, it is stated that circular economy projects will be implemented in cooperation with companies, and in *Carbon-neutral Helsinki 2035 Action Plan* one of the declared actions is that the city would be implementing a carbon-neutral circular economy by 2050. (City of Helsinki Urban Environment Division 2020, 4.) Additionally, in the City of Helsinki's new procurement strategy it is stated that it is important to actively analyze the supplier markets in order to find new service models early on (Helsinki 2020, 9). This thesis will provide an extensive support for the city's several target programs, and it can assist in a transition to more sustainable operating models.

The thesis contains seven main chapters. The second chapter of this thesis is the analytical framework, which will introduce the reader to the theoretical assumptions and perspectives that motivate the need for this study. The third chapter will provide information about the City of Helsinki's state of affairs in the context of this study. The selected methodological approaches and the utilized data will be introduced to the reader in the fourth chapter, and the fifth chapter will provide the results that were obtained by these methods. The sixth chapter will consider the limitations of this research, and in this chapter the results are also linked to the theoretical assumptions that were introduced in the second chapter. Finally, in the seventh chapter the main finding and conclusions of this study will be made.

2 Analytical framework

The first aim of this chapter is to review the topical nature of technological development. This will be the focus of the first section 2.1. This section is divided into subsections 2.1.1 where the exponential growth of technological acceleration will be considered through various descriptions presented by different scholars and intellectuals, and to 2.1.2 where the implications of this development for a highly digitalized welfare state will be analyzed. The following section 2.2 will consider the sustainability challenges that are related to ICT. The section is divided into two subsections in which the most significant environmental challenges of ICT will be presented. Subsection 2.2.1 will focus on the increasing greenhouse gas emissions and energy consumption and subsection 2.2.2 on the increasing material consumption. The last section of this chapter, 2.3, will present the concept of circular economy, and consider it as a possible solution for the environmental challenges that are related to ICT procurements.

2.1 Technological and social development

Technological development is one of the most important social phenomena, as technology has started to blend into almost every aspect of life and manifests as various social trends that each shape the society (Ahmed, Naeem & Iqbal 2016, 43; Dufva 2020, 2, 39; Røpke & Christensen 2012, 349). One of the key features of technological development has been its long-lasting exponential acceleration (e.g. Mollick 2006; Brynjolfsson and McAfee 2014), which indicates that the impact on society could also accelerate in the future. To some extent these impacts can be seen to contribute to socially pursued goals, such as economic and social progress, but on the other hand, technological development also poses various risks for the society and the environment (e.g. Dufva 2020, 40–42; Ojala et al. 2020). Technological acceleration is an important concern when considering opportunities for a more circular economy, since it entails a rapid pace of change in materials and products.

2.1.1 Technological acceleration

On the 1960s Intel’s former chairman Gordon Moore predicted that the number of transistors that can be fitted into a microchip would double every year or two, which later became known as Moore’s law. While no longer valid as a ’law’, the prediction of exponential technological development has remained rather successful for several decades. (Mollick 2006, 62; Brynjolfsson and McAfee 2014, 40–41; Lange, Pohl & Santarius 2020, 5.) This exponential development speed has in recent decades revolutionized the society in many ways, but according to many scholars, the greatest revolutions are yet to come.

Klaus Schwab (2016, 7), the founder and executive chairman of the World Economic Forum, has for example argued that we are in the middle of the fourth industrial revolution, which can be characterized as *“*a profound shift across all industries*”*. Correspondingly, according to Schwab (2016, 12) and Massachusetts Institute of Technology (MIT) Professors Brynjolfsson and McAfee (2014), we are now on an inflection point, after which the effects of technological development really start to manifest. Brynjolfsson and McAfee (2014) argue of the significance of the force of change, by referring to the current period as the second machine age. This concept refers to an idea, that computers have started to do the same thing for mental work that steam engines did for muscle work; that is to exceed the previous limitations. Technological acceleration can also be seen as a self-propelling process, because economic operators are under the pressure to adopt the latest technology, as otherwise they will be outdated (Rosa & Scheuerman 2009, 88–89).

In addition to exponentially increasing computer speed, a crucial assumption of Moore’s law is the affordability of computing power. Moore noticed that computing power obtained per every spent dollar doubled yearly from 1962 to 1965. (Ahmed et al. 2016, 43; Brynjolfsson & McAfee 2014, 40–41; Mollick 2006, 65.) The reason why the improvement of computers has been so radical, is that the physical limitations in digital world are much looser than in many other forms of manufacturing. In addition, engineers have been able to find many ways to overcome the obstacles that physics have set for development. (Brynjolfsson & McAfee 2014, 42.) Next, the aim is to review how this constant increase in computing power, and decrease in its price, has affected people and society in Finland, which is one of the world’s leading countries in digitalization (Ojala et al. 2020, 13).

2.1.2 Information society and sustainability in a Finnish context

The internet and the development of ICT devices have increased labor productivity (Brynjolfsson & McAfee 2014, 98–99; Castells & Himanen 2002, 2, 21; Lange, Pohl & Santarius 2020, 2). Various studies show that ICT development has a positive impact on a country's economic growth and this relation seems to be especially pronounced in high-income countries (Lange, Pohl & Santarius 2020, 5). Finland has been regarded as a prime example of a Nordic information society and as one of the world's leading countries in digitalization, because of the strong information and communication sector. (Ojala et al. 2020, 13; Castells & Himanen 2002, 5). The Finnish model has been a target of academic interest as different scholars have contemplated the reasons behind the success (see e.g. Castells & Himanen 2002; Miettinen 2013).

According to the studies by Castells & Himanen (2002, 141–146) and Miettinen (2013, 2), Finland has been able to form a self-reinforcing system, in which social and economic sustainability goals are being achieved in a mutually supportive way. However, although Finland has ranked globally well in terms of various measures of well-being, it has not been as successful in terms of ecological sustainability (Ojala et al. 2020, 13). According to the ORSI joint project, the current level of social welfare in Finnish society cannot be considered as being on an environmentally sustainable basis, because the carbon dioxide emissions and the use of natural resources are on a high level compared to the rest of the world. Finland is not alone with this challenge, since no other welfare state has presented a credible plan for transition to eco-welfare state yet either. (Häikiö & The ORSI consortium 2020.)

Finland aims to be carbon neutral by 2035, which requires that emissions are reduced in all sectors. There is a need for coherent and transparent measures for tackling the environmental and climate impacts of the ICT sector, as the sector has continued to advance, and the environmental impact has continued to increase. (Ojala et al. 2020, 12–13.) As a later review shows, the environmental impacts of ICT sector contribute to those challenges that have been remarked by ORSI joint project as especially challenging for Finland (Häikiö & The ORSI consortium 2020; Dufva 2020, 42; Ojala et al. 2020, 24). Changes in consumption patterns are an essential measure for a state's ability to reach the sustainability goals of Agenda 2030, that Finland as a member state of the United Nations has agreed on (Ministry for Foreign Affairs of Finland 2020). Cities are considered as important drivers of this change (Häikiö & The ORSI consortium 2020.), as they account for 75% of the natural resource consumption and produce 50% of the global waste and 60–80% of greenhouse gas emissions (Ellen MacArthur Foundation 2019A, 3).

2.2 Sustainability challenges of ICT

The economic development and growing middle classes are driving changes in Earth's life support system (WWF 2018, 23; Ellen Macarthur Foundation 2013, 14), and as mentioned in the subsection 2.1.2, no technologically advanced welfare state has been able to provide their standard of living on an environmentally sustainable basis (Häikiö & The ORSI consortium 2020). The technological progress is an important driver of social and economic development, but it is important to understand its true costs. Moreover, as the progress is accelerating, the environmental risks should be mapped expeditiously, as there is a chance that they also worsen with an accelerating pace in the future.

The environmental impacts of the ICT sector have only recently begun to arouse public interest, and the focus has so far been mainly on the digitalization's potential in emission reductions (Ojala et al. 2020, 12, 14). The ICT sector provides enormous potential in lowering other sectors' carbon emissions through optimizing, replacement of physical products, and resource efficiency enhancing (Ojala et al. 2020, 23; Lange, Pohl & Santarius 2020, 4–5), but it is also associated with significant negative environmental impacts. The most significant of them are related to greenhouse gas (GHG) emissions that stem from growing energy use and material consumption (Dufva 2020, 42; Ojala et al. 2020, 24), which will be considered in the following subsections 2.2.1 and 2.2.2. In the context of Finland, the consumption of data has been growing exponentially in approximately two years cycles (Wirén, Vuorela, Müller & Laitinen 2019, 9–10). The demand for energy is also increasing exponentially (Ahmed et al. 2016, 43), and therefore it is likely that the environmental impacts of digitalization will continue to increase in the future.

2.2.1 Increasing greenhouse gas emissions and energy consumption

The environmental impacts of ICT have been studied since the early 1990s, and special focus has been put on energy consumption (Røpke & Christensen 2012, 348). The progress in digitalization has had a positive correlation with increases in energy consumption and GHG emissions during the last decades, which is a problem as a great proportion of the global electricity production is generated by burning fossil fuels (Ojala et al. 2020, 27). This increase has resulted from the rising production, use and disposal of ICT devices. (Lange et al. 2002, 2.) Improving energy efficiency and increasing the share of low-emission electricity have been proposed as direct means for reducing the environmental impacts of ICT (Ojala et al. 2020, 98). Energy efficiency on the ICT sector, has continuously improved during the last decades, but as the sector's growth has been more significant than the growth in efficiency, the energy consumption has not been decreasing (Lange et al. 2020, 4).

A situation, in which increase in energy efficiency does not lead to decrease in energy consumption, is referred to as the Jevons' paradox. The notion was put forward by an economist William Stanley Jevons (1865), and the original context of the paradox was the increasing demand of the British coal resources. Later this finding has been cited in various contexts, and the concept of a rebound effect has been used as an umbrella term for such mechanisms (Sorrell 2009, 1456–1457). As mentioned in the previous chapter, the mechanisms seem to also apply to energy efficiency on the ICT sector, as the sector has grown more rapidly than its energy efficiency (Lange et al. 2020, 4). Yet, many governmental and non-governmental operators still assume that the efficiency lowers consumption and the environmental impacts (Alcott 2005, 9). If the apparent mechanism explains the growing energy use on ICT sector, it would have profound implications for the discussion of carbon emissions (Sorrell 2009, 1456). There is still not a unanimous perception of whether this is the case, but the majority of the rebound effect researchers argue that the effect is significant enough to prevent sufficient reduction in energy use (Lange et al. 2020, 5). It is important that the governmental and non-governmental operators adopt a critical standpoint, when studying the potential environmental impacts of energy efficiency. This does not imply that the focus on energy efficiency should be neglected in reviews, but the existence of the rebound effect must be recognized when designing sustainability measures for the ICT sector.

Another important factor influencing the environmental impacts of ICT is the source of the energy being used. Electricity is often produced by burning coal, natural gas, or oil (Ahmed et al. 2016, 43–44), which generates carbon dioxide (CO_2) missions. ICT companies can reduce their CO_2 footprint by utilizing renewable electricity (Ojala et al. 2020, 28), and some scholars argue that due to the rebound effect, this measure is more effective in coping with the ICT related CO_2 emissions than focusing on the energy efficiency (Herring 2006). Globally only 20–25% of the total energy is collected from hydro, nuclear or renewable sources, so internationally compared, the electricity consumed in Finland is relatively carbon-free, as approximately 35% comes from renewable sources and 27% is produced by nuclear power (Ahmed et al. 2016, 44; Ojala et al. 2020, 27, 143).

There are different research results on the distribution of energy consumption in the ICT sector. According to some studies, it is precisely the role of data centers in energy consumption that is significant, and according to others, the consumption takes mostly place in consumer devices. (Ojala et al. 2020, 25.) In addition, the use of ICT also increases energy consumption through the production and running of the products (Røpke & Christensen 2012, 349). It is undeniable that due to digitalization, a larger share of the societal energy use will be in a form of electricity. However, this development is crucial, since ICT has an important role in making the infrastructures more energy efficient. (Ahmed et al. 2016, 45.)

2.2.2 Increasing material consumption

In addition to growing CO_2 emissions and energy consumption, the construction and use of ICT infrastructure also consume an increasing amount of materials. The extraction of raw materials is a significant cause of greenhouse gas (GHG) emissions, but it also has other environmental impacts, such as habitat loss and deterioration. (Ojala et al. 2020, 22.) Electronic waste (e-waste) contains toxic elements, such as lead, mercury, and chromium, that can potentially harm humans and nature if the waste is being placed on municipal solid waste landfills (Kahhat 2012, 7–8). It has been estimated that the amount of e-waste continues to grow as much as 6.5% annually, which makes it the fastest growing waste stream in the world (Ojala et al. 2020, 75). In order to reduce the material consumption, it is important to locate the different processes of the life cycle, in which the material consumption is formed.

The material basis of ICT devices forms in a so-called upstream and downstream processes. Upstream processes refer to mining and extraction, refining, and production of the raw materials, production of components, and lastly the product itself. Downstream processes, again, refer to the use of the product, material recovery, and disposal. (Wäger, Hischier & Widmer 2014, 3.) The largest share of the materials that are used in terminals are metals, polymers, and glass. Some of the most commonly used metals are aluminium, copper, and iron. In addition, the devices contain scarce metals, such as gold, indium, platinum group metals, and rare earth elements. (Ojala et al. 2020, 78; Wäger et al. 2014, 2.) Laptops and tablets are considered as the most valuable form of e-waste, due to the high content of essential metals in relation to their size. Being more compact, tablets have a very high content of those materials, but the compactness also makes it more challenging to recycle the devices. (Cucchiella et al. 2015, 265.)

The problem with the material consumption is that a large proportion of the materials does not end up in a circulation at the end of the device's life cycle, even though they have a lot of value embedded in them. Printed circuit boards (PCBs), for example, are components that are significant in terms of their environmental impacts (see later subsection 5.1.5). Yet, 40% of them end up in landfills, because recycling is difficult due to their complex composition and structure (Cucchiella et al. 2015, 265). As a result of the rapidly evolving performance of the devices, new devices are introduced and old ones are discarded at an accelerating rate, and a rather large proportion of the discarded devices would still be usable. (Ojala et al. 2020, 75.)

2.3 Circular economy

The growing amount of e-waste reflects the issue that the value of the resources that are used in products are not fully utilized, after the product has come to the end of its life cycle. These kinds of problems are related to the so-called linear consumption model, which relies on take-make-dispose principles. Linear consumption creates supply chains that are material and energy intensive, as the material flows come to a dead end by the end of the product’s life cycle. In order to meet the current level of material demand, circular economy has been proposed as a key to a system level redesign. Such transition could not only lower the pressure on resource supply, but also lead to significant economic opportunities. (Ellen MacArthur Foundation 2013, 5, 14, 23–24.)

Circular economy is an economic model that is restorative by intension and the aim in this model is to manage material flows carefully. The goal of minimizing the amount of waste is already considered in the product design phase, since the product’s life cycle is mainly determined already during its development. The technical materials and components are already in this stage designed in a way that they can be recovered, refreshed, or upgraded if needed. Reducing, reusing, and recycling form a taxonomy of the so-called 3R practices. (Ellen MacArthur Foundation 2013, 26; Sihvonen & Ritola 2015, 639–640.) Reducing refers to extending the product’s life cycle, for example by making it high-quality or emotionally attachable, so that the need to purchase new products decreases. Reusing refers to using either the whole product or its components again for example by repairing, refurbishing, or remanufacturing them. Reusing can also be carried out for example by reselling the product for a lower price into a different market segment. Recycling refers to any operation, in which the waste material is transformed into new products or materials. Sometimes also a fourth R has been added to the taxonomy, standing for recovery, which refers to the practices that recover, for example, valuable or hazardous materials after the product’s life cycle. (Sihvonen & Ritola 2015, 640–642.)

However, the problem with the concept of circular economy is its ambiguous nature. In their study, Kirchherr et al. (2017, 221) mapped out 114 definitions for circular economy, and the most common depiction was the 3R framework. The ambiguity is especially important to highlight when conducting a case study of a company that portrays itself as an operator that follows the principles of circular economy. Based on the extensive mapping by Kirchherr et al. (2017) the most important determinants for circular economy principles are following the practices of the 3Rs.

One way of implementing circular economy is the so-called product-as-a-service model, in which the supplier retains the ownership of the products, and the customer procures them as a service. This model is essentially linked to the reducing practices of the 3R framework, as it redefines how the products are used. (Vermunt et al. 2018, 893.) Utilizing this business model can lead to an extension of the product’s lifespan due to the companies’ product take-back programs that keep the products in use as long as they have service value (Kerdlap et al. 2020, 331). In some circular business model taxonomies, the product life cycle extension has also been considered as a separate business model, which is mostly related to the reusing practices in the 3R framework (Vermunt et al. 2018, 893). Although the life cycle extension category has been separated as a distinct circular business category in some taxonomies, PaaS-based business models can still often lead to product’s life cycle extension as well.

Implementing circular economy -based business solutions is not only related to lowering the products’ material impacts, but it also provides significant potential in reducing the CO_{2e} emissions of key industrial materials, such as steel, aluminium, and plastics (Ellen MacArthur Foundation 2019B, 26). As mentioned in previous subsections, the most important environmental impacts of ICT sector are CO_{2e} emissions and material consumption. Thus, as the principles of circular economy have been proposed to provide solutions for both environmental challenges of ICT, it is important to study the potential environmental savings of implementing circular economy principles in the ICT sector.

3 The City of Helsinki and the research context

As mentioned in subsection 2.1.1, cities offer a great potential for supporting the transition to more sustainable procurement practices due to their exceptionally large procurement volumes. In the case of the City of Helsinki, for example, the annual procurement volume is approximately four billion euros, making the City of Helsinki the largest public procurement operator in Finland (Helsinki 2020, 5). Thus, reviewing the environmental savings potential of the ICT procurements in the context of the City of Helsinki can have significant environmental impact potential, contributing not only to the city's strategies but also on a country level to the *Carbon-neutral Finland by 2035* programme.

Many large cities around the world have started to notice the capability of circular economy solutions in promoting their environmental, social, and economic interests (Crocker et al. 2018, 3). The need for a shift from linear economy into circular economy in solving the global sustainability challenges has also been recognized by the City of Helsinki. In the *Helsinki city strategy for 2017–2021*, circular economy projects were stated to be implemented in cooperation with companies and citizens, and the *Carbon-neutral Helsinki 2035 Action Plan* was approved in 2018. One of the declared actions of this action plan was to form a roadmap for circular and sharing economy.

The aim of this thesis is to support the City of Helsinki in achieving the circular economy goals of this roadmap in terms of procurements, which has been defined as one of the key target areas. These actions include moving to service-based procurement model for those product groups that it is rational and increasing understanding of procurement models that can provide savings in terms of life cycle impacts. (City of Helsinki Urban Environment Division 2020, 13.) Additionally, the city's procurement strategy has been updated in 2020 into a form that takes responsibility in procurements more extensively into account. In the new procurement strategy, it is stated, that in order to recognize the available solutions early on, it is important to actively analyze the supplier markets and build market dialogue with different suppliers (Helsinki 2020, 9).

Conducting this study provides the City of Helsinki a chance to have a deeper review of the two procurement types, that are representing different business models. The first supplier was selected for the review, because the City of Helsinki was already familiar with the company's ICT services, and it was considered to be a supplier whose services could potentially be utilized in the future. The second company, on the other hand, had been noticed by the City of Helsinki's procurement officers, as it markets itself as an ICT company that follows the principles of circular economy and operates as a platform for service-based product procurements. Assessing the environmental impacts of the two companies' operations will support the City of Helsinki's pursuit of lowering the environmental impacts of their ICT procurements. However, as mentioned in subsection 2.3, the problem of the concept of circular economy is its ambiguous nature. Thus, to truly understand whether the operations of the Company 2 correspond with the general understanding of circular economy, it is important to consider the products' and their components' life cycles in both procurement options (see figures 2 and 3).

Carbon-neutral Helsinki 2035 Action Plan states that in order to achieve its goal, it is necessary to implement circular economy principles in all of the possible procurement areas (Helsinki 2020, 11). The City of Helsinki procures approximately 20,000 laptops each year, and as the typical office laptop weighs around 1.8 kg, the city's annual laptop procurements weigh around 36,000 kg (Lehtinen 2018, 7). Furthermore, focusing on the environmental impacts of the ICT procurements is especially important, because as stated in subsection 2.2.2, e-waste is one of the fastest growing forms of waste, and the laptops and tablets are the most valuable form of e-waste. Therefore, studying the life cycle impacts of alternative laptop and tablet procurement measures can provide an exceptionally influential approach for affecting the city's environmental footprint.

The city has formed a fixed term contract with the current supplier, who takes care of the secure disposal of the equipment. The minimum responsibility requirements for the supplier in tenders is that they accept as many old devices for secure and environment friendly recycling as they have provided as new ones. Once the devices are delivered, they are entered into the ICT equipment register and the maintenance and repair are taken care of by the warranty provider. Currently the most common reason for disposal is that the device has become unusable due to damage or end of service life. (Lehtinen 2018, 5–7.)

However, the city is not obligated to return the used devices back to the supplier. A part of the disposed devices has been directed to the Uusix workshop, which is a work rehabilitation center operating under the City of Helsinki's Social Services. There the devices are repaired and security processed, after which they are directed for reuse. Some of the working components of the otherwise unusable devices have been used in repairing other devices. According to the foreman of Uusix, during 2018 around 8500 items had gone through their accounts. Of those items a relatively larger share was reused than disposed. (Lehtinen 2018, 7–8.)

However, information presented in here can be considered to some extent outdated, as it reflects the situation in 2018. In order to gain more recent information, the original plan was to interview the foreman of Uusix as a part of this study. However, as Uusix operates under the City of Helsinki's Social Services, the unit's need for a research permit would have caused broad scheduling challenges for the progress of this study. For this reason, information related to Uusix was based on an internal report by Lehtinen (2018), in which the cycle of the City of Helsinki's ICT devices is reviewed.

As Lehtinen (2018) points out, the City of Helsinki is already engaging in circular economy of ICT devices to some extent, by utilizing the services of the Uusix workshop for extending the products' life cycles. Yet, the procurement volumes are relatively large, and only a portion of the disposed devices is reused through Uusix. Therefore, it is important to study the differences in environmental impacts of implementing different procurement models and the end-of-life treatments that are related to them.

4 Methods and data

In this chapter the reader will be familiarized with the methods and data that are used in this study. The study is conducted as a streamlined life cycle assessment (sLCA), and the focus of this approach is on the two of the devices' most significant impact categories, CO_{2e} impacts and material consumption. The principles of life cycle assessment (LCA) are presented in section 4.1, and subsections 4.1.1 and 4.1.2 provide more details about the stages, simplifying, and limitations of the process. The first step of this study is to understand the most important stages and components in laptops' and tablets' life cycles, in terms of CO_{2e} emissions and material consumption. In this step, a systematic literature review (SLR) of already existing LCA articles is conducted, as it is often an efficient way to start LCA by utilizing data that has been already collected in previous studies (Baumann & Tillman 2004, 94). SLR is often used to support other research measures (Salminen 2011, 9–10), and it offers a good basis for the later steps of this study. Thus, the aim of the SLR step is to provide answers to the RQ1 and to guide in the creation of the devices' flowcharts in different end-of-life treatment options (see subsection 5.1.1). SLR as a research measure is presented in section 4.2, and section 4.3 considers the actual screening process, in which the inclusion and exclusion criteria will be defined, and the selected search terms and database will be presented. At the end of the section the actual literature search is also conducted, but the analysis will be presented in chapter 5.

The second step of the sLCA is to assess the differences in the life cycle stages and their impacts in the context of the ownership-based procurement model and service-based procurement model. The conduction of this step relies on expert interviews, in which the representatives of the case specific companies are interviewed about the procedures that their companies use at the end of the devices' life cycles. One of the case companies represent a business model, in which the customer owns the devices, and the other case company represents service-based business model, in which the customer procures the devices as a service. The interview questions are formed based on the findings of the SLR, and the results of the expert interviews put the information that is obtained by the SLR, into the context of the City of Helsinki's procurement choices that are under consideration. Section 4.4 will provide details about the expert interviews as a scientific method. The companies, who's representatives are being interviewed, will be presented in section 4.5. The aim of the interviews is to provide information about the devices' life cycles in the different procurement contexts. Based on this information, it is possible to answer the RQ2.

4.1 Life cycle assessment

Life cycle assessment (LCA) is a method that is used to track the product's or service's environmental impacts during its whole life cycle, for example, from raw material extraction to disposal phase (Baumann & Tillman 2004, 19). This measure can be used to support the decision-making process, when the operator is considering between different alternative operating models (Baumann & Tillman 2004, 40; Kjaer, Pigosso, McAloone & Birkved 2018, 666–667). LCA principles have been assembled as ISO 14040 standard series, and the most important standards for working with LCA are undoubtedly the ISO 14040 and ISO 14044 standards (Beemsterboer, Baumann & Wallbaum 2020, 2160). These standards offer a terminologically and methodologically systematic review for the implementation of LCA, by focusing on principles and main features of the LCA, and the requirements and guidelines for conducting it (ISO 14040, 2006; ISO 14044 2006). Environmental impacts are difficult to estimate on a very detailed level, and transparent reporting of research phases is important, in order for the reader to understand the possible complexities and shortcuts that have been taken in the process (Baumann & Tillman 2004, 21, 207). Obtaining all the data that is required for documentation can also be difficult, and the use of assumptions to fill data gaps is not unusual. Informing the reader about missing information is also important, so that the process remains transparent (Baumann & Tillman 2004, 228.)

Using a full LCA is not always a possible or suitable methodological solution, due to the lack of time or resources, and LCA has been simplified into many different versions (Pesonen & Horn 2013, 1781–1782). Streamlined LCA is a concept that refers to qualitative or semi-quantitative form of LCA, or a quantitative LCA that is based on already existing data. The streamlined version is particularly suitable for supporting decision-making, and for detecting the aspects that need to be optimized in terms of organizations' sustainability and life cycle perspectives. Also, it should be highlighted that the researchers' finding that have been obtained by these measures, have led to actual changes in the ways that the studied organizations have been operating. (Pesonen & Horn 2013, 1781–1783.)

4.1.1 Stages of LCA

In this study, the ISO 14040 (2006) and ISO 14044 (2006) standards are used as guidelines for conducting the LCA, as they offer a reliable and high-quality framework for the work. According to these standards, the LCA process can be divided into four different phases, which are: 1. the goal and scope definition phase, 2. the inventory analysis phase, 3. the impact assessment phase, and 4. interpretation phase (ISO 14040 2006, 8–9; ISO 14044 2006, 8–9).

Considering the subject and the intended use for the study is important, when defining the goal and scope of the study. In this first phase, the functions of the compared systems, the limitations of the study, the assumptions taken, the functional unit, and the data requirements are defined. The data is collected in the life cycle inventory (LCI) analysis phase. Relevant objects for data gathering are the inputs, waste, and emissions that are related to the products or services under consideration. In the third step, the life cycle impact assessment (LCIA), the aim is to assess the potential environmental impacts, based on the results of LCI. The limitation of LCIA is that it only focuses on the environmental aspects that are reviewed and it cannot provide information about all the environmental aspects that are related to the product or service. There also is not a generally accepted method for accurately connecting the LCI data into potential environmental impacts. The last phase of the LCA is interpretation, and in this phase the conclusions and recommendations are made. If the LCA is conducted for a third party and LCIA is included, it is important to inform the reader about the data quality, selection process of impact categories, and other relevant aspects that might impact the quality of the assessment. (ISO 14040 2006, 30–41.)

4.1.2 LCA in the context of this study

The public sector is often assumed to be a pioneer in sustainable procurements, and LCA is a suitable environmental tool for supporting this goal (Baumann & Tillman 2004, 293), which is why it is chosen as a methodological approach for providing answers to the research questions. The LCA being conducted in this study is a streamlined version of the

LCA. The reason for selecting this approach is the shortage of time and data for conducting a full scale LCA of the case companies. Pesonen & Horn (2013, 1781) for example state that sLCA is a faster assessment tool than full LCA and provides results that are easier to understand by the stakeholders.

The sLCA in this study is simplified in terms of excluding the assessment of the impacts of life cycle stages that are similar in both procurement models. According to ISO 14044 (2006, 24–25), it is important to also present the excluded stages when such approach is taken and articulate why they can be left out of the review. As the aim of this thesis is to review the differences of the impacts in different procurement models, it is sensible to only focus on the stages that differ. The excluded stages are presented for the reader in the devices' flowcharts (see subsection 5.1.1). Another simplifying strategy that is taken in this sLCA, is to include only those impact categories, that are considered in chapter 2 as the most significant ones in the case of the devices in question. These categories are CO_{2e} emissions and material consumption. However, it is worth highlighting that by focusing only on specific impact categories, the ability to predict the total environmental impacts suffers. (Beemsterboer et al. 2020, 2157–2158; Baumann & Tillman 2004, 25.).

An important step of the LCA study is to define the functional unit, to which the LCIA is related, as it determines what is being studied and ensures that all analyzes are relative to a similar unit. (ISO 14040 2006, 22–23.) The functional unit in this study is ”one year of access to the device". Although it can be argued that reused devices are not functionally equivalent to new ones, similar functional unit was taken in a resembling study by André et al. (2019), which is included into the SLR. In this study, André et al. (2019, 270) argue that due to the devices' as-new condition and the subjective nature of the functionality, the devices' can be considered functionally equivalent even after the first life cycle.

The proceeding of this LCA is conducted by following the stages that are presented in the ISO 14040 (2006) standard, but in an order that fits better to the structure of a thesis work (see appendix 1). The first step is to define the goal and scope of the study, which are defined in the introduction chapter. The limitations of the study and the assumptions taken are presented later in section 6.1, the functional unit is defined in this subsection, and the functions of the compared systems are presented in section 5.2. The second stage is the LCI, in which the data is collected. For this stage, systematic literature review (SLR) is used for gathering data of the environmentally most impactful components and stages of life cycle of the devices in question. In the case of ICT, it can be difficult to collect all the needed data, as the products are very complex. However, during the last two decades it has become possible to utilize already available databases or already existing LCA studies. (Beemsterboer et al. 2020, 2158–2159; Baumann & Tillman 2004, 94.)

After the data has been collected, it is used to support the creation of the interview frames (appendix 4 and 5) for the expert interviews, which provide data of the context related differences in different procurement models. Analyzing the differences becomes more efficient, if the most impactful stages of the life cycle can be known in advance (Beemsterboer et al. 2020, 2157). The third stage is the LCIA, in which the potential environmental impacts are assessed. This assessment is carried out in section 5.3. The last stage is the interpretation phase, in which the conclusions and recommendations are made. This stage is presented in subsection 5.3.3.

4.2 Systematic literature review as a research method

The general characterization of a literature review is that it is a research method intended to gather results from other scientific sources in order to create new results. The process needs to follow precise rules and guidelines, as otherwise it might lack systematicity and reproducibility. (Salminen 2011, 1, 5.) The aim is to collect and retrieve the available evidence of a specific topic, and to obtain a comprehensive understanding of what is known about it. Comparing and reviewing the results of an individual study with several studies on the same topic can also be seen to add value to an individual piece of research, as it is seen in a broader context. (Aveyard 2014, XV.) Literature review is not a lightly discussed bibliography, but the quality is measured by the depth, precision, consistency, and the effectiveness of the analysis and synthesis. (Hart 1998, 1.)

There are several reasons for selecting a literature review as a research method. It can be used, for example, in cases where the aim is to build a comprehensive picture of a particular issue or identify problems that should be addressed (Salmela 2011, 3). Literature review is a hypernym for several measures, and it is often distributed into three different subcategories: descriptive literature review, meta-analysis, and systematic literature review (SLR). The aim of the SLR measure is to find, pick out, evaluate, and combine all relevant research that is related to the research question (Bettany-Saltikov 2012, 5). Along with the meta-analysis, the SLR is the most detailed form of literature review, as the process follows a strict protocol and a search strategy (Aveyard 2014, 10–11). In addition, for being used as a research method on its own, often it is also used as a measure to support other study methods and to build an introduction for a study. Due to the rapid growth of the amount of information available, using SLR is practical solution in case there is a need to collect information that supports decision-making process. (Salminen 2011, 9–10.)

As the aim of this study is to support the City of Helsinki's decision-making in selecting an environmentally sustainable ICT procurement measure, using systematic literature review is a relevant method for mapping the products' life cycles and life cycle impacts. It allows an extensive assessing of the existing literature that is relevant for the topic and provides a basis for conducting the expert interviews. Also, due to the exponential growth of technological development (e.g. Mollick 2006; Brynjolfsson and McAfee 2014; Lange, Pohl & Santarius 2020), it is well reasoned to assume that the data collection should proceed systematically, as the studies being utilized must represent current state of affairs. It is also generally considered that if literature review is being used as a research method in a thesis or dissertation, the approach should be systematic (Aveyard 2014, XVI). Lastly, it is possible to save a lot of effort when conducting a LCA, if the data collection can be implemented by relying on studies that have already been carried out (Baumann & Tillman 2004, 98).

The systematic protocol of conducting SLR can be divided into separate steps. The so-called Fink's (2005, 3–5) model is presented in the work by Salminen (2014, 10–11), and in this model the process of conducting a SLR is divided into seven distinct steps. Another comparatively similar modeling is presented by Bettany-Saltikov (2012), but in this model the steps are arranged in a slightly different manner. The steps presented in this paper are formed based on these two comparatively similar models, and they are presented in figure 1. Due to the slight differences in order of the steps presented by Fink (2005) and Bettany-Saltikov (2012), the steps produced by the combination of these models formed a six-step procedure for SLR conduction.

The first step is to choose a research topic and to form a research question. The question should be answerable and focused, and it should be justified why it is worth investigating. The second step is to form a study plan and to introduce the background for the study. Forming a study plan minimizes the risk of bias, as the researcher should not change the way they review the papers after seeing the results. Introducing the background, again, outlines the context of the study and the reasons why investigating it is important. The third phase is to choose the inclusion and exclusion criteria that will be used in the screening. The criteria can concern for example the articles' publishing year, language, or content, and they should be transparently reported to allow the study's reproducibility. The fourth step is to select the databases and the search terms. By selecting the proper databases and search terms, the material being examined is more likely to answer the research question. Usually, it is useful to utilize multiple databases, and the keywords being used can be either single words or phrases.

The fifth step is to conduct the literature search. The aim is to examine the scientific quality of the articles and their suitability for review and filter out any irrelevant articles. The sixth step is to conduct the actual study and to analyze the selected papers' content, which is usually the most challenging stage of SLR. The aim is to gather all the information from the articles that is relevant in answering the research question. For the results to be valid and the process to be systematic, it is helpful to create a data extraction form that describes the article-specific results (see appendix 2 and 3). Lastly, the seventh step is to synthesize and summarize the results that arise from the selected papers. Current information and demonstration of research needs are being reported, and the similarities and differences in data are being examined. These different steps are portrayed in figure 1 (Fink 2005, 3–5; Salminen 2014, 10–11; Bettany-Saltikov 2012.)

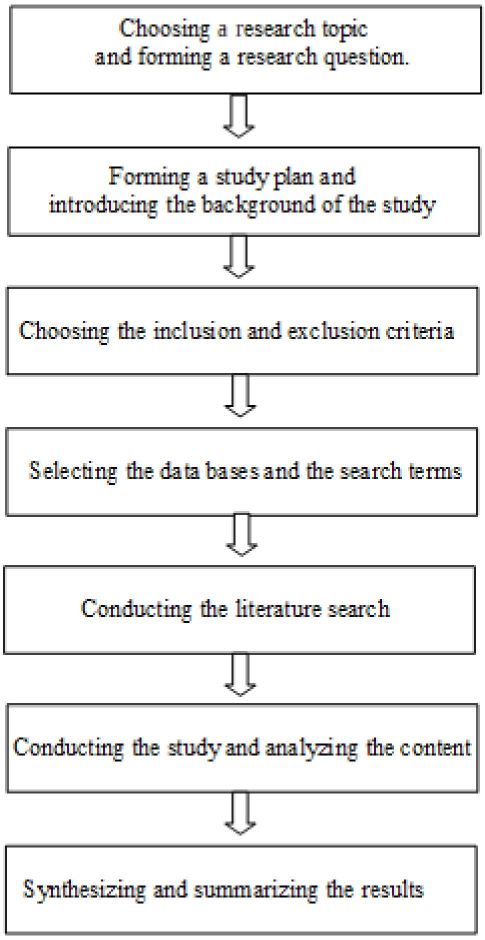

Figure 1. The steps of conducting a SLR (Fink 2005, 3–5; Salminen 2014, 10–11; Bettany-Saltikov 2012)

By this paragraph, the first two steps have already been conducted. The remaining steps are more focused on the actual screening process (Salminen 2014, 10), and the steps from three to five will be presented in the next section. The last two steps will be presented in chapter 5. The data extraction forms will also be displayed in the appendices (appendix 2 and 3).

4.3 Screening

Strictly and transparently reported inclusion and exclusion criteria are a precondition for a high-quality systematic literature review. Setting them allows one to target only to the papers that are relevant to the research question and to exclude the irrelevant ones. (Bettany-Saltikov 2012, 55.) It also ensures that the focus stays on answering the research questions, and that the study does not start to stray too far from the original emphasis. As the aim of this review is to map the laptops' and tablets' life cycle, and the environmental impact on different stages of the cycle, the inclusion and exclusion criteria must also be selected in a way that supports this matter.

One important criterion in this context is the publishing year. As ICT devices develop on an accelerating speed (e.g. Mollick 2006; Brynjolfsson and McAfee 2014; Lange, Pohl & Santarius 2020), it is important that the reviewed papers are published recently, as the relevance of an ICT related paper can become obsolete quickly. In addition, financial constraints limit the accessibility in a context of this thesis, which adds another criterion of a free access to the resource. Material review is also limited to electronic databases only, and only publications in English are included in the review in order to ensure a clear understanding of the content. The last criterion for the inclusion is the methodological approach that has been taken. As one goal of the SLR is to collect and combine information from already implemented LCA studies, it is important that the articles that are included in the SLR are methodologically equivalent. Thus, only those articles that use LCA, or a LCA related methodological approach, are included into this review.

Table 1. Inclusion and exclusion criteria for the literature

Inclusion criteria	Exclusion criteria
- Published in/after 2015 - Access available - In English - LCA or LCA related research method	- Published before 2015 - Access unavailable - In other language than English - Not LCA related method

A systematic literature review was conducted by utilizing Scopus, which is an enormous electronic reference database, that covers many other well-known databases (e.g. Kuusniemi 2013). As several different research methods are being used in this thesis, it is practical to rely on one large database, due to the schedule and the intended scope of the study. An important aim of SLR is to provide systematic theoretical background for the implementation of the expert interviews. Therefore, it should be thoroughly and carefully conducted, but also in a way that it does not use up too much resources, affecting thus other parts of the study.

Keywords for the literature search were selected based on their suitability for finding articles on the life cycles of laptops and tablets, as well as finding out about the environmental impacts that are caused during the life cycles. Potential synonyms for these words were also examined by utilizing www.thesaurus.com -website. Both, literature search from the Scopus database and synonym search from Thesaurus, were conducted in October 19, 2020. As the goal of the SLR was to combine already published LCA related studies, both “life cycle assessment” and “LCA” were selected as search terms, since it is likely that these measures have been used in many relevant papers. Other LCA related keywords that were used were “ISO 14040”, “life cycle impact assessment”, and “LCIA”.

Different keywords were selected to target the devices under consideration. The term “information communication technology” (ICT) was considered to give important search results that are related to laptops and tablets, and for that reason both “information communication technology” and “ICT” were selected as keywords. Another keyword that was added was “laptop”. Thesaurus provided few synonyms for laptop, such as “desktop computer” and “workstation”, which were ranked as the most relevant ones according to the website. However, test searches revealed that the use of these search terms generated results that did not refer to laptops, which is why they were not included in the actual search. According to Thesaurus, the synonyms for the word “tablet” were, for example, “pad” and “notebook”. However, neither of these terms were utilized in the actual search, as the test search “LCA AND Pad” or “LCA AND Notebook” did not appear to provide relevant search results on Scopus. All the used search terms are presented on table 2.

Table 2. Used search terms

Life cycle and life cycle impact	**Devices**
life cycle assessment LCA ISO 14040 life cycle impact assessment LCIA	ICT information communication technology laptop tablet

Based on these search terms, the following search query was formed: (ICT or “information communication technology” or laptop or tablet) AND (LCA or “life cycle assessment” or LCIA or “life cycle impact assessment” or “ISO 14040”). The search was targeted to the articles’ title, abstract and keywords. This search provided 207 results. After this, the other inclusion criteria were added to the search. Limiting the searched articles’ publishing year to 2015 onwards and language to English generated a new search query: TITLE-ABS-KEY ((ict OR "information communication technology" OR laptop OR tablet) AND (lca OR "life cycle assessment" OR lcia OR "life cycle impact assessment" OR "ISO 14040")) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (LANGUAGE , "English")).

This query provided 82 results, which were first screened based on the title and the abstract. After selecting the topic relevant articles, 32 articles were chosen for further screening. Of these 32 articles 11 were inaccessible freely, which further limited the sample size to 21 articles. Lastly each of these articles were carefully read, and 11 articles were selected to form the research material. The selection was based on the relevance of the used methods and the relevance of the targeted product groups. Some of the articles that were selected made references to other articles in terms of information that was considered valid for this study. The articles that were referred to were also included as secondary references. The data extraction form, which also presents the secondary references’ primary articles can be found as an appendix 2. When secondary articles are included, a total amount of 16 articles were included into the SLR analysis. The results of the SLR are presented and analyzed in section 5.1. The articles that were included as a research material, and the key findings are also presented as an appendix 2 by the end of this thesis.

4.4 Expert interviews

Expert interviews are the second method that is used in this study. The results that are obtained from the SLR can be used in constructing the interview guides, and correspondingly, through the interviews it is possible to link the SLR’s results into the context of the companies under consideration. The idea of the expert interviews is to collect data about the devices life cycle stages in a given context.

Expert interviews are an efficient and concentrated measure for data collection (Bogner, Littig & Menz 2009, 2), and as for example in this section the aim is to understand the processes of individual companies, it provides an easy access to the case specific information. If the experts have practical insider knowledge, the measure can be considered as extremely efficient (Bogner et al. 2009, 3). Expert interviews are often carried out as semi-structured interviews (Alastalo, Vaittinen & Åkerman 2017), and this approach is also taken in this study. In semi-structured interviews, the addressed topics are pre-determined, but the interviewees are given a lot of freedom in the wording and length of the answers, and they are encouraged to tell things in their own words (Packer 2011, 43).

Expert interviews also contain some special features that, compared to other forms of interviews, must be given an extra thought. The importance of groundwork is emphasized for many reasons. If enough background information has not been collected, it is challenging to bring up problems from the data, as the answers might be given on a very general level (Alastalo & Åkerman 2010). Another challenge that might occur, is that the interviewee discusses the organization they represent on a PR (public relations) manner and focuses only on the positive aspects of the organization. However, thorough preparation allows the interviewer to get deeper into the matters. (Alastalo et al. 2017.)

In this study, two ICT supplier companies were selected for the interviews. One of the companies represented a procurement model that is based on equipment ownership, and the other company represented a procurement model that is argued to be based on the principles of circular economy. Both companies are Finnish owned. A different amount of information was found in advance for them, and for this reason the interview guides could also be formed slightly differently for each company. The articles that were included in the SLR were used in designing the interview guides, and in the case of the service-based company, the company’s sustainability report was also used in this designing process. As answering some of the interview questions required information that is not directly related to the interviewees’ positions, the interview guides were sent in advance, so that the interviewees could seek the information if necessary.

Conducting the interviews face to face, and possibly visiting on site would have been convenient, but due to the ongoing COVID-19 pandemic, the interviews were carried out through Microsoft Teams, and recorded into Microsoft Stream. The recordings were stored in the interviewer's password-protected profile, and later on they were transcribed with the precision that was necessary for describing the companies’ device-specific practices. The interviews were carried out in Finnish, but in this study their content is referred to in English, while still trying to preserve the original content as well as possible. The interview guides, translated into English, can be found at the end of the thesis as appendices (appendix 4 and 5).

4.5 Selection of interviewees and ethical considerations

In both interviews, the main focus was to study the end of the devices’ life cycles. Until the point when the devices are delivered to the customer, the devices’ life cycles can be considered to be identical, as in both procurement models the production and assembly are conducted by the manufacturer (figures 2 and 3). According to the SLR results (see section 5.1), the manufacturing phase is the most important stage of the life cycle in terms of environmental impacts, and an efficient way to decrease the environmental impact of small electronic devices, is to reuse or recycle them (Clément, Jacquemotte & Hilty 2020). The results of the SLR also highlighted the devices’ most important components in terms of environmental impacts, and thus the focus of the interview could be directed especially into the treatments of those components.

Company 1 was selected for the study to represent a procurement model, that is based on the customer’s ownership of the devices. This company is referred to as C1. The representative of the company was contacted by e-mail and the time for the interview was arranged through phone. The company was interviewed about its practices in general, about its possible reuse practices, and about the recycling measures for the most important materials. The representative of this company is referred to as R1 (Representative 1).

Company 2 was selected into the study to represent a service-based procurement model, which provides devices through leasing. This company is referred to as C2. In the case of this company, it was challenging to define a suitable person for contacting, so the interview was arranged by calling into the company’s general phone number. We agreed on a group interview with two experts, who are suitable for the interview due to their job description. In this study they are referred to as R2 (Representative 2) and R3 (Representative 3). The company's sustainability report 2019 provided valuable information, which could be used for modifying the interview guide to be more precise. However, the main themes were identical to those of the other interview.

All the representatives were informed about the ethical principles of the research before the interviews. They were informed about their right to leave any question unanswered and right to withdraw from the interview any time. It was also clarified that the interview would be recorded to Microsoft Stream for transcription, where it would be stored password protected till the research is ready. The interviewees were also informed that the recordings would be deleted afterwards and that they, and the companies that they represent, would be anonymized. Finally, they were informed that the City of Helsinki will utilize the results to support their procurements and that the representatives will have a right to read the research once it is ready.

5 Analysis and results

In this chapter the analysis processes and achieved results will be presented. These stages are presented individually for each used method. In section 5.1, the results of the SLR are presented and the aim of this section is to answer to the first research question. In section 5.2, again, the interview results are presented, and the general practices and end-of-life treatment operations of the case companies are reviewed. Lastly, in section 5.3 the previous results are combined in order to describe the case companies' functional unit specific environmental impacts in terms of CO_{2e} emissions and material impacts. Finally, the differences between the case companies in terms of these impacts are assessed. The goal of this section is to answer to the second research question.

5.1 Results of the SLR

In this chapter the results that emerged from the SLR are reviewed. A systematic screening process was targeted to answer RQ1: "What are the most important stages and components in laptops' and tablets' life cycles, in terms of CO_{2e} emissions and material consumption?". In subsection 5.1.1 the life cycle stages, and the most impactful components of laptops and tablets are presented and visually demonstrated by creating flowcharts of the devices and their end-of-life treatments. In subsection 5.1.2, the focus is put on the environmental impacts of the phases of raw material extraction, production, assembly and use. Subsection 5.1.3 focuses on the impacts of solution options for the treatment at the end of the products' life cycles, and finally subsections 5.1.4 and 5.1.5 describe the concrete impacts in terms of CO_{2e} emissions and material consumption.

However, it is important to notice that ICT's environmental impacts can be divided into direct and indirect effects. Direct effects include the emissions and resource usage that stem from production, use, and disposal. Indirect effects refer to the ICT-induced changes in consumption and production patterns in other domains than ICT. (Bieser & Hilty 2018, 1.) In this analysis, the focus is only on the direct effects, as the assessment of indirect effects is not possible within the scope of this study.

5.1.1 Life cycle stages and the most impactful components

Laptop and tablet production is based on resource and energy intensive processes (André et al. 2019, 268; Kasulaitis, Babbitt, Kahhat, Williams & Ryen 2015, 2). As a result of technological acceleration, along with other factors, such as manufacturers' planned obsolescence and predominating values and norms (Sabbaghi & Behdad 2017, 1), the devices become prematurely obsolescent and are being underutilized by consumers (André et al. 2019, 268). The growing markets of ICT devices cause a need to find more sustainable production measures (Meyer & Katz 2015, 369), as the waste electrical and electronic equipment (WEEE) are one the fastest growing forms of waste. WEEE can cause many social and environmental hazards if not treated properly, but it also provides enormous resource potential if utilized efficiently. (Van Eygen, De Meester, Tran & Dewulf 2015, 53.) In order to understand better the environmental impacts of laptops and tablets, it is important to form a comprehensive picture of the life cycle impacts, so that the measures can be targeted to the environmentally most harmful phases and components of the cycle. Several researchers also argue that there is an important gap at the studies considering environmental impact of circular economy measures, due to the lack of real-world commercial business-related case studies (André et al. 2019, 269).

The lack of transparent LCA studies for tablets is especially critical, and according to Clément et al. (2020, 3), the only previous studies available are from Teehan and Kandlikar (2013) and Hischier, Achachlouei & Hilty (2014A). In the approach that is taken by Teehan and Kandlikar (2013), the component life cycles are divided into life cycle phases, after which the most significant sources of impact were considered for these stages. Lastly, they measured the impact of the components in terms of CO_2 emissions and electricity consumption. In their article, Clément et al. (2020, 2) take a similar approach, but due to the lack of data, they could not observe the electricity consumption in the use phase. A similar approach is also taken in this part of this study, as the already formed formula offers a systematic procedure for analyzing the results of the SLR. However, in this study the impacts will be directly reviewed as CO_{2e} emissions instead of assessing the electricity consumption. The data is collected from already conducted LCA studies, and in these studies the material impacts and the CO_{2e} emissions for different stages and components are readily available. However, it should be noted that the impacts of electricity consumption are directly linked to the burning of fossil fuels (see subsection 2.2.1).

The first step of the SLR is to identify the life cycle phases of the devices' components and the significance of their impact. In their article André et al. (2019, 271) present a flowchart for the life cycle of a new laptop. In this flowchart the life cycle is divided into phases of raw material extraction and production, assembly, use, and disposal. Disposal phase is divided into WEEE recycling and landfilling. The life cycle review by André et al. (2019) is based on dividing the device into several components, and the significance of their impacts is separately considered. The separate components that were taken into consideration were printed circuit boards (PCBs), casing, liquid-crystal display (LCD) screen's light-emitting diode (LED) backlights, LCD module, and cables. Based on an extensive literature review, the impacts of these components were considered to represent the majority and diversity of laptop's environmental impacts. For some of the components the greenhouse gas emissions from production stage are significant, and for some of them the impact is related to the material composition. (André et al. 2019, 269–270.)

Clément et al. (2020, 3) also conclude that in the case of tablets the PCBs, displays, and integrated circuits (ICs) are the most significant greenhouse gas emission sources, followed by the casing and the battery. The difference between the two studies seems to be that in the case of tablets, the battery has a relatively higher impact significance than in the case of the laptops, as they were excluded from the review by André et al. (2019). However, it is worth noticing that there is a lot of variance in ICT related LCA studies considering the component specific impacts. This can occur, for example, due to the modelling uncertainties, such as limited access to representative data, uncertainties caused by technological development, or any other factors that force the researchers to rely on estimations (André et al. 2019, 269).

Other studies that have been included into this SLR confirm the significance of some of these components. According to Alcaraz et al. (2018, 822) displays, ICs, and printed wiring boards (PWBs) account for large shares of the tablets' CO_{2e} impact, ICs being especially impactful. Kasulaitis et al. (2015, 7) again highlight the significance of motherboards, which consists of a large share of the laptop's ICs and semiconductor materials. Despite the small differences in the stand of the included studies, the most impactful components in the case of laptops and tablets seem to be relatively similar, those being PCBs/PWBs, ICs, display, and casing.

In addition to mapping out the devices’ most impactful components, it is also important to map out the devices’ life cycle stages and their significance for the total life cycle impact. In their study, André et al. (2019, 271) present flowcharts of scenarios where the laptop is either recycled or reused. The life cycle stages in both models consist raw material extraction and production, assembly, use, and end-of-life treatments. If the devices are not reused, the end-of-life treatment consists of alternative terminals for the components, which are landfill or WEEE recycling. If the device is reused, preparation for reuse and reuse are extra stages before these terminals. (André et al. 2019, 271.) The articles that were included in the SLR did not provide a similar flowchart for tablets. However, the article by Andrae & Vaija (2017, 6) present the most significant stages of a tablet’s life cycle, which are part production, use, and end-of-life treatments. Clément et al. (2020, 3–4) add transportation as another stage for tablet’s life cycle, yet they state that the production and use phases represent over 90% of the devices’ total impact. There is still no reason to assume that the tablet’s life cycle would not contain assembly phase, and it can be concluded that the life cycle stages of laptops and tablets are identical. The most impactful components and the life cycle phases in different end-of-life treatments are presented in figures 2 and 3. Figure 2 represents the operation model, in which the devices are recycled, and figure 3 represents a model, in which the devices are also reused. Both figures are applied versions of the flowcharts presented by André et al. (2019, 271), and they are modified to represent both devices in question.

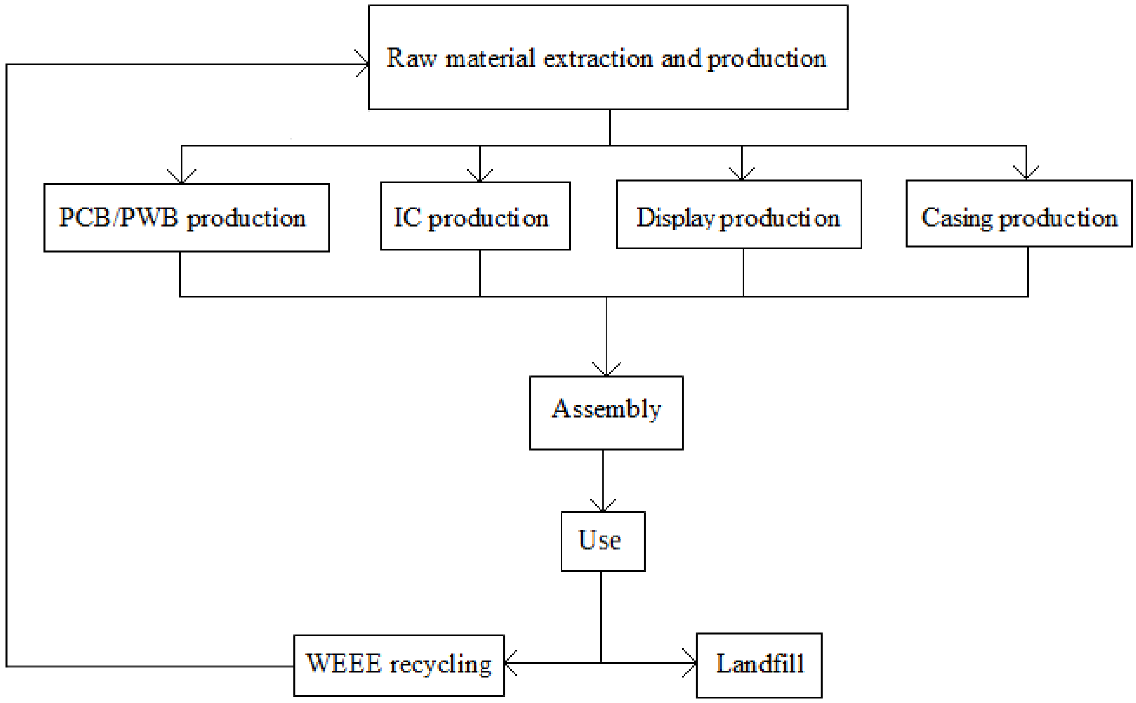

Figure 2. Flowchart of laptop's/tablet's life cycle if only recycled (applied from André et al. 2019, 271)

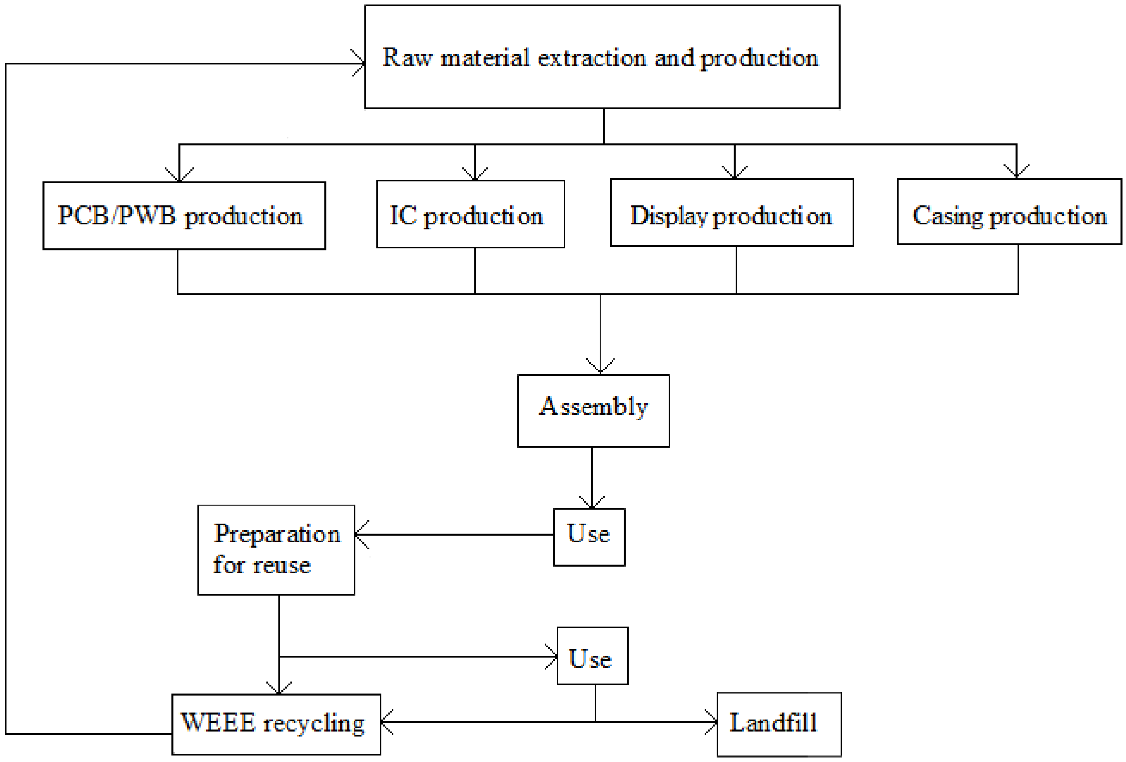

Figure 3. Flowchart of laptop's/tablet's life cycle if reused (applied from André et al. 2019, 271)

5.1.2 Raw material extraction, production, assembly, and use

According to Alcaraz et al. (2018, 819), the materials and manufacturing phase drive the environmental impacts of the tablets' life cycle, ICs and PWBs being especially impactful in this stage of the product's life cycle. Alcaraz et al. (2018, 822) indicate that the ICs account for over 15% of the total impacts in the material and manufacturing stages. The main contributors in the case of IC manufacturing are the water and energy that are needed in production. However, the amount of available data is limited and for this reason there are uncertainties and differing results related to the impacts of IC production. The largest IC manufacturers are located in South-Korea and Taiwan, and these countries rely on energy production sources with high GHG emissions. The electricity mix has also an important role for the impacts in the case of PCBs. (Clément et al. 2020, 3–8.) Fossil carbon dioxide emissions are the most important contributors to climate change, and the ICs that are contained in the PCBs are responsible for approximately a third of all the laptop's climate change impacts (André et al. 2019, 273). PCBs also contain a lot of precious metals, and the concentration can be over ten times higher compared to the respective metal ores (Van Eygen et al. 2015, 53). Climate change, resource use, and human toxicity are considered as the most important impact categories of the devices in question. (André et al. 2019, 272). The human toxicity can be effectively mitigated by proper end-of-life treatment processes (Clément et al. 2020, 3). Yet, due to the scope of this study, the impacts are only considered in the impact categories of climate change and material resource consumption.

Of the four different components that were selected for this review, displays represent a group of which there was the least amount of information available. According to Andrae and Vaija (2014), the GHG emissions in LCD production are mainly linked to the electricity production (Clement et al. 2020, 4). For the casing again, the climate change impacts are mainly linked to the production of the magnesium alloy, which forms a relatively large mass of the component (André et al. 2019, 272; Meyer & Katz 2015, 61). Casing can be made of different materials, and Meyer and Katz (2015) have compared the environmental impacts of polycarbonate/acrylonitrile butadiene styrene (PC-ABS) plastic and aluminium casings. For both materials, the impacts in different categories can be decreased by increasing the share of post-consumer recycled (PCR) materials (Meyer & Katz 2015, 381). However, a large share of the PC-ABS plastics is still landfilled rather than recycled, as it is challenging to separate different polymers of the waste stream. Aluminium has a significantly higher recycling rate (see subsection 5.1.5). (Van Eygen et al. 2015, 57–60.)

The broad scale of impact categories that were taken into consideration by Meyer and Katz (2015, 375) were ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion. The preferability of aluminium versus PC-ABS use in casings depends on the share of PCR in these materials. If the share of PCR in aluminium is as low as reported in the econinvent database (32%), then PC-ABS causes lower impacts in terms of smog formation, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and ecotoxicity. If the PCR share of PC-ABS is 60%, it becomes a better option also in terms of fossil fuel depletion. However, the share of PCR in aluminium casings can also be increased, which would decrease the need for primary metal extraction. (Meyer & Katz 2015, 379–381.)

The impacts of the assembly phase were not comprehensively considered in the articles that were selected for this review. Hischier et al. (2014B, 8) argue that the impacts are very marginal compared to the more impactful stages. However, according to André et al. (2019, 274), in the case of laptops, the impacts are to certain extent significant in terms of climate change (see table 3). The arrows in figures 2 and 3 represent the transportation processes, which are also presented very briefly in the literature. However, according to André et al. (2019, 274) the impacts are very minimal, even when compared to assembly.

In addition to raw material extraction and production, use is another highly impactful phase of the life cycle and together they are undoubtedly the most contributing phases. Different results show that approximately 85–90% of the total impacts are caused by the manufacturing and use phases. The most important factor for the variation in use phase is the energy mix being used and this applies also for the production phase. Other relevant variables that effect the impacts of the use phase are device's lifetime, charger efficiency, duration of the battery's lifetime, and charger's plugged-in time. (Alcaraz et al. 2018, 822–823; Clément et al. 2020, 1–2.) However, in the case of small electronic devices, such as laptops and tablets, the production phase is more dominant than the use phase in terms of environmental impacts (Boldoczki, Thorenz & Tuma 2020, 1).

5.1.3 End-of-life stages

The end-of-life treatments options are reusing the device, recycling it, or disposing it to the landfill (e.g. André et al. 2019; Boldoczki et al. 2020). These alternative treatments are presented in figures 2 and 3. The most preferable option is usually considered to be reusing the device, because the materials maintain the highest value in this solution. However, this is not the case for all electronic equipment. For some devices, the main environmental impacts stem from the high energy consumption that is related to the use of the product. Therefore, in this case replacing the device with new and more energy efficient version can actually be a more sustainable option than reusing it. (Boldoczki et al. 2020, 1.) The preferable option depends on the device in question. The worst-case option, however, is disposal to landfill (Meyer & Katz 2015, 373), because in this option the value of the materials is wasted. Compared to landfilling, recycling of a laptop saves approximately 87% of natural resources (Van Eygen et al. 2015, 53, 62). In North Europe, around half of the laptops are being recycled, but there are no reliable estimates available about the other pathways (Buchert et al. 2012).

In the case of small electronic devices, such as laptops and tablets, production is environmentally a more impactful phase than the use phase. As a result, for these devices reusing is a better alternative than recycling in various impact categories, such as global warming, mineral resource scarcity, and terrestrial ecotoxicity. (Boldoczki et al. 2020, 1–2.) The benefits of using second-hand laptops, however, depend on the length of use extension and reuse efficiency. A typical use extension is approximately 2–3 years, and the length of the first use is around 3–5 years. If the first use period is for example three years, and the reuse period is four years, almost half of the production impacts of a laptop can be reduced by the reuse activity. (André et al. 2019, 270, 273, 276.) However, the used product may not be functionally equivalent to a new one, but this can be also seen to some extent as a matter of user preferences, as a significant number of completely working devices are disposed every year, because the owners consider them to be obsolete (e.g. Raghavan 2010; André et al. 2019, 269).

The process of WEEE recycling is usually divided into three steps, which are collecting and sorting, dismantling and mechanical separation, and end-processing. Dismantling and separation is an important phase, as it defines the amounts of materials that end up in an efficient end-of-life processing. Some components, such as PCBs, are directly sent for end-processing, while some components, such as displays, are further separated to different materials. In the last step of the recycling, the materials are turned into secondary raw materials. The treatment for preparing the components for end-processing can be carried out in different ways. PCBs, for example, are shredded and send into smelter, as well as parts that are made of steel, aluminium, magnesium, or copper. Plastic polymers are also separated and processed into pellets. (Van Eygen et al. 2015, 54–55, 57.) First the plastics are shredded and put into a froth flotation process, in which the different plastics are separated and finally they are formed into a PCR resin. The use of PCR plastic has significant benefits over virgin materials in terms of environmental impacts. (Meyer & Katz 2015, 370, 373.) However, as the separation of plastics is relatively difficult (Van Eygen et al. 2015, 60), it is currently not often economically viable to recycle them (Meyer & Katz 2015, 373). In addition to the difficulties in plastic recycling, the low collection rate of WEEE is another bottleneck for efficient ICT recycling. Lastly, the improved pre-treatment of PCBs could decrease the share of precious metals that end up in the landfill. (Van Eygen et al. 2015, 57, 60) The most significant benefits of efficient recycling are related the impact categories of resource consumption and human toxicity (André et al. 2019, 269).

5.1.4 CO_{2e} impacts per functional unit

In this section, the functional unit specific CO_{2e} impacts are considered in terms of different life cycle stages and components. CO_{2e} refers to carbon dioxide equivalent emissions, which describe the total impacts of CO_2 and other GHG emissions (Clément et al. 2020, 1). The impacts of laptops are presented first, and the results are rather extensively based on the article by André et al. (2019), which has the most similar research design with this study (see appendix 2). The article does not present detailed quantitative information about the CO_{2e} impacts, but it contains a figure showing the functional unit specific emissions approximately on an accuracy of one kilogram. The functional unit for of this study is also one year of laptop use. The information of the article is based on ecoinvent data, literature sources, and data that is provided by a Swedish IT refurbishment company (André et al. 2019, 272). The figure by André et al. (2019, 274) provides information about CO_{2e} impacts of PCBs, display, casing, assembly, transportation, end-of-life treatment, and the total CO_{2e} impact of a laptop. The magnitudes of the impacts are presented in tables 3 and 4.

In their article Hischier et al. (2014B, 8) provide information about the climate impacts of laptop's production, use, and end-of-life treatment phases. In terms of end-of-life treatment, the results support those that are provided by André et al. (2019). Hischier et al. (2014B) do not provide quantitative information either, but they present a figure of the life cycle phase specific shares of non-renewable energy consumption and global warming potential (GWP). The shares between these two categories are relatively identical, and it can be assumed that the share of non-renewable energy consumption and GWP also describe the relative shares of CO_{2e} emissions, as the emissions are directly related to the share of fossil-fuel based energy in the electricity mix (see subsection 2.2.1). The product life cycle stage impacts are based on an assumption that the life cycle of a laptop would be four years, and it would be used daily for two hours. The share of production phase is approximately 65–70% and the share of use phase is approximately 30–35%. End-of-life treatment does not cause significant CO_{2e} emissions. (Hischier et al. 2014B, 8.)

As the total CO_{2e} impact of a laptop is approximately 54 $kgCO_{2e}$ per one functional unit (André et al. 2019, 274), and the share of production for non-renewable energy consumption and GWP is 65–70% (Hischier et al. 2014B, 8), the share of production causes approximately 36.5 $kgCO_{2e}$ emissions in one functional unit. Again, as the share of use is 30–35% in the same impact categories, the share of use causes approximately 17.5 $kgCO_{2e}$ emissions in one functional unit. Although the ICs contribute significantly to the devices' total environmental impacts, the articles that were included into this study did not provide information about the share of the CO_{2e} emissions of these components. However, as mentioned in subsection 5.1.2, the ICs on the laptop's PCBs are responsible for approximately a third of the device's total climate change impacts (André et al. 2019, 273). Therefore, an assumption is taken that the CO_{2e} emissions of the ICs are 18 $kgCO_{2e}$ per one functional unit.

As mentioned in subsection 5.1.1, there are only very few LCA studies available about the impacts of tablets. Alcaraz et al. (2018, 823) state that there are also large brand specific differences in terms of the impacts. For example, one of the devices that they present in their study is a tablet device by Dell, for which the total emissions are 45 $kgCO_{2e}$, and 45% of the emissions are caused by manufacturing, 15% by transportation, and 40% by use. Again, other tablets that they examine are Apple devices, for which the total emissions are 270 $kgCO_{2e}$ and 170 $kgCO_{2e}$. The device which has an impact of 270 $kgCO_{2e}$ has larger screen size, but the significant differences can also be partly explained by the discrepancies between different studies. In the case of these devices, 86% of the emissions are caused by production, 3% by transportation, 10% by use, and 1% by recycling. (Alcaraz et al. 2018, 823.)

For all of these devices, the order of the impact significance is the same, but there are large differences on the percentage shares. Based on the results of Alcaraz et al. (2018, 823) the average percentage shares for the CO_{2e} impacts of the reviewed tablets are 65.5% for manufacturing, 9% for transportation, 25% for use, and 0.5% for recycling. The study by Clément et al. (2020, 3) provides similar results for the share of manufacturing, stating that the share is 68.4 ± 21.3% of the total impacts. While Alcaraz et al. (2018) compare a relatively narrow selection of different devices, Clément et al. (2020, 5) compare the total CO_{2e} emissions of 30 different tablet models. There are also relatively broad differences among these models, but the median emissions are approximately 120 $kgCO_{2e}$. Due to the broadness of the comparison by Clément et al. (2020), this amount is assumed to represent the total emissions of tablet's life cycle.

An average life cycle of a tablet is approximately three years (Clément et al. 2020, 3). The CO_{2e} emissions per functional unit are then acquired, when the 120 $kgCO_{2e}$ emissions are divided by three. As the emissions per functional unit for a laptop are approximately 54 $kgCO_{2e}$, the 40 $kgCO_{2e}$ impact per functional unit of tablets would support the estimation by Hischier et al. (2014B, 13), according to which the share of non-renewable energy consumption is approximately ¾ for tablets compared to the laptops. When the total CO_{2e} impact per functional unit is divided into the percentage shares of different life cycle stages (Alcaraz et al. 2018, 823), the life cycle stage specific emissions can be calculated for one functional unit. These shares are presented in the table 3.

Clément et al. (2020, 5) also present the CO_{2e} emissions for the tablet's components, but as the model specific differences are relatively large, there are also differences in component specific emissions. However, the device that represents the median emissions of those 30 devices that were assessed by Clément et al. (2020), also represents relatively accurately the typical emission shares of different components, when compared to the other devices under consideration. Approximately 36 $kgCO_{2e}$ of these emissions are caused by ICs, 30 $kgCO_{2e}$ by PCBs, 33 $kgCO_{2e}$ by display, and 18 $kgCO_{2e}$ by casing. The functional unit specific shares are acquired when these amounts are divided by three. According to Clément et al. (2020, 5), the assembly phase does not produce significant amount of emissions. Yet, this stage is likely to cause certain amount of emissions, which is why it was marked as not available in the table 3.

The estimated CO_{2e} emissions for different life cycle stages and components are presented below in the tables 3 and 4. Despite the variation between different studies and different devices, it seems that when the impacts of different stages are summed up together, the results correspond relatively well with the total emissions. Same applies when the impacts of different components are summed up together. However, as some of the ICs are mounted into PCBs/PWBs (André et al. 2019, 269), they should not be counted as separate shares of emissions. The article specific differences are still visible. For example, in the case of tablets the transportation and end-of-life treatment were assumed to cause emissions (Clément et al. 2020, 5), while in the case of laptops it was estimated that these stages do not cause emissions (André et al 2019, 274). However, these stages are not emission-free stages, which is why instead of giving them a value of 0, the information was marked as not available in the table 3.

Table 3. Life cycle stage specific emissions (kgCO$_{2e}$) per functional unit

	Laptop	Tablet
Production	36.5*	26****
Transportation	N/A	3.5****
Assembly	4**	N/A
Use	17.5*	10****
End-of-life treatment	N/A	1****
Total (approx.)	54**	40***

* When laptop is used 2 hours/day (Hischier et al. 2014B, 8)

**André et al. (2019, 273–274)

*** Clément et al. (2020, 3–5)

**** Alcaraz et al. (2018, 823)

Table 4. Component specific emissions (kgCO$_{2e}$) per functional unit

	Laptop	Tablet
PCBs/PWBs	31**	10*
ICs	18**	12*
Casing	14**	6*
Display	4**	11*
Total (approx.)	54**	40*

* Clément et al. (2020, 3–5)

**André et al. (2019, 273–274)

5.1.5 Material impacts per functional unit

In this subsection, the devices' material impacts are considered for one functional unit. As the devices consist of a variety of different materials, it is challenging to create very precise estimations of the impacts for all of the materials that are included in the devices. Different studies also highlight the importance of different materials, depending on the definition of being impactful. For example, some metals are considered important because of their scarcity, while others are considered important because of the environmental impacts that are related to extraction and production processes (André et al. 2019, 269). Despite the challenges of forming an impact assessment for all of the different materials, it is still possible to use certain materials, whose significance is mentioned in several studies, for demonstrating the material savings that can be achieved from implementing different end-of-life-treatment options.

Of those articles that were included into this review, a relatively smaller share focused on material impacts compared to CO_{2e} emissions, when considering the devices' life cycle impacts. The significance of recycling is higher for material consumption impact category than for the CO_{2e} emissions (André et al. 2019, 269). Reusing can even be a worse option than recycling in terms of material impacts, because if reusing takes place in a country that does not have an effective recycling system, the materials will go to waste after the second life cycle. Compared to landfilling, laptop recycling saves approximately 87% of the material resources. (Van Eygen et al. 2015, 55, 62.)

For this reason, it is important to also consider the role of recycling for the devices' material impacts. As only a certain share of the materials is not efficiently treated, mapping out the recycling rates will help in understanding the shares that are actually wasted per one functional unit. In order to understand the impact of the recycling shares, it is also important to review how large the device specific shares of different materials are. The differences between the material composition of devices from different model years are relatively low, but there are large differences depending on the size of the device. For example, comparison by Kasulaitis et al. (2015, 5) demonstrates that the product weight loss is less than 2% annually when comparing different model years, while the dematerialization for HP's smallest and largest laptop is approximately 30%. Kasulaitis et al. (2015, 5) also point out that when comparing laptops from 1999 to those from 2007, the relative material shares have remained rather similar, and the biggest change is a shift from plastic casings to aluminium casings.

As mentioned in subsection 2.2.2, the largest share of the materials that are used in the devices are metals, polymers, and glass. The most common metals are aluminium, copper, and iron. In addition, the devices contain scarce metals, such as gold or platinum group metals. However, there is a lack of information concerning scarce metals used in the tablet devices (Clement et al. 2020, 3), so the present study only covers aluminium, copper and plastics for tablets, whereas precious metals are additionally included in the analysis for laptops. As mentioned in the previous paragraph, device's size has a significant impact on its material consumption. In this study the laptop's material composition is studied by first reviewing material composition of 1000 kg of disposed laptops, following the procedure demonstrated by Van Eygen et al. (2015, 60). Then the material composition is calculated for a single 14.1-inch laptop, that weights approximately 2.5 kg (Kasulaitis et al. 2015, 5). In the case of tablets, again, the material composition is reviewed for a 10-inch LCD tablet device, and the material shares are based on the results of Hischier et al. (2014A, 29–30).

The material of the casing makes up the biggest share of a laptop's mass, and aluminium and plastics are some of the most commonly used casing materials (Van Eygen et al. 2015, 57). The material shares of a laptop and the recycling rates are based on the results of Van Eygen et al. (2015, 60). However, it should be still noticed that the study focuses on the recycling rates in Belgium in 2013, which is why it does not offer an exact estimation for the context of this study. However, according to The Global E-Waste Statistics Partnership (2021) tracking, the collection rates for e-waste in Belgium and Finland have been relatively similar between the years 2015 to 2019. During this period the e-waste recycling rate in Belgium has stayed in 55%, while for Finland the percentage has varied from 57% to 61%.

In terms of tablets, the study by Hischier et al. (2014A, 29–30) only provides information about the material specific recycling rates for aluminium, which is why the material specific recycling rates that are provided by Van Eygen et al. (2015, 60) are also used in assessing the tablets' material impacts. Hischier et al. (2014A, 29–30) estimate that approximately 51% of tablet's total weight can be directly recycled and approximately 15% of the remaining aluminium can be taken into material recycling. Thus, it is estimated that the recycling rate for aluminium in the case of tablets is approximately 58.4%.

Material specific shares of weight, recycling rates, and the shares of materials that are wasted are presented in the table 5 for a 14.1-inch laptop and a 10-inch LCD tablet. In addition, functional unit specific shares of wasted material are presented by dividing the amounts of wasted materials by the average length of the device's lifespan. A typical life cycle for a laptop is approximately 4 years (André et al. 2019, 270; Hischier et al. 2014B, 8) and the average life cycle for a tablet is estimated to be 3 years (Clément et al. 2020, 3). Because the laptop's device specific material shares are calculated from the results of Van Eygen et al. (2015,60), the shares are presented in percentages and grams. However, in the case of tablets the material shares are only presented in grams, since Hischier et al. (2014A, 29–30) provide information about the device specific shares.

Table 5. Laptop's and tablet's material composition, recycling rates and share of materials that are wasted in recycling

Materials	Laptop (2.5kg)	Tablet
Aluminium		
Share of weight (%)	8.45*	N/A
Weight in one device (g)	211	135**
Recycling rate (%)	75*	58.4**
Wasted material/one device (g)	53	57
Wasted material/functional unit (g)	13.25	19
Copper		
Share of weight (%)	6.85*	N/A
Weight in one device (g)	171	12.5**
Recycling rate (%)	85*	85*
Wasted material/one device (g)	26	2
Wasted material/functional unit (g)	6.5	0.66
Plastic		
Share of weight (%)	40.6*	N/A
Weight in one device (g)	1000	17**
Recycling rate (%)	13*	13*
Wasted material/one device (g)	870	15
Wasted material/functional unit (g)	217.5	5
Precious metals		
Share of weight (%)	0.029*	N/A
Weight in one device (g)	0.7	N/A
Recycling rate (%)	63*	N/A
Wasted material/one device (g)	0.26	N/A
Wasted material/functional unit (g)	0.065	N/A

Source: *Van Eygen et al. 2015, ** Hischier et al. 2014A

5.2 Interview results: reuse and recycling practices in the two case companies

The focus of this chapter is to review the company-specific processes at the end of the devices' life cycles. The aim of this chapter is to define how the life cycles' stages differ in traditional ownership-based procurement model and service-based procurement model. Subsection 5.2.1 focuses on the C1 (Company 1), and subsection 5.2.2 focuses on the C2 (Company 2). The interviews were divided into three sections, which contain the company's repair practices, company's reuse practices, and company's recycling practices.

5.2.1 Company 1: Ownership-based model

A. Repair practices of Company 1

By repairing the broken devices, it is possible to extend their life cycle. According to the 3R framework (see section 2.3), life cycle extension provides an efficient way to mitigate the product's environmental impacts. However, if the costs of the repairing activities exceed a certain threshold, consumers are unwilling to do so, and they replace the product instead (Sabbaghi & Behdad 2017). Thus, it is important to study the warranty policies in both companies.

According to the R1 (Representative 1), the warranty period is defined by the manufacturer, and different manufacturers have differing warranty periods. C1 also provides different warranty solutions for their devices. A typical warranty time is three years for the laptops and one year for tablets. Clients have, for example, an option to pay for extra warranty, which extends the warranty time, or it is possible to purchase a service that provides a repairing within 24 hours. In terms of volume, only very few office devices need to be repaired, while the difference with student devices is clear.

"*Well, they are not repaired very often considering the volume ... the difference is like night and day. When talking about student devices, we talked about thousands annually ... when used by adults we talk about few dozen devices, which are repaired.*"

The devices have only very few hardware failures that are independent from the consumer. R1 describes that they only appear on 1% or less of the devices. The most common repairing operations that C1 takes care of outside of the warranty are, that the user has spilled something on the keyboard, or that the screen or keyboard has broken due to the cable or pencil that has been forgotten between them. For example, replacement of screens and keyboards are done very often, because it is cost-effective in relation to the value of the device. In the case of a more extensive damage, the repairing costs may turn out to be very expensive and it is not profitable to repair the device.

"*Motherboard defects are not repaired ... if some liquid has gone there, because the motherboard is almost as expensive, if not more expensive, than buying a completely new device*".

C1 receives devices that are considered as removals by the customers, and they are securely recycled. According to R1, the main reason why the devices are returned by customers as removals is, that they have become to the end of their life cycle, or the warranty time has ended and they are irreparable. When asked for further details for the meaning of the end of the life cycle, they specified:

"*Well, it is the devices age. So of course the programs develop, despite if it is city or municipality or whatever, so the old devices become to the end of their life cycle so to speak. So PC is that kind of device that… well of course updates are also being made, but to the old devices it simply is pointless to conduct them. And then, some of them are rather worn, and like I said, in student use they are pretty dented and scratched, and then when they stop working we conduct this [cyber] secure recycling for them*."

R1 thought that a typical length for the devices' life cycles is difficult to define, because there are differences between manufacturers. However, for tablets, the lifespan is from two to three years, and most often the reason for withdrawal is a screen related problem. In terms of laptops, the lifespan for student devices is approximately from three to four years, but in office use the devices can have a significantly longer lifespan, such as four to five years.

B. Reuse practices of Company 1

After a device no longer serves the consumer, it is possible to lower the environmental impact by reusing or recycling the device, or its components. In the case of small electronic devices, such as laptops and tablets, it is more convenient to reuse than recycle the devices, as the main source of their impact is not the use, but the manufacturing (Boldoczki et al. 2020). For this reason, it is important to review how companies 1 and 2 carry out the possible reuse or recycling operations.

According to R1, C1 does not provide a service, in which the used devices would be updated and sold again, because typically the devices that are collected after the use are in such a condition, that they can be considered to be at the end of their life cycle. However, the subcontractor, who is responsible for handling the recycling, repairs few of the devices for reusing them. R1 did not have information about where these repaired devices go, but they assumed that they are sold somewhere in large batches. The main processing treatment is recycling.

"*We do not have this kind of arrangement for the city, that we would, like, update the devices and sell them to the workers, so these devices that come to us are, as I said, mainly pretty much at the end of their life cycle. They do go to reuse from us, yeah, so our partner, who we do this together with ... like some of the devices are in such a condition that you cannot really save anything from them, other than the memory comb, and the rest is recycled. ... It [preparing for reuse] is being done by the subcontractor who repairs the devices if possible, and tries to get them back on track, so to speak, but the material that comes is pretty old. ... Mainly it is recycling, pretty rarely they go to reuse, but of course it also happens. But that is a demanding process, like the hardware is renewed and it requires investments to put it back on track. ... I cannot really say how it happens, but I have understood that they are sold in bigger quantities ... I have understood that for example Swedes and Danes use old PC devices in the school world. But I cannot give you any specific address where they go.*"

R1 was also asked if they know if C1 has had discussion about starting to provide reuse services. R1 said that they had personally discussed with clients about the possibility that the devices that are still working would be updated and new hardware would be installed, and that the devices would be returned to the customers' use. The last discussion, regarding customers' devices in student use, had been two-three months prior to the interview.

C. Recycling practices of Company 1

Apart from reuse, one way to impact devices' environmental footprint is to recycle them, and therefore it is also important to review the companies' recycling practices. The recycling in C1 has been conducted through a partner, which is a recycling company, that has ISO 19001, ISO 14001, and OHSAS 18001 certificates. Recycling is conducted securely, which means that the components that contain memory are crushed. Of those memory-containing components R1 mentions SSD disks, that are mainly made of plastic. Metals are separated from the crush, and according to R1, the crush is used for example in producing containers. However, more detailed information was not available, as reflected in the following quote.

"*I have heard that for example the hard drive powder can be used for making containers. ... Not for food sector, but for some other sectors ... I cannot describe it more precisely, but once I just for fun asked how the crush is reused, and they answered that it can be used for [making] some kind of containers*."

C1 often receives broken screens, which cannot be repaired. R1 estimates that approximately 94% of the screens' materials can be recycled, 4% is used in energy production, and 2% go to disposal. Microcircuits and printed circuit boards are reportedly sorted properly, and the recycling rate of precious metals is good. Aluminium is collected and sorted, and the material is simple to reuse. Plastic materials are melted and used for making recycled plastic. For more precise information R1 recommended to contact the recycling partner. However, within the scope of this study, it was not possible to conduct extra interviews.

5.2.2 Company 2: Product-as-a-service-based model

C2 represents a procurement model, which according to the company, follows the principles of circular economy. In this model the devices are leased for the customer, and after the customer no longer uses them, C2 offers them a second life. Two representatives of C2 were interviewed, and they are referred to as R2 (Representative 2) and R3 (Representative 3). R2 is responsible for marketing, communication, and responsibility for the company's Finnish operations. R3 is responsible for the company's relations with public administration. The interview was divided into three different themes, which are the company's operating model in general, the company's reuse activities, and the company's recycling activities.

A. The operating model of Company 2 in general

The company's operating strategy is that they purchase the devices from the supplier and rent them for the customer. The supplier and the devices are selected by the customer, and in the case of municipalities, procurement takes usually place on a competitive basis. The winner of the tendering is selected as the supplier, and the leasing contract allows a more even distribution of the ICT related costs for the customer. According to R2, the company's operating model does not include warranty repairs, but the equipment supplier is responsible for repairs during the warranty period. C2 takes care of other forms of devices' life cycle management, for example by maintaining device register, which sorts the organization's devices, their users, whether latest software and application updates have been conducted successfully, and if the antivirus protection is up to date. According to R2, monitoring and anticipation make it possible to avoid broader maintenance procedures.

"*So we are brand independent actor, so the customer themselves choose devices and where they want to purchase them. So we do not, kind of, have a role in defining this for the customer, for example, like deciding which devices and from which channel ... So we do not have, like R3 said, that kind of maintenance role, but then again ... we do have this device registry maintenance, in which these customers' devices are registered, so then again, we can know how they work, if the updates have gone through properly and if like the whole fleet that the customer has, is properly used and optimized, and so on. And then from this, the customer gains valuable information, like the IT people, so they can anticipate and ... anticipate possible maintenance.*" -R2

The other operating model that C2 has, is to buy the existing devices from the customer. The customer receives money from selling the devices, and if they want, they can also rent the devices back after selling them. This will free up resources, while the same devices will remain in use. Also, in this case the life cycle management is taken care of by the company in a similar manner as in their other operating model. Compared to many other IT-companies, the difference of C2 is that their business model is based on reselling the devices after the customer no more uses them. Another difference is that the supply chains processes, such as logistics and the treatments for the devices are carried out by C2, as it does not use subcontractors in these processes. However, it is worth mentioning that it does use a subcontractor for the recycling processes.

"*Well, we provide two different services. ... We purchase the devices from the customer, we also give money for them, but then they are retrieved, packed, secured, the same way as these devices that return from leasing.*" - R3

Typical first service life is three to four years for the laptops and two to three years for the tablets. The length of the rental agreement depends for example on the intended use. Devices that are in office use last longer than those that need to be actively travelled with. According to R3, cities and municipalities normally procure devices that have relatively high-quality components, which partly increases the service life, and encourages the use for the second service life. Customers have an option to decide, whether they want for example three or four years cycle for the device renewing, and having the same devices longer decreases the monthly rent.

"*Municipalities and cities also procure, good professional laptops, corporate level laptops, so then you have better memory, better battery, better hard drives, processors. So they are like different devices than like maybe these consumer devices. And and, well, the intended use also ... how long they last ... well, they last longer with office workers than those kinds of workers who move a lot, use it a lot, and are not at the office. ... So, so, the professional devices also serve still well on the second use cycle.*" - R3

According to the representatives, a surprisingly large share of the devices, that are in the ownership of the customer, does not return to the second-hand markets, but remain unused in a storage. Thus, by having rental devices, the customer does not have to think about the end-of-life treatment, but the devices are returned into the market by C2. This way resources, that would risk being untapped, are held in circulation. Also, if other customer organizations do not have a need for brand-new equipment, they can save natural resources by offering a second life for the devices, instead of buying new devices.

"We have studied if as many devices end up to the secondhand markets as new ones are procured. And surprisingly large amount of the devices, laptops, tablets and phones, never return to recognized secondhand markets." -R3

B. Reuse practices of Company 2

"*We collect them from the customer and practically pack them for the customer, so that they remain operational. They come to our logistics center, where we inventory them, after which we overwrite the data, and conduct a quality assessment, regarding what kind of condition the returning devices are in. And then we sell those reconditioned devices forward, into the secondhand markets."* - R3

According to the representatives, approximately 97–98% of the devices can be reused after C2 has made the necessary updates to them. The representatives could not provide very specific details about these updating processes, but they note that the processes can relate for example to renewing the components, such as battery or the hard drive. Both new and used components are used in these repairing activities, and some of the components of those devices that cannot be repaired anymore, can still be used as a spare parts. R2 states that of those 2–3% of the devices that cannot be repaired anymore, 80% can still be used as spare parts.

"*Approximately 80% of those devices that have basically been stated not to work can be, in one way or another, in our so-called repair program to, well, be reused and used ... so that we can fix the devices, which means that we reduce 56% of the e-waste through these activities."* -R2

When selling the used devices, C2 also checks the customer's backgrounds, and there are several requirements that need to be met. C2 does not sell to countries that are not covered by the e-waste scheme, and mainly operates with reliable long-term partners. Most of the customers are from Europe, and the main markets are in Poland and Sweden. Some of the customers are also from Asia. The representatives did not have very detailed information about what kind of use the devices go into, but they assumed that they mainly go to companies and schools. Reusing typically doubles the total period that they are being used. R3 points out that the authorities require that the devices going on sale abroad are still intact. C2 also ensures that all the data on the device has been deleted and that the reselling is secure.

"*It is also a part of being responsible, that when we acquire the devices, we are very strict about who we resell them to. So, so, we have there checking that one is not on any banned list and we check the backgrounds and cooperate with long-term business partners. So we also do not sell them for everyone. ... The main markets are specifically in Europe ... It is very strictly supervised by authorities that the devices that are leaving from Finland are actually working."* - R3

C. Recycling practices of Company 2

The remaining 2–3% of the devices are so damaged that they cannot be reused, and are sent to the recycling center, which is the same subcontractor that C1 uses. According to R2, the components are crushed and the materials are separated at the center. Circuit boards are sorted separately, and non-ferrous metals, copper and aluminium are melted and utilized as raw materials, for example for the automotive and electronics industries. R2 was not sure but recalled that 95% of the materials can be reused as they go through the recycling center's treatment.

"*From all of the devices the renewable metals and minerals are collected into utilization in there, through these different programs, very well. ... I do not know about percentage, but I know that at least the aluminium and copper are melted and then they go further into an automotive and electronic industries to be used as raw materials, and the circuit boards are treated, like completely as an own form of waste."* - R2

"*I do not remember very precisely but was it that 95% of those acquire a new life of those 2% that goes through the recycling center's program. ... So even if they are not used as computers anymore, but they can be used as raw materials, and then ... So there are* *pretreatments and crushing and then there are different immersing, floating and crushing ... and these kinds of [measures], through which the different raw materials go into reusing."* - R2

5.3 Impact assessment

In this section the differences between companies 1 and 2 are examined based on the information that was obtained through conducting the SLR and the interviews. The functional unit specific CO_{2e} impacts are first assessed for both companies in subsection 5.3.1 and in subsection 5.3.2 the focus is on the functional unit specific material impacts. Finally, in subsection 5.3.3 the differences between the companies are assessed in terms of CO_{2e} and material impacts. The goal of this chapter is to respond to the second research question.

5.3.1 CO_{2e} impacts of alternative procurement options

In order to calculate the functional unit specific CO_{2e} impacts for the devices in both procurement options, the total CO_{2e} impacts of these devices must be divided by the length of the devices' lifespans in both procurement options. The end-of-life treatments that are practiced by the companies have an important role in defining the average lifespan of the devices. The practices of C1 does not include reuse practices, but as it was pointed out in chapter 3, the City of Helsinki also carries out reuse operations through the Uusix workshop if the devices are owned by the city. Due to this option, even if the devices are not reused by the supplier company, the ownership-based procurement model allows reusing of some of the devices through Uusix, which expands the average lifespan.

As it was not possible to interview the foreman of Uusix, it is challenging to estimate the share of the devices that is annually made reusable by the workshop. However, according to the report by Lehtinen (2018, 7) the annual procurement volume for the City of Helsinki is approximately 20,000 workstations and the number of objects that Uusix had processed was approximately 8500 in year 2018. In the report, it is also stated that a larger share of these 8500 devices was reused than recycled (Lehtinen 2018, 8). Based on this information, it is possible to define an interval, for which the reusing rate could potentially settle. If it is assumed that for example 5000–7000 devices are reused annually, it means that 25–35% of the annual procurements of 20,000 devices would be reused through Uusix. The same way as C1, also Uusix steers the nonreusable devices and components into WEEE recycling (Lehtinen 2018, 8). This indicates that the remaining share of the devices would be recycled efficiently in both procurement options.

R1 states that typical life cycle for their laptops in office use is approximately 4–5 years, which corresponds with the SLR results. There is no information available about the length of the life cycle extension period by Uusix, but R3 from C2 argues that reusing practices can double the length of the life cycle. Due to the slight difference between the results of SLR (see subsection 5.1.3) and the view of R3, it can be estimated that the second life cycle for laptops would be approximately 3 years. If 25–35% of the devices gain these additional life cycle years, the average life cycle for a laptop would be 5.4 years if it is procured from Company 1.

As pointed out in subsection 5.1.4, various articles propose that the average life cycle for tablets is 3 years. This corresponds with the answer by R1, who states that the average life cycle for the tablets is approximately 2–3 years. The articles that were included into SLR did not provide information about the life cycle extension that can be acquired if a tablet is reused. The only estimation that is available for this information is the statement by R3 from C2, who argues that the devices' life cycles can be twice as long with the reusing practices. If the lifespan can be doubled for a similar share of the devices by Uusix, the average life cycle for tablet in this procurement option is 3.25 years. Based on the calculations that are presented in appendix 6, it can be estimated that the functional unit specific CO_{2e} impacts in this procurement option are approximately 40 $kgCO_{2e}$ for laptop and 37 $kgCO_{2e}$ for tablet. Considering the argument that non-renewable energy consumption is approximately ¾ for tablets compared laptops (Hischier et al. 2014B, 13), it may seem surprising how similar the functional unit specific CO_{2e} emissions for the devices are. However, this is mainly because the service life of the tablets is considerably shorter.

In the case of C2, the devices' life cycles resemble figure 3, which presents a flowchart for devices that are being reused. It should be mentioned, however, that the share that goes to landfills or even recycling in the preparation for reuse phase, is very small for C2.

According to R3, the first service life for laptops is typically 3–4 years. They also mention that municipalities usually procure devices that are relatively high-quality and as they are in office use, they tend to last for a relatively long time. For this reason, in this review it is assumed that the contract would be four years.

As mentioned earlier, R3 argues that reusing can double the devices life cycle. In order to maintain comparability between companies, it is assumed that the life cycle extension would be three years, as it was expected to be in the case of Uusix. However, the share of the devices that are reused is significantly higher for the C2. According to R2, approximately 97–98% of the devices are being reused, and 80% of the remaining 2–3% can still be reused as components. This makes the total reuse share 99.5%. Using a similar calculation as was being used for C1, the functional unit specific CO_{2e} emissions for laptops are approximately 31 $kgCO_{2e}$ (see appendix 6).

According to R3, the first use cycle for tablets is 2–3 years also in this procurement option. Separate reuse percentages were not offered for tablets, so in this review an identical reuse share of 99.5% is also assumed for tablets. It is also assumed that doubling the life cycle through reuse practices is also possible for tablets, as it was assumed in the case of C1. Based on these evaluations, the functional unit specific CO_{2e} emissions for tablets are approximately 24 $kgCO_{2e}$ in this procurement option.

Table 6. Companies' reuse shares, devices' average lifetimes, and CO_{2e} emissions per functional unit (calculations based on appendix 6)

	Company 1 (reuse through Uusix)	Company 2
Laptops		
Share of devices reused (%)	30	99.5
Average lifetime of device (years)	5.4	7
Device's total emissions ($kgCO_{2e}$)	216	216
CO_{2e}/one year of use (kg/device)	40	31
Tablets		
Share of devices reused (%)	30	99.5
Average lifetime of device (years)	3.25	5
Total emissions ($kgCO_{2e}$)	120	120
CO_{2e}/one year of use (kg/device)	37	24

5.3.2 The material impacts of alternative procurement options

In this subsection, the functional unit specific material impacts in different procurement options are reviewed. The reviews are based on similar assumptions that were taken in the previous subsection, considering the reuse shares carried out by Uusix and C2, and the life cycle extensions that are achieved through these reuse practices. The problem is that it was not possible to interview the recycling partner that the companies use, and thus it was not possible to acquire context specific information about the companies' material recycling shares. For this reason, recycling share estimations are based on the results of the SLR.

As it was pointed out by Boldoczki et al. (2020, 1–2) reusing the devices is a better option than recycling in terms of various impact categories, such as mineral resource scarcity. However, Van Eygen et al. (2015, 55) argue that in some cases reusing can also be a worse option than recycling in terms of material impact, if the devices are shipped to be reused in a country with poor recycling facilities. The devices that are reused by Uusix stay in Finland. R3 also pointed out that C2 is very strict about who they resell the devices to, and they are only shipped to countries that cover an e-waste scheme. According to R3, the main markets for used devices are in Sweden and Poland. The data from The Global E-Waste Statistics Partnership (2021), demonstrates that the e-waste collection rate in Poland has been 61% from 2017 to 2019, and for Sweden the rate has been 70%. As the similar rate for Finland was 61%, it can be assumed that in the case of C2, the devices are recycled after second life cycle as efficiently as those that are recycled after the first life cycle.

The functional unit specific shares of material consumption in different procurement options can be calculated by dividing the devices' total material waste by the devices' life cycle lengths in these procurement options. The total shares of wasted material are presented in table 5 and the average lifespans of the devices in these procurement options are presented in table 6. The functional unit specific material impacts are presented below in table 7. In reality, the material impacts do not occur annually through the use, but as the devices' are updated to new ones after the life cycle, longer life cycle decreases the material waste that stems from the old devices' recycling process, while also decreasing natural resource consumption.

Table 7. Functional unit specific material impacts (grams) in different procurement options

	Company 1	Company 2
Laptops		
Aluminium wasted/functional unit	9.8	7.6
Copper wasted/functional unit	4.8	3.7
Plastic wasted/functional unit	161	124
Precious metals wasted/functional unit	0.05	0.04
Tablets		
Aluminium wasted/functional unit	17.5	11.4
Copper wasted/functional unit	0.6	0.4
Plastic wasted/functional unit	4.6	3

5.3.3 Interpretation

Finally, in this subsection the functional unit specific differences between the environmental impacts in different procurement options are reviewed in terms of CO_{2e} emissions and material impacts. This review is based on the City of Helsinki's annual procurement volumes. However, it is again important to highlight that due to the lack of context specific information, several assumptions had to be taken to provide a basis for this review stage, and it might not perfectly mirror the context of the case studied companies.

The City of Helsinki is estimated to procure 20,000 laptop devices annually (Lehtinen 2018, 7) and the functional unit specific CO_{2e} emissions for a single laptop in the case of buying it from C1 and utilizing the reuse services of Uusix are 40 $kgCO_{2e}$. Therefore, the total annual impact of applying this option is worth of 800,000 $kgCO_{2e}$ emissions. Due to the laptop's longer lifespan in the case of procuring them from C2, the functional unit specific emissions for a single laptop are approximately 31 $kgCO_{2e}$. Considering the annual volume of the procurements, the total impact in this option is approximately 620,000 $kgCO_{2e}$. The difference between these options is 180,000 $kgCO_{2e}$ annually, which denotes a 22.5% decrease if the devices are reused more regularly in the latter option. However, it should be noticed that even if the devices are owned by the city, the difference can also be mitigated by extending the contract period or utilizing the services of Uusix more comprehensively.

There was no exact information available about the City of Helsinki's procurement volumes for tablets. However, it was estimated by the city's IT specialist that the procurements are probably between 5000 to 6000 devices annually. Thus, it can be expected that the annual procurement volume is approximately 5500 tablet devices. If the devices are procured from C1 and the services of Uusix are utilized in reusing a share of them, the functional unit specific impact of a tablet is approximately 37 kgCO$_{2e}$. Thus, the total annual impact that stem from this procurement option is 203,500 kg worth of CO$_{2e}$ emissions. The similar annual impact for a single device in the case of procuring it from C2 is 24 kgCO$_{2e}$ emissions, and therefore the total annual impact is 132,000 kg worth of CO$_{2e}$ emissions. When the total annual impacts in both procurement options are considered, it seems that the higher extent of reused devices decreases the CO$_{2e}$ emissions by 71,500 kg annually.

Table 8. Annual CO$_{2e}$ emission and the differences between the procurement options

	Laptops	Tablets
Company 1: Total annual emissions (kgCO$_{2e}$)	800000	203500
Company 2: Total annual emissions (kgCO$_{2e}$)	620000	132000
Difference (kgCO$_{2e}$)	180000	71500

The functional unit specific material impacts were measured for laptops by focusing on the material shares that are wasted due to the recycling inefficiencies. When procuring the laptops from C1 and utilizing Uusix for reusing some of the devices, it was estimated that approximately 9.8 g of aluminium, 4.8 g of copper, 161 g of plastic, and 0.05 g of precious metals go to waste annually per one laptop. When these quantities are multiplied by the procurement volume of 20,000 devices, it can be estimated that approximately 196 kg of aluminium, 96 kg of copper, 3220 kg of plastic and 1 kg of precious metals are annually wasted if this procurement option is utilized.

The annual quantities of wasted materials are smaller in the case of C2, as a larger share of the devices are reused. It was estimated earlier (see subsection 5.3.2) that in this option approximately 7.6 g of aluminium, 3.7 g of copper, 124 g of plastic, and 0.04 g of precious metals are annually wasted per laptop. When these quantities are correspondingly multiplied by the procurement volume, estimated 152 kg of aluminium, 74 kg of copper, 2480 kg of plastic, and 800 g of precious metals are annually wasted when utilizing this procurement option. To conclude, the material waste shares in this option are smaller, as 44 kg of aluminium, 22 kg of copper, 740 kg of plastic, and 200 g of precious metals are annually saved compared to the first option.

The shares of the annually wasted materials were smaller for tablets, and in the first procurement option an estimated quantities of 17.5g of aluminium, 0.6 g of copper, and 4.6 g of plastic are annually wasted per device due to the recycling inefficiencies. As the city's annual procurement volume is approximately 5500 tablets, the total annual material impacts in the first procurement option are approximately 96 kg of aluminium, 3.3 kg of copper, and 25.3 kg of plastic. Similar device specific material impact shares in the second procurement option were 11.4 g of aluminium, 0.4 g of copper, and 3 g of plastic. Thus, the total annual impact in this option is 62.7 kg of aluminium, approximately 2.2 kg of copper, and 16.5 kg of plastic being wasted. Based on these calculations, it can be estimated that in the case of tablets, the total annual material saving potential is 33.3 kg of aluminium, 1.1 kg of copper, and 8.8 kg of plastic, when the devices are reused more systematically in the second procurement option.

However, it should be highlighted that in reality the material waste does not occur annually during the product's life cycle, but the waste shares that stem from recycling inefficiencies were only fitted into the format of the functional unit as part of this study. In addition, the recycling shares and the shares of wasted materials do not accurately represent the case specific context of the studied companies, but they are estimations that were based on the results of the SLR. However, as mentioned in subsection 5.1.5, the e-waste collection rates in Belgium, which was used as a reference for the recycling rates, and the collection rates in Finland are relatively similar. Defining the recycling rates of the subcontractor who is responsible for the companies recycling practices was not possible to carry out within the schedule of this study. Furthermore, there was no information available about the recycling operators that are used by Uusix or those who purchase the devices from C2 as secondhand. It should be noticed that despite the positive environmental impacts of reusing the devices, it also makes it more challenging to track the devices' material flows, as the devices are circulated internationally.

Table 9. Annual material impacts and the differences between the procurement options

	Company 1	Company 2	Difference
Total aluminium waste in a year (kg)			
Laptops	196	152	44
Tablets	96	62.7	33.3
Total copper waste in a year (kg)			
Laptops	96	74	22
Tablets	3.3	2.2	1.1
Total plastic waste in a year (kg)			
Laptop	3220	2480	740
Tablets	25.3	16.5	8.8
Precious metals in a year (kg)			
Laptops	1	0.8	0.2

6 Discussion

In this chapter, the limitations of this study are considered and the results that have been obtained are linked to the broader social implications that were presented in chapter 2. The assumptions and limitations are acknowledged in section 6.1, and it is typical for LCA studies that there are several data gaps that require assumption making (Baumann & Tillman 2004, 228). The social implications of the results of this study are discussed in section 6.2.

6.1 Assumptions and limitations

A research process always contains certain limitations, but as it was mentioned in section 4.1, it is important to report the complexities and shortcuts in a transparent manner. This also allows the reader to be aware of the motives for different solutions that have been made. The limitations section of this study is relatively broad, because conducting an LCA study requires certain number of assumptions to be taken due to the data gaps. As it was also mentioned in section 4.1, it is also important to notify the reader about the missing pieces of information, but this is mainly done already in the method sections. The limitations of this research are presented separately for each method in the following paragraphs.

The challenge for this study was the relatively large scope considering the timetable. As the time available had to be utilized as effectively as possible, it was necessary to keep the individual methods relatively succinct. Only one broad database was used in the SLR, as it provided an access to multiple databases and thus saved time. A broader literature review could have provided a larger amount of suitable articles, because now a relatively large share of the laptop related information was obtained from the article by André et al (2019) and for tablets the information was rather extensively based on the article by Clément et al. (2020). However, as it is highlighted several times in this study, the problem is that the amount of suitable LCA studies is still limited. It seems, especially in the case of tablets (see e,g, Clément et al. 2020, 3), that even a broader SLR would not have provided a significantly higher number of relevant articles, while it would have still consumed time. In addition, both previously mentioned articles, for example, utilized several data sources in their studies. Despite relying only on Scopus, the SLR section provided an extensive amount of information in relation to the time that was invested.

One limitation of the study was the extent of the impact categories, in which the impacts were studied in. For example, human toxicity is a relevant impact category for ICT devices life cycle impacts, but the scope of this study did not allow studying the differences in all of the relevant categories. The decision to focus on CO_{2e} emissions and material impacts was based on the report by Ojala et al. (2020) which was used in chapter 2 as a background material for designing the content and the structure of this study. This report states that according to previous reviews, the most significant environmental impacts of ICT are energy and material consumption (Ojala et al. 2020, 24), while some of the articles in SLR also include human toxicity into the most significant impacts (see e.g. André et al. 2019, 272). However, the CO_{2e} emissions and material consumption were not excluded in any of the articles that considered most important impacts, but including human toxicity is also highly relevant to consider in similar studies that are conducted in the future.

In addition, the scope of this study was limited only to direct emissions, which rise from production, use, and disposal (Bieser & Hilty 2018, 1). Including the indirect emissions was not possible within the scope of this study, but in order to achieve a more comprehensive impact assessment of the devices in question, it is also important to study these indirect impacts in the future. Finally, for some of the devices' components there was no CO_{2e} impact information available from SLR articles. In order to form a chart about the life cycle stages' and components' CO_{2e} emissions that is as illustrative as possible, certain assumptions had to be taken. For some components or life cycle stages the information that was obtained from different articles seemed to be in conflict, as different devices were used in comparisons. Using a median of the model specific CO_{2e} emissions as an assumed standard was not an ideal mean, but due to large device specific differences, it was considered to be the best solution available. In addition, the assessment of the laptops' life cycle stage specific CO_{2e} impacts was based on an assumption that the devices are only used daily for two hours. In the office use, however, the devices are often used much more and thus it should be noticed that in terms of CO_{2e} impacts the significance of use stage is likely to be higher in the context of this study. It was also assumed that the devices are functionally equivalent during their second life cycle.

Similar assumption was made in the study by André et al. (2019), but it should be still noticed that even if the devices are in as-new condition, different organizations have different requirements for the devices.

Certain limitations were also related to the measuring of the material impacts. As it was mentioned in subsection 5.1.5, different studies have different approaches for defining the importance of certain materials, and some of them highlighted material scarcity, while others focused on materials' environmental impacts (André et al. 2019, 269). For this reason, the focus on this study was put on several materials, and some of them are considered important because of the scarcity, while others are considered important because of their large share in devices.

In this study, the material composition of a laptop was based on the general composition of disposed laptops, and this approach might neglect the device specific differences that stem, for example, from different casing materials and device sizes. On the other hand, this approach allows independence from these differences, and focusing only on the composition of one device would give a biased understanding of the laptops' general composition. Another limitation that was related to the laptops' material impacts was the limited amount of information about the recycling shares. The study that was used in this section (Van Eygen et al. 2015) was based on information that was collected in Belgium in 2013. As the study is relatively old, the recycling efficiency might have improved and there might also be company specific differences in the WEEE recycling efficiency, although the e-waste collection rates are relatively similar between the countries in question. For this reason, interviewing the recycling company that both of the case companies use, would have provided more context specific information, but unfortunately it was not possible to carry out this interview as a part of this study within the schedule. In the case of C2 it was only stated that the main markets for the used devices are in Poland and Sweden. Although it is possible to consider the e-waste recycling rates of these countries, it is still difficult to get precise information of the end-of-life treatments that are used for these reused devices. However, this is a relevant observation, because it highlights the importance of supply chain transparency, if the end-of-life treatments are carried out through international cooperation.

An important limitation for studying the material impacts of tablets was the lack of previous studies. Clément et al. (2020, 3) state that there are only two previously existing transparent LCA studies of tablets, and only one of them focused on the material impacts. For this reason, there were no studies available that could be used for comparing the results by Hischier et al. (2014A). The article by Hischier et al. (2014A) did not provide material specific recycling shares for tablets, and for this reason the recycling shares had to be based on those for laptops. However, it is possible that these shares differ between different devices and in the future it is important to study how efficiently different materials are recycled for tablets as well. Despite these limitations, this study provides an illustration of the recycling shares, device specific material shares, and impacts of some of the key materials that are used in these devices. On a general level, it can be said that in addition to the suppliers' practices, for example, the size and casing materials of the devices have also a key role for the material impacts when considering procurements.

It is also worth noticing that only two companies were included into the study, and thus it should be kept in mind that the interview results only represent the practices of these case companies and cannot be used for making generalizations about other ICT companies' practices. Quantitative information concerning Company 2's reuse shares was drawn from the company's sustainability report and verified through an interview with company representatives. As it was pointed out by André et al. (2019, 269) there is a lack of real-world business-related case studies of circular economy measures. In that sense this study, despite the narrowness, provided valuable information on a topic that has not yet been extensively studied.

Another challenge that emerged during the interviews was that the company's representatives had limited knowledge of how the recycling company would carry out the recycling operations. In this sense it would have been beneficial to interview the recycling company's representative, but this realization came up only when the company interviews were already carried out and at that stage it was already too late to include extra interviewees. However, asking these questions from the case companies' representatives was also important because it allows the identification of knowledge gaps. For C1 only one representative was interviewed, while for C2 there were two interviewees. This might also create an imbalance on how much the representatives are able to tell about the company that they represent.

It would have also been more convenient to conduct the interviews face to face, but due to the ongoing COVID-19 pandemic they were conducted on Microsoft Teams. Another interview setting related challenge was that the thesis is carried out in English, while interviews were carried out in Finnish. Selecting Finnish as an interview language made the interview situation flow more naturally, than it probably would have, if the interviews would had carried out in English. It was assumed that a possibility to answer the interview questions in one's native language would have a positive impact on quality of the answer. The original interview questions and answers were translated into English in such a way that the original meaning was preserved as well as possible, but the meanings always change slightly due to the translation process. As the focus of the interviews was to obtain factual information about the companies' practices, the translating could be done well without changing the most essential information content.

As it was pointed out by Alastalo et al. (2017) there is also a risk that when companies' representatives are interviewed, they have an incentive to describe the company's practices from public relations (PR) point of view. This challenge was acknowledged during the interviews. However, the most important factors that were obtained from the interviews for the impact assessment were the devices' life cycles in years and the companies' reuse rates for these devices. These pieces of information that were provided by the representatives about the life cycles, seemed to correspond with the results of the SLR. For C2 the reported reuse rates corresponded with their sustainability report. For C1 there were no clear estimations about the reuse rates that their recycling operator carries out, thus these operations were excluded from the impact assessment. As C2 uses the same recycling partner, the impact assessment was still balanced, as these possible reuse operations were excluded for both companies.

In addition, it would have been convenient to interview the representative of the Uusix workshop. The original intention was to carry out this interview as well, but neither the author of this thesis nor thesis commissioners were aware that conducting this interview would require a research permit. Acquiring this permit would have taken too long in terms of the research schedule and the interview had to be left out. It was fortunately possible to find relevant information about Uusix from the report by Lehtinen (2018). However, as this report was carried out in 2018, it is possible that some of the information, such as reuse rates, can be outdated. Also, as there is no clear number for the share of reused devices, the impact assessment had to be based on an estimation that was based on the information that was available. The report by Lehtinen (2018, 8) also states that Uusix recycles the nonreusable devices through a company that accepts electronic waste, but there is no further information about the company available.

Lastly, there were certain limitations related to the conduction of the LCA. However, making assumptions is a distinctive feature for LCA studies and it has been observed that even LCA studies that focus on similar subjects can provide very different results (Andrea & Vaija 2014, 410). A precise modeling of impacts is always difficult and using databases always involve limitations (Teehan & Kandlikar 2013, 3998). Many of the LCA related limitations of this study were related to the limitations of the methods that were used to collect the data, such as scarcity of previous studies and uncertainties in context specific recycling shares. As the information was collected from several different articles, there might be different article specific assumptions that were taken in these earlier LCA studies.

Yet, streamlined LCA, which relies on already existing data, has been described as a particularly suitable tool for supporting organizations' decision-making. Conducting a full LCA is often not possible because of the time limitations (Pesonen & Horn 2013, 1781–1783.), and relying on a streamlined version was considered as an optimal measure for the purpose of this study. It should still be noticed that when the procurement volumes are as large as they are in this study, the significance of estimation errors multiplies. Therefore, the results of the streamlined LCA should be considered as guidelines, rather than as precise quantitative measures.

6.2 Results and the analytical framework

Finally, it is important to regard what the broader social implications of the results of this study are and how the results can be linked to the theoretical perspectives that were presented in chapter 2. As mentioned in chapter 2, e-waste is the fastest growing form of waste (Ojala et al. 2020, 75) and energy consumption is increasing exponentially due to rapid digitalization (Ahmed et al. 2016, 43). Thus, it is likely that the environmental impacts of this progress will continue to accelerate in the future. In chapter 2, circular economy was proposed as a potential reform to cope with these challenges, and the 3R framework, consisting of practices of reducing, reusing, and recycling, was presented in the chapter. Although this study mainly focused on assessing the environmental savings that can be acquired through reusing and recycling practices, the reducing step was also indirectly considered through the interview results.

The length of the devices' life cycles has a key role in defining the functional unit specific environmental impacts and in addition to reusing the devices, the lifespan can also be prolonged by extending the contract period. During the interview, R1 mentioned the possibility to update the devices in order to keep them in use longer without having to sell them for second life cycle. Correspondingly R3 mentioned that extending the contract period also decreases the monthly costs, which means that reducing the need to procure new devices is not only environmentally more sustainable, but also more cost efficient.

However, R1 also highlighted that if the repairing activities are too expensive, consumers are instead more willing to replace them with new ones. This observation relates to the notion by Sabbaghi & Behdad (2017, 1) about how the manufacturers' planned obsolescence and the values and norms lead to the underutilization of the devices, as the repairing activities are generally considered from the perspective of economic viability. Differing norms were also visible in the interviews, as R1 considered the devices to be at the end of their life cycle when they are collected back from the consumer, while R3 argued that the devices' lifespans can be even doubled through reusing practices. The defining factor for the possibilities to extend the lifespan are the requirements that the consumers set for the devices' capacity. R3 noted that not all organizations need very powerful devices, which is why the circulation can be extended by selling them to another market segment (Sihvonen & Ritola 2015, 641).

The conflict between the environmental and economic savings that can be acquired by extending the devices' contract period and the capacity requirements for the devices applies also in the case of the City of Helsinki. More powerful ICT devices increase the labor productivity (Brynjolfsson & McAfee 2014, 98–99; Castells & Himanen 2002, 2, 21; Lange, Pohl & Santarius 2020, 2), but more regular renewal of the devices also increases the environmental burden. For this reason, it is important to define what the organizational requirements for the devices are and whether these requirements could be given in for achieving environmental savings. This disharmony relates to the standpoint of Rosa and Scheuerman (2009, 88–89), who argue that organizations are under the pressure to adopt the latest technologies in order to avoid becoming outdated. Furthermore, according to Moore's law, the computing power not only increases exponentially, but it also becomes more affordable in an accelerating speed (Ahmed et al. 2016, 43; Brynjolfsson & McAfee 2014, 40–41; Mollick 2006, 65). Thus, the incentive to renew the devices more often is also greater due to this factor. In the future it has been estimated that the digitalization continues on an exponentially growing acceleration (Schwab 2016, 12; Brynjolfsson & McAfee 2014) and it is possible that the dilemma between increasing efficiency and the environmental burden will become even more urgent.

Although it is important to consider the possibilities of lowering the environmental impacts by reducing the need for new devices, the main purpose of this study was to focus on the environmental impacts of reusing and recycling practices. The results of SLR demonstrated that as the main impacts stem from the production phase, reusing is a better option than recycling in both impact categories, as long as it is ensured that the devices will be treated properly after the second life cycle. According to Boldoczki et al. (2020), for some electronic devices it can also be a more environmentally sustainable option to replace them with more energy efficient versions, but this is the case if the impact mainly stems from the use phase. For this reason, energy efficiency should not be considered as a valid argument for renewing in the case of laptops and tablets. As mentioned in chapter 2, it can also be the case that increasing energy efficiency does not lead to decreasing energy consumption due to the Jevon's (1865) paradox.

The devices' functional unit specific impacts can be decreased by extending their lifespan, and as it was mentioned earlier in this section, this can be achieved also by selling the devices to another market segment that has lower criteria for the devices' capacity (Sihvonen & Ritola 2015, 641). According to R3, this ensures that the devices are not forgotten in storages after the first life cycle, which often happens to be the case with the devices that are owned by customers. This leads to a situation where the devices become obsolete, and the use potential is wasted. Thus, if reducing the need for new devices, for example through longer contract periods, is not considered possible by the City of

Helsinki, it is possible to extend the devices' life cycles by reselling them to an operator that does not have such strict requirements for the capacity.

Lastly, the devices' impacts can be decreased by recycling them. Recycling mainly decreases the material impact, while the effect on CO_{2e} emissions is lower (André et al. 2019, 269). For the material impact, it is important that the devices are also recycled efficiently after the second life cycle if they are reused. This appeared to be the case for both of the reuse providers in this study, but it should be noticed that reselling the devices internationally also makes it more challenging to receive information about the recycling efficiencies that the devices are dealt with. The additional fourth R, standing for recovery, is also directly related to recycling, as it extensively defines how efficiently for example the valuable and hazardous materials are collected.

Given the assumptions on which this sLCA is based, it was important that different life cycle stages' and components' impacts were mapped in this study, so that the measures for lowering the environmental impact can be targeted as effectively as possible. To conclude, the most significant measures for tackling the impact take place at the end of the life cycle. These measures reduce the need to produce new devices, which is the most impactful stage of the devices' life cycles. However, use is another relevant life cycle stage in terms of the devices' GHG emissions. The energy mix that is used in the use phase has also an important role in defining the emissions (Clément et al. 2020, 2–3.) and if the goal is to lower the total environmental footprint, it is also important to utilize renewable forms of energy in the use phase.

7 Conclusions

This final chapter presents the conclusions that can be made from this research. The aim of this study was to provide evidence-based support for the City of Helsinki for mitigating the environmental impacts of their ICT procurements. This assessment was carried out by examining how the circular economy -based solutions impact the environmental burden in the case of laptops and tablets. This topic was approached through two research questions: 1. What are the most important stages and components in laptops' and tablets' life cycles, in terms of CO_{2e} emissions and material consumption? 2. How are these stages and their impacts different in ownership-based procurement model and service-based procurement model?

The study was conducted as a streamlined life cycle assessment, which was based on already existing data. The data was collected from previous ICT related LCA studies by using systematic literature review. The goal of the SLR was to answer the first research question by providing information about the most impactful life cycle stages and components. Based on this information it was possible to create the devices' flowcharts for both procurement options and illustrate the magnitude of the impacts in the considered impact categories. To answer the second research question, it was necessary to interview the representatives of the case companies about their practices in the 3R framework. The information that was obtained through expert interviews was used for conducting the context specific impact assessments and interpretation, which were carried out in order to answer the second research question.

It is common that the researcher faces several data gaps and is forced to rely on assumptions and estimations when conducting an LCA study. This was also the case in this study, and it was not possible to carry out impact assessment on a very detailed level, because some of the context specific data was not available. However, this does not mean that the study could not provide valuable results, and despite these shortcomings, sLCA is considered to be a particularly suitable tool for supporting organizations' decision-making when their aspiration is to optimize their operations in terms of sustainability and life cycle perspectives. Previous sLCA studies have also demonstrated that the results that have been obtained by using the measure can lead to actual changes in the ways that the organizations operate. (Pesonen & Horn 2013, 1781–1783.) In addition, it was important to study the impacts in the context of ICT, because of the research gaps that considered the life cycle assessments of the tablets and the real-world business-related case studies.

Despite the inexactness of the impact assessment phase, various concrete results were obtained. The results indicate that the most important impact categories that should be considered in the case of laptops and tablets are CO_{2e} emissions and the material impacts, human toxicity being another relevant impact category in terms of end-of-life impacts. The most impactful life cycle stages are production and use, and some of the most impactful components are PCBs/PWBs, ICs, display, and casing. The functional unit specific impacts are strongly impacted by the device's lifespan and thus reusing can be considered as a better option for both impact categories, as long as the devices are also efficiently recycled after the second life cycle. C2 was able to provide second life cycle for almost all of the devices that are procured through them, and they had also taken into account the recycling intensity after the second life cycle. C1 does not provide reuse services, but in their case the City of Helsinki can organize reuse by utilizing the services of Uusix workshop. Lastly, the lifespan can also be extended by lengthening the contract period if the devices' capacities are still considered as functionally sufficient.

These pieces of information support the City of Helsinki in achieving the targets of the procurement related actions of *The City of Helsinki's Roadmap for Circular and Sharing Economy*. The results also support the City of Helsinki in their other strategies, such as *Helsinki City Strategy for 2017–2021*, *Carbon-neutral Helsinki 2035 Action Plan*, and the new procurement strategy. Cities have been considered as especially important drivers for the transition to circular economy, and changes in city level practices will also impact the transition on a country level. Finland being one of the most highly digitalized countries in the world, and the City of Helsinki being the largest public procurement operator in Finland, it is possible for the City of Helsinki to act as a leading example in the circular economy transition process. Due to the significant procurement volumes of the city, changes in procurement practices can lead to significant environmental savings in both studied impact categories. According to various scholars, digitalization will continue to accelerate in the future, and early reacting to this societal development allows effective mitigation of the environmental impacts that stem from this development.

Due to the lack of real-world business-related case studies of the potential environmental savings that can be acquired through circular economy -based measures, it is important to carry out more such studies in the future. The concept of circular economy is still relatively ambiguous, and although the conceptualization of circular economy in different studies has already been assessed, it is also important to assess how it is being conceptualized by different companies that argue to follow the principles of circular economy in their operations. Precise definition of the concept makes it more challenging to use the concept as a tool for green washing, and it clarifies the desired tendencies of this societal transition. Tablet being relatively new kind of terminal, it is also important to carry out more research about the material impacts of tablets and their components. As digitalization is considered to be an accelerating process, it is important that the research field actively seeks to keep up to date with this development and its consequences. Further research needs to also focus on the impacts of ICT devices on human toxicity, as it is another relevant impact category that was not assessed as a part of this study.

Finally, it is important for the City of Helsinki to actively keep track of their procurement volumes and the course of their devices. If the end-of-life treatments are not carried out in a systematic manner, there is a risk that after the first life cycle the devices remain unused in a storage and the remaining use potential will be wasted. The companies that were interviewed did not have detailed information about the recycling efficacy of their subcontractor and in the future it is important that in order to achieve transparency, both companies and the City of Helsinki should require this information. In addition to life cycle management, it is also important to consider the role of the electricity mix in defining the environmental impacts of the use phase and aim to utilize renewable energy. If the devices are sold to secondhand markets, it is also essential to ensure the recycling efficiency that the devices will ultimately be treated with. This will make the reusing practices and the material cycles more transparent.

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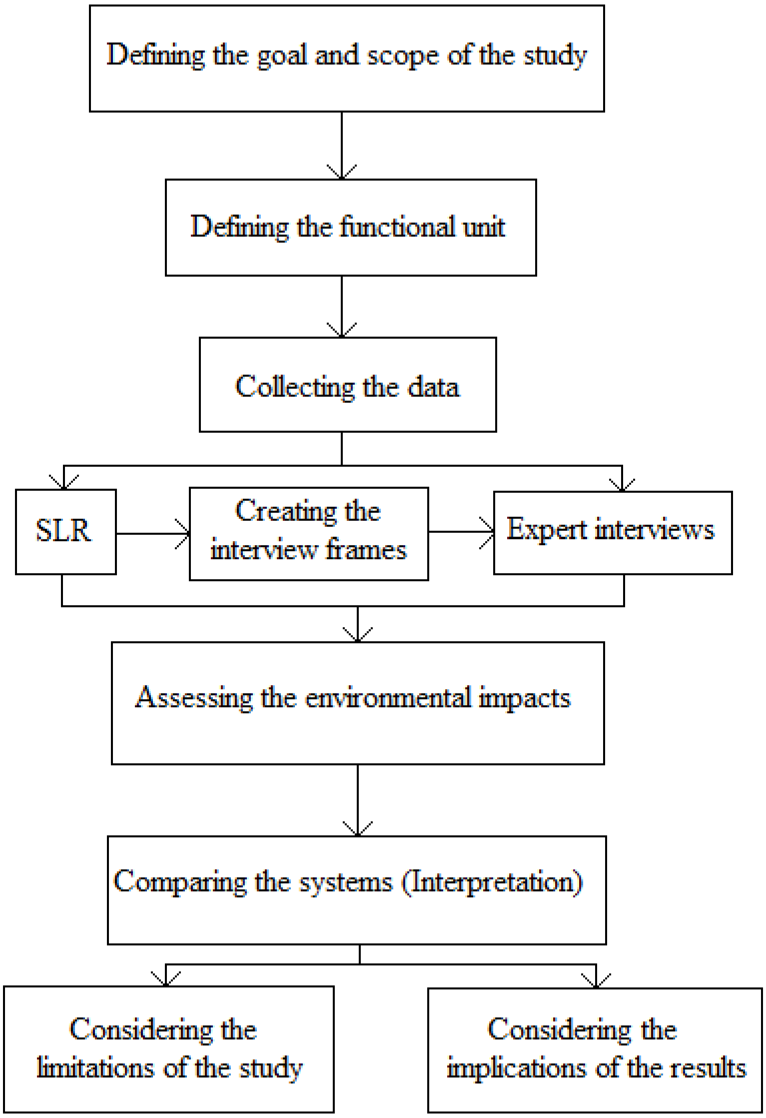
Appendices

Appendix 1. Proceeding of the study



Appendix 2. Results of SLR

Article and publishing information	**Theme/Topic**	**Methods**	**Key findings/results for this study**
Alcaraz, M., Noshadravan, A., Zgola, M., Kirchain, R. & Olivetti, E. (2018) Streamlined life cycle assessment: A case study on tablets and integrated circuits. Journal of Cleaner Production, Vol. 200, 819–826.	To carry out the structured under-specification and probabilistic triage method and to develop metrics for determining when enough data has been collected to carry out reliable streamlined LCA. The efficiency of this method is demonstrated on a case study on tablets.	Streamlined life cycle assessment/Structured under-specification and probabilistic triage	- Most impactful components for tablets. - Manufacturing phase is most important in terms of the devices' environmental impacts. - Shares of different life cycle stages for the devices' total CO_{2e} emissions. - Variables that define the impact of the use phase. - There are brand specific differences in terms of the devices' impacts.
Andrae, A. & Vaija, M. (2017) The life cycle assessments of an optical network terminal and a tablet: Experiences of the product environmental footprint methodology. Advances in Environmental Research.	To use product environmental footprint method (PEF) to study the impact of two goods: optical network terminal (ONT) and a tablet device.	Screening life cycle assessment Product environmental footprint method	- The most significant stages of tablets' life cycle in terms of climate change. - Tablets' environmental impacts are mostly found in production phase
André, H., Söderman, M–L. & Nordelöf, A. (2019) Resource and environmental impacts of using	How the use of second-hand laptops reduces different types of environmental impact, through reuse and recycling, compared to use of new ones.	Life cycle assessment	- The devices become prematurely obsolescent and are being underutilized by consumers. - There is an important gap at the

second-hand laptop computers: A case study of commercial reuse. Waste Management, Vol. 88, 268–279.			studies considering environmental impact of circular economy measures, due to the lack of real-world commercial business-related case studies. - Flowcharts for recycled and reused laptops. - Consideration of the impact of different laptop components. - There is lots of variance in the results of different ICT related LCA studies. - ICs and PCBs are responsible for significant share of the laptop’s impacts. - The most important impact categories for laptops are climate change, resource use, and human toxicity. - Climate change impact of the casing is mainly linked to production of magnesium alloy. - The impacts of transportation are very minimal. - Different end-of-life treatment options. - The most significant benefits of recycling are not related to climate change, but to material consumption and human toxicity. - Total CO_{2e} impact of a laptop. - The significance of different materials are considered important for different reasons in different studies.

			- Typical life cycle for a laptop is approximately 4 years and the second life cycle is approximately 2–3 years.
Bieser, C. & Hilty, L. (2018) Assessing Indirect Environmental Effects of Information and Communication Technology (ICT): A Systematic Literature Review. *Sustainability,* Vol. 10 (8).	To assess different approaches that have been taken in studies considering indirect environmental impacts of ICT.	Systematic literature review of existing assessments of ICT's indirect environmental impacts.	- Definitions of direct and indirect ICT emissions.
Boldoczki, S., Thorenz, A. & Tuma, A. (2020) The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany Journal of Cleaner Production Vol. 252.	Exploring the potential benefits of preparation for reuse (PfR) to other waste management options, including a review for laptops.	Life cycle assessment	- For small electric devices, such as laptops, the production phase is most dominant, and reuse leads to large savings in almost every impact category. - The optional end-of-life treatments. - Recycling can be more beneficial than reusing, if the emissions are mainly caused by use phase. But if the manufacturing phase is the main cause, reuse is better option in terms of environmental impacts.
Clément, L–P., Jacquemotte, Q. & Hilty, L. (2020) Sources of variation in life cycle	Analysing the studies that report the environmental impacts of smartphones and tablets. Identifying the	Literature review of LCA studies/Meta-analysis of LCAs	- Production phase is the most important part of the tablet's life cycle in terms of environmental impacts. Together

assessments of smartphones and tablet computers. Environmental Impact Assessment Review, Vol. 84.	main sources of variation in their LCAs.		with use phase they account for over 90% of the total impacts. - There are only two previously conducted transparent LCA studies for tablets. - The most impactful components of tablets and their CO_{2e} emissions. - The electricity mix that is used has also important role for the impacts. - Average life cycle of a tablet is approximately 3 years. - Assembly phase does not contribute significantly to the CO_{2e} emissions.
Hischier, R., Coroama, V–C., Schien, D. & Achachlouei, M– A. (2014B) Grey Energy and Environmental Impacts of ICT Hardware. In: ICT Innovations for Sustainability, eds. Hilty, L. & Aebischer, B., 171–189, Springer, Cham.	To form a more comprehensive picture of the total energy requirement and releases during the whole life cycle of the assessed ICT devices.	Life cycle assessment	- The impacts of assembly and end-of-life treatment phases are not significant. - Impacts of the most important life cycle stages of laptops. - Compared to a laptop, the share of non-renewable energy being used with tablet is smaller by the factor of ¾. - Typical life cycle for a laptop is approximately 4 years.

Kasulaitis, P., Babbitt, C., Kahhat, R. & Williams, E. (2015) Evolving materials, attributes, and functionality in consumer electronics: Case study of laptop computers. Resources, Conservation and Recycling, Vol. 100, 1–10.	To study material intensity of laptop computer for different model years and to understand the variance and dematerialization that occurs due to product development. Also, to study potential of life cycle inventory approximations for consumer electronics.	Life cycle assessment Bill of attributes	- Semiconductor manufacturing contributes significantly to electronic products' environmental impacts, and majority of these are contained e.g. in motherboard. - Product weight loss is less than 2% annually between different model years, but there are significant differences between different sized devices. Most significant change is the shift from plastic casings to aluminium casings. - An average laptop weights approximately 2.5 kg.
Meyer, D. & Katz, J. (2015) Analyzing the environmental impacts of laptop enclosures using screening-level life cycle assessment to support sustainable consumer electronics. Journal of Cleaner Production, Vol. 112, 369–383.	To form a better understanding of promoting environmentally sustainable electronics by using different laptop case materials. Different materials are compared, such as plastic, bamboo, and aluminium.	Screening life cycle assessment	- Majority of laptop's CO_2 emissions stem from manufacturing. - A large share of the plastic in the casings ends up in the landfills, as the separation of plastics is difficult and not economically viable. - Use of PCR has significant environmental benefits compared to the use of virgin materials. - Using recyclable aluminium is not better option than using plastic, if the post-consumer recyclability is too low.
Sabbaghi, M. & Behdad, S. (2017)	To investigate the environmental impact	Life cycle assessment	- Consumer behavior is affected by

Environmental Evaluation of Product Design Alternatives: The Role of Consumer's Repair Behavior and Deterioration of Critical Components. Journal of Mechanical Design, Vol. 139.	of components' deterioration and consumers' decisions to repair the devices.		manufacturer's planned obsolescence and the release time of new technologies. - If the repair costs exceed a threshold, consumers are not willing to repair their devices. - The decision to repair a device is also impacted by the norms, values, and beliefs.
Van Eygen, E., De Meester, S., Tran, H-P. & Dewulf, J. (2015) Resource savings by urban mining: The case of desktop and laptop computers in Belgium. Sustainable Materials Management, Report no. 17, Leuven.	Assessing the performance of WEEE recycling of laptops and desktop computers in Belgium.	Life cycle assessment Material flow analysis (MFA) Cumulative Exergy Extraction from the Natural Environment (CEENE) method	- PCBs contain lots of precious metals. - Large share of PC-ABS plastics is landfilled. - Recycling a laptop saves approximately 87% of the natural resources compared to landfilling. - Recycling treatments for different components and materials. - Casing material forms the biggest share of the laptop's materials. - Material composition of 1000 kg of disposed laptops and their recycling rates. - Reusing can also be worse option than recycling in terms of material impact, if the devices are not treated properly after the second life cycle.

Appendix 3. Results of the secondary references

Article and publishing information	**Primary reference**	**Theme/Topic**	**Methods**	**Key findings/results for this study**
Buchert, M., Manhart, A., Bleher, D. & Pingel, D. (2012) Recycling Critical Raw Materials from Waste Electronic Equipment. Öko-Institut eV, Freiburg.	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, Vol. 88, 268–279.	To produce a life cycle inventory of the critical raw materials in different electronic devices.	Life cycle inventory analysis	- In North Europe, around half of the laptops are being recycled, but there is not enough information available about the other pathways.
Andrae, A. & Vaija, M. (2014) To which degree does sector specific standardization make life cycle assessments comparable? - The case of global warming potential of smartphones. Challenges, Vol. 5 (2), 409–429.	Clément, L–P., Jacquemotte, Q. & Hilty, L. (2020) Sources of variation in life cycle assessments of smartphones and tablet computers. Environmental Impact Assessment Review, Vol. 84.	To demonstrate how the methodological decisions impact the results in LCA studies.	Comparing the differences between the results of different LCA modelings.	- The GHG emissions in LCD production are mainly linked to the electricity production.
Hischier, R., Achachlouei, M.A. & Hilty, L.M., (2014A). Evaluating the sustainability of electronic media: Strategies for life cycle inventory data collection and	Clément, L–P., Jacquemotte, Q. & Hilty, L. (2020) Sources of variation in life cycle assessments of smartphones and tablet computers.	To demonstrate how the methodological decisions impact the results in LCA studies.	Comparing the differences between the results of different LCA modelings.	- The material specific shares of a tablet device. - Approximately 51% of the tablet’s weight can be directly recycled and approximately 15% of the remaining amount can be taken into material recycling.

their implications for LCA results. Environmental Modelling & Software, Vol. 56, 27–36.	Environmental Impact Assessment Review, Vol. 84.			
Teehan, P. & Kandlikar, M. (2013) Comparing embodied greenhouse gas emissions of modern computing and electronics products. Environmental Science & Technology, Vol. 47(9), 3997–4003.	Clément, L–P., Jacquemotte, Q. & Hilty, L. (2020) Sources of variation in life cycle assessments of smartphones and tablet computers. Environmental Impact Assessment Review, Vol. 84.	To estimate and compare GHG emissions of different ICT devices, including laptops and tablets.	Life cycle assessment	**-** Methodological guidance for this study. - The shortcomings of currently existing studies that focus on the impacts of ICT.
Raghavan, S. (2010) Don’t Throw It Away: The Corporate Role in Product Disposition. *Journal of Business Strategy,* Vol. 31 (3), 50–55.	Sabbaghi, M. & Behdad, S. (2017) Environmental Evaluation of Product Design Alternatives: The Role of Consumer’s Repair Behavior and Deterioration of Critical Components. Journal of Mechanical Design, Vol. 139.	To understand consumers’ disposal decisions from environmental and marketing perspectives.	Literature review	- Significant amount of working products are disposed every year, because consumers consider them to be obsolete.

Appendix 4. Interview questions in English for the Company 1

Section 1: General practices

1. Could you describe Company 1's warranty policies for the devices? (Is it common that the devices that are in the office use need to be repaired during the warranty period? If so, can you say what kind problems are most typically repaired within the warranty period?)

2. Can you tell me about the reasons why a laptop or tablet computer purchased from the Company 1 most often arrives back to you as a disposal? (Is it more often, for example, that the pre-defined service life of the equipment has been reached, or that the equipment has broken down after the warranty period, or for some other reason?)

3. What is the average length of the life cycle of the laptops or tablets, after which they will be returned to you as disposals?

4. Can you name a certain manufacturer or model that would have been particularly popular in office use, and which represents a significant proportion of the equipment provided by Company 1?

Section 2: Reuse of the devices

5. Does the Company 1 provide some kind of reuse service for incoming devices, such as replacing damaged components and reselling the device for a lower price?

5.1 If yes,

5.1.1 Are there any specific components that need to be most often renewed in order to make the device reusable? Could you estimate a percentage share for the devices that need these kinds of replacements in order to make them reusable?

5.1.2 Do you use new or used components for making the devices reusable?

5.1.3 How long are the second life cycles for reused laptops and tablets?

5.1.4 How big is the share of discarded laptops and tablets that can be given a second life cycle by replacing components?

5.1.5 Which customer groups are mainly interested in purchasing reused equipment? Would you be able to estimate the percentage shares of these customer groups?

5.2 If no,

5.2.1 In your opinion, what are the main challenges for the provision of reuse services from the perspective of the IT-device supplier?

5.2.2 Can you say whether there has been a discussion about the possibility to provide reuse services by the Company 1?

Section 3: Recycling of the devices

6. Could you describe the recycling process for those laptops and tablets, that have arrived back to you as disposal? (Which components are distinguished from the devices for separate recycling treatments? What happens to those components that are not distinguished? How it is ensured that the recycling partner operates responsibly, and do they have environmental certificates?)

6.1 Recycling of printed circuit boards and integrated circuits

6.1.1 What happens to the devices' printed circuit boards and integrated circuits during the recycling process?

6.1.2 How are the components that are sent for secure recycling treated in further processing? (Are metals contained in printed circuit boards and integrated circuits collected for reuse for example? If so, can you estimate how much of the value of the metals is returned to the material cycle and for which metals the collection is particularly successful?)

6.1.3 How are the non-security sensitive (PCB/IC) components treated in further processing? (Are metals contained in printed circuit boards and integrated circuits collected for reuse for example? If so, can you estimate how much of the value of the metals is returned to the material cycle and for which metals the collection is particularly successful?)

6.2 Recycling of displays and casings

6.2.1 Can you indicate what proportion of the recycled devices are equipped with a plastic/aluminium casings?

6.2.2 How are the plastic and aluminium casings recycled? How effectively are the plastic and aluminium casings utilized in the production of recycled materials?

6.2.3 How are the devices' displays recycled? Is it possible to collect materials for displays in order to produce recycling materials?

Appendix 5. Interview questions in English for the Company 2

Section 1: General practices

1. Can you tell what is the most common length for laptops and tablets first life cycle (or for the leasing period)? How common it is that the devices break, and thus have to be renewed in the middle of the contract period?

2. Could you describe Company 2's warranty policies for rental devices? (Is it common that the devices that are in the office use need to be repaired during the warranty period? If so, can you say what kind problems are most typically repaired within the warranty period?)

3. Can you name a certain computer manufacturer or model that would have been particularly popular in office use, and which represents a significant proportion of the equipment provided by Company 2?

4. Can you name other companies that are similar to Company 2 and supply IT-equipment in a similar manner?

Section 2: Reuse of the devices

5. Could you describe the Company 2's reuse services for the devices that arrive to you as a removals from the customers?

5.1 Are there any specific components that need to be most often renewed in order to make the device reusable? Could you estimate a percentage share for the devices that need these kinds of replacements in order to make them reusable?

5.2 Do you use new or used components for making the devices reusable?

5.3 How long are the second life cycles for reused laptops and tablets?

5.4 How big is the share of discarded laptops and tablets that can be given a second life cycle by replacing components?

5.5 Which customer groups are mainly interested in purchasing reused equipment? Would you be able to estimate the percentage shares of these customer groups?

5.6 In your opinion, what are the main challenges for the provision of reuse services from the perspective of the IT-device supplier?

Section 3: Recycling of the devices

6. Could you describe the recycling process for those laptops and tablets, that have arrived back to you as disposal and for which the reusing is not possible? (Which components are distinguished from the devices for separate recycling treatments? What happens to those components that are not distinguished? How it is ensured that the recycling partner operates responsibly, and do they have environmental certificates?)

6.1 Recycling of printed circuit boards and integrated circuits

6.1.1 What happens to the devices' printed circuit boards and integrated circuits during the recycling process?

6.1.2 Are the metals that are contained in printed circuit boards and integrated circuits collected? If yes, can you estimate how much of the value of the metals is returned to the material cycle and for which metals the collection is particularly successful? For which metals the recycling is particularly challenging?

6.2 Recycling of displays and casings

6.2.1 Can you indicate what proportion of the recycled devices are equipped with a plastic/aluminium casings?

6.2.2 How are the plastic and aluminium casings recycled? How effectively are the plastic and aluminium casings utilized in the production of recycled materials?

6.2.3 How are the devices' displays recycled? Is it possible to collect materials for displays in order to produce recycling materials?

Appendix 6. Calculations for the functional unit specific CO2e impacts in different procurement options

Company 1

Laptops $\mathbf{216\ kgCO_{2e} \div \{(4.5+3)x[(0.25+0.35) \div 2]+4.5x[(0.75+0.65)/2]\}= 40\ kgCO_{2e}}$

Tablets $\mathbf{120\ kgCO_{2e} \div \{(2.5+2.5)x[(0.25+0.35) \div 2]+2.5x[(0.75+0.65)/2]\} \approx 37\ kgCO_{2e}}$

Company 2

Laptops $\mathbf{216\ kgCO_{2e} \div \{[(4+3)x0.995]+(4x0.005)\} \approx 31\ kgCO_{2e}}$

Tablets $\mathbf{120\ kgCO_{2e} \div \{[(2.5+2.5)x0.995]+(2.5x0.005)\} \approx 24\ kgCO_{2e}}$