From Smartphone to Futurephone

Assessing the Environmental Impacts of Different Circular Economy Scenarios of a Smartphone Using LCA

Merve Güvendik - MSc thesis Industrial Ecology

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Merve Güvendik

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First supervisor: Dr.ir. J.B. Guinée, Institute for Environmental Sciences, Leiden University
Second supervisor: Dr.ir. S.F.J. Flipsen, Faculty of Industrial Design Engineering, Delft University of Technology
Company supervisor: M.Sc. Miquel Ballester Salva, Fairphone B.V.
Third supervisor: M.Sc. S.P. Deetman, Institute for Environmental Sciences, Leiden University
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Preface

I would like to thank Jeroen Guinée (CML) and Bas Flipsen guiding me through the thesis project and their helpful approach. Thanks to Sebastiaan Deetman for answering many questions I had during the project.

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Executive Summary

The lack of literature on using life cycle assessment (LCA) for increasing environmental performance raises the need for concepts or eco-design tools to be combined with LCA to answer the question of how to strategize and take actions based on LCA results. This study intends to address this need by using mobile phones as a case study and answering the question: How can the environmental performance of the Fairphone be improved?

In order to answer this question, an LCA was performed for the Fairphone to evaluate its current environmental impacts. The boundaries of the system consist of the material extraction, production of the components, assembly of the Fairphone, transportation of the components to the assembly plant, transportation of the Fairphone from the assembly plant to customers, electricity use for charging the phone and recycling of the Fairphone and the battery. The functional unit of the system is defined as "the use of a Fairphone and its battery with an average lifetime (3 years) and with the average daily use time of the Fairphone users". The data obtained from the bill of materials and dismantling of a Fairphone was used to model the system in CMLCA software using the ecoinvent database. Additional data was collected from the assembly plant and Fraunhofer Institute. Data about the use phase of the life cycle was collected from 823 Fairphone users via an online user questionnaire. Using the ReCiPe 2008 method, the characterization results were calculated for three impact categories: metal depletion, climate change and human toxicity. Fairphone results in 4.0425 kg Fe-eq in metal depletion, 16.404 kg CO_2-eq in climate change and 13.961 kg 1,4-DCB-eq in human toxicity. Contribution analysis was applied in order to identify the components and phases with the highest impact within the three categories. Subsequently, ideas are provided to improve the environmental performance of the identified hot spots.

In addition, eco-design tools and different concepts are evaluated to improve the environmental performance of the case study. After a thorough evaluation of potential tools, circular economy was chosen and applied to the case to create four scenarios. Even though in the main LCA the functional unit has been set to "3 years use of Fairphone", for the comparison of the scenarios, the functional unit is chosen "6 years use of Fairphone smartphone". Scenario 1 was created to represent a Fairphone smartphone that is used for 2 years by a consumer. Scenario 2 shows the current situation of the Fairphone users in which the consumer uses Fairphone for three years. Scenario 3 represents the first step of Fairphone to create a circular system, which is extending the product lifetime to six years with refurbishment activities. In the fourth scenario (Circular Fairphone), in addition to an extended lifetime of six years, a dismantling process is put into practice when the phone reaches the end of its functional lifetime. These scenarios were evaluated

using LCA in order to find out the benefits to the system. Finally, improvement ideas were given for the system and the components.

If the system is changed to the refurbishment scenario (scenario 3), the reductions will be as follows: 35% in metal depletion, 16% in climate change and 26% in human toxicity. This scenario can be a short-term strategy of Fairphone. Persuading the customers to use their mobile phones for six years instead of three years and providing an efficient refurbishment service could easily lead to the above-mentioned improvements without having to alter the system substantially.

If the company can change the system to circular Fairphone (scenario 4), significant reductions could be achieved compared to their current state (baseline scenario): 53% in metal depletion, 24% in climate change and 42% in human toxicity. This scenario could be a long-term strategy for the company. Customers should still be persuaded to use the mobile phone for six years. More investments are needed to achieve this scenario, for instance having a dismantling facility that collects the functioning components from the Fairphone to be used for refurbishing others. However, a feasibility analysis should be made to evaluate possible business models.

In general, scenario 1 shows that Fairphone can and should take an action concerning the decreasing lifetimes of smartphones. If the Fairphone customers use their Fairphone for only two years due to lack of communication and awareness of the environmental impacts, there will be an increase in metal depletion by 21%, climate change by 18% and human toxicity by 24% when compared to the baseline scenario.

As a result, in both scenario 3 and scenario 4, circular economy improves the environmental performance of the Fairphone in three impact categories, which are representative for other impact categories. With these results, the conclusion can be made that circular economy applications improve the environmental performance of the Fairphone.

Chapter 1 - Introduction

Consumer electronics have become more and more popular over the past several decades. They have changed the way we communicate, get information and entertain ourselves. From 2011 to 2012, the sales of the iPhones went up from 72 million units to 125 million units, showing a 74% increase in one year (Apple, 2014a).

While manufacturers are adding many models with new functions to the market each year, the lifetime of the products are decreasing dramatically. The average lifetime of the mobile phones varies significantly in different studies. Based on Dutch data, Wang et al. (2013) calculated the median lifespans of mobile phones in 2000 as 4.8 years and in 2005 as 4.6 years. The average lifetime is estimated 2.5 years (Nokia, 2005) and 2.0 years (Gaidajis et al., 2010). According to the U.S. Environmental Protection Agency, mobile phones are only used for an average of 1.5 years before being replaced, even though they can function for much longer (EPA, 2004). This short life span of product cycles causes an increase in e-waste generation. The U.S. Environmental Protection Agency states that 141 million mobile devices entered end-of-life management in 2009 (EPA, 2011).

1.1. Fairphone

Fairphone is a social enterprise, founded with the mission to create a movement to build a fair economy in the electronic industry by producing smartphones. According to Fairphone, a fair economy means: extracting raw materials which come from conflict-free mines; paying fair wages to workers along the life cycle; and running an open source operating system that anyone can modify. Fairphone has defined five action areas in order to generate a positive impact in the life cycle of the Fairphone. These areas are: 1) Precious Materials: responsible and transparent sourcing of minerals and metals. 2) Made with Care: workers' empowerment and improved working conditions. 3) Smart Design: open, responsible design. 4) Clear Deals: fair pricing and financial transparency. 5) Lasting Value: address the full life span, including use, reuse and recycling (Fairphone, 2014a). The company has produced 25000 smartphones after starting an online crowd-sourcing campaign. Fairphone is a company promising to make a change in the electronics industry by bringing transparency into the market and increasing the awareness of the consumers. Consumers adopted the mission of Fairphone very quickly and this helped the company to build a community eager to learn more about the life cycle of a phone.

1.2. Problem description

The increasing number of phones produced and their shortening life span increase the environmental impacts created throughout the life cycle of the phone. Not only does the quantity of produced phones increase, but also the need for precious metals used for one mobile phone, due to increasing performance requirements in a highly competitive market (Buchert et al., 2012). As e-waste continues to accumulate and precious metals become increasingly scarce, understanding the environmental impacts created by this industry is becoming more important.

One key challenge for understanding these impacts is the complexity of the product and its value chain. The different metals used in one phone come from suppliers who are located in different parts of the world. As components become more complex, a higher number of suppliers are added to the production list to deliver the needed materials. As a result, the origins of components are mostly unknown by the Original Equipment Manufacturer (OEM) (Schischke et al., 2002). It is difficult to trace back the materials and find out where they were extracted, processed, and used in the component. Some of the metals used in a mobile phone travel at least three continents during different processes before they arrive at the assembly plants (Fairphone, 2013).

As part of its mission for more transparency in the value chain of mobile phone production, Fairphone has made it a priority to trace back the different components used in their phones. The company is closely tracking the origins of several metals used in the components. An emphasis is thereby put on minerals whose extraction is associated with conflict, mostly originating in the Democratic Republic of Congo. Two such minerals are Tin and Tantalum, whose journey in the value chain of the Fairphone is shown in Figure 1 (Fairphone, 2013).

Although Fairphone seeks to monitor the origins of materials closely, insufficient information on the materials used for the components and a lack of industry-wide transparency beyond 1st tier suppliers create several challenges. However, transparency in the value chain and the possibility of tracing back materials to know the material used in components is important for an understanding of the environmental impacts of mobile phone production.

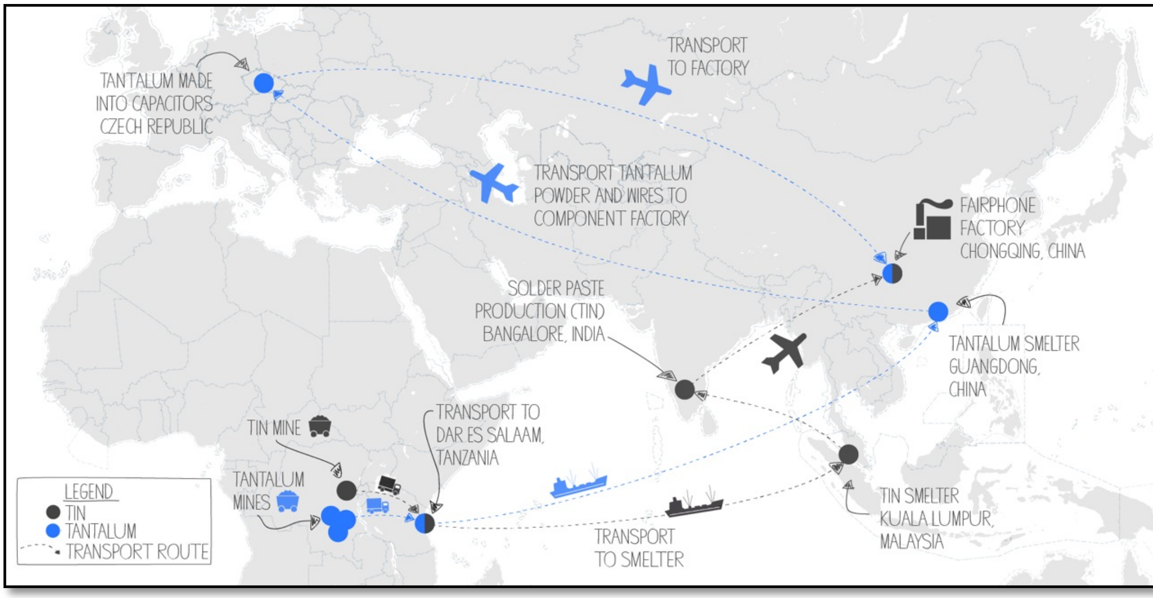

Figure 1. The track of Tin and Tantalum used in components of Fairphone (Fairphone, 2013).

In addition to these challenges in the supply chain, a lack of post-sale monitoring of the phones (i.e. in terms of disposal, recycling and take-back programs) adds to the difficulties of assessing the environmental impacts of a phone throughout its life cycle. Lastly, and beyond these operational challenges, more and more consumers want to know where their products come from and under what circumstances they are produced. As a result, companies are looking for ways to reduce the environmental impacts of a phone.

A number of tools and concepts exist that can be used to address the sustainability of products, including cleaner production, zero emissions, life cycle assessment (LCA), ecological footprint etc. LCA has been broadly used among many other tools (Baumann & Tillman, 2004). It is the most widely used and recognized tool due to its reliable, scientifically sound and holistic approach.

1.3. Purpose of the study

A few studies have already applied LCA to mobile phones (Ercan, 2013; Nokia, 2005; Nusselder, 2013; PE International, 2008; Seppala and Mattila, 2013). Frey et al. (2006) also applied an ecological footprint analysis to a mobile phone. Although there are different tools to assess the environmental performance of a phone, it is often not clear how to proceed in improving the environmental performance. According to Robert et al. (2002), LCA does not provide useful information for integrated and comprehensive strategic planning to improve the environmental performance of a product or service system, which makes it difficult to influence final business decisions. The lack of literature on using LCA for increasing environmental performance raises the need for concepts or eco-design tools to be combined with LCA to answer the question on how to strategize and to take actions based on LCA results. This study intends to add to this need.

From Fairphone's point of view, there are various reasons to collaborate in this study. First, the company wants to improve the next edition of the Fairphone by identifying the environmental hot spots in the product life cycle using LCA. Secondly, it aims to track and trace the components as much as possible in order to analyze the impacts of each component and improve the supply chain interactions. Thirdly, Fairphone wants to integrate life cycle thinking into the decision making process. Finally, it wants to publish the results about its environmental performance in order to bring transparency into the market and educate members of the Fairphone community about the life cycle of the smartphone.

1.4. Research question

The main research question of this study is:
How can the environmental performance of the Fairphone be improved?
In order to answer this question, the main research question has been broken down into a number of sub-questions:

1. What is the environmental impact of the Fairphone throughout its life cycle?
2. Which eco-design tools (or other concepts) can be used to improve the life cycle environmental impact of the Fairphone?
3. What is the environmental gain of applying options for improved design of the Fairphone?

1.5. Thesis structure

The next chapter describes the approach and method of the thesis and includes the literature review on the environmental impacts of mobiles phones. Additionally it includes an evaluation of different concepts and eco-design tools, as well as a choice for one method in order to find the answer to research sub-question 2. Chapter 3 gives an overview of the goal and scope definition of the LCA. The data collection and details of the LCA model is explained in Chapter 4. Chapter 5 includes the impact assessment of the study, with a selection of the impact categories and results of the characterization.

Chapter 6 looks at the last phase of the LCA and answers research sub-question 1. Chapter 7 presents the application of the chosen concept to the Fairphone, scenarios and a discussion of the impacts of the each scenario. The final chapter discusses the limitations, summarizes the study and offers suggestions for further improvements and research topics.

Chapter 2 - Approach and Method

This chapter describes the approach that has been taken and methodology used in the study. It gives a brief explanation of Life Cycle Assessment with example studies on the mobile phone. It also includes an evaluation of different concepts, eco-design tools and a choice of circular economy in order to find the answer to the research sub-question 2.

2.1. Approach

An extensive literature review on different mobile phone life cycle assessments helped to develop an understanding of the issue. The ISO standards on LCA were used to define the goal and scope of the study, together with Fairphone. Fairphone supplied the bill of materials of the mobile phone. To obtain further information on the weights and materials of the components, one Fairphone was dismantled. In case of insufficient or unclear data, additional information from the literature was used. An online questionnaire on smartphone usage was prepared in order to understand the use phase, which was responded to by 823 Fairphone users. All the information was analyzed in CMLCA software. A hotspot assessment enabled the identification of components with the highest environmental impact.

To improve the environmental performance, another literature review was completed in order to evaluate different eco-design tools and discussed in Section 2.3. At the end of the review, circular economy was the method chosen and applied. Circular economy criteria helped to develop scenarios for the Fairphone. Using the results of the previous LCA as a benchmark, the scenarios were tested to determine if the lessons from circular economy improves the sustainability of the mobile phone. A comparison analysis was made to see the advantages and disadvantages of the scenarios.

2.2. Life cycle assessment methodology

LCA is a tool to analyze "the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal (in effect, therefore, 'from the cradle to the grave')" (Guinée et al., 2001, p. 3). LCA gives a holistic approach while looking into the system. With a cradle-to-grave approach using LCA, the so-called "problem shifting" is avoided. For example, using a hydro-oleophobic coating for mobile phones makes a phone water and oil repellent and might prolong the lifetime of the phone. On the other hand, this application prevents the possibility for battery replacement and might result in more frequent replacement of phones due to short battery life.

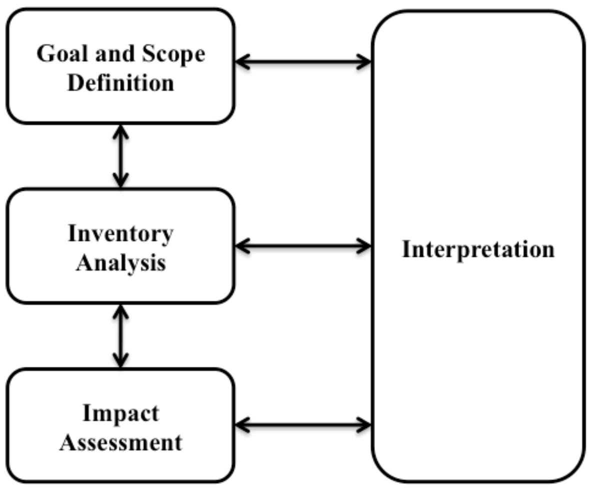

Figure 2. LCA framework (Guinée, 2002)

LCA is applied according to the framework that forms the basis of ISO standards (Figure 2). The analysis starts with the goal and scope definition phase, continues with an inventory analysis, then impact assessment and concludes with an interpretation of the results. The phases of the framework will be explained in the following chapters.

LCA can be used for product development and improvement, strategic planning, public policy making and marketing. Also LCA can be applied to the design phase in order to create more environmental friendly products.

2.2.1. Limitations and benefits of LCA

As a tool, LCA is very hard to use in a company for daily decisions, since the analysis requires detailed information and it takes time to gather the data. This makes LCA unpractical to use in companies.

According to Nokia (2005), the lack of available process and environmental data for the components in mobile phones is the main constraint of using LCA for phones. Specifically, there is insufficient data on the toxicity of the end-of-life stage.

2.2.2. LCA studies on mobile phones

There are studies on mobile phones conducted by researchers and also mobile phone manufacturers. Frey et al. (2006) made an overview of the LCA studies published before 2005 in their ecological footprint analysis of mobile phones. There is also a comprehensive LCA study done by Bergelin (2008) for the mobile phone Sony Ericsson W890 as a master thesis, but her study is not publicly available. Nevertheless, Ercan (2013) states that she has improved the study of Bergelin in 2013 by doing her master thesis in the same company. Table 1 summarizes some details of these LCA studies.

Andrae and Andersen (2010) discussed the consistency of life cycle assessments of consumer electronics. Even though there are inconsistencies for TVs and laptops, the studies on mobile phones are rather consistent (Table 2). The consistency can be a result of using the same data from GaBi database. Nokia published an article that shows the inconsistencies they faced during their LCA research. They took four phones and applied LCA to measure greenhouse gas emission of each phone from 2010 to 2012. Each year, they changed the assumptions and scope of the studies and conducted LCA for the same phone. They have seen that, each year the GHG emissions were different for the same phone (Figure 3). For example for phone 4, GHG emission was found 40 kg CO_2 eq. in the 2010 analysis, while the next year the same phone 4 resulted in 15 kg CO_2 eq. and in 2012, GHG emission increased to 35 kg CO_2 eq. They claim that the variations can stem from the impacts of different assumptions which the researchers at Nokia made each time, different LCA software tools, Life Cycle Impact Assessment (LCIA) methods, Life Cycle Inventory (LCI) databases and scenarios when assessing impacts on the product level (Santavaara & Paronen, 2013). This study shows that comparison of the different studies is difficult. The results might change even though the same researcher conducts the exact study for the same product.

In addition to these LCAs of mobile phones, there are a few studies made to improve environmental performance of consumer electronics. The researchers of the PROSUITE (PROspective SUstaInability Assessment Technologies) project developed a sustainability assessment methodology based on LCA approach and named it as Prosuite (PRe, 2013). Finnish Environment Institute applied this methodology to a study focusing on smartphones and their associated product system (including devices, accessories, networks and internet data transfer). With the PROSUITE approach, sustainability is measured along five pillars: aspects of human health, social well-being, natural environment, natural resource availability and economic prosperity (Seppala & Mattila, 2013). This research provides detailed information on product composition of mobile phones.

Study	Nokia (2005)	PE International (2008)	Nusselder (2013)	Ercan (2013)
Model	3G Mobile phone	250 g handheld mobile phone	Average of 29 mobile phones sold in 2013	Sony XperiaTM T smartphone
System boundaries	Raw material acquisition, production of components, components transport from the first tier to assembly, assembly, transportation of thephone and the use of the phone. EoL and network use are excluded.	Raw material acquisition, production, transportation, use (only charging), end-of-life	Raw material acquisition, production of components, assembly and packagin. EoL and network use are excluded.	Raw material acquisition, production, in- and outbound transportation, use and end-of-life treatment
Functional Unit	Use of a Nokia 3G mobile phone, its battery and charger, with an average life time (2 years) and average daily use time.	Unspecified	A packaged mobile phone without adapter, which can be used by a consumer for two years.	Use of one smartphone during the lifetime of 3 years
Life time (years)	2.5	4	2	3
Sources	GaBi Life Cycle Inventory data	GaBi Life Cycle Inventory data	The ecoinvent database & literature review	Data from suppliers, GaBi Life Cycle Inventory (LCI) data
Impact Assessment Tool	Unspecified	Unspecified	ReCiPe 2008	CML 2001, focus on GWP
Software	GaBi v3.0	GaBi	CMLCA	GaBi 6.0

Table 1. Comparison table for LCA of mobile phones

Device and technology, nation, reference, system boundary	Lifetime (years)	Electricity usage in use stage (kWh)	PEU in use stage (kWh)	Electricity usage in manufacturing (kWh)	PEU in manufacturing (kWh)
3G mobile phoone, Finland, Nokia (2005), cradle-to-grave	2.5	7.1-9.3	28	-	42
3G mobile phoone, Sweden/China, Bergelin (2008), cradle-to-grave	3.5	6.2	23	12	64

Table 2. Summary of benchmarking data for mobile phones (Andrae and Andersen, 2010).

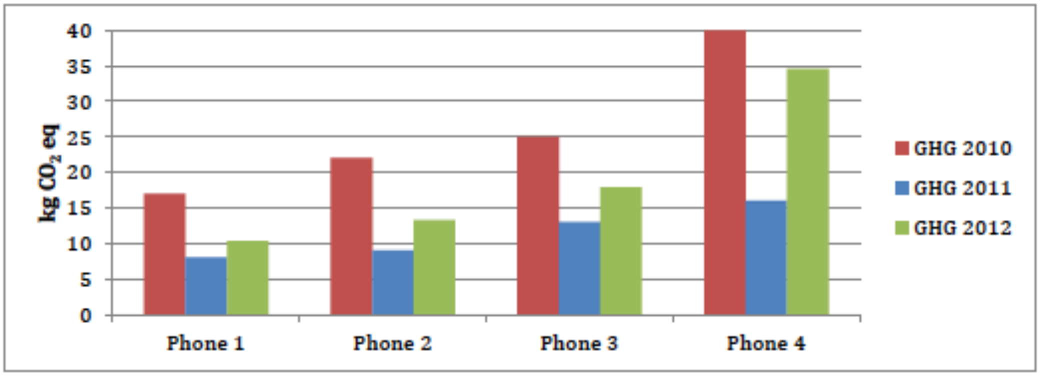

Figure 3. GHG emissions of four phones based on calculations made in 2010, 2011 and 2012 (Santavaara and Paronen, 2013).

2.2.3. Conclusion

The previous chapter showed that many researchers have already investigated the environmental impacts of mobile phones. In each study different software tools and system boundaries were chosen. The previous studies mostly analyzed the current situation of the product. Ercan (2013) developed a parameter model to be easily applied to different mobile devices, as Nusselder (2013) developed a "quick and dirty" LCA analysis for an average smartphone. The studies ended by analyzing the hot spots of the chosen impact category, rather than suggesting solutions to improve the environmental performance. This study intends to analyze the impacts of the current smartphone, and to suggest solutions for future design of the product and product system by using the circular economy concept.

The previous studies show the importance of choosing the most suitable dataset for the study. There are several other factors that can affect the results of the study significantly: assumptions, different LCA software tools, Life Cycle Impact Assessment (LCIA) methods, and scenarios. In conclusion, it is crucial to explain all the factors used in the study. The next chapter informs the reader about these choices.

2.3. Evaluation of the tools to improve the LCA results

In this section, different sustainability tools, eco-design tools and concepts are analyzed to choose an approach for improving the environmental performance of the Fairphone.

2.3.1. Possible tools to use for the improvement

In the literature, many frameworks are proposed for strategic sustainability management. Some of them create a general strategy for the company but not exactly a detailed solution in terms of design. The Natural Step is an international non-for profit NGO developed framework and one the most used frameworks (Schmidt-bleek et al., 2002). The framework is based on backcasting from sustainability principles in order to foster a new general approach to the management of materials and products (Ny et al., 2006). Even though this framework gained a lot of attention from the industry and has been applied to companies like Nike and IKEA (Mackrael, n.d.; the Natural Step, n.d.; Reichert, 1998), an application to this project would exceed the scope and time limitations of this thesis. However, another thesis project could apply the framework to Fairphone.

For eco-design researchers, consumer electronics is a popular topic as well. Park et al. developed a method to combine the bottom-up approach of UNEP and top-down approach of LCA (Park et al., 2006). A case study on mobiles phones was used to evaluate their proposed method. In their methodology, benchmarking is done according to the best performing competitor in the area. This approach makes the framework unreliable when all the companies in the industry do not perform well enough in terms of environmental impacts. In addition to that, a similar analysis is made in Section 5.4., and the results show that it is very difficult to gain a full understanding of other products since they do not disclose the details of the study.

Moreover, Byggeth and Hochschorner (2006) evaluated 15 eco-design tools in terms of support for different types of trade-off situations and existence of a life cycle perspective. According to their evaluation, nine out of the 15 tools include a valuation, but they provide insufficient support in a trade-off situation (Byggeth & Hochschorner, 2006). For this study, two of the 15 tools were analyzed because of their potential to create solutions and their life cycle perspective: the EcoDesign Checklist and the Strategy List (Table 3). EcoDesign Checklist identifies the main environmental problems along the life cycle of the product, which is actually a quick version of the hot-spot analysis. This could be helpful if the hot-spot analysis had not been already applied to LCA. Secondly, Strategy

List gives suggestions based on the following criteria: optimize material input, optimize energy use, reduce amount of land use, increase service potential, reduce pollutants, reduce waste, reduce emissions, reduce health and environmental risks. These suggestions are too general to fit to this study. In essence, these eco-design tools can be helpful for designers who would like to use these tools instead of conducting an LCA.

Description	EcoDesign Checklist	Strategy List
Purpose	- Identifies the main environmental problems along the life cycle. - The user has to evaluate whether the solutions in the checklist are good, indifferent, bad or irrelevant.	- To improve the environmental performance of a product concept or to compare different product concepts. - Consists of a list of suggestions for each life cycle phase to improve the environmental performance. - The suggestions are based on: optimize material input, optimize energy use, reduce amount of land use, increase service potential, reduce pollutants, reduce waste, reduce emissions, reduce health and environmental risks.
Life Cycle Perspective	Yes	Yes
Qualitative/ quantitative	Qualitative	Qualitative
General/ concrete	Concrete	Concrete
Valuation in the tool	Yes	Yes

Table 3. Comparison of eco-design tools. Adapted from Byggeth and Hochschorner (2006)

NGOs are also contributing to the improvement of the environmental performance of the products in the electronics industry. Greenpeace is one of the pioneers and has published a “Guide to Greener Electronics” (Greenpeace, 2012). This guideline includes ranking criteria, which can be easily implemented by the electronics industry. The Fairphone meets most of their criteria, while some of the criteria were not applicable for the scope of this study, for instance having a clean energy plan. Hence, this guideline is not considered as an improvement tool or concept.

Circular Economy (CE) is a concept which is gaining more and more attention from companies. CE aims at redesigning the linear life cycle flows to more circular flows. The concept has been evolving since 1960 and has had lots of influences from different concepts (Bechtel et al., 2013). The aim of CE can be summarized as closing the material loops, and treating them in two separate cycles: biological nutrients, which can safely re-enter the biosphere since they are non-toxic and biodegradable, and technical nutrients which can be reused again (McDonough & Braungart., 2002) (Figure 4).

2.3.2. Choice of the tool/concept

The choice of the CE concept for this study is motivated by the following presuppositions. First, previous research on the design of a mobile phone has identified the need to find out whether the CE concept, when applied to a mobile phone, actually improves its environmental performance (Poppelaars, 2013). Second, after presenting the previously mentioned possible methods to the Fairphone team, CE was the method that was most appealing for the team, due to its potential for further organization-wide innovation and the integration of design aspects and systems thinking. In addition, several aspects of the CE concept have already been integrated into Fairphone's thinking in previous business decisions. For example, the company has introduced a take-back program for the phones and offers refurbishment components online. These activities were introduced without the use of CE as a guiding conceptual framework. CE could be a welcoming opportunity to monitor and further develop these and other sustainability activities under the umbrella of the CE concept. However, this only makes sense if there are proven environmental benefits to future business decisions, to which this study intends to provide, with possible scenarios and answers.

2.4. The concept of circular economy

The idea of moving the current economic model from a linear to a more circular one has been expressed in different schools of thought. The concept of CE has been developed over the course of several years. One of the first to define the CE concept was Kenneth Boulding. He defined it as "a long-term aim compatible with economic growth, sustainability and zero waste" (Greyson, 2007, p.1383). According to the Ellen MacArthur Foundation (EMF, 2012) CE "has deep-rooted origins and cannot be traced back to one single date or author" (p.26). Yuan, Bi, and Moriguichi (2006) claim that CE stems from the field of industrial ecology and that the notion of closed-loops was first put into practice in German and Swedish environmental policy. Aspects of the circular economy can also be found in John T. Lyle's ideas on regenerative design, Walter Stahel's expression of a "vision of an economy in loops", Michael Braungart's and Bill McDonough's Cradle to Cradle concept and Janine Benuys' ideas on Biomimicry (EMF, 2013b)

As a result of these different ideas and perspectives, there is no coherent view on what a circular economy entails and how it can be achieved. To date, no coherent definition capturing the different aspects of all schools of thought on CE has been formulated. Due to its widespread influence in advancing the popularity of the concept of CE, this study will adopt the definition given by the Ellen Mac Arthur Foundation. This foundation states to work “in education, business innovation and analysis to accelerate the transition to a circular economy” (EMF, 2014) and states that CE “refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and hopefully eliminates the use of toxic chemicals; and eradicates waste through careful design” (EMF, 2013a).

Figure 4 shows the ‘butterfly diagram’, i.e. the conceptual framework of CE according to the EMF. As can be seen, there are several loops on both sides of the value chain of industrial activity. One side deals with the technical materials and the other with biological materials. There are several types of loops, i.e. for reuse, recycling or soil restoration. The different loops thereby stand for the cascading of components and materials, which means “putting materials and components into different uses after end-of-life across different value streams and extracting, over time, stored energy and material ‘coherence’ (EMF, 2012, p. 25). It should be noted here that the inner circles have a higher value or priority than the outer cycle in terms of energy conservation and restoration capacity. For example, the maintenance loop can be achieved at a lower cost (i.e. via the simple repair activities) than the recycling, which requires a lot of energy for decomposing products and integrating them again at the initial stage of the value chain. Furthermore, it should be noted that even though the material loops look like they are closed in the sense that materials return to the original manufacturer – other manufacturers could actually use them as well, as long as the materials flow back to their original material pool.

The CE concept takes insights from living systems, which are often referred to as ‘design to fit’. It puts the management of material flows as priority and distinguishes between consumer and user. As EMF puts it, “circular economy advocates the need for a ‘functional service’ model in which manufacturers or retailers increasingly retain the ownership of their products and, where possible, act as service providers—selling the use of products, not their one-way consumption” (EMF, 2012, p. 22). As such it has a few simple principles:

Design out waste - When fit into a closed material cycle, the biological and technical components should not create any waste. Biological components can be composted and technical material inputs can be used again “with minimal energy and highest quality retention” (EMF, 2012, p. 22).

Build resilience through diversity - Modularity, versatility, and adaptivity should be emphasized as important aspects of designing product systems that should have the ability to withstand sudden and surprising external shocks in an increasingly uncertain environment (EMF, 2012, p. 22).

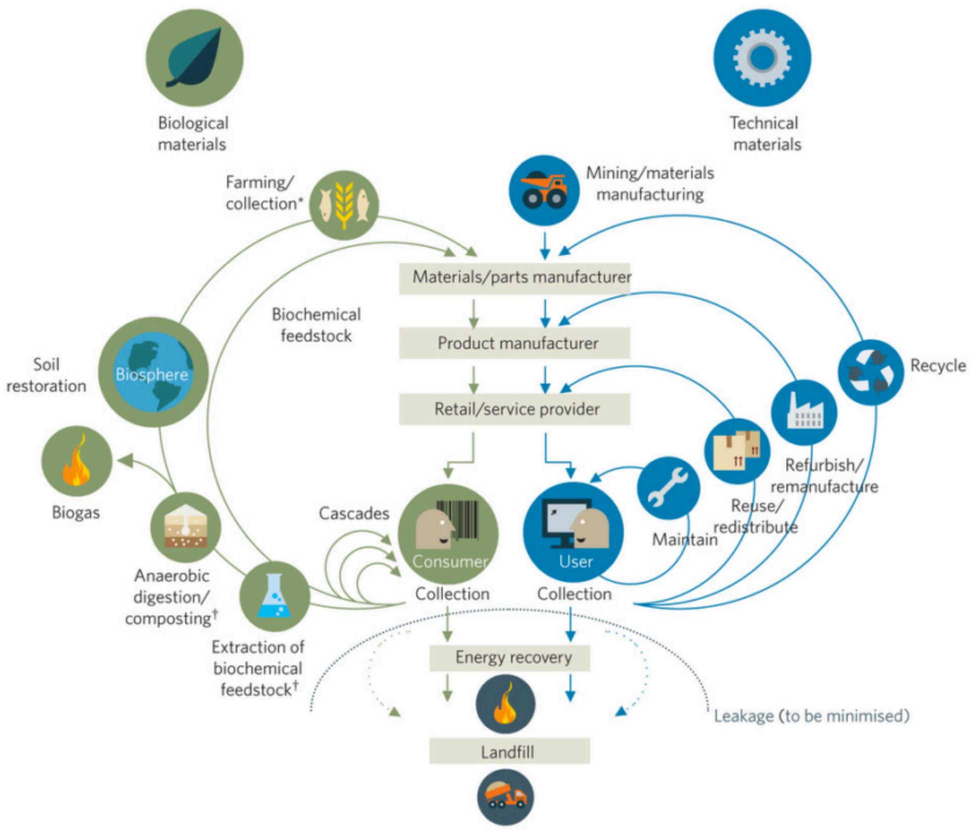

Figure 4. Two cycles of the CE (EMF, 2012, p. 24)

Rely on energy from renewable sources - Any endeavor to create a circular product system should look at the energy sources used in the production processes (EMF, 2012, p. 22-23).

Think in 'systems' – An understanding of how different components of a system influence each other is crucial. "Systems thinking usually refers to non-linear systems (feedback-rich systems). In such systems, the combination of imprecise starting conditions plus feedback leads to multiple, often surprising consequences and to outcomes that are not necessarily proportional to the input" (EMF, 2012, p. 23).

Waste is food – The composting of organic material on the biological nutrient side, the shift of consumables from the technical to the biological nutrient side and cascade effects in every stage of the value chain – including improvements in quality ('upcycling') along the way – mark the last principle of a circular economy (EMF, 2012, p. 23).

2.5. Conclusion on the choice of CE

This chapter aims to answer the second sub-question of the study:

Which eco-design tools (or other concepts) can be used to improve the life cycle environmental impact of the Fairphone?

The Natural Step Framework (Ny et al., 2006), benchmarking method developed by Park et al.(Park et al., 2006b), EcoDesign Checklist, the Strategy List, Guide to Greener Electronics (Greenpeace, 2012), and Circular Economy were evaluated and CE was chosen as the concept to improve the environmental impact of the Fairphone.

CE is chosen as the concept to improve the sustainability of the Fairphone for three reasons. Firstly, in the literature, there are no studies yet, which prove that the application of the CE concept makes product systems more sustainable. Secondly, after presenting the previously mentioned possible methods to the Fairphone team, CE was the method that was most appealing for the team. Finally, several aspects of the CE concept have already been integrated into Fairphone's thinking in previous business decisions.

Chapter 3 - LCA Case Study: Fairphone

3.1. Goal of the study

In the goal definition of a LCA – the goal, intended application, initiator, performer and the intended audience are described in this chapter.

3.1.1. Goal Definition

This LCA study uses a cradle-to-grave approach and aims to:

- Identify options for improving the environmental performance of mobile phones through circular economy criteria
- Create impact reduction strategies for the future design of the mobile phone.

3.1.2. Intended application of the study results

There are mainly four intended applications of the study results. Firstly, Fairphone wants to improve the next model of the smartphone by using the results of the LCA as the results could identify the environmental hot spots in the product life cycle. Secondly, the results could help Fairphone to integrate life cycle thinking into their decision-making process. In the last part of the study, strategic scenarios will be analyzed by using LCA. Thirdly, the study will help Fairphone to track and trace the materials used in the components as much as possible in order to analyze the sources of the materials and improve the supply chain interactions. Finally, the results of the study will be published on the website of Fairphone in order to bring transparency to the market and to inform members of the Fairphone community about the environmental impacts of the smartphone.

3.1.3. Initiator

This study is performed out of the initiative of Fairphone Company in the Netherlands.

3.1.4. Performer

This study is performed by Merve Güvendik as her graduation project in obtaining the level of Master of Science in Industrial Ecology under the supervision of Jeroen Guinée (Institute of Environmental Sciences, Leiden University), Bas Flipsen (Industrial Design Engineering, TU Delft), Miquel Ballester Salva (Fairphone) and Sebastiaan Deetman (Institute of Environmental Sciences, Leiden University).

3.1.5. Targeted audiences

The target groups of this study are the Fairphone Company, its customers, associates from the Industrial Ecology field, the information and communications technology (ICT) sector and other associates interested in the developments of environmental performance of electronic devices.

3.2. Scope of the study

3.2.1. Level of sophistication

The various levels of sophistication are often distinguished and presented in separate sets of guidelines: one for a simplified and one for a detailed level (Guinée et al., 2002). For this study, a detailed LCA is carried out. The default methods and sensitivity analysis are conducted using the ISO guidelines and complying with ISO's third party reporting guidelines.

3.2.2. Type of analysis: attributional LCA (ALCA) or consequential LCA (CLCA)

This study mainly focuses on finding the hot spots to improve the design of the mobile phone and processes. Hence, this study is aimed to be an ALCA.

3.2.3. Functional Unit

The functional unit describes the primary function(s) fulfilled by a (product) system, and indicates how much of this function is to be considered in the intended LCA study. It is used as a basis for selecting one or more alternative (product) systems that might provide these function(s) (Guinée et al., 2002, p. 468).

Function:
Smartphones have various functions, including: connecting to the internet; acting as a personal digital assistant, media player, digital camera and GPS navigation unit; running applications developed by third parties; accessing emails and Bluetooth.

Spatial Context:
Since it is very difficult to have a complete supply chain map for electronic devices, most of the time the origin of the raw material extraction of the components is unknown. For this data, processes from the ecoinvent database are used for the components with the set data of raw materials. For the mobile phone assembly, location specific data is used for the electricity usage. For the use phase, the electricity use for charging a mobile phone is set to electricity mix of Germany and the Netherlands, since half of Fairphone's customers are from Germany. For the recycling phase, the process is modeled on location specific data for the electricity use.

Temporal Context:
The study aims to assess the environmental impact of the Fairphone, which was produced in 2013. The ecoinvent dataset used in the modeling of this study was released in 2007, and most of its data come from studies which are more than ten years old. The recent improvements in the electronics sector are not covered by the data used in the study, which can result in lower environmental impact especially for the integrated circuits and printed wiring board. This should be kept in mind while interpreting the results of the study. In the model, the results are used to compare the different scenarios for the smartphone; therefore it reduces the limitations of the ecoinvent database. The data used

to estimate the electricity consumption of the users was obtained by a questionnaire conducted during this study.

User Behavior:
User behavior of mobile phone owners may differ between countries, age, and occupation. Even though there are different estimations about the lifetime of the mobile phones (as can be seen in Chapter 1), for this study the life span of mobile phones is set to 3 years based on the survey conducted with Fairphone users (823 respondents). The questionnaire can be seen in Appendix F. The average use of a phone is also obtained from the user questionnaire, which resulted in an average recharge of the battery every 30 hours. Average use is calculated according to battery charge (Section 4.6.).

All this gathered information leads to the following functional unit:

The use of a Fairphone and its battery with an average life time (3 years) and average daily use time of the Fairphone users.

The functions of a smartphone can be compared to the other products like an MP3 player, a camera, a basic mobile phone, a GPS navigator and a tablet. But smartphones provide a variety of functions, which cannot be replaced by any of the products mentioned above.

3.2.4. Initial choices on methods and data

System boundaries:
In the LCA, the system is modeled using a cradle-to-grave approach, which takes into consideration material acquisition, production, transportation, use and end-of-life treatment. Charger, USB-cable and headset will not be included in the system since they are not part of Fairphone's product package. Fairphone uses a standard micro-USB type B charger; the buyers can use their old charger, can buy the charger from any local store or can order it from Fairphone's web page. The product package, which includes the cardboard box, phone manual and wrappings material, will be evaluated as part of the system. The packaging of the components is not included in the analysis.

For ICT products, boundary selection is complicated by efforts to model the Internet backbone (cables, routers, switches and data centers) that delivers digital media (Bull & Kozak, 2014), hence internet usage is excluded from the system.

In Figure 5, the flow diagram shows the system boundaries and relations between the processes. This product system is almost valid for all mobile phones. Dashed lines show the process out of the system boundary. Even though collection rates of the mobile phones are rather low, there are no studies about the percentage of mobile phones which end up in incineration facilities or landfill areas. Also there is no comprehensive data available for the environmental impact of landfilling and incineration of electronic devices. Consequently, these waste treatment options were excluded from the system.

Fairphone has been sold since January 2014. Fairphone had an agreement with Teqcycle, which is a service company for individual business-to-business (B2B) take-back programs. Teqcycle will collect the phones via post and process them in their collection facilities. Teqcycle has various networks for refurbishing.

In the LCA study, only the recycling process was modeled. In the second part of the study, scenarios were created to show different applications of the circular economy concept. In the following section, a detailed description will be given for each of the considered processes.

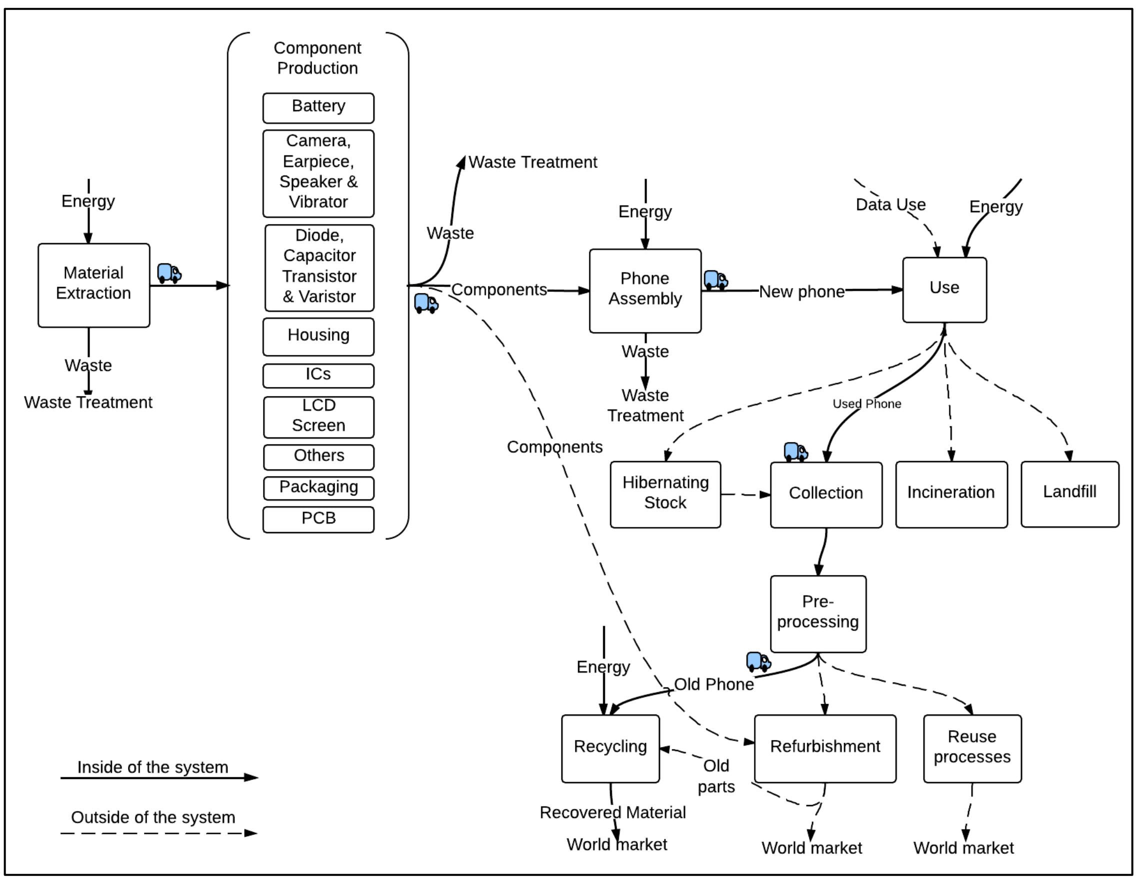

Figure 5. System boundaries of the study

Criteria for inclusion of data and data quality:

Where possible in the study, the primary data was obtained from Fairphone Company and the assembly factory. Since a mobile phone has more than 500 components, the data for the raw material extraction and component production was used from the ecoinvent database due to difficulties obtaining data from the suppliers within the time frame of this study. When data was missing or incomplete, data from other studies was used. More detailed information on this is provided in Inventory Analysis.

Allocation procedures:

Allocation is only needed for recycling of the mobile phones. In the ecoinvent database, allocation is already done for the background processes. For the recycling process, economic allocation is applied according to the price of the recovered materials obtained from the recycling company. The procedure is described in more detail in Section 4.8.

Main assumptions

The main assumptions of the system are described in each process in the inventory analysis.

Applicability of the study

The results cannot be used for comparative assertion.

Chapter 4 - Inventory Analysis

In the beginning of the inventory analysis, data was collected from the literature and the company. The main information used to build the inventory of the product was obtained from the bill of materials (BOM) of the mobile phone and by dismantling and weighing the components. The flow chart in Figure 6 shows the simplified version of the flow chart with the processes modeled during the inventory analysis.

To model the system for the study, two different software tools were used: (1) openLCA, which is an open source software tool developed by a sustainability consulting and software company, GreenDelta; (2) CMLCA, which is a software tool developed at the Institute of Environmental Sciences (CML). Both of them were used since the former was more user-friendly in order to build the inventory data, and the latter provided more detailed analysis options during the interpretation as it provides unique analyses (that can be applied either at the level of inventory or impact assessment results) compared to other software packages. Because of the problems faced by application of the allocation model to the openLCA software model, the study was completed using only CMLCA software.

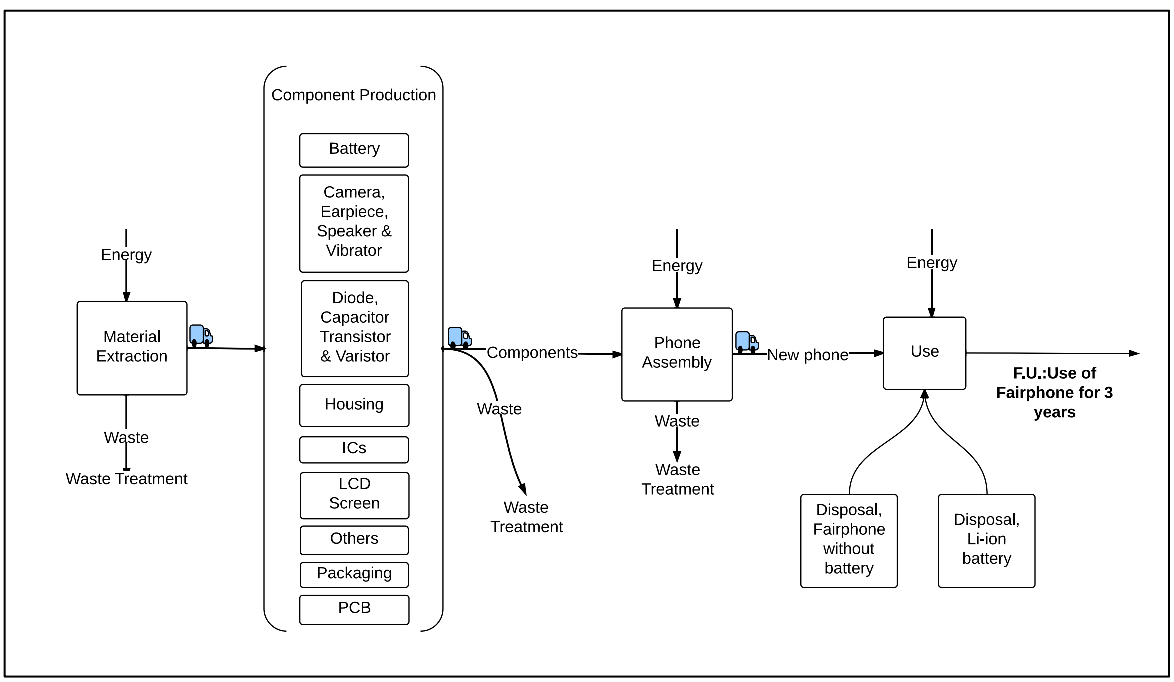

Figure 6. Flow chart of the study

4.1. Material extraction

Material extraction is referred to as a background process in this study. Data from the ecoinvent database is used for the defined component productions. For the components that do not have any process defined in the ecoinvent database, results of a product composition analysis were used to compile the model. These components are the camera, the earpiece, the speaker and the vibrator. More detailed information about modeling these components is provided in the following section.

4.2. Production of the components

Fairphone Company provided the bill of materials (BOM), which is a total list of components used to manufacture a Fairphone. The disclosed version of the BOM can be seen in Appendix A. When additional information was needed, the data sheets of the components, which explain the performance and technical characteristic of the components, were found on the Internet or supplied by Fairphone. Even though the BOM was very detailed, most of the components did not include the weight of the individual pieces. In order to retrieve the data, a Fairphone was dismantled with the help of a heat gun, down to the smallest component possible. The components were weighed using a high precision scale (0.01mg), Sartorius BP 211D, at the Gorlaeus laboratory of Leiden University[1]. After collecting the data for the weight of the components, the inventory list was created by analyzing and matching the components with the data on the ecoinvent database (Table 4). In Figure 7, the components of the Fairphone are showed according to their numbers in the inventory list in Table 4. Photo is taken after the dismantling the Fairphone.

In the following sections, the main assumptions for the components are explained.

<u>Integrated Circuits</u>
There are ten integrated circuits in the mobile phone. Two of them are recognized as memory type, one is on the printed circuit board; the other one is attached to the flexible printed circuit of the LCD screen. Since the rest could not be identified, the weight was divided by two and attributed to both of the types.

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[1] Special thanks to John van Dijk at the "Metals in Catalysis, Biomimetics & Inorganic Materials" research group of the Faculty of Science.

Since most of the ICs are coming from Taiwan, all of the ICs were assumed to be transported from Taiwan by airfreight. The details of the process can be seen in the Appendix B.

No.	Component	Ecoinvent Type	Quantity	Total Weight (g)
	Printed Circuit Board:			
1	Mainboard	PWB, surface mount, Pb-free	1	5.28
2	Daughterboard	PWB, surface mount, Pb-free	1	1.15
	LCD Screen:			
3	Flexible Printed Circuit	PWB, surface mount, Pb-free	1	0.58
4	Flexible Printed Circuit	PWB, surface mount, Pb-free	1	0.31
5	LCD Screen	(mod.) LCD glass	1	33.92
6	Plastic	Polycarbonate	1	0.68
7	Shell	Chromium steel 18/8	1	9.75
8	LEDs	Light emitting diode, LED	10	0.41
9	IC	Integrated circuit, IC, logic type	1	0.01
	Housing:			
10	Shell	Chromium steel 18/8	1	20.16
11	Front Housing	Polycarbonate	1	3.50
12	Back Housing	Polycarbonate	1	7.62
	Battery:			
13	Li-ion Battery	Battery, Li-Io, rechargeable, prismatic	1	38.60
	Capacitors, Diodes, Varistors & Transistors:			
14	Diodes	Diode, glass-, SMD type	58	0.15
15	Varistors	Diode, glass-, SMD type	142	0.37
16	Transistors	Transistor, SMD type	3	0.02
17	Capacitor	Capacitor, SMD type	283	0.46
18	Tantalum Capacitor	Capacitor, Tantalum	1	0.02
19	SAW	Capacitor, SMD type	3	0.04
	Integrated Circuits:			
20	IC, memory	IC, memory type	5	0.65
21	IC, logic	IC, logic type	4	0.41
	Camera, Speaker, Earpiece & Vibrator:			
22	Front Camera	Electronic component, passive, unspecified	1	0.16
23	Vibration Motor	Electronic component,	1	0.72

		passive, unspecified		
24	Earpiece	Modeled	1	0.51
25	Camera	Electronic component, passive, unspecified	1	0.92
26	Speaker	Modeled	1	1.33
	Others:			
27	Battery Cap	Chromium steel 18/8	1	24.91
28	PCB Covers	Copper, primary, couple production nickel	3	3.94
29	Simcard Holder	Chromium steel 18/8	1	1.29
30	Ctioils	Inductor, miniature RF chip type, MRFI	37	0.06
31	Magnetic bead	Ferrite, at plant	13	0.02
32	Unspecified	Electronic component, passive, unspecified		0.37
33	Cable	Cable, ribbon cable, 20-pin, with plugs	1	0.19
34	Screws	Copper	6	0.22
35	Copper coil	Copper	1	0.03
36	Brass screw	Brass	5	0.14
37	Connectors	Connector, computer, peripherical type		1.91
38	Thin film	PET, granulate, amorphous		0.31
39	Plastic tape	PET, granulate, amorphous		0.24
40	Net	Glass fibre reinforced plastic, polyester resin		0.78
41	Plastic pieces	Polycarbonate		1.34
	TOTAL:			**163.45**

Table 4. Inventory list of the components

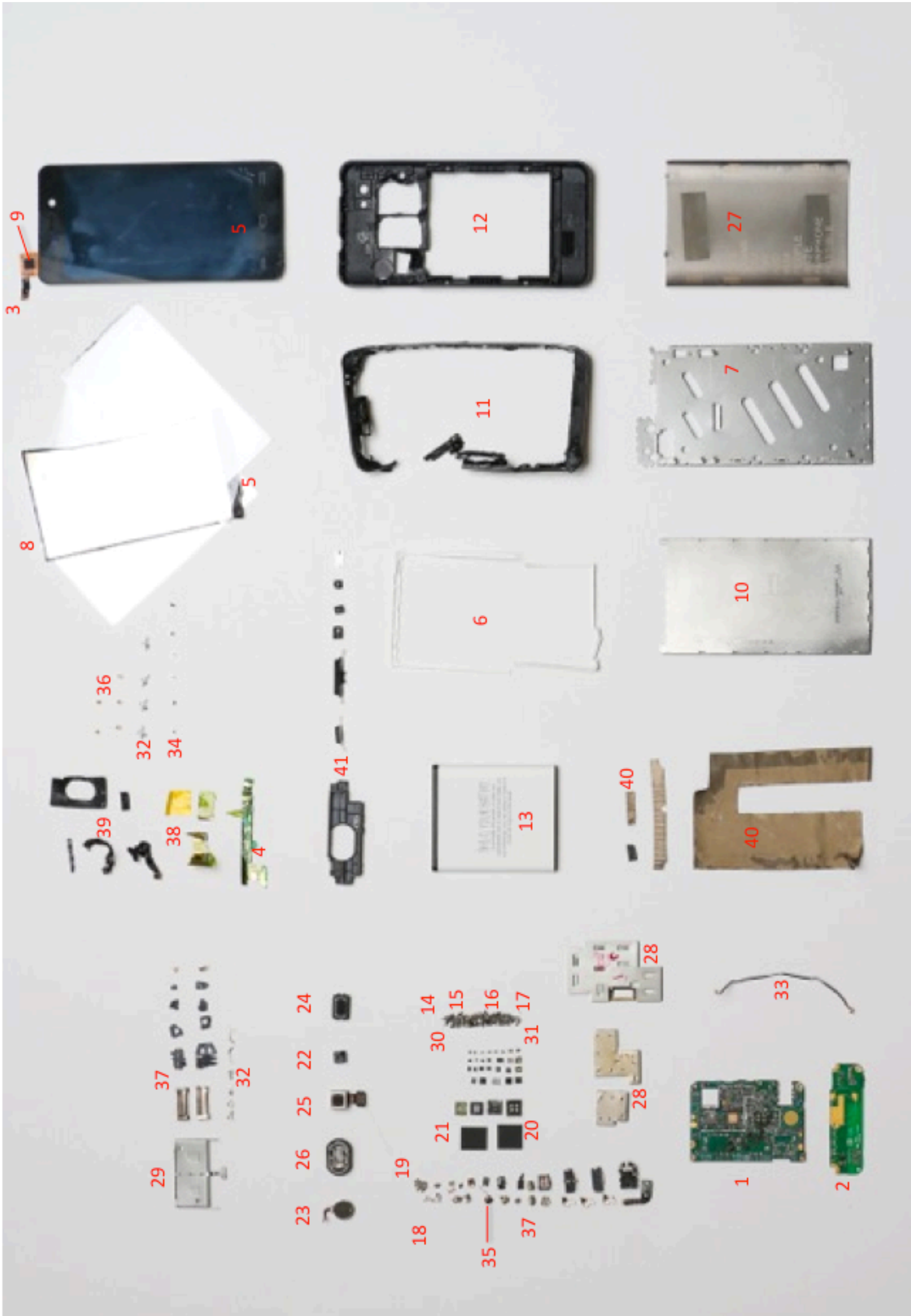

Figure 7. Components of the Fairphone according to their numbers in the inventory list. The photo was taken after dismantling a Fairphone.

Camera, Earpiece, Speaker and Vibrator

As mentioned in Section 3.1.2., there is no data available on the production of these components in the ecoinvent database. Even though metallic content of the mobile phones was detected in material composition analysis (Wu et al., 2008), this data could be used for an estimation for the complete mobile phone, but not for the specific components. Hence these parts were sent to the Fraunhofer Institute for the composition analysis.

The material composition results for the earpiece and loudspeaker are given in Table 5. For the modeling, the highest possible percentage of each material is used. The weight of the materials was calculated by the percentage of the material and the weight of the component. For the material where the range of the percentage is given by the Fraunhofer Institute[2], highest values were chosen for the calculation and materials were added to the model by using the ecoinvent database. To represent the production activities of the specified metals, the process "production efforts, inductor" was added to the value of the total weight of the identified materials (0.814g). The weight of the unidentified materials in the loudspeaker and the earpiece (1.028g) were added to the model by using the "electronic components, passive, unspecified, at plant" dataset from the ecoinvent database. Since no information could have been found about the materials of the camera and vibration motor, these components were also represented by "electronic components, passive, unspecified, at plant" dataset.

Battery

The Fairphone comes with a 38.6 g, 2110 mAh, 3.7V Li-ions battery. The product "Battery, Li-Io, rechargeable, prismatic" from the ecoinvent database is used to represent the battery.

Loudspeaker	**Percentage**	**Earpiece**	**Percentage**
Zn	13%	**Fe**	48.4% - 49%
Fe	10% - 11.5%	**Zn**	14.67%
Cu	2% - 2.1%	**Cu**	8% - 9.38%
Nd	0.8% - 0.9 %	**Cr**	7.90% - 9.7%
Pr	0.20% - 0.233 %	**Ni**	2.17%
Co	0.122% - 0.196 %	**Nd**	0.9% - 0.964%
Gd	0.113% - 0.133%	**Others**	14% - 15.35%
Others	69% - 71%		

Table 5. Material composition of the Loudspeaker and the earpiece

[2] Special thanks to Karsten Schischke for making this material composition analysis possible and for his critical feedbacks to the study

Printed Circuit Board

Two printed circuit boards were weighed and the weight was translated to surface area by using the value of the ecoinvent database which is 3.26 kg/m2.

LCD Screen

Dismantling the mobile phone gave detailed information on the LCD screen. With the collected data, the LCD screen was modeled by using the LCD data of a 17-inch computer in the ecoinvent database. Modifications were needed, since the mobile phone screen did not contain the amount of plastics and metals used for the LCD screen of a computer. Instead of using the LCD module defined in the ecoinvent database, the parts of the process were modeled by using the weights of the LCD screen of the Fairphone LCD screen.

ITO sputtering was calculated by using the ecoinvent report on LCD screen which specifies the ITO sputtering amount as 0.04% of the weight of the LCD module (Lehmann et al., 2007). The details of the model can be seen in Appendix B.

4.3. Assembly of the phone

The study of Yamaguchi et al. (2003) shows that during the assembly process of a mobile phone 361 Wh electricity is used. For this study, data from the assembly factory of Fairphone in Chongqing was used. The data describes the total electricity usage and total smartphone production in year 2013. The electricity usage per phone is 0.44 kWh, which is calculated by dividing the total electricity usage by the total number of phones produced in the Chongqing factory. It is consistent with the data from Yamaguchi's paper, and it is understandable that the electricity usage has increased with the increasing complexity of the phones. The electricity production mix of China from the ecoinvent database is used in the inventory analysis.

4.4. Packaging

The data for the packaging of the mobile phone was given in the BOM. The user guide, weighing 68 grams, is made out of better quality paper and the most relevant dataset in the ecoinvent database is the light-weight coated (LWC) paper. This paper is mainly used for magazines and journals which require higher work quality (Hischier, 2007). For the phone package kraft paper is used, which is represented by the corresponding process in the ecoinvent database.

For the industrial packaging material of the components from the supplier to the assembly plant, assumptions were made according to the weight of the each component. If the component weighed more than 0.5 grams, then the weight of the packaging was estimated as 10% of the weight of the component based on the rough estimation at the company. The packaging was assumed to consist of plastics and cardboard. “Packaging film, LDPE, at plant [RER]” and “packaging, corrugated board, mixed fibre, single wall, at plant [RER]” are used for the packaging and both are estimated to weigh half of the packaging weight.

For the components weighing less than 0.5 grams, more packaging was used compared to the components, which was heavier than 0.5 grams. For the estimation, the packaging data of the tantalum capacitor was used. 36000 tantalum capacitors are packaged and weigh 1.8 kg. Using the weight divided by the amount of tantalum capacitors, the weight per piece including the packaging was calculated (1800g/36000piece=50 mg). Since the weight of one tantalum capacitor is 17 mg, the weight of the packaging of the tantalum capacitor was calculated as 33 mg. This number was converted to a factor to be multiplied with the weight of the components, which is (33/17)=1.94. Reels and tapes were generally used for packaging of the small electronic components and these components were made out of antistatic plastic, which is mainly polystyrene. For the packaging, the processes of “polystyrene, high impact, HIPS at plant” and “packaging, corrugated board, mixed fibre, single wall, at plant [RER]” were used and they were both estimated to weigh as the half of the packaging weight.

4.5. Transportation

In the Bill of Materials, the location information of the suppliers was also given. This information was integrated into sourcemap.com to calculate the distance between the suppliers and assembly plant[3]. Transportation types of the components were obtained from the company. For the lorry transportation, “transport, lorry, 16-32t, EURO5[RE] was used for all components. For the air flights, “transport, aircraft, freight, intercontinental” and “transport, aircraft, freight”, for the canal transportation in China, “transport, barge[RER]” and for the rail transportation “operation, coal freight train, diesel[CN]” were used in the model.

For modeling the transportation of the components from supplier to the assembly plant, the total weight of the components was estimated, including the weight of packaging. The multiplication factors (explained in Section 4.4.) were used to calculate the total weight

[3] http://free.sourcemap.com/view/7842#

of the components. The transportation type, distance, locations of the suppliers, weight of the components, and the total weight of the components including the packaging estimations are shown in Appendix C.

4.6. Use

A questionnaire was sent to Fairphone customers, and 823 responses were received. The questionnaire can be seen in G. The question about the usage of their previous mobile phone was asked to determine the lifetime of the mobile phone for this study.

As seen in Figure 8 and Figure 9, the results show that Fairphone users used their old phone on average for three years. To analyze the details of the usage, they were asked about what kinds of phones they had previously. The owners of the basic phones, which are only capable of having calls and sending message, used their phones on average for four years. This number drops to three years for feature phones which have more features than a basic phone but less than a smartphone. Finally, smartphone use time is almost two years. Using this information, two scenarios were created for the lifespan of a mobile phone: 2-year use of Fairphone and 3-year use of Fairphone. These scenarios are used in Chapter 7.

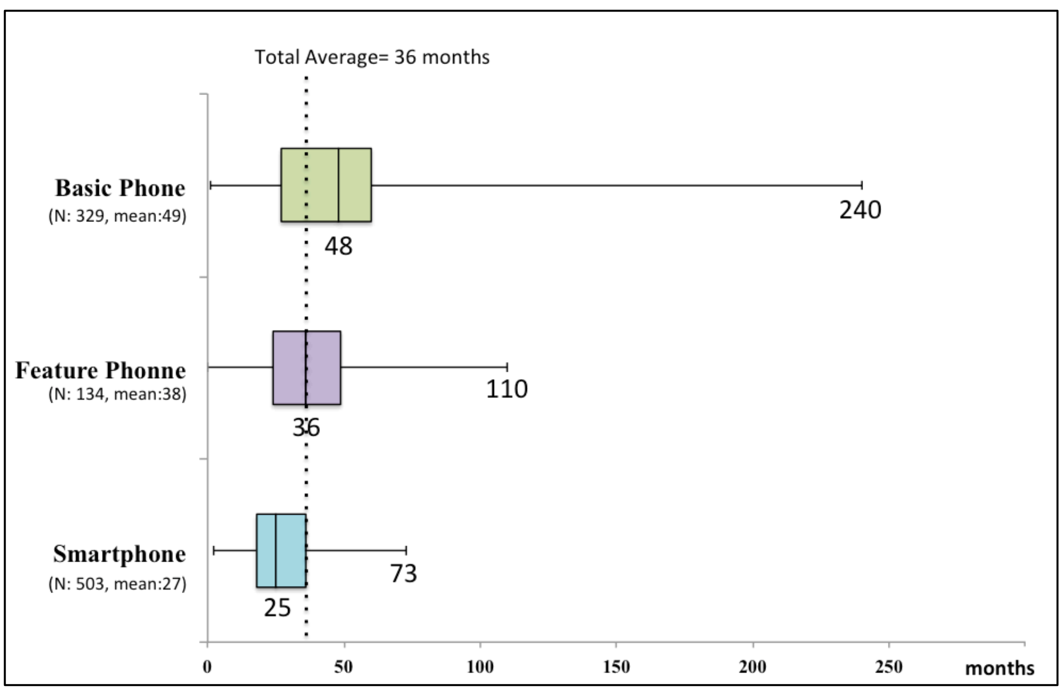

Figure 8. Fairphone users' use of their previous phones

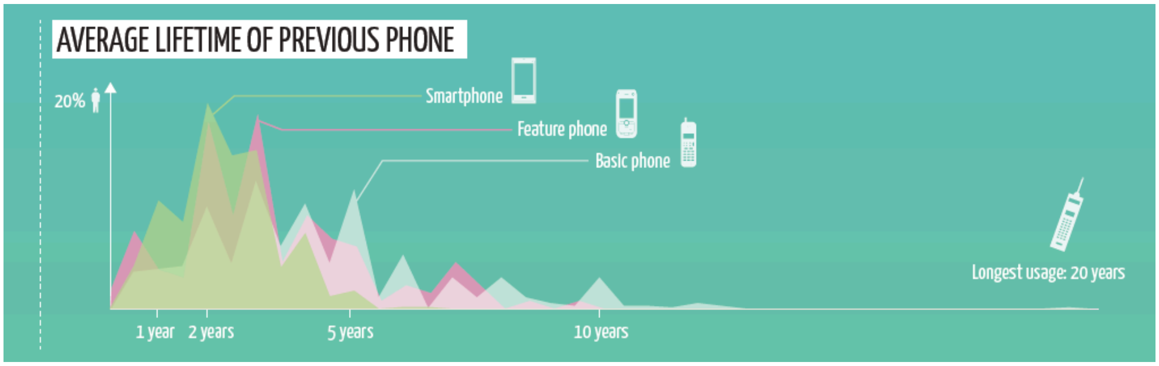

Figure 9. Infographic created for the results of the user questionnaire

To calculate the electricity consumption of the Fairphone owners for two and three years, the electricity usage for a full charge and the charge cycle time, which shows the frequency of charging, were needed.

The charge cycle time is obtained from the responses of a question in the questionnaire: "After a full charge, how long does your battery last on an average day?". Users responded that they could use a full battery on average for 30 hours.

A charger is not provided with the Fairphone, but Fairphone sells the charger separately if requested. Electricity consumption of a full charge was firstly calculated by the specifications of the Fairphone charger (66% efficient 1A, 5V) and Fairphone the battery (2110 mAh, 3.7V) (Fairphone, 2014). According to the calculation, a full charge requires 11.8Wh.

Then the number of charging of the phone was calculated for 2-year use and 3-year use scenarios. The calculation was made using the following equation:

Number of charging = [(number of years) x (Hours in a year)] / (30 hours)

Number of charging is 584 for 2-year use scenario and 876 for 3-year use scenario. The assumptions made for this calculation are that users charge their phone until fully charged and use the battery until totally emptied. Internet usage is not included in the system.

After the results of the contribution analysis showed that the electricity usage had a very high contribution to climate change impact and assumptions could change the results significantly, more accurate data was needed. In order to consolidate the data, a test was done in the Applied Lab of Delft University of Technology[4] by using Hameg

[4] Special thanks to Martin Verwaal from the Applied Lab of Industrial Design Engineering for helping to set up the experiment

Instruments, Programmable Power Meter HM8115-2 (Figure 10). The test was carried out with the charger that Fairphone sells (66% efficient 1A, 5V). The testing showed that fully charging takes 2 hours and 27 minutes, and consumes 13.47 Wh.

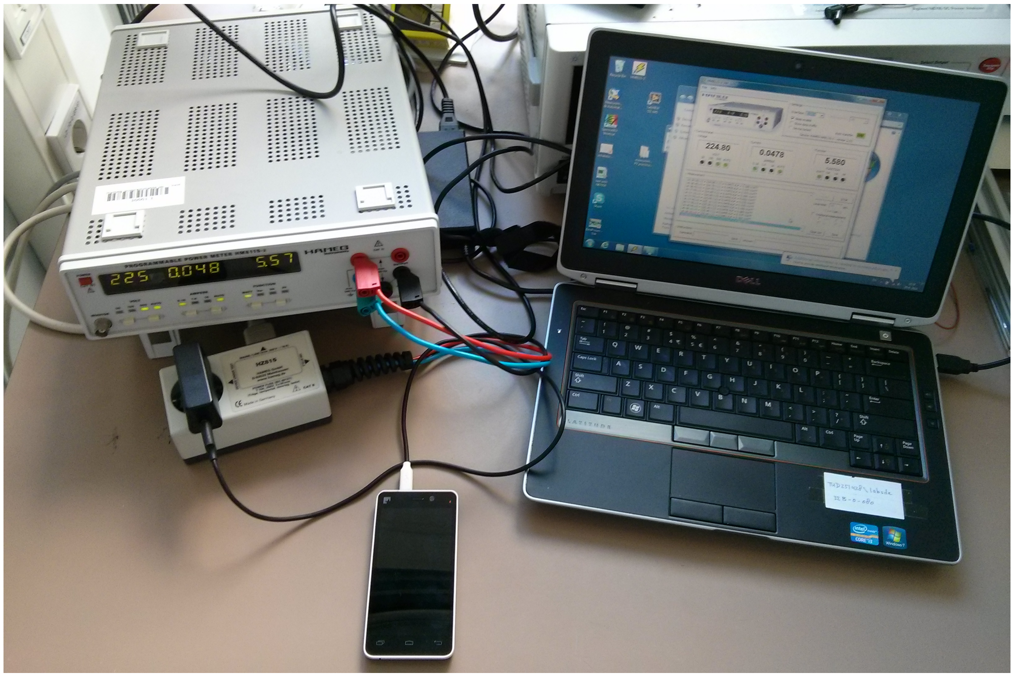

Figure 10. Measurement of the battery charging time and the electricity consumption

For the stand-by power of the charger, users were asked if they leave the charger in the outlet after removing the phone. 19% of the participants leave the charger always, 29% leave sometimes, and the rest never does. Charger stand-by mode is calculated by assuming that the participants who answered as "sometimes" leave the chargers on the outlets 50% of the time and the participants who answered as "always" leave the chargers on the outlets 100% of the time. Using this assumption, the stand-by mode is calculated using the following equation:

Stand-by mode (% per day) = Percentage of the user x Stand-by mode (for all the user types)

$$=0.19 \times 100 + 0.52 \times 0 + 0.29 \times 50 = 33.5$$

This calculation means that an average Fairphone user leaves the charger in the outlet 33.5% of the time during the day.

Stand-by Electricity Consumption per year = Stand-by mode x Stand-by power x 24 hour x 365

As can be seen in Table 6, total energy consumption is modeled with a result of 12.06 kWh. To insert the electricity use to the model, electricity mix of Germany and Netherlands is equally used due to the fact that they are the countries where most of the Fairphone users are from.

3-year use	
Number of charging	876
Electricity consumption for a full charge (Wh)	13.47
Total Electricity use for Charging (kWh)	**11.80**
Charger Stand-by Mode	33.5%
Stand-by Power (W)	0.03
Stand-by Electricity Consumption (kWh)	**0.26**
Total Energy Consumption (kWh)	**12.06**

Table 6. Energy consumption calculations of the charger

In order to calculate the number of the batteries used during the three years, data from Apple is used. According to the report, 2000 mAh batteries retain up to 80% of its original capacity at 500 full charge and discharge cycles failure (Apple, 2014b). Taking into account the number of charging per year (292 cycles), battery starts loosing its capacity after 1.7 years. In this study, the lifetime of the battery is assumed to be two years based on the calculations. Since the functional unit is the use of the Fairphone for three years, it is assumed that the user will buy an additional battery during the 3-year use of the Fairphone. The additional battery is included in the inventory analysis.

4.7. Recycling

In Germany, approximately 5% of the mobile phones were collected by official return and collection systems in 2007 (Buchert et al., 2012). According to the US Environmental Protection Agency (EPA), the collection rate of mobile phones in the USA is around 10% (EPA, 2009).

The questionnaire revealed that 56% of the Fairphone owners still keep their previous phones at home in personal storage after they bought a Fairphone (Fig. 11). Only 1% of the owners sent their phones to take back programs of the phone producers, 2% of them donated to a non-profit campaign and 2% sent their phones to recovery points of the telecommunication shops. For this study, it is assumed that all the mobile phones sold since January 2014 will be collected and sent for recycling at the end of their life cycle.

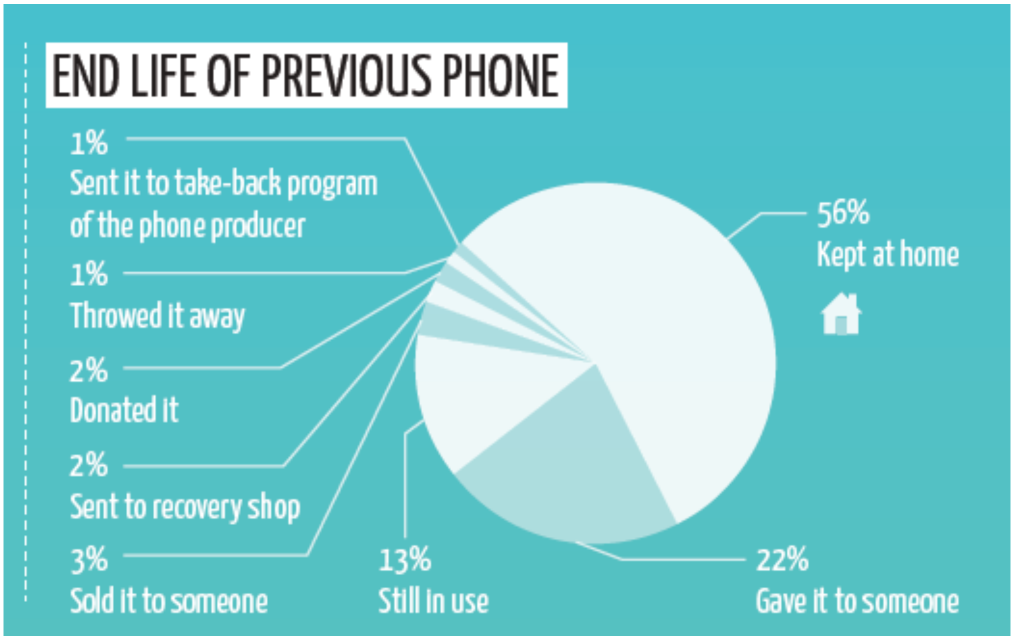

Figure 11. Fairphone users' end of life decisions for their previous phones

Even though the most popular mobile phone collection channels include: dropping the mobile phone in a bin, mailing it in a prepaid envelope, and organizing one-day e-waste collection events, the decision still depends upon the suitable program/player and convenience to the end-user (Neira et al., 2006). 60% of the Fairphone buyers are from Germany; therefore Fairphone contracted Teqcycle, a service company in Germany for individual business-to-business take-back programs. Teqcycle provides an option for the Fairphone users to send their phones by mail (dropping them off at the post boxes) and collaborates with DHL for the transportation of the posts to the processing center in Germany. Collected mobile phones are sorted in the facility of Teqcycle in Munich, Germany. According to the personal communication with Rogier Goed (co-founder of Teqcycle), 85-90% of the donated phones are sent to recycling after sorting and 10-15% of them are sold to the second-hand market. During the sorting, in addition to the functionality of the mobile phones, the company also analyzes the price of the phones. If the mobile phone value is under 10 Euro, it does not sell it to the second-hand market, but sends it for recycling instead. The reason behind this is to prevent mobile phones from ending up in landfill after a short second life (R. Goed, personal communication, June 24, 2014). Teqcycle chooses its recycling partners according to the price bid of the recycling companies, but they mainly work with Electrocycling GmbH in Goslar, Germany and Umicore N.V. in Hoboken, Belgium (R. Goed, personal communication, June 24, 2014). The distance between Teqcycle sorting facility and both recycling companies is calculated. The total transportation of the mobile phones from the user to the recycling facility is estimated as being around 1500 km. This estimation is also parallel with the estimation of the ecoinvent database for recycling of printed wiring boards of the computers (Hischier et al., 2007) in which they use the literature of Hischier et al (2005). 75% of the transportation is estimated to be done by lorry ("transport, lorry 20-28t, fleet average"), and 25% by train.

For the sake of simplicity of the LCA, 100% of the collected phones are estimated to be recycled at one of the facilities of Teqcycle' partners.

Mobile phones are separated from the batteries before recycling, and the batteries are recycled in special plants. Two technologies are used mainly for recycling of the electronic waste: the pyrometallurgical process and a combined pyro-hydrometallurgical process (Navazo et al., 2014). Umicore uses a combined pyro-hydrometallurgical process (Navazo et al., 2014), on the other hand Electrocycling uses pyrometallurgical process (Electrocycling, personal communication, June 25, 2014).

To model the recycling process of the Fairphone, a material flow analysis (MFA) of recycling one tonne of mobile phones (Navazo et al., 2014) is used. Although the MFA models both a pyrometallurgical process and a pyro-hydrometallurgical process, since the MFA has more detailed data on the emissions of pyrometallurgical recycling process, pyrometallurgical recycling process is chosen for this study. The process can be seen in Appendix B, The process is modeled for the recycling of 124.85 gram of mobile phone, which is the weight of the Fairphone without the battery.

For recycling the Li-ion battery of the Fairphone, "disposal, Li-ions batteries, mixed technology" process from the ecoinvent database was used. This process is a mixture of the hydrometallurgical and pyrometallurgical recycling of the Li-ions batteries. The mixture of both processes was chosen, because the batteries could be recycled by one of those systems according to the price of those technologies in the future.

4.8. Allocation

"Disposal, Fairphone without battery" is the only multifunctional process in the system due to the fact that old mobile phones enter the process as waste and there are seven economic outflows from the process. An economic allocation technique is applied according to the economical values of the functional flows (Guinée et al., 2004).

The cost of recycling mobile phones and the value of the materials are obtained from Fairphone according to their contract with the phone recycling company. Allocation factors are calculated using the proceeds which is the multiplication of quantity (kg) by price (Euro/kg) of the functional flows (Table 7). The values of recycled tin, antimony and nickel could not be obtained from the company, thus the values are given as 0 and the burden is distributed onto the rest of the functional flows.

Functional Flows	**Quantity (kg)**	**Price (€/kg)**	**Proceeds (€)**	**Allocation Factor**
Disposal, Fairphone without battery	0.125	Confidential	Confidential	0.30
Tin, secondary, at recycling plant (EU)	1.25E-03	Confidential	Confidential	0.00
Palladium, secondary, at recycling plant (EU)	1.87E-05	Confidential	Confidential	0.12
Copper, secondary, at recycling plant (EU)	0.016	Confidential	Confidential	0.03
Gold, secondary, at recycling plant (EU)	4.33E-05	Confidential	Confidential	0.47
Silver, secondary, at recycling plant (EU)	4.53E-04	Confidential	Confidential	0.08
Antimony, secondary, at recycling plant (EU)	1.25E-04	Confidential	Confidential	0.00
Nickel, secondary, at recycling plant (EU)	1.87E-03	Confidential	Confidential	0.00
Total	-	-	-	1

Table 7. Allocation factors of the economic allocation

4.9. Inventory results

The inventory data calculated by CMLCA software is provided in a separate Excel file, which can be accessed on the university depository.

Chapter 5 - Impact Assessment

In this phase, the magnitude and importance of the potential environmental impact of the product system is evaluated. Emissions and resource extractions in the inventory are associated with environmental impact categories and category indicators in order to assess the impacts. The modeling results are calculated in the characterization step, “in which the environmental interventions assigned qualitatively to a particular impact category (in classification) are quantified in terms of a common unit for that category, allowing aggregation into a single score: the indicator result; these scores together constitute the environmental profile” (Guinée, 2002). The characterization factors change according to different impact categories.

After characterization, there is an optional stage of normalization, which relates the characterization results to a reference value of a worldwide or regional total. At the end, there are two more optional steps: grouping and weighing of the category indicator results. Normalization, grouping and weighting were not applied to this study. The results of the impact assessment phase are used in the interpretation phase.

5.1. Selection of the impact categories

ReCiPe 2008 is chosen as the method to calculate the impact assessment results. This method has harmonized modeling principles and choices for the calculations of the midpoint and endpoint characterization factors for the same impact categories. Even though the calculations are gathered into a single and consistent method, it still offers the results separately for midpoint and endpoint level. This improvement enables the LCA-approach to be both flexible and more uniform (Goedkoop et al., 2012). In this study, midpoint characterization is used.

Schischke applied an ABC analysis in order to understand which impact categories are relevant for each life stage of the electronic devices. According to Schischke (as cited in Szilágyi, 2013, p. 8), Climate Change, Human Toxicity, Particulate Matter, Acidification and Metal Depletion are the most relevant impact categories for electronic devices (Table 8). Three impact categories were chosen out of the five categories from Schischke’s analysis due to their relation to Fairphone's mission, which are climate change, metal depletion and human toxicity. In Section 5.3., the results of all impact categories are reported, and the three impact categories are shown in bold because they are part of Fairphone's mission.

	raw materials acquisition	processing / manufacturing	distribution	use	end-of-life
Climate change	A	A	C	A	C
Ozone Depletion	C	C	C	C	C
Human toxicity	B aluminium, gold	C	C	B	C except for uncontrolled treatment
Particulate Matter	C	C	C	C	B
Ionizing Radiation	C	C	C	C	C
Photochemical ozone formation	C	C	C	C	C
Acidification	C	C	C	A	C
Eutrophication	C	C	C	C	C
Ecotoxicity	C	C	C	C	C except for uncontrolled treatment
Land use	C	C	C	C	C
Resource depletion	B	C	C	B	B

Table 8. Schischke's ABC Analysis of likely affected impact categories for electronic devices (A: very important, B: important, C: marginally important contribution to the impact category) (as cited in Szilágyi, 2013, p. 8)

5.2. Evaluation of the impact categories

Moberg et al. (2014) tested the importance of different life cycle stages for different impact categories in order to test the effects of excluding impact categories. This test was applied to this study to investigate if the chosen impact categories could be representative to show the sustainability of the smartphone life cycle or not. The contributions of different life cycle stages to the impact categories are shown in Figure 12. As seen in the figure, the use and the production stages generally have the highest contribution to all of the impact categories, followed by the transportation process. In the figure, there are three main patterns: (1) the production stage contributes to more than 90% of agricultural land occupation and metal depletion; (2) production and use stages contribute to more than 90% of the following impact categories: marine ecotoxicity, water depletion, ionizing radiation, freshwater ecotoxicity, urban land occupation and human toxicity; (3)

transportation contributes to more than 10% of the following impact categories: natural land transformation, marine eutrophication, freshwater eutrophication, particulate matter formation, terrestrial acidification, terrestrial ecotoxicity, fossil depletion, photochemical oxidant formation, climate change and ozone depletion.

Since each chosen impact category is an example of one of the patterns (metal depletion for the first pattern, human toxicity for the second pattern and climate change for the third pattern), it can be said that the three key impact categories of Fairphone's mission can be representative for the other impact categories. The data used to create Figure 12 is shown in Table 9.

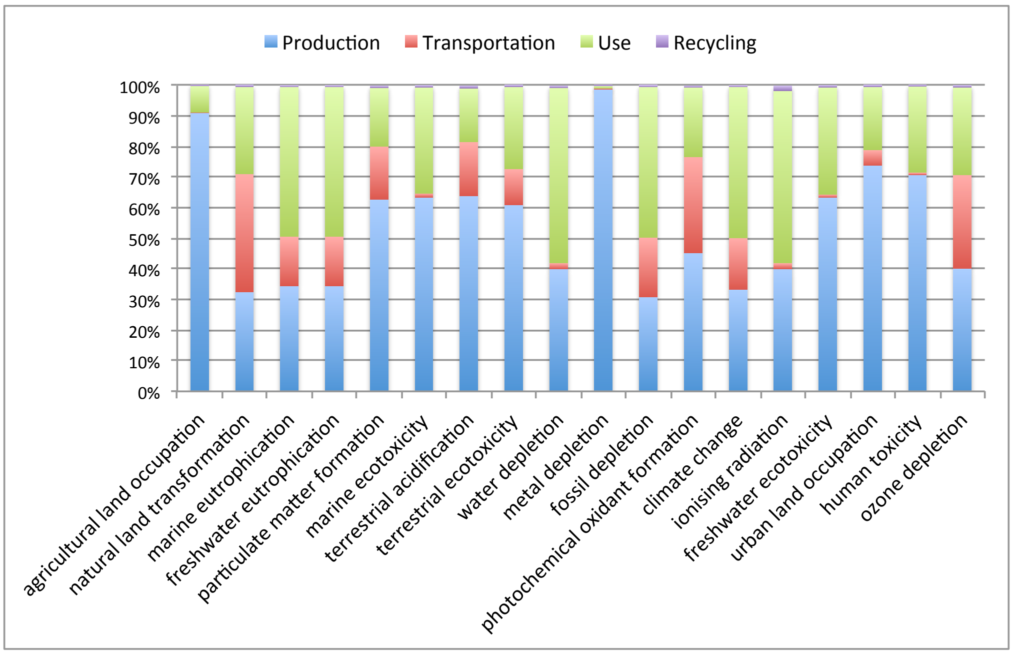

Figure 12. Contribution of the each process on the each of the impact categories

5.3. Environmental profile of the baseline system

The impact assessment results of the 3-year use of Fairphone for all the ReCiPe impact categories are shown in Table 9. The three impact categories are shown in bold characters.

ReCiPe Midpoint (H)	Production	Transportation	Use	Recycling	TOTAL	Unit
agricultural land occupation	1.1453	0.0022	0.1084	0.0011	1.2570	m2a
natural land transformation	0.0012	0.0014	0.0010	0.0000	0.0035	m2
marine eutrophication	5.9782	2.7956	8.4518	0.0743	17.3000	kg N-Eq
freshwater eutrophication	5.9782	2.7956	8.4518	0.0743	17.3000	kg P-Eq
particulate matter formation	0.0128	0.0036	0.0039	0.0001	0.0204	kg PM10-Eq
marine ecotoxicity	0.1551	0.0032	0.0847	0.0011	0.2441	kg 1,4-DCB-Eq
terrestrial acidification	0.0380	0.0105	0.0105	0.0005	0.0594	kg SO2-Eq
terrestrial ecotoxicity	0.0013	0.0002	0.0006	0.0000	0.0021	kg 1,4-DCB-Eq
water depletion	0.0315	0.0016	0.0450	0.0006	0.0786	m3
metal depletion	**3.9954**	**0.0118**	**0.0326**	**0.0027**	**4.0425**	**kg Fe-Eq**
fossil depletion	1.5103	0.9467	2.4050	0.0181	4.8801	kg oil-Eq
photochemical oxidant formation	0.0200	0.0138	0.0100	0.0002	0.0441	kg NMVOC
climate change	**5.3401**	**2.7266**	**7.9063**	**0.0708**	**16.0440**	**kg CO2-Eq**
ionising radiation	1.7037	0.0797	2.3934	0.0693	4.2461	kg U235-Eq
freshwater ecotoxicity	0.1554	0.0025	0.0858	0.0011	0.2448	kg 1,4-DCB-Eq
urban land occupation	0.0888	0.0062	0.0248	0.0004	0.1202	m2a
human toxicity	**9.8951**	**0.0986**	**3.9395**	**0.0281**	**13.9610**	**kg 1,4-DCB-Eq**
ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	kg CFC-11-Eq

Table 9. Impact assessment results for the use of Fairphone for 3 years.

5.4. Comparing the impact of other mobile phone studies

LCA studies for the smartphones have already been conducted by researchers and producing companies. For the studies conducted by the leading corporates, the system boundaries and methodologies are mostly unknown. Even though this limits the comparability of the studies, in order to have a benchmark with other studies, the climate change results of some mobile phones are provided.

Apple states that their results are in accordance with the ISO 14040 and 14044 standards (Apple, 2014c, 2014d, 2014e). Apple's life stages consist of production, transportation, customer use and recycling. Production includes the extraction and transportation of raw materials, manufacturing the components, transport, and assembly and packaging. Transport considers air and sea transportation of the finished product from manufacturing site to continental distribution hubs. Customer use includes user power consumption, assumed as a three-year period with an intensive daily use of the product. Recycling includes transportation from collection hubs to recycling centers, and the energy used in mechanical separation and shredding of parts (Apple, 2014e).

The Nokia LCA studies and also Ercan's study states that they are in accordance with the ISO 14040 and ISO 14044 standards and they both cover raw materials acquisition, component production, primary data for factory processes, inbound & outbound logistics, usage of three years and recycling stages (Ercan, 2013; Nokia, 2013b).

As shown in Table 10, there are many differences between the smartphones. As explained in the sensitivity analysis, a change in the LCD screen by 1%, could affect the climate change results by 0.12%. Looking at the benchmarking analysis for the smartphones from the same company, it looks like there is a correlation between the screen size and the climate change results.

As seen from the values of Figure 13, it is noticeable that the results differ from each other significantly. This could be an interesting topic for future studies. It is very difficult to draw any conclusions until more detailed information is gathered on the scope of the studies and the methods they used and choices they made.

The main reason of this analysis is to show the different factors of the phones and the different results. It does not aim to compare the products.

Smartphone	**Climate Change, GWP (C02-e)**					**Specifications**		
	Production	**Transportation**	**Use**	**EoL**	**Total**	**Lifetime (yr)**	**Weight (gr)**	**Screen size (")**
Fairphone	5.3	2.7	7.9	0.1	16.0	3	163	4.3
Nokia Lumia 820	10.9	2.2	2.7	0.2	16.0	3	160	4.3
Nokia Asha 311	5.7	1.7	1.5	0.1	9.0	3	98	3
Nokia Lumia 1520	26.6	1.9	8.1	0.4	37.0	3	209	6
iPhone 4S	35.2	3.9	14.9	1.1	55.0	3	140	3.5
iPhone 5c	43.8	2.4	12.6	1.2	60.0	3	132	4
iPhone 5S	62.3	3.0	9.0	0.8	75.0	3	112	4
Sony Xperia T	35.7	5.1	9.2	1.0	51.0	3	169	4.55
Sony Ericsson W890	11.2	2.2	3.4	0.2	17.0	3.5	78	2

Table 10. Comparison of the different smartphone specifications and global warming potentials (Apple, 2014d, 2014e; Ercan, 2013; Nokia, 2012, 2013a, 2013b)

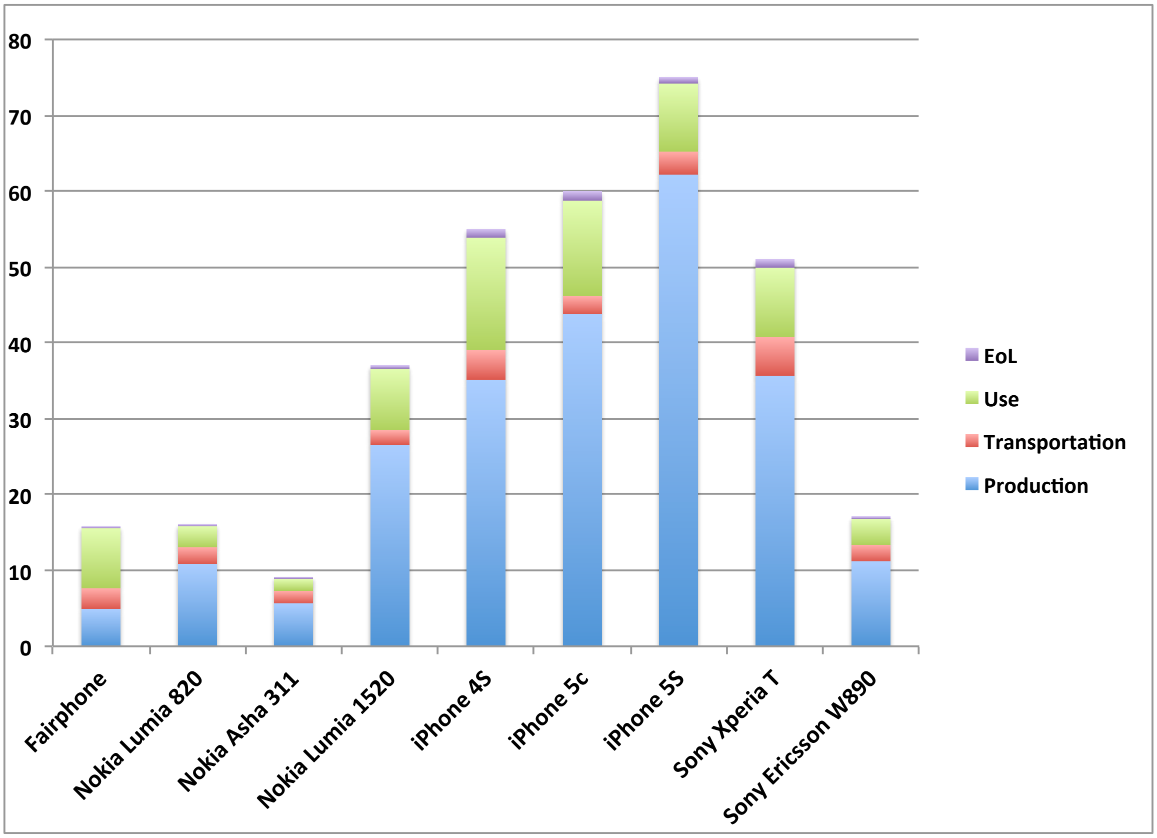

Figure 13. Contribution of each process to the characterization results for climate change

Chapter 6 - Interpretation

6.1. Consistency and completeness check

The objective of the consistency check is to determine whether the assumptions, methods and data are consistent with the goal and scope. Completeness check aims to ensure that all relevant information and data are available and complete.

Since Fairphone was founded in 2012 and only has a small production line compared to other companies like Apple and Samsung, it does not have a significant influence on the suppliers. As a consequence, complete data collection directly from the suppliers could not be achieved within the scope and time limitations of this study. Therefore to model the components needed for the phone, data from the ecoinvent database was used. In order to improve the data, Fairphone supplied the bill of materials and one Fairphone was dismantled to analyze the specifications of the components. There was no available data in the ecoinvent database about the camera, vibration motor, loudspeaker and earpiece of the mobile phones. Hence these components were sent to the Fraunhofer Institute for material composition analysis and the results were used in the model. For the assembly process, primary data about the electricity consumption was obtained from the assembly plant in Chongqing with the assistance of Fairphone's close connections with the assembly company.

Even though the dataset of the ecoinvent database used in the modeling was released in 2007, most of its data comes from studies that are older than ten years. Most of the technological developments of the electronics sector are not represented in the database. As mentioned in Section 2.2.2., the change in the database affected the results of a study done by Nokia significantly (Santavaara & Paronen, 2013). In this study, the results are used to compare the different scenarios for the Fairphone, for this reason the limitations of the database is reduced. In Section 5.4., the other studies of the smartphones are analyzed and the possible reasons for the differences in the climate change impacts are discussed.

The process information used to model the recycling of the batteries was found in the ecoinvent database. To model the recycling of the mobile phone, data from a study of the material flow analysis of mobile phone recycling was used.

For the use phase of the life cycle, primary data was collected by conducting a user questionnaire to the Fairphone users. 823 Fairphone users responded to the online questionnaire. The average lifetime of the mobile phone for the functional unit was decided according to the average mobile phone usage of the respondents. Electricity consumption during the 3-year use of Fairphone was also modeled according to the results of the questionnaire and the primary data of the measurement was taken in the laboratory of the Delft University of Technology.

6.2. Contribution analysis

In order to find out the hotspots of the mobile phone life cycle, a contribution analysis was conducted. In Figure 14, contribution of each phase to the selected impact categories can be seen. Production phase consists of the characterization results of the production of the components and the assembly activities. Transport phase represents only the characterization results of transportation of the mobile phone from the assembly plant to Europe. Recycling phase is the combination of characterization results of the process of the recycling of the battery and the Fairphone without the battery.

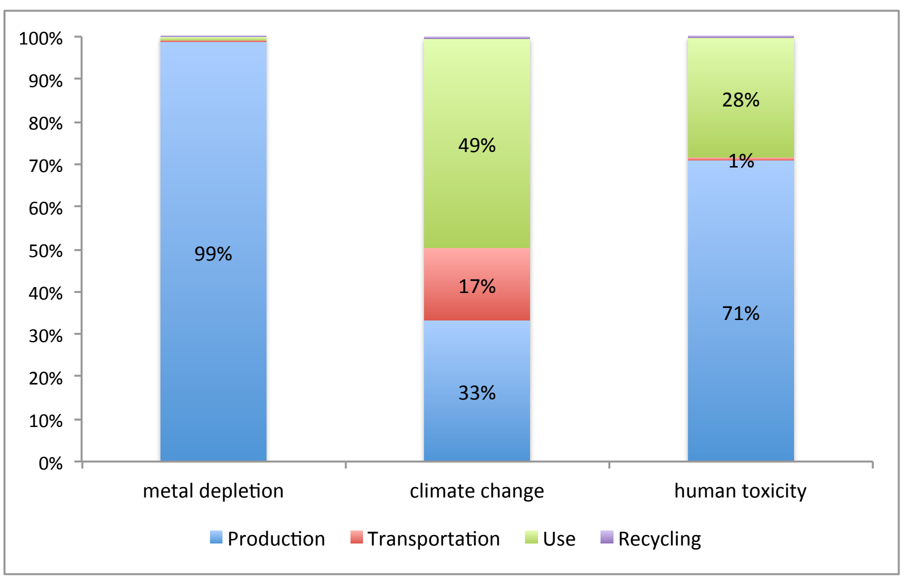

Figure 14. Contribution of the each phases to the characterization results for the three impact categories

In the following chapters, each impact category is analyzed in detail. The data used to draw the following four charts are given in a table in Appendix D.

6.2.1. Contribution analysis on metal depletion

Metal depletion is the impact category in which production has the highest contribution with 99%. The detailed contributors of the production stage can be seen in Figure 15. The battery has the highest contribution (37%) with 1.5 kg Fe-eq. As explained in the inventory analysis, in 3 years of use time, Fairphone users are assumed to buy an additional battery based on the maximum charge cycle of the battery and average charging times per year. If the phone is designed with energy efficient user interface, the battery life could be longer and the maximum charging cycle would not be exceeded in 3 years. This would half the impact coming from the battery. The PCB has 17% of the contribution with 0.69 kg Fe-eq, integrated circuits have 12%, and LCD screen has 9% of the contribution.

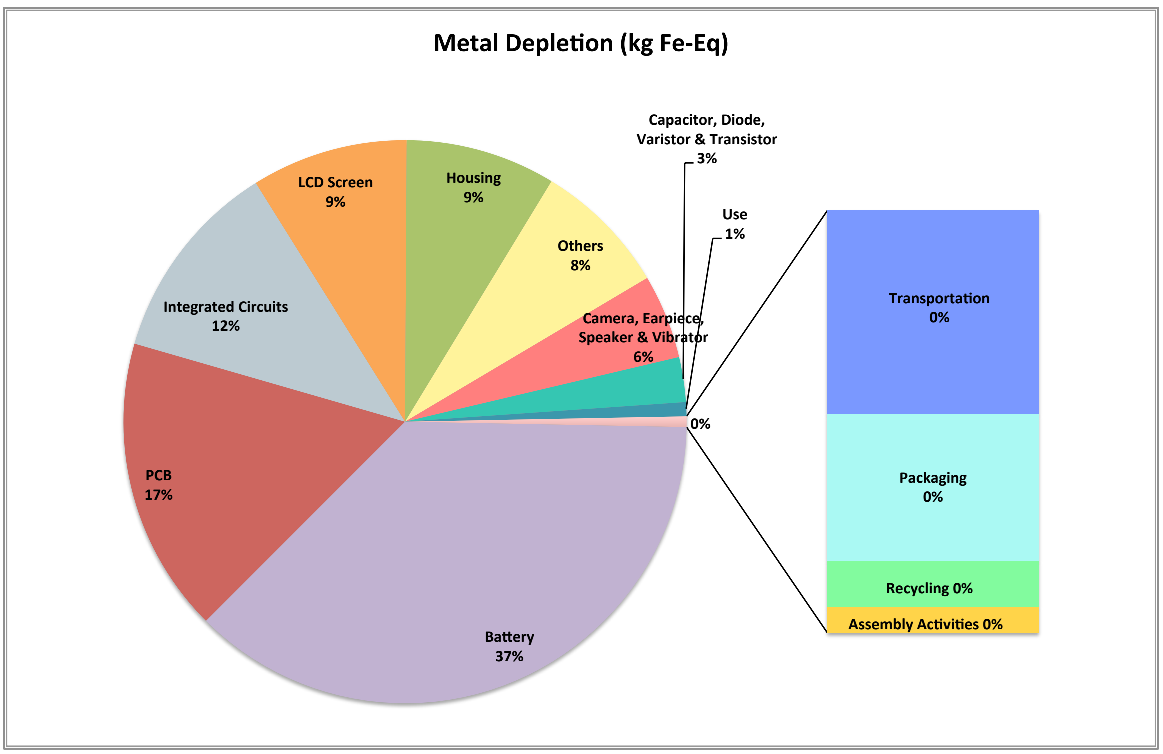

Figure 15. Contribution of use, transportation and recycling phases and each components of the mobile phone to the characterization results for metal depletion

6.2.2. Contribution analysis on climate change

Climate change has a high contribution in three stages: use (49%), production (33%) and transportation (17%). The contribution of use, transportation and recycling phases and each components of the mobile phone to the characterization results can be seen in Figure 16. As mentioned in the inventory analysis, the use phase only includes the electricity consumption from charging the phone (excluding the network usage). This result shows that for future design, it is very important to find solutions to reduce electricity consumption, i.e., more efficient batteries, energy saving applications, or the color of the display screen which helps increase battery savings.

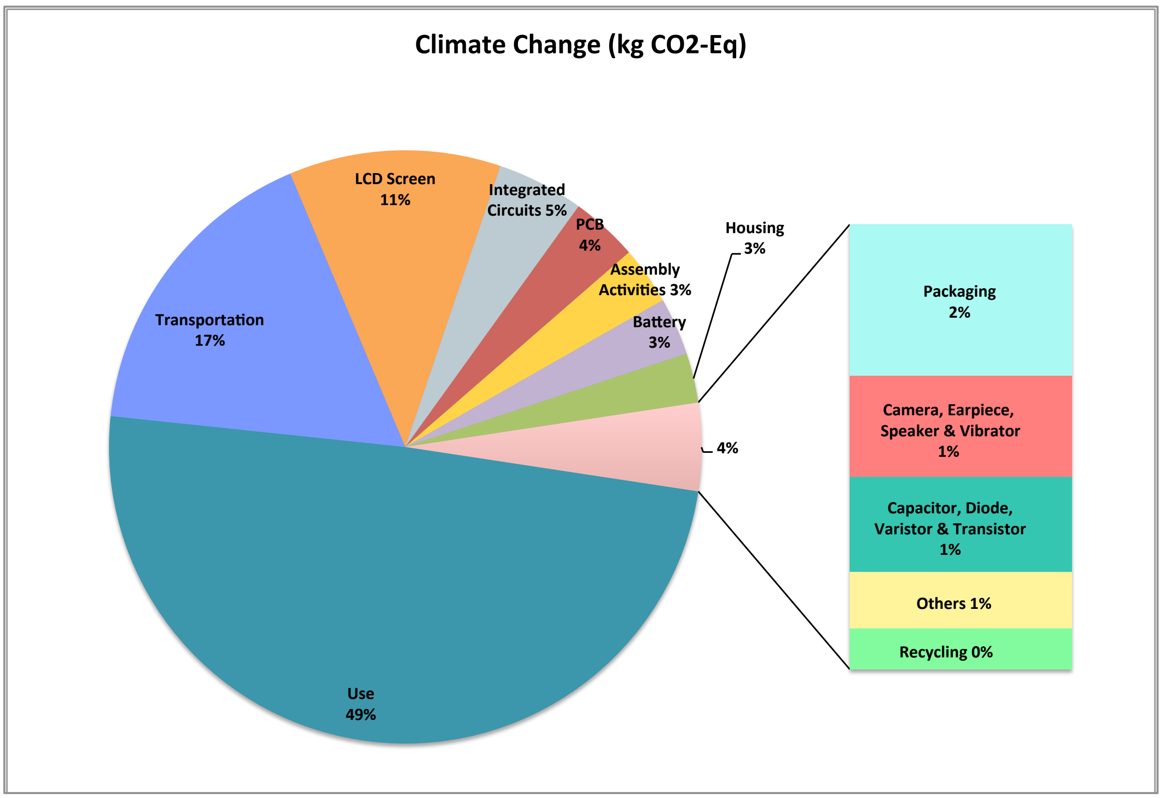

Figure 16. Contribution of use, transportation and recycling phases and each components of the mobile phone to the characterization results for climate change

The LCD screen has the biggest contribution (11%) among the components of the mobile phone with 1.8 kg CO2-eq. Improvement strategies could be:

1. Using AMOLED screen instead of the LCD screen:
   AMOLED screen is using more recent technology than LCD screen, and is more efficient in terms of battery usage (Lin et al., 2009). But there are no studies analyzing the environmental impact of the production of AMOLED screen.
2. Improving the design to reduce screen crashes:

There are many customers (3% of the Fairphone users) that already crashed their screen since January. This means that the actual environmental impact is higher than what is calculated with the LCA. Future study is needed to analyze the causes for the screen crashes in order to use them for the future phone design.

Integrated circuits are the second biggest contributor among the other components with 0.76 kg CO2-eq, followed by 0.59 kg CO2-eq of PCB. For the integrated circuits, it is hard to change the design of the phone, but for the PCB, it is possible to design a phone with a smaller PCB.

Transportation has an important impact on the climate change, which mainly stems from the transportation of the Fairphone from China to Germany by air. If the phones are shipped or sent by rail, this impact could easily be reduced. When these solutions were discussed at Fairphone, it became clear that timing was a big concern for the company since both proposed options take much longer than the current means of transport. Security concerns for rail transportation was also raised as another issue.

6.2.3. Contribution analysis on human toxicity

As discussed in the previous chapter, human toxicity shows a pattern in which the production and use stages contribute more than 90% to the impact category. To analyze from which component of the Fairphone this impact stems, an analysis was made (as shown in Figure 17). Integrated circuits are the biggest contributor of the production process with 3.42 kg 1,4-DCB-eq, followed by the battery with 2.2 kg 1,4-DCB-eq. LCD screen and the PCB have a very close contribution of 1.30 and 1.14 kg 1,4-DCB-eq, respectively. The solutions proposed in Section 6.2.1 and Section 6.2.2. would also improve the characterization results of the human toxicity.

6.3. Sensitivity analysis

Sensitivity analysis is carried out to investigate how assumptions in the model could affect the results of the assessment. The perturbation analysis option in the CMLCA is one of the ways to apply a sensitivity analysis. It basically identifies the most influential process flows for the system. It perturbs the data one by one by a small amount and recalculates the impact assessment.

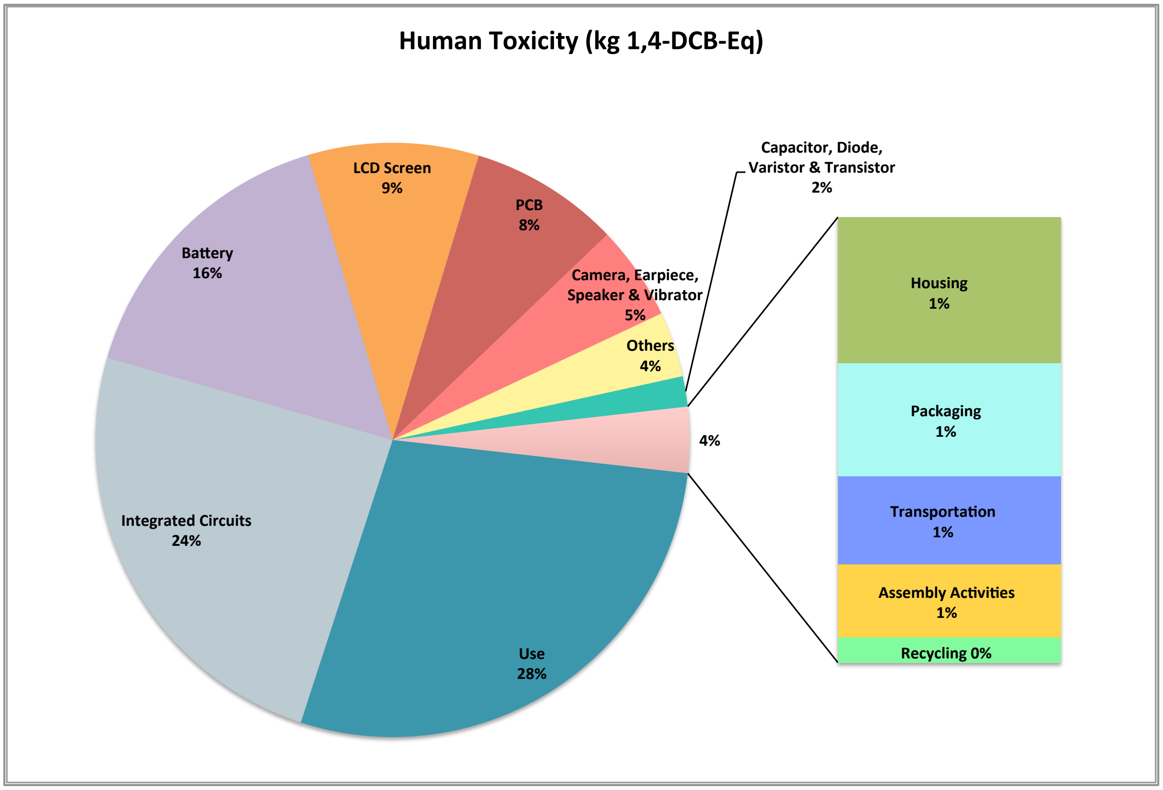

Figure 17. Contribution of use, transportation and recycling phases and each components of the mobile phone to the characterization results for human toxicity

Product	Process	Metal Depletion	Climate Change	Human Toxicity
Phone Battery	Phone Assembly	**0.3719**	0.0315	**0.1593**
Electricity Mix [DE]	Phone use for 3 years	0.0047	**0.2409**	**0.2088**
Electricity Mix [NL]	Phone use for 3 years	0.0034	**0.2519**	**0.0733**
Integrated Circuits	Phone Assembly	**0.1164**	0.0474	**0.2447**
PCB	Phone Assembly	**0.1698**	0.0367	0.0817
Transportation	Phone Assembly	0.0027	**0.1685**	0.0069
LCD Screen	Phone Assembly	0.0898	**0.1156**	0.0929
Housing	Phone Assembly	0.0862	0.0270	0.0117
Other Components	Phone Assembly	0.0777	0.0060	0.0356
Camera, Earpiece, Speaker & Vibrator	Phone Assembly	0.0484	0.0108	0.0515
Assembly Activities	Phone Assembly	0.0004	0.0315	0.0059
Capacitor, Diode, Varistor & Transistor	Phone Assembly	0.0258	0.0103	0.0165
Packaging	Phone Assembly	0.0021	0.0163	0.0091
Disposal, Li-ions batteries	Phone use for 3 years	0.0004	0.0022	0.0014
Disposal, Fairphone without battery	Phone use for 3 years	0.0002	0.0022	0.0006

Table 11. Results of the sensitivity analysis. Sensitive processes are shown in bold.

The results of the analysis shown in Table 11 and the processes are ordered according to their influence on the impact categories. The values can be read as follows: For instance, if the coefficient for the battery in the process of the mobile phone assembly is increased by 1%, the system-wide metal depletion impact will increase by 0.3719%, climate change impact by 0.0315% and human toxicity impact by 0.1593%. The values which influence the impact categories the most are shown in bold. The results are discussed in the following sub-sections.

6.3.1. LCD screen production

As seen in Table 11, LCD screen production is a sensitive process for three of the impact categories. If the coefficient of the LCD screen is increased from 1 to 1.01 in the process of mobile phone assembly, then the system-wide metal depletion impact will increase by 0.0898%, climate change impact by 0.1156% and human toxicity impact by 0.0929%.

Also in the contribution analysis, the LCD screen has a high contribution on the selected impact categories: 10% on human toxicity, 12% on climate change and 11% on metal depletion. This reveals the need for an accurate process modeling for the LCD screen of the phone. As explained in the inventory analysis, the LCD production process is manually modeled to represent the mobile phone screen by using the data for a computer screen. Hence the process is one of the main concerns for uncertainty/inaccuracy. Until future research is done with more specific data, this model represents the best possible assumption. For future research, it is highly recommended to have primary data from the supplier.

6.3.2. Battery

According to the perturbation analysis, the change in the product battery has the highest influence on metal depletion comparing to the other products. 1% increase in the coefficient of the battery in mobile phone assembly will result in 0.3719% increase in metal depletion impact and 0.1593% in human toxicity impact. As explained in the inventory analysis, the assumption is made that an additional battery will be used in a 3-year use of a mobile phone according to battery's total charging cycle and the results of the user questionnaire.

Also in order to compare the assumption of using two batteries in three years (one original and the additional one), the results of using only the original battery and using the original battery and one additional battery is compared and the results are shown in

Table 12. The high increase in the metal depletion impact (22.85%) shows that this assumption is very important. In a future research, a question about the frequency of buying a new battery should be asked to the users, because some of them could still use the battery even tough it has a low performance.

Sensitivity analysis for battery	**metal depletion (kg Fe-Eq)**	**climate change (kg CO2-Eq)**	**human toxicity (kg 1,4-DCB-Eq)**
3-year Fairphone use (with the original battery)	3.2907	15.791	12.849
3-year Fairphone use (with the original battery and one additional battery)	4.0425	16.044	13.961
Change	22.85%	1.60%	8.65%

Table 12. Sensitivity analysis results for the battery

6.3.3. Camera, vibration motor, loudspeaker and earpiece production

As explained in Section 4.2., there was no representative data in the ecoinvent database for the camera, vibration motor, loudspeaker and earpiece. To model the components, product composition analysis results were used which were 22% of the total weight of the components. The rest of the weight is modeled by using the process "electronic components, passive, unspecified, at plant".

If the coefficient for the process is increased by 1% in the mobile phone assembly, the system-wide metal depletion impact will increase by 0.0484%, climate change impact by 0.0108% and human toxicity by 0.0515%. This means the changes in the process is relatively more for metal depletion impact results than the human toxicity and climate change impact results.

According to the calculation of Ercan (2013) with primary data collected from the camera supplier of the Sony smartphone, the camera causes 0.155 kg CO2-eq emissions. In this study, total emission of the components is calculated as 0.174 kg CO2 eq. Even though this number is close to the results of Ercan (2013), these assumptions have a high influence on metal depletion. Therefore more accurate data is required for future calculations.

6.3.4. Disposal, Fairphone without batteries

For the recycling of the Fairphone, a process is modeled according to the results of a material flow analysis of a pyrometallurgical recycling facility (Navazo et al., 2013). The contribution of the process is less than 1% in the selected impact categories. Also the results of the sensitivity analysis are negligible for the process. Hence it can be used as an estimation of the recycling process until primary data is obtained from the recycling company.

6.3.5. Electricity Mixes of Use Phase

As explained in Section 4.6., the lifetime of the phone is taken as 3 years according to the results of the user questionnaire. The electricity mix of Netherlands and Germany are calculated separately in the sensitivity analysis. 1% increase in the electricity consumption of Germany during the use phase increases the climate change impact by 0.2409% and human toxicity by 0.2088% while the change in the metal depletion is negligible. The same change in the electricity use of Netherlands will result in an increase of 0.2519% in climate change and 0.0733% in human toxicity. These numbers show that the choice of the lifetime of the mobile phone is very sensitive especially for the climate change and human toxicity impact results. After the first sensitivity analysis showed that the assumptions are very critical for the results, a battery test was conducted to obtain more accurate data for the electricity consumption of charging the Fairphone. Also in the second part of the study different scenarios are created according to the different number of years of the Fairphone. Additionally, the difference of the impact stemming from electricity mixes of the countries in the human toxicity shows that the choice of the country is very sensitive for the characterization results of human toxicity.

6.3.6. Packaging

As explained in Section 4.4., there are two factors used for the packaging materials of the components. The factor is calculated as 1.94 of the weight of the components which are lighter than 0.5g. For the components which are heavier than 0.5g, the multiplication factor is chosen as 0.1. As seen in the Table 11, the influence of the coefficient of the packaging in the process of the mobile phone assembly is negligible. Thus the estimation can be used for the packaging process until a more detailed measurement is made for the components.

6.4. Conclusion

This chapter aims to answer the research sub-question 1 and to find potential improvement areas of the Fairphone's life cycle.

What is the environmental performance of the Fairphone through its life cycle?

Metal Depletion:
Fairphone results in 4.0425 kg Fe-eq. of metal depletion for the functional unit. 99% of this impact comes from the production phase, which consists of the characterization results of the production of the components and the assembly activities. Among the components used to produce a Fairphone, battery has the highest contribution to the metal depletion with 1.5 kg Fe-eq. Contribution of the battery is followed by the PCB with 0.69 kg Fe-eq., integrated circuits with 0.47 kg Fe-eq. and the LCD screen with 0.36 kg Fe-eq.

Climate Change:
Climate change is the impact category in which Fairphone has the highest interest. In total, the system emits 16.404 kg CO2-eq. Almost half of the green house gas emission comes from the electricity use to charge the phone for 3 years. As mentioned in the inventory analysis, the use phase only includes the electricity consumption from charging the phone (excluding the network usage). If the network usage were included, then this result would be even higher. The reason why it was excluded from the study is explained in Section 3.2.4.

The use phase is followed by the production phase (33%) and transportation (17%). The top three contributors among the components of the Fairphone are the LCD screen with 11% (1.85 kg CO2-eq.), integrated circuits with 5% (0.76 kg CO2-eq) and PCB with 4% (0.59 kg CO2-eq).

Human Toxicity:
Production of components for the Fairphone is the main reason for human toxicity impact. Highest contributors to human toxicity are integrated circuits (24%), battery (16%), LCD screen (9%) and PCB (8%). Use phase also cause 28% of the human toxicity. Transportation and recycling phases have very low contributions, at around 1% in total.

Potential Improvements
Another goal of the study, which was to analyze the hot spots of the Faiprhone's life cycle, is achieved by conducting a contribution analysis. To sum up, the hot spots of the system are the use phase, LCD screen, PCB, integrated circuit and battery productions

and transportation of the phone from the assembly plant to Europe by air. The ideas to improve the environmental performance are presented in the study:

- Battery and use phase:

Fairphone users are assumed to buy an additional battery based on the maximum charge cycle of the battery and average charging times per year. If the phone is designed with energy efficient user interface, the battery life could be longer and the maximum charging cycle would not be exceeded in 3 years. This would half the impact coming from the battery. This result shows that for future design, it is very important to find solutions to reduce electricity consumption by looking into more efficient batteries, energy saving applications, or the color of the display screen which helps increase battery savings.

- LCD screen:

Using AMOLED screen instead of the LCD screen could be a solution for the high contribution of LCD screen to the categorization results of the three impact categories. AMOLED screen uses more recent technology than LCD screen, and is more efficient in terms of battery usage (Lin et al., 2009). But there are no studies analyzing the environmental impact of the production of AMOLED screen.

Another unforeseen impact comes from the replacement of the LCD screen because of the high number of crashes. 3% of Fairphone users had already crashed their screen since January. This means that the actual environmental impact is higher than what was calculated with this LCA. Future study is needed to analyze the causes for screen crashes in order to improve future phone design.

- Transportation:

Transportation has an important impact on the climate change impact, which mainly stems from the transportation of the Fairphone from China to Germany by air. If the phones are shipped or sent by rail, this impact could easily be reduced. When these solutions were discussed in the company, it became clear that timing was a big concern for the company since both proposed options take longer than the current means of transport. Security concerns for rail transportation was also another issue.

Chapter 7 - Circular Economy Application To Mobile Phones

7.1. Circular economy criteria for mobile phones

The principles of the circular economy (CE) are discussed in Section 2.3.2. Poppelaars (2013) studied the applicability of the CE to mobile phones explained the different ways of a mobile phone could follow in Figure 18. The application of these different paths to the Fairphone and modeling of these paths are discussed in Section 7.2.

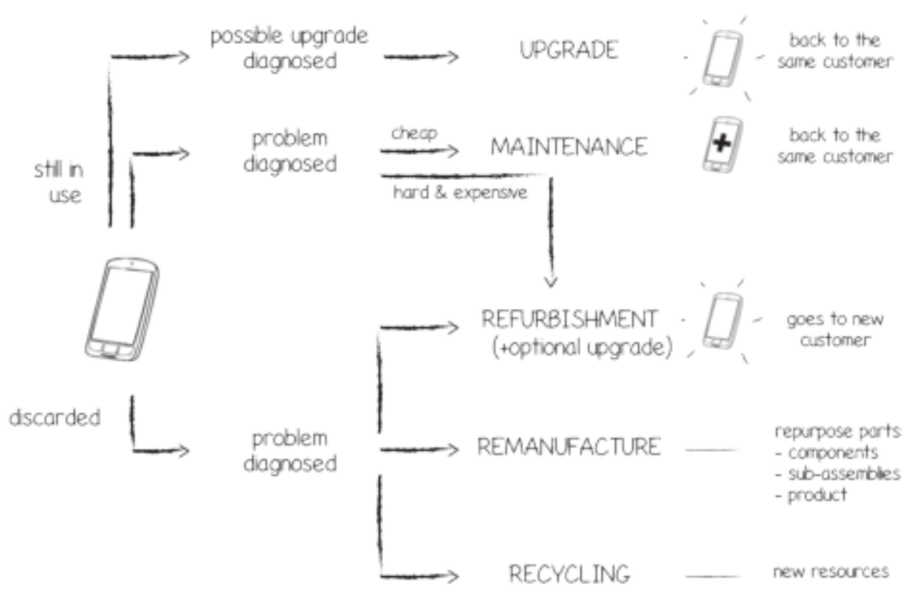

Figure 18. Explanation of the CE for mobile phones (Poppelaars, 2013)

In order to evaluate the embedded value of the components, Poppelaars constructed a table analyzing the price, disassembly score, lifetime, maturity and risks specifications for each component of the mobile phone. Components of the Fairphone were assessed according to those criteria in order to find the ways to apply circular economy principles to Fairphone. This matrix has been adopted and upgraded by adding a column for reuse options for the components and creating a disassembly score (Table 14). Since Fairphone is selling the spare parts of the mobile phone online, the prices of the components are obtained from the web page (Fairphone, 2014b).

In the company, Miquel Ballester Salva dismantled a Fairphone in order to measure the time to replace each of the components in the mobile phone and to create the disassembly score of the Fairphone (Figure 19). The disassembly testing was recorded, and then translated into seconds to create the score (Table 13). The scores are created according to seconds and in order to represent any small improvements of the next phone the ranges for the score taken are very minor (60 seconds). For instance, if changing a component takes between 0-60 seconds, then this component gets Score 1. If it is between 61-120 seconds, it gets Score 2. For components unable to be replaced, Score 0 is given.

For modeling of the scenarios, lifetime of the components are analyzed. The potential duration of the components (unless of technical failure) is taken as the lifetime. The only component in the table - which reaches its lifetime in three years - is the battery with its life of two years. Maturity information of the components is used to decide when the component needs to be upgraded even before it reaches its lifetime. Reuse and remanufacturing options are discussed to give ideas to Fairphone for the possible future use of the components. Moreover, a column for ideas is added to the table for Fairphone to utilize the results of the assessment. The results of the matrix at the end are used to create the scenarios, which will be presented in the next chapter.

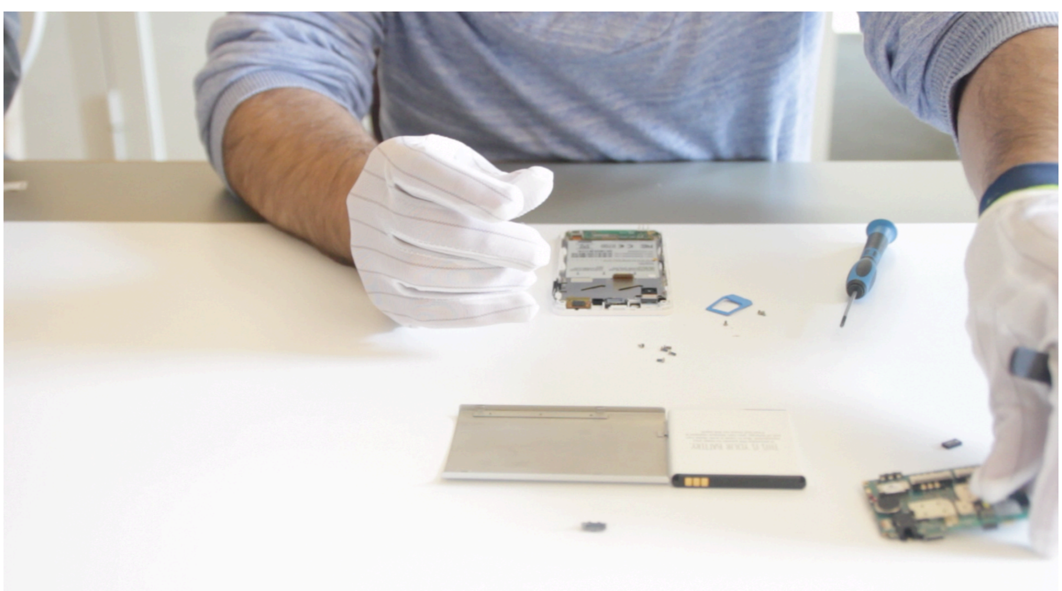

Figure 19. A photo from the disassembly testing of the Fairphone

	Dismantling Time (s)	Assembly Time(s)	Total Time (s)	Disassembly Score
Battery Cap	13	3	16	1
Battery	16	5	21	1
Screws	83	65	148	3
Simcard	16	5	21	1
Back housing	195	121	316	6
Plastic buttons	197	133	330	6
Power button	197	136	333	6
Volume Button	197	137	334	6
Inside screws	251	201	452	8
Main PCB	321	323	644	11
Camera	336	323	659	11
Earpiece	347	338	685	12
Loudspeaker	249	141	390	7
Daughterboard	241	223	464	8
Cable	205	186	391	7
Front camera	321	323	644	11
Wifi antenna	195	121	316	6

Table 13. Results of the disassembly testing of the Fairphone and the scores given according to the total time of changing the each component

Components	Price	Repairability	Lifetime	Maturity	Reuse/ remanufacturing Options	Recommendations
Battery	€ 18.15	Score 1	Estimated as 2 years. The fastest degrading component	Mature technology. Dimensions of the batteries is getting bigger	If the capacity of the discarded battery is still high, it can be sold for a cheaper price	Further research is needed about the relation between the battery size and total energy consumption
Motherboard	€ 118.64	Score 11	Not degrading in time	Mature technology. Shape changes for each model	Supercomputer, refurbishment of the same model	Designing a PCB to be able to change the memory chips
Daughterboard	€ 4.96	Score 8	Not degrading in time	Mature technology. Shape changes for each model	Supercomputer, refurbishment of the same model	-
Display and touch panel	€ 71.39	Score 11	Produced as one piece with the front housing	Increasing size, and improvements in the technology	Toys, devices for educational purposes	Display and touch panel could be easier to separate to only change the broken part
B-Stock Display	€ 48.19	Score 11	Same as above	Same as above	Same as above	Same as above
Rear camera	€ 28.07	Score 11	Not degrading in time	Constant improvement in the technology	Medical tools, biometrics, toys, mobile phone	Cameras should be produced in Identical shapes to easily upgrade

Front camera		-	Soldered on the PCB. Score 0	Not degrading in time	Constant improvement in the technology	Medical tools, biometrics, toys, mobile phone	Shouldn't be soldered on the PCB
Earpiece	€	1.21	Score 12	Not degrading in time	Slight technological improvements	Toys, mobile phone	-
Loudspeaker	€	1.33	Score 7	Not degrading in time	Slight technological improvements	Toys, phones, mobile phone	-
Vibration motor	€	1.33	Soldered on the front housing. Replacement requires a solder machine. Score 12	Mean time to failure is 132.9 hours. (Assuming 1 min/day, average lifetime would be 21.8 years)	Mature component. Dimensions are getting smaller.	Toys, mobile phone	-
Back	€	11.86	Front and back casing are screwed and can be removed by using common tools. Score 6	Not degrading in time	Technically mature	Could be used for refurbishing a same model mobile phone	Use one material for the whole piece
Front		-	Assemblied to the display and needs to be changed together. Score 3	3 years	Technically mature	Could be used for refurbishing a same model mobile phone	Use one material for the whole piece
Stainless Steel Back Cover	€	7.50	Esily removed using fingernail with the help of the indentation in the side of the phone. Score 1	6 years	Technically mature	Could be used for refurbishing a same model mobile phone	Simplfy the component by removing the printing process
Capacitors, Diodes, Varistors and Transistors		-	Soldered on the PCB. Score 0	Not degrading in time	Technically mature	Could be used together with the PCB	-
Integrateg Circuits		-	Soldered on the PCB, it cannot be removed without damaging the component. Score 0	Near to infinite lifetime (Poppelaars, 2014)	Most upgraded part. However hardware upgrades may in the future be replaced by software (cloud) update	Refurbishment	A slot could be added to the PCB like in SD card or Memory Stick to personally change the memory chipset.
Screws, 10 piece	€	1.21	outer screws: Score 3, inside screws: Score 8	Not degrading in time	Mature	Refurbishment, other devices	Instead of the screws, other methods could be used (snapfits, etc.)
SIM Casette		-	Soldered on the PCB. Score 0	Not degrading in time	Mature. Size is getting smaller	Could be used for refurbishing a same model mobile phone	Nano simcard casette could be used to reduce the usage of the PCB area
Flash light	€	1.69	Soldered on the PCB. Score 0	Replaced by using the solder machine. Not easy	Mature	Refurbishment	Instead of soldering, could be added with a slot
RF Cable	€	4.96	Score 7	Not degrading in time	Mature	Refurbishment	-

Table 14. Assessment of the components according to price, reparability, lifetime, maturity, reuse options and recommendations for circularity.

7.2. Scenarios for the future

The user questionnaire showed that Fairphone users used their previous smartphones for two years, feature phones for three years and basic phones for four years. Even though in the main LCA the functional unit has been set to “3 years use of Fairphone”, for the comparison of the scenarios, the functional unit is chosen “6 years use of Fairphone smartphone” because use of 6 years was feasible to scale up the use of 2 and 3 years to compare the impact of different uses with each other. Scenarios were created mainly to analyze how the difference in the use time of the Fairphone and the circular economy implementations to the product system affect the environmental impacts. The scenarios are shown in Figure 20.

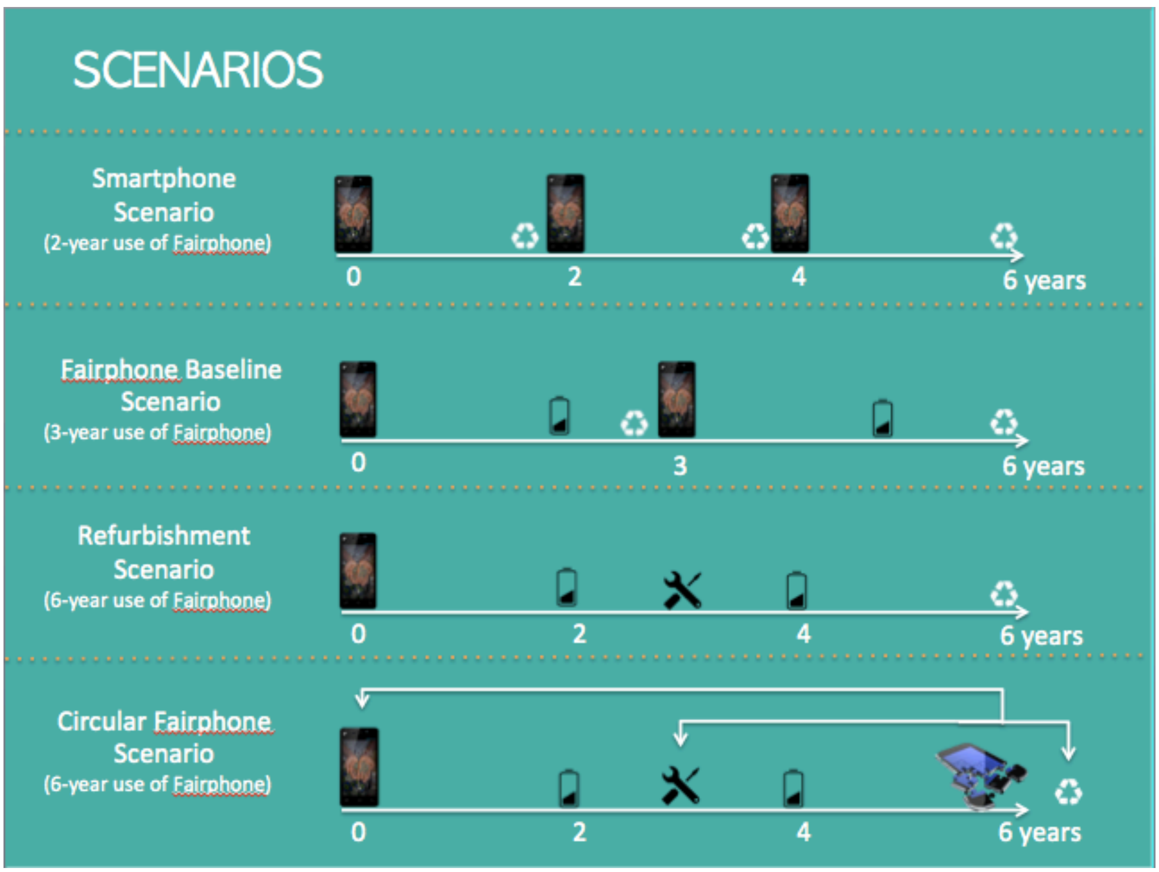

Figure 20. Visual explanation of the four scenarios

7.2.1. Smartphone scenario (2-year use of a Fairphone)

The user questionnaire showed that users are using the smartphones for shorter time than the feature and basic phones. This scenario aims to show the environmental impacts of decreasing lifetime of mobile phones.

Scenario 1 was created to represent a Fairphone smartphone that is used for 2 years by a consumer. Firstly, the LCA was conducted for one phone, one battery (with an assumed life span of 2 years) and two years use of electricity. Then, the results of the scenario were multiplied by 3 in order to find the impact of three phones during six years. Since battery and smartphone are recycled after 2 years of use, in total three Fairphones and three batteries are recycled. All the three phones are assumed to be identical and have the same electricity consumption throughout the six years. Calculations of the electricity use of the scenarios are shown in Table 15.

	2-year use	3-year use	6-year use
Number of charging	584	876	1752
Electricity consumption for a full charge (Wh)	13.47	13.47	13.47
Total Electricity use for Charging (kWh)	**7.866**	**11.800**	**23.599**
Charger Stand-by Mode	33.5%	33.5%	33.50%
Stand-by Power (W)	0.03	0.03	0.03
Stand-by Electricity Consumption (kWh)	**0.176**	**0.264**	**0.528**
Total Energy Consumption	**8.042**	**12.064**	**24.128**

Table 15. Electricity consumption calculations for different years of usage

7.2.2. Fairphone baseline scenario (3-year use of a Fairphone)

Scenario 2 represents the current situation of the Fairphone users in which Fairphone is used for three years by the consumer. Similar to the calculations of Scenario 1, the LCA was conducted for one phone, two batteries and three years use of electricity. Then the LCA results were multiplied by 2 in order to provide the functional unit "6 years use of Fairphone". As two batteries and one smartphone are recycled after three years of use, in total two Fairphones and four batteries are recycled. The transportation model is adapted to include the transportation of the batteries.

7.2.3. Refurbishment scenario (6-year use of a Fairphone)

Scenario 3 represents the first step of Fairphone to create a circular system, which is extending the product lifetime. In the model, the lifetime of the phone is extended to six years, and refurbishment service is given. The LCA is calculated for one Fairphone, three batteries and six years use of electricity. The LCA results do not need any multiplication now to provide the functional unit. An additional LCD screen is added to the scenario under the assumption that the user will break the display only once in six years. It is assumed that the camera will be changed once due to the technical problems of the component. As a result, the phone and battery recycling processes are adapted to cover the recycling of two LCD screens, two cameras and three batteries. Transportation of two additional batteries, one rear camera and one LCD screen from the assembly plant to Amsterdam is included into the model.

7.2.4. Circular Fairphone scenario (6-year use of a Fairphone)

This scenario shows the case in which Fairphone applies the circular economy to its current business model. The new model aims to close the loops with the overall goal to reuse the components in remanufacturing or refurbishment instead of recycling.

Circular Fairphone scenario is exactly the same as the third scenario, but in addition a dismantling process is put into the practice. After six years use of a Fairphone, it is assumed that the Fairphone will be collected from the consumer and will be processed in the dismantling facility where the Fairphone will be dismantled into its components and each component will be tested if it still functions or not. The functioning components will be reused to refurbish other Fairphones, and the rest will be recycled.

The LCA is calculated for one Fairphone, 3 batteries and 6 years use of electricity. The new flows of the system are shown in Figure 21. To be able to model the system on the software, more information is needed about which components will be still functioning and could be used for refurbishing other Fairphones, and which of them will go to recycling. According to the lifetime and maturity of the components assessed in Table 14, assumptions were made for all of the components used for modeling the system (Table 16).

The phone and battery recycling processes are adapted to cover the three batteries, one rear camera, one front camera and two LCD screen. Also transportation model is changed to cover the transportation of the additional components.

7.3. Results

To compare the scenarios, the models were created in CMLCA by making changes on the baseline LCA model of the Fairphone. The results were analyzed on the three impact categories: metal depletion, climate change and human toxicity. The full data used for the following three graphs can be found in Appendix E.

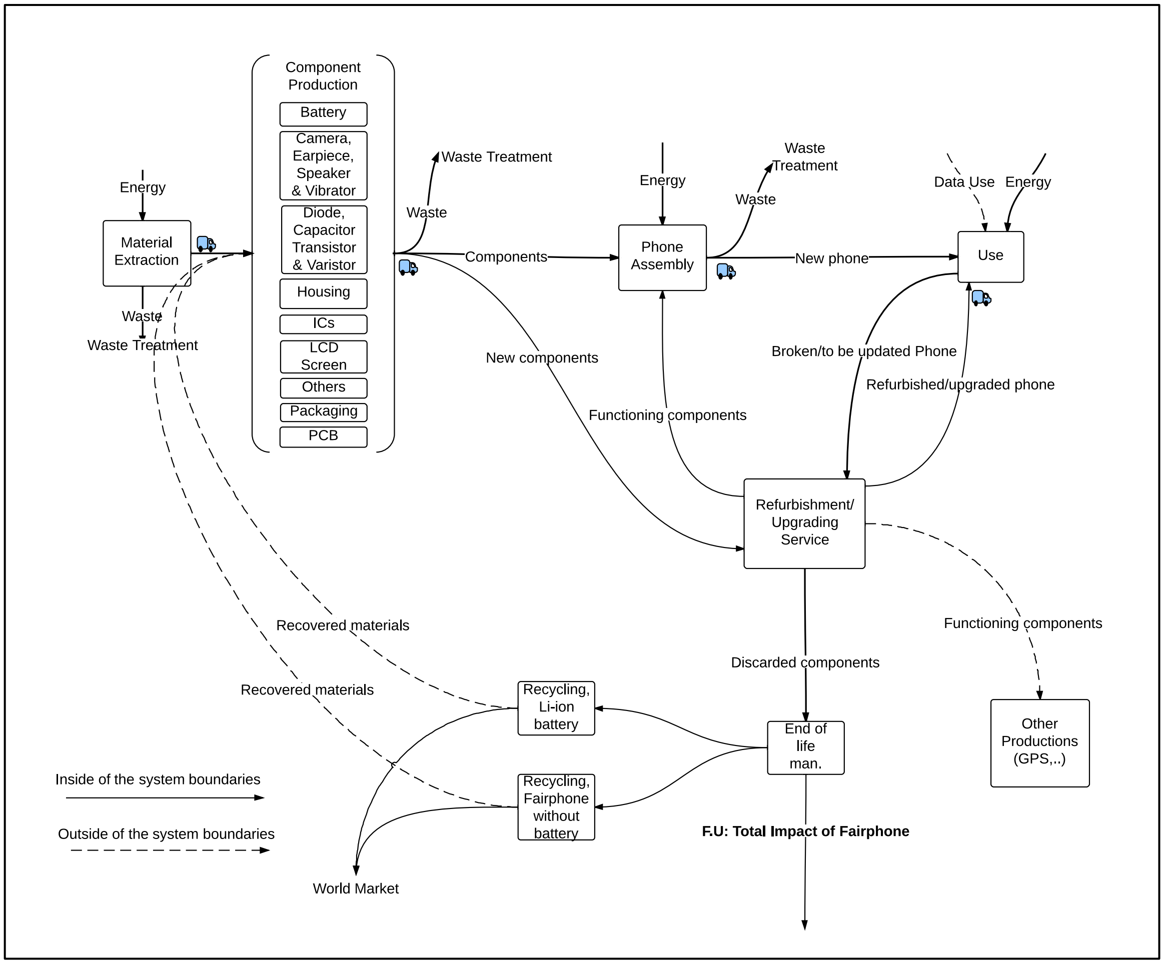

Figure 21. The new circular economy system for scenario 4

7.3.1. Metal depletion

As discussed in Section 6.2.1., more than 90% of the impact come from the production process. Reduction in the use of the components significantly affects the metal depletion impact. Battery is the highest contributor towards metal depletion and the baseline scenario has the highest impact coming from the battery. This stems from the usage of 4 batteries in total for the baseline scenario during 6 years, whereas the usage is 3 batteries for the other scenarios.

The results of the impact assessments show that the Circular Fairphone has 53% less material depletion impact than the baseline Fairphone scenario (Figure 22). This is a considerable difference for the companies, which want to become more independent especially in terms of critical metals.

Components	Number of units used in 6 years	Weight per unit (g)	Sent for recycling	Total weight sent for recycling (g)	Sent for reuse	Total weight sent for reuse
Battery	3	38.60	100%	115.80	0%	0.00
Rear camera	2	0.92	50%	0.92	50%	0.92
Front camera	2	0.16	50%	0.16	50%	0.16
Vibrator	1	0.72	50%	0.36	50%	0.36
Earpiece	1	0.51	50%	0.26	50%	0.26
Speaker	1	1.33	50%	0.66	50%	0.66
LCD	2	45.65	50%	45.65	50%	45.65
Capacitor, transistor, diodes, varistors on the PCB	1	1.05	50%	0.53	50%	0.53
PCB_Mainboard	1	5.28	50%	2.64	50%	2.64
PCB_Daugterboard	1	1.15	50%	0.57	50%	0.57
Housing	1	31.29	75%	23.47	25%	7.82
Others	1	10.84	50%	5.42	50%	5.42
IC	1	1.06	50%	0.53	50%	0.53
Battery Cap	1	24.91	50%	12.46	50%	12.46
TOTAL		163.45		209.41		77.97
without battery		163.45		93.61		77.97

Table 16. Assumptions about the end of life options for the components of the Fairphone

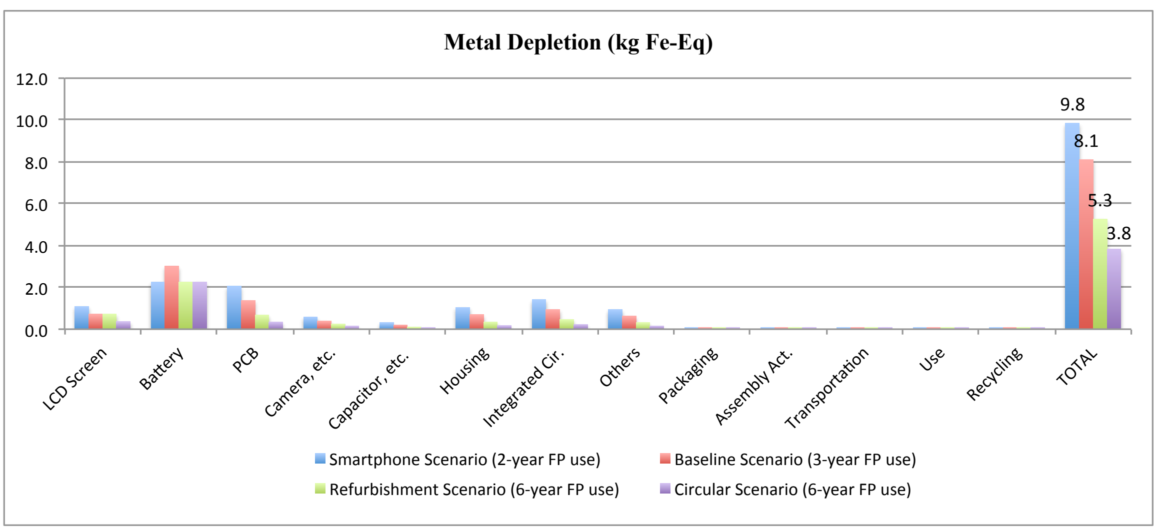

Figure 22. Metal depletion category results of the scenarios

7.3.2. Climate change

As seen in the Figure 23, the baseline scenario causes 33.5 kg of CO2 emission, and total number drops to 25.3 kg of CO2-eq if the company achieves the circular Fairphone scenario. This 24% reduction in climate change potential between two scenarios mainly comes from less transportation of the phones needed from the assembly plant to Netherlands. However, this could also be achieved by changing the type of transportation from air to ocean or rail. The second contributor to the decrease is the LCD screen. For scenario one, three LCD screen is used to produce three Fairphones. This number decreases for the other scenarios. Circular Fairphone scenario has the lowest impact coming from LCD screens, since it is assumed that the LCD screen of a phone can be used at the end of the life cycle of the phone.

Even though circular economy provides a 24% reduction in climate change impact comparing baseline scenario to the circular Fairphone scenario, the difference between the refurbishment scenario and circular Fairphone scenario is not high enough to motivate the company. This does not provide enough incentive for Fairphone, who is looking for ways to improve their environmental performance by applying the circular economy concept to its business. On the other hand, this difference between scenario 3 and scenario 4 is around 3 kg CO2-eq per phone, and this number sums up to 75 tonnes of CO2-eq while thinking in the total production of Fairphone (25000 phones for the first batch).

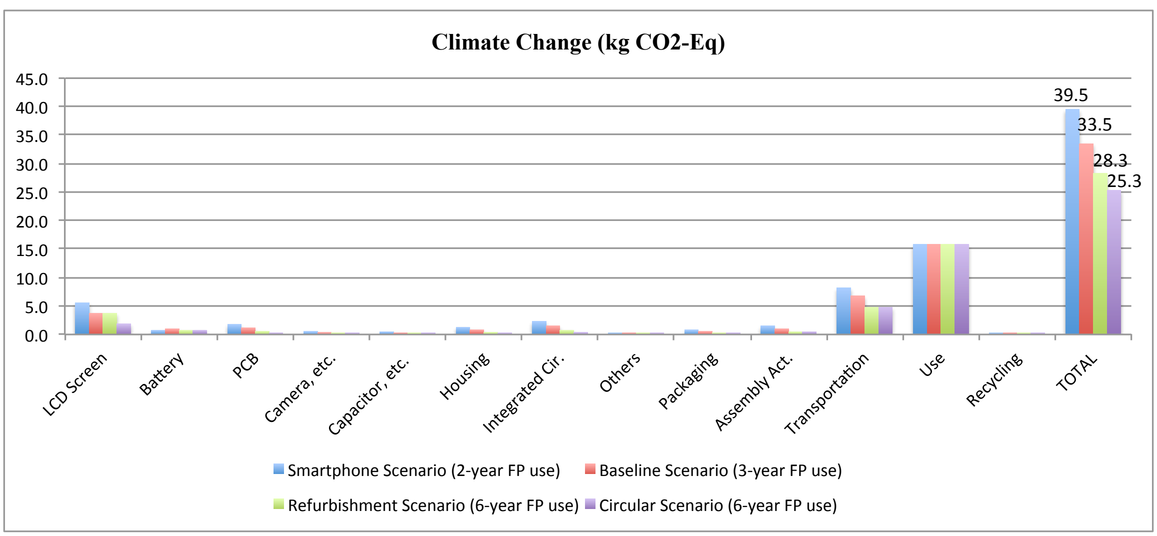

Figure 23. Climate change category results of the scenarios

In order to reduce the climate change impact of the Fairphone, the first step refurbishment scenario can be achieved more easily in the short-term without much investment cost. To achieve the refurbishment scenario, Fairphone needs to communicate with its customer about the environmental benefits of using their Fairphone for a longer period of time. During the 6 years use period of the Fairphone, service and all spare parts should be provided to the customers whenever required.

7.3.3. Human toxicity

The main impact for human toxicity comes from the production and use stages. Since the electricity consumption is assumed to be the same during the use for all the scenarios, different scenarios does not bring any changes to the net impact on human toxicity. There can be more research done to analyze the effects of the increasing battery size and battery efficiency of the new phones, and also the possible rebound effect, which might be the result of these two technological improvements.

The main impact comes from the production stage, specifically production of the integrated circuits, the PCB and the LCD screen (Figure 24). As can be seen in the figure, the circular Fairphone scenario results in the reduction on the components results in a 42% decrease of impact compared to the baseline scenario. If the Fairphone users use their Fairphones only for 2 years and buy a new Fairphone every 2 years, this behavior will increase the human toxicity by 24% comparing to the baseline scenario where the customers are supposed to use their phones for 3 years.

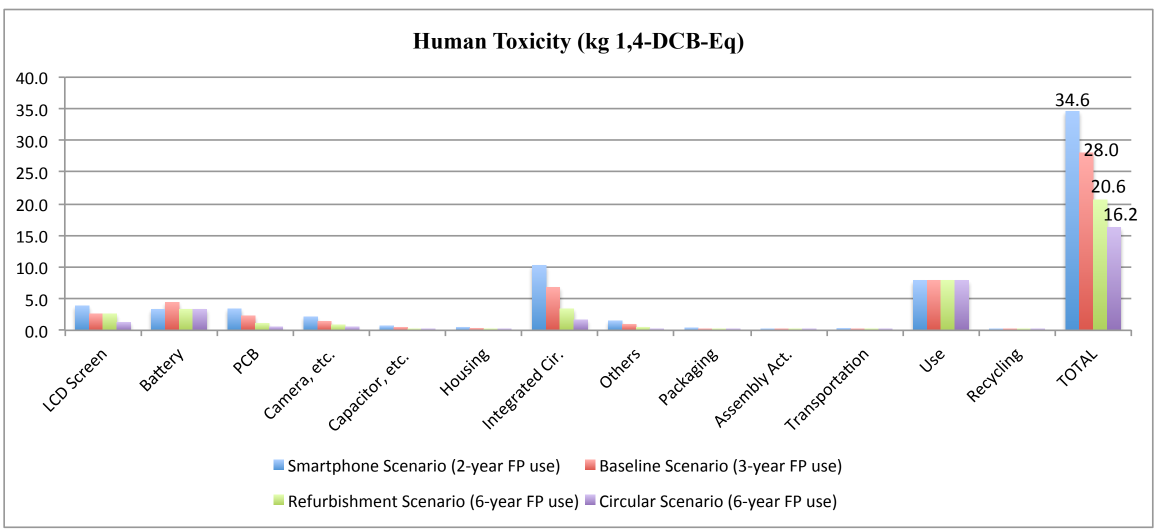

Figure 24. Human toxicity category results of the scenarios

7.4. Conclusion

This chapter aims to answer the last research question:

What is the environmental gain of applying options for improved design of the Fairphone?

The impact assessment results of the scenarios have shown that the application of circular economy to the Fairphone reduces the impact on metal depletion by 53%, climate change by 24% and human toxicity by 42% when compared to the baseline scenario.

As a result, circular economy improves the environmental performance of the Fairphone in three impact categories, which are representative for other impact categories. Hence, it can be said that the circular economy concept helps improve the environmental performance of the Fairphone.

On the other hand, a feasibility analysis should be made for the application of circular economy to smartphones.

Furthermore, the small difference between scenario 3 and 4 should not be ignored. If scenario 3 is chosen for the future phone, metal depletion impact will be reduced by 35%, climate change by 16% and human toxicity by 26%. As a short-term goal for the company, if they manage to persuade the customers to use their Fairphone for six years instead of three years while providing a healthy refurbishment system for the full six years, they could directly improve their environmental impact without making major adjustments in the system.

Scenario 1 shows the importance of the decreasing lifetimes of smartphones. If Fairphone customers use their Fairphone for only two years due to lack of communication and awareness of the environmental impact, there will be an increase in metal depletion by 21%, climate change by 18% and human toxicity by 24% when compared to the baseline scenario.

Chapter 8 - Discussions

8.1. Answers to the research questions

In this study, life cycle assessment was used as the tool to evaluate the environmental impact of the Fairphone. The boundaries of the system consisted of the material extraction, production of the components, assembly of the Fairphone, transportation of the components to the assembly plant, transportation of the Fairphone from the assembly plant to customers, electricity use for charging the phone and recycling of the Fairphone and the battery. The data obtained from the bill of materials and dismantling a Fairphone was used to model the system in CMLCA software using the ecoinvent database. Additional data was collected from the assembly plant about the electricity consumption, and from Fraunhofer Institute about the material composition of several components. Three impact categories were chosen to represent the environmental impact of the Fairphone. Using the ReCiPe 2008 method, the characterization results were calculated for metal depletion, climate change and human toxicity. Contribution analysis was applied in order to find out the components and phases with the highest impact to the three categories. According to the results, ideas are given to improve those problematic areas.

This research aims to fill the gap of application of LCA to create strategic decisions for the companies. To be able to improve the environmental performance of the system, different eco-design tools and concepts were evaluated and circular economy was chosen as the concept. The concept is applied to the Fairphone to create four scenarios. These scenarios are evaluated using LCA in order to find out the benefits to the system. Finally, improvement ideas were given for the system and the components.

8.1.1. Sub-question 1: What is the environmental impact of the Fairphone through its life cycle?

Metal Depletion:

In total, the system causes 4.0425 kg Fe-eq of metal depletion. Production phase contributes to 99% of the results. Production phase includes the production of the components and the assembly activities of the mobile phone. Production of the battery has the highest impact with 37% of the total impact. Whereas the contribution of the battery is followed by PCB with 17%, integrated circuits with 12% and LCD screen with 9%.

Climate Change:
The company is mainly interested in the climate change impacts. The carbon emission of the system is 16.404 kg CO2-eq. Electricity usage for charging the phone for three years has the highest contribution to the impact category (49%). Network usage is not included in the system as explained in Section 3.2.4. The production phase is the second highest contributor (33%), and it is followed by transportation phase (17%)

The highest contributors among the components to the characterization results of climate change are the LCD screen with 1.85 kg CO2-eq. (11%), integrated circuits with 0.76 kg CO2-eq (5%) and PCB with 0.59 kg CO2-eq (4%).

Human Toxicity:
Production of the components and the use phase are the main contributors of the human toxicity as they cause more than 90% of the human toxicity. In total, production of the components and assembly activities are responsible for 71% of the results. This mainly comes from the integrated circuits (24%), battery (16%), LCD screen (9%) and PCB (8%). Use phase causes 28% of the human toxicity. Contribution of the transportation and recycling phases are negligible, at around 1% in total.

8.1.2. Sub-question 2: Which eco-design tools (or other concepts) can be used to improve the life cycle environmental impact of the Fairphone?

Eco-design tools (EcoDesign Checklist and the Strategy List), The Natural Step Framework, a benchmarking method developed by Park et al. (2006b), a guideline from Greenpeace and the concept of circular economy (CE) were evaluated in terms their ability to create systematical solutions and finally CE was chosen as the concept to improve the environmental impacts.

The main reason to choose the CE concept was to analyze whether the CE concept, when applied to a mobile phone, actually improves its environmental performance since there was a research gap in the literature about the quantitative results of CE. This research aimed to fill this gap by answering the question using the LCA to assess the scenarios that are created based on CE. The second reason was that Fairphone has already integrated several aspects of CE and there was a potential for further applications of the concept.

8.1.3. Sub-question 3: What is the environmental gain of applying options for improved design of the Fairphone?

If the system is changed to refurbishment scenario (scenario 3), the reductions will be as following: 35% in metal depletion, 16% in climate change and 26% in human toxicity. This scenario can be a short-term strategy of Fairphone. Persuading the customers to use their mobile phones for six years instead of three years and providing an efficient refurbishment system could easily bring the improvements mentioned above without making major changes in the system.

If the company can change the system to circular Fairphone (scenario 4), then significant reductions could be achieved comparing to their current state (baseline scenario): 53% in metal depletion, 24% in climate change and 42% in human toxicity. This scenario could be a long-term strategy of the company. Customers should still be persuaded to use the mobile phone for six years. More investments are needed to achieve this scenario, for instance having a dismantling facility to collect the functioning components from the Fairphone and use them for refurbishing others. On the other hand, a feasibility analysis should be made for setting up a dismantling facility.

On the other hand, Scenario 1 shows that Fairphone needs to take an action about the decreasing lifetimes of the smartphones. If the Fairphone customers use their Fairphone for only two years because of lack of communication and awareness of the environmental impact, there will be an increase in metal depletion by 21%, climate change by 18% and human toxicity by 24% when compared to the baseline scenario.

As a result, in both Scenario 3 and Scenario 4, circular economy improves the environmental performance of the Fairphone in three impact categories, which are representative for other impact categories. With these results, the conclusion can be made that circular economy applications improve the environmental performance of the Fairphone.

8.1.4. Main Question: How can the environmental performance of the Fairphone be improved?

Circular economy strategies

The main answer to this question is the application of the circular economy concept to the system. As explained in the scenarios, the main improvement in the environmental performance comes from prolonging the lifetime of the mobile phones. Fairphone's stated mission can be achieved by educating the customers to use their mobile phones for longer than they used to and by combining this change in user behavior with good product service. This is the first option that Fairphone can easily achieve.

The second option is to ensure that Fairphones, which reach the end of their lifetime, are collected and if it is possible to make use of them as a refurbished mobile phone. If the phone is no longer functional, it should be recycled.

The third option is to explore new business models for the Fairphones. Instead of selling the Fairphones, leasing would be a better option as the Fairphones could be fixed before being leased again in different markets instead of being kept in the personal storage of users.

The fourth option is to have a dismantling facility for the Fairphones. When the Fairphone is no longer functioning and instead of being recycled, it can be dismantled and the functioning components used for refurbishing other phones. The components can also be used for other products. For example, old cameras can be used for medical devices, toys, etc.

The solutions for the phases or the components of the mobile phone

The solutions are categorized according to the life cycle phases and components:

- **Battery and use phase:**

Designing the Fairphone with energy efficient user interface, lifetime of the battery could be extended. If the battery life could be extended to 3 years, in all of the characterization results of the impact categories, the contribution of the battery production would be the half of the current value. The other ideas to reduce the electricity consumption to charge the battery are more efficient batteries, energy saving applications, or the color of the display screen which helps increase battery savings.

- **LCD screen:**

Choice of AMOLED screen instead of LCD screen would consume less electricity due to high efficiency in terms of battery usage (Lin et al., 2009). On the other side, there are no studies analyzing the environmental impact of the production of AMOLED screen. Hence, it should be further investigated.

Another improvement could be preventing the unforeseen impact comes from the replacement of the LCD screen because of the high number of crashes. 3% of the Fairphone users already crashed their screen since January. Future studies could find out the results of screen crashes and create solutions.

- **Transportation:**

Even tough transportation causes 17% of the carbon emissions; in other impact categories its contribution is negligible. The transportation of the Fairphone from China to Germany by air is the main responsible for the emissions. The other means of transportation could easily reduce the emissions. On the other side, company has other concerns about the solution; such as, longer time it takes and security.

8.2. Limitations: approach and assumptions

To assess the environmental impact of the Fairphone, the model is created based on the data, which was mainly collected by dismantling the Fairphone, weighing the components and matching the components with the data on the ecoinvent database. The database is published in 2007 and mainly the datasets used in the model comes from the studies, which are mostly older than 10 years. This data might not accurately represent the current technological developments in the electronics sector. This brings the limitations to the study to have a result as a number for the environmental impact. But the main goal of the study is not only to assess the environmental impacts, also to have an understanding of the current problems of the system in order to find solutions to improve.

With the sensitivity analysis, the importance of the assumptions to the final results of the LCA was assessed. Especially the assumptions made about the electricity use of the Fairphone users while charging the phone is a very sensitive data for the results of the characterization of the climate change, since the use phase is responsible for almost half of the green house gas emissions. Moreover, the contribution of the production phase might have been underestimated because of using the data of the ecoinvent database that is more than 10 years old.

Other assumptions were made for modeling the circular economy scenarios; for example, electricity use of a phone stays the same for 6 years. More information is needed in the mobile phone use behavior, since the increased energy efficiency could result in rebound effect which means user might offset the benefits of the new technology.

8.3. Conclusions and recommendations

This thesis study made a quick screening on the environmental impacts of a life cycle of a mobile phone. Metal depletion, climate change and human toxicity were chosen as the three impact categories since they were the most critical impact areas in the electronics industry. Using the contribution analysis, the most problematic components or phases were obtained. Furthermore, the concept of circular economy is applied to the product system to find out the environmental benefits of it to the system.

This study assessed basic applications of circular economy to the mobile phone system by various scenarios with different assumptions. This research is aiming to look at the environmental impact of future scenarios, but for the future research, it would be valuable to provide economical information with a feasibility analysis of the scenarios. This could be researched in a future study. For example, a viability assessment could be done to decide if a dismantling facility is a viable option for the mobile phone companies.

In order to develop more realistic scenarios, more information is needed about the environmental impact of landfilling and "primitive" recycling of mobile phones. One current problem is that companies collect the mobile phones via different methods and functioning mobile phones are being sold to second-hand markets. The company lose track of the mobile phones, which potentially ends up in landfill or primitive recycling areas. Leasing the mobile phones could be a solution to this problem. The business model of leasing the mobile phones in developing countries could be a future study topic. Creating incentives for people to bring their mobile phones back would be a very important aspect of the business.

Electronic waste during production is another important topic to explore in order to fully understand the real environmental impact of the product. Since the components are expensive, companies are placing more importance on quality management. On the other side, there are not many studies about the environmental cost of defect rates. During this study, no data was collected from the suppliers about their defect rates. It could create a significant difference in the total environmental impact of the electronic devices.

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Appendix A. Bill of materials of the Fairphone

Category	Item	Supplier	HQ in / Made in	Website/Address if no website
Platform chipset	System SOC	Mediatek	Taiwan	http://www.mediatek.com
Embedded System Memory	Embedded Memory Package (LPDDR2 and eMMC NAND Flash)	Sandisk	US	http://www.sandisk.com
Radio / Modem	Transceiver	Mediatek	Taiwan	http://www.mediatek.com
	2G Quad-Band RX/TX Module	RFMD	US	http://www.rfmd.com/
	3G PA Modules	Skyworks	US	http://www.skyworksinc.com/
	3G UMTS SAW Filters	Epcos	Germany / Japan	http://www.epcos.com
Power Management	PMIC	Mediatek	Taiwan	http://www.mtk.com.tw/
	Switching Charger	Texas Instruments	US	http://www.ti.com
Connectivity	Connectivity Module	AzureWave	Taiwan	http://www.azurewave.com/
	Connectivty Chip (WLAN/BT/GPS/FM)	Mediatek	Taiwan	http://www.mediatek.com
	GPS LNA	Infineon	Germany	http://www.infineon.com
	GPS/BT-WLAN Diplexer	Epcos	Germany / Japan	http://www.epcos.com
Sensors & User Interface	Light & Proximity Sensor	Sitronix	Taiwan	http://www.sitronix.com.tw
	Accelerometer	Bosch	Germany	http://www.bosch-semiconductors.de
	Gyroscope / Motion Processing Unit	InvenSense	US	http://www.invensense.com
	E-Compass	MEMSIC	US	http://www.memsic.com
	Speaker	Shenzhen Sounde Electronic	China	No.4 Fengye Rd, Fenghuang 1st industrial zone, Fuyong, Shenzhen, China
	Audio Power Amplifier	Will Semi	China	http://www.willsemi.com
	Receiver	Shenzhen Guangxun	China	http://www.szgxgd.com/
	Audio Jack Cross Point Switch	Fairchild Semiconductors	US	http://www.fairchildsemi.com/
	Microphones	Knowles	US	http://www.knowles.com
	Motor	Dongyyang Hendian DMEGC Motor	Zhejiang, China	http://www.chinadmegc.com
	LEDs	Liteon	Taiwan	http://www.liteonit.com/
Display Assembly	TFT Panel	LG Display	Korea	http://www.lgdisplay.com/
	Touch Panel	Success Electronics	Changsha, China	http://www.szsuccess.com.cn
	Panel Glass	Asahi Glass	Japan	http://www.agc.com
	LCD Controller	Novatek	Taiwan	http://www.novatek.com.tw
	Backlight LED Driver	Texas Instruments	US	http://www.ti.com
	Touch Panel Controller	Himax	Taiwan	http://www.himax.com.tw
Cameras	Primary Camera	Sunny Optical	China	http://www.sunnyoptical.com
	Primary Camera Sensor	Sony	Japan	http://www.sony.net/Products/SC-HP/
	Primary Camera Lens	Shenzhen Real Optical Electronic	China	http://rogx.china.b2b.cn/companydetail.htm
	Secondary Camera	Q-Technology Limited	Jiangsu, China	http://www.qtechglobal.com/
	Secondary Camera Sensor	Aptima Imaging	US	https://www.aptina.com
Connectors and buttons	Data/Charge Port	Shenzhen Linkconn Electronics	China	http://www.linkconncn.com/
	Dual SIM Slot	Shenzhen Linkconn Electronics	China	http://www.linkconncn.com/
	Headphone Jack	Shenzhen Linkconn Electronics	China	http://www.linkconncn.com/
	Memory Card Slot	JTCONN	China	http://www.jtconn.com/
	Microswitch Buttons	Citizen Eletronics	Japan	http://ce.citizen.co.jp
	FPC Connectors	Hirose	US	http://www.hirose.com
	RF Connectors, RF Cable	Everett Charles Technology (ECT)	US	http://www.ectinfo.com
	Spring Connectors, Single Pin connectors	Sunway Communication	China	http://www.sz-sunway.com
	Board-to-board connectors	Panasonic	Japan	http://www.panasonic.com
PCBs	Printed Circuit Boards	China Circuit Technology Corporation	Shantou, China	http://www.cctc-pcb.com/cctc_en/
	Flexible Printed Circuits	ZE FPC	Shenzhen, China	www.zefpc.com
Battery	Battery	Fenghua-lib company	Zhaoqing, China	http: //www. fenghua-lib.com
Housing & Buttons	Plastic Housing and buttons (Injection Moulding)	Dongguan Zhouquan Plastic and Hardware	Dongguan, China	http://www.chou-quan.com/
	Plastic buttons (Injection Moulding)	Shenzhen Dixuan Technology	Shenzhen, China	Building B2, Xu Jing Chang Industrial Park, Fu Yong, Shenzhen
	Housing Material	Samsung Chemical (Samsung Cheil)	Korea	http://www.samsungchemical.com
	Paint	Musashi Paint	Japan	http://www.musashipaint.com/
	Metallic Rear Cover - Punching and assembly	MOD	Shenzhen, China	http://cn.szmzf.com/
	Metallic Rear Cover - Painting	Dongguan Rui Yuan	Donguan, China	Yang Wu First Industrial park, Dongguan, China

Passives and Discretes	Tantalum Capacitor	AVX	US / Czech Republic	https://www.avx.com/
	Capacitors	Eyang	China	http://www.szeyang.com
	Resistors, Capacitors, Inductors, Ferrite Beads, Varistors	Murata	Japan	http://www.murata.com
	Capacitors	TDK	Japan	http://www.global.tdk.com
	Inductors	Sunlord	China	http://www.sunlordinc.com
	Diodes	Toshiba	Japan	http://www.toshiba.com/
	Zener voltage regulators, Schottky Diodes	Prisemi	Shanghai, China	http://www.prisemi.com
	Transient Voltage Suppressors	Will Semi	China	http://www.willsemi.com
	Transient Voltage Suppressors	ON Semi	US	http://www.onsemi.com
	Transient Voltage Suppressors	Leshan Radio Company (LRC)	China	http://www.lrc.cn/
	EMI Filters	Panasonic	Japan	http://www.panasonic.com
	Coin Type Capacitor	Seiko Instruments	Japan	http://www.sii.co.jp
	Crystals	Epson	Japan	http://global.epson.com/
	Oscillators and crystals	TXC	Taiwan	http://www.txc.com.tw/
Other Build Materials	Soldering Paste	Alpha/Cookson	US	http://alpha.alent.com/
	Soldering Thread	AIM Metals & Alloys	Canada	http://www.aimsolder.com/
	Silicone Audio and Light Waveguides	Shenzhen Taiqi Electronic	China	http://www.sztaiqi.cn/
	Adhesives	Tesa	Germany	http://www.tesa.com
	Adhesives	3M	US	http://www.3m.com/
	Thermal Conductive Tape	HCF	China	http://www.emigasket.com
	Thermal Conductive Tape	Chongqing Zhenghuai	Chongqing, China	No. 71 Kochen Rd, Chongqing, China
	Screws	Dongguan Weite Electronic	Dongguan, China	http://dgwittis.vip.cali-light.com/
Packaging	Quick Guide	Chongqing MeiZhuYuan Printing	Chongqing,China	No. 9 Ying Chun Rd. Nan'an District, Chongqing, China
	Gift Box	Chongqing MeiZhuYuan Printing	Chongqing,China	No. 9 Ying Chun Rd. Nan'an District, Chongqing, China
	Postcards	Chongqing MeiZhuYuan Printing	Chongqing,China	No. 9 Ying Chun Rd. Nan'an District, Chongqing, China
Operating System	Mobile OS	Google	US	http://www.android.com
	Fairphone OS	KwameCorp	Portugal	http://www.kwamecorp.com/
Phone Assembly	PCBA and Systems Assembly	Chongqing Guohong Technology Development Company	Chongqing, China	No. 8 Yuma Road, Nan'an District, Chongqing, China
Phone Charger	Charger	Salcomp	Shenzhen, China	http://www.salcomp.com/
	Cable USB A to Micro-B	Richstar	Jiangxi, China	http://www.szrichstar.com.cn/

Appendix B. Inventory Data of the Modeled Processes

Process = [P4098] Phone Assembly				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G2176]	transport, aircraft, freight, intercontinental[RER]	2.54	tkm	1894
[G2949]	electricity, production mix CN[CN]	0.44	kWh	6689
[G3396]	transport, lorry 16-32t, EURO5[RER]	0.117	tkm	7305
[G4088]	Phone Battery	2	unit	-
[G4089]	Phone Camera, Earpiece, Speaker & Vibrator	1	unit	-
[G4090]	Phone Capacitor, Diode, Varistor & Transistor	1	unit	-
[G4091]	Phone Housing	1	unit	-
[G4092]	Phone Integrated Circuits	1	unit	-
[G4093]	Phone LCD Screen	1	unit	-
[G4094]	Phone Other Components	1	unit	-
[G4096]	Phone PCB	1	unit	-
[G4097]	Phone Packaging	1	unit	-
Economic outflows				
[G4098]	New Phone	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4089] Camera, Earpiece, Speaker & Vibrator Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G5]	copper, at regional storage[RER]	7.57E-05	kg	1074
[G136]	zinc, primary, at regional storage[RER]	0.000248	kg	1156
[G477]	nickel, 99.5%, at plant[GLO]	1.12E-05	kg	1121
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.000327	kg	2105
[G672]	disposal, polystyrene, 0.2% water, to municipal incineratio	0.000153	kg	2116
[G754]	packaging film, LDPE, at plant[RER]	0.000174	kg	1854
[G834]	disposal, polyethylene, 0.4% water, to municipal incinerati	0.000174	kg	2114
[G857]	injection moulding[RER]	0.000327	kg	1853
[G1238]	chromium, at regional storage[RER]	4.99E-05	kg	1073
[G1364]	polystrene, high impact, HIPS, at plant[RER]	0.000153	kg	1837
[G1473]	pig iron, at plant[GLO]	0.000405	kg	1132
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.000327	kg	1698
[G2568]	cobalt, at plant[GLO]	2.60E-06	kg	5836
[G3085]	neodymium oxide, at plant[CN]	1.69E-05	kg	6950
[G3086]	praseodymium oxide, at plant[CN]	3.10E-06	kg	6951
[G3087]	samarium europium gadolinium concentrate, 94% rare ear	1.77E-06	kg	6952
[G3242]	electronic component, passive, unspecified, at plant[GLO]	0.00282	kg	10163
[G3244]	production efforts, inductor[GLO]	0.000814	kg	10157
[G3396]	transport, lorry 16-32t, EURO5[RER]	0.00686	tkm	7305
Economic outflows				
[G4089]	Phone Camera, Earpiece, Speaker & Vibrator	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4099] Disposal, Fairphone without battery				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G11]	transport, lorry 20-28t, fleet average[CH]	0.14	tkm	1942
[G327]	sodium carbonate from ammonium chloride production, at	4.99E-05	kg	7246
[G602]	lime, hydrated, packed, at plant[CH]	0.000106	kg	487
[G952]	electricity, medium voltage, production BE, at grid[BE]	0.257	kWh	639
[G3999]	transport, freight, rail[BE]	0.0468	tkm	11325
Economic outflows				
[G4099]	Disposal, Fairphone without battery	1	unit	-
[G4100]	tin, secondary, at recycling plant (EU)	0.00125	kg	-
[G4101]	palladium, secondary, at recycling plant (EU)	1.87E-05	kg	-
[G4102]	copper, secondary, at recycling plant (EU)	0.016	kg	-
[G4103]	gold, secondary, at recycling plant (EU)	4.33E-05	kg	-
[G4104]	silver, secondary, at recycling plant (EU)	0.000453	kg	-
[G4105]	antimony, secondary, at recycling plant (EU)	0.000125	kg	-
[G4106]	nickel, secondary, at recycling plant (EU)	0.00187	kg	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
[E14]	Nitrogen oxides[air_high population density]	2.24E-05	kg	3269
[E15]	Particulates, < 2.5 um[air_high population density]	4.81E-08	kg	3304
[E16]	Particulates, > 10 um[air_high population density]	1.50E-08	kg	3309
[E17]	Particulates, > 2.5 um, and < 10um[air_high population de	2.87E-08	kg	3314
[E40]	Hydrogen chloride[air_high population density]	4.48E-07	kg	3024
[E41]	Hydrogen fluoride[air_high population density]	4.48E-08	kg	3029
[E66]	Sulfur dioxide[air_high population density]	4.48E-05	kg	3529
[E289]	Arsenic[air_high population density]	9.36E-10	kg	2609
[E296]	Copper[air_high population density]	1.56E-09	kg	2789
[E297]	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[	2.24E-16	kg	2819
[E302]	Lead[air_high population density]	3.50E-09	kg	3119
[E305]	Nickel[air_high population density]	5.31E-10	kg	3254
[E1096]	Arsenic, ion[water_unspecified]	5.78E-10	kg	4309
[E1125]	Cadmium, ion[water_unspecified]	5.08E-10	kg	4413
[E1160]	Copper, ion[water_unspecified]	2.23E-08	kg	4613
[E1221]	Nickel, ion[water_unspecified]	2.06E-05	kg	5053
[E1319]	Zinc, ion[water_unspecified]	1.20E-08	kg	5669

Process = [P4095] Phone Packaging Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G76]	kraft paper, unbleached, at plant[RER]	0.054	kg	1732
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.0361	kg	2105
[G531]	EUR-flat pallet[RER]	0.001	unit	2526
[G533]	paper, woodcontaining, LWC, at plant[RER]	0.068	kg	1715
[G754]	packaging film, LDPE, at plant[RER]	0.0071	kg	1854
[G834]	disposal, polyethylene, 0.4% water, to municipal incinerati	0.0071	kg	2114
[G857]	injection moulding[RER]	0.0071	kg	1853
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.0361	kg	1698
[G3396]	transport, lorry 16-32t, EURO5[RER]	0.13774	tkm	7305
Economic outflows				
[G4097]	Phone Packaging	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4091] Phone Housing Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G27]	sheet rolling, steel[RER]	0.0451	kg	1174
[G56]	chromium steel 18/8, at plant[RER]	0.0451	kg	1072
[G102]	transport, barge[RER]	0.0132	tkm	1966
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.00337	kg	2105
[G754]	packaging film, LDPE, at plant[RER]	0.00337	kg	1854
[G834]	disposal, polyethylene, 0.4% water, to municipal incinerati	0.00337	kg	2114
[G857]	injection moulding[RER]	0.0145	kg	1853
[G1531]	transport, aircraft, freight[RER]	0.0536	tkm	1892
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.00337	kg	1698
[G2081]	polycarbonate, at plant[RER]	0.0111	kg	1826
[G2176]	transport, aircraft, freight, intercontinental[RER]	0.0244	tkm	1894
Economic outflows				
[G4091]	Phone Housing	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4097] Phone Use for 3 years				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G1141]	electricity mix[NL]	6.03	kWh	704
[G1143]	electricity mix[DE]	6.03	kWh	706
[G3810]	disposal, Li-ions batteries, mixed technology[GLO]	0.0386	kg	10946
[G4098]	New Phone	1	unit	-
[G4099]	Disposal, Fairphone without battery	1	unit	-
Economic outflows				
[G4095]	Fairphone use for 3 years	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4090] Phone Capacitor, Diode, Varistor & Transistor Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.00104	kg	2105
[G672]	disposal, polystyrene, 0.2% water, to municipal incineratio	0.00104	kg	2116
[G857]	injection moulding[RER]	0.00104	kg	1853
[G1364]	polystrene, high impact, HIPS, at plant[RER]	0.00104	kg	1837
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.00104	kg	1698
[G2093]	capacitor, Tantalum-, through-hole mounting, at plant[GL(	1.70E-05	kg	7013
[G2176]	transport, aircraft, freight, intercontinental[RER]	0.00148	tkm	1894
[G3209]	capacitor, SMD type, surface-mounting, at plant[GLO]	0.000506	kg	7010
[G3255]	diode, glass-, SMD type, surface mounting, at plant[GLO]	0.000517	kg	7075
[G3258]	transistor, SMD type, surface mounting, at plant[GLO]	1.50E-05	kg	7078
[G3396]	transport, lorry 16-32t, EURO5[RER]	0.00364	tkm	7305
Economic outflows				
[G4090]	Phone Capacitor, Diode, Varistor & Transistor	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4096] Phone PCB Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.000321	kg	2105
[G754]	packaging film, LDPE, at plant[RER]	0.000321	kg	1854
[G834]	disposal, polyethylene, 0.4% water, to municipal incinerati	0.000321	kg	2114
[G857]	injection moulding[RER]	0.000321	kg	1853
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.000321	kg	1698
[G3206]	printed wiring board, surface mount, lead-free surface, at p	0.00197	m2	10995
[G3710]	mounting, surface mount technology, Pb-free solder[GLO]	0.00394	m2	10788
[G3923]	operation, coal freight train, diesel[CN]	0.00691	tkm	11097
Economic outflows				
[G4096]	Phone PCB	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4093] Phone LCD Screen Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G27]	sheet rolling, steel[RER]	0.00975	kg	1174
[G56]	chromium steel 18/8, at plant[RER]	0.00975	kg	1072
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.00487	kg	2105
[G672]	disposal, polystyrene, 0.2% water, to municipal incineratio	0.000398	kg	2116
[G754]	packaging film, LDPE, at plant[RER]	0.00448	kg	1854
[G834]	disposal, polyethylene, 0.4% water, to municipal incinerati	0.00448	kg	2114
[G857]	injection moulding[RER]	0.00555	kg	1853
[G1364]	polystrene, high impact, HIPS, at plant[RER]	0.000398	kg	1837
[G1531]	transport, aircraft, freight[RER]	0.0316	tkm	1892
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.00487	kg	1698
[G2081]	polycarbonate, at plant[RER]	0.000675	kg	1826
[G2088]	integrated circuit, IC, logic type, at plant[GLO]	1.19E-05	kg	7016
[G2176]	transport, aircraft, freight, intercontinental[RER]	0.104	tkm	1894
[G3190]	LCD glass, at plant[GLO]	0.0339	kg	10167
[G3191]	assembly, LCD module[GLO]	0.0339	kg	7105
[G3192]	sputtering, ITO, for LCD[RER]	3.66E-09	m3	10962
[G3206]	printed wiring board, surface mount, lead-free surface, at p	0.000271	m2	10995
[G3256]	light emitting diode, LED, at plant[GLO]	0.00041	kg	7077
Economic outflows				
[G4093]	Phone LCD Screen	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4088] Battery Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.00193	kg	2105
[G754]	packaging film, LDPE, at plant[RER]	0.00193	kg	1854
[G834]	disposal, polyethylene, 0.4% water, to municipal incinerati	0.00193	kg	2114
[G857]	injection moulding[RER]	0.00193	kg	1853
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.00193	kg	1698
[G3146]	battery, LiIo, rechargeable, prismatic, at plant[GLO]	0.0386	kg	7003
[G3396]	transport, lorry 16-32t, EURO5[RER]	0.0685	tkm	7305
Economic outflows				
[G4088]	Phone Battery	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4094] Phone Other Components Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G5]	copper, at regional storage[RER]	0.000256	kg	1074
[G56]	chromium steel 18/8, at plant[RER]	0.00129	kg	1072
[G60]	glass fibre reinforced plastic, polyester resin, hand lay-up,	0.000779	kg	1816
[G102]	transport, barge[RER]	0.00153	tkm	1966
[G127]	brass, at plant[CH]	0.000144	kg	1066
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.000733	kg	2105
[G672]	disposal, polystyrene, 0.2% water, to municipal incineratio	0.000472	kg	2116
[G754]	packaging film, LDPE, at plant[RER]	0.000261	kg	1854
[G797]	sheet rolling, chromium steel[RER]	0.00129	kg	1172
[G857]	injection moulding[RER]	0.00207	kg	1853
[G858]	cable, ribbon cable, 20-pin, with plugs, at plant[GLO]	0.000185	kg	7116
[G1364]	polystrene, high impact, HIPS, at plant[RER]	0.000472	kg	1837
[G1502]	copper, primary, couple production nickel[GLO]	0.00394	kg	1089
[G1555]	casting, brass[CH]	0.000144	kg	1159
[G1961]	polyethylene terephthalate, granulate, amorphous, at plant[	0.000544	kg	1827
[G2081]	polycarbonate, at plant[RER]	0.00134	kg	1826
[G2176]	transport, aircraft, freight, intercontinental[RER]	0.000692	tkm	1894
[G3159]	ferrite, at plant[GLO]	1.70E-05	kg	7090
[G3242]	electronic component, passive, unspecified, at plant[GLO]	0.000375	kg	10163
[G3396]	transport, lorry 16-32t, EURO5[RER]	0.00628	tkm	7305
[G3562]	copper product manufacturing, average metal working[RE	0.0042	kg	8339
[G3636]	inductor, miniature RF chip type, MRFI, at plant[GLO]	6.05E-05	kg	10155
[G3638]	connector, computer, peripherical type, at plant[GLO]	0.00191	kg	10162
Economic outflows				
[G4094]	Phone Other Components	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Process = [P4092] Phone Integrated Circuits Production				
CMLCA Label	**Name**	**Value**	**Unit**	**Ecoinvent ID**
Economic inflows				
[G530]	disposal, packaging cardboard, 19.6% water, to municipal	0.00104	kg	2105
[G672]	disposal, polystyrene, 0.2% water, to municipal incineratio	0.00104	kg	2116
[G857]	injection moulding[RER]	0.00104	kg	1853
[G1364]	polystrene, high impact, HIPS, at plant[RER]	0.00104	kg	1837
[G1564]	packaging, corrugated board, mixed fibre, single wall, at p	0.00104	kg	1698
[G2088]	integrated circuit, IC, logic type, at plant[GLO]	0.00041	kg	7016
[G2176]	transport, aircraft, freight, intercontinental[RER]	0.00496	tkm	1894
[G3150]	integrated circuit, IC, memory type, at plant[GLO]	0.000652	kg	7015
Economic outflows				
[G4092]	Phone Integrated Circuits	1	unit	-
Environmental resources				
-	-	-	-	-
Environmental emissions				
-	-	-	-	-

Appendix C. Transportation and Packaging Information of the Components

Component	From	To	Transportation Type	Distance (km)	Component Weight (g)	Packaging Factor	Packaging Weight (g)	Total Weight (g)	t*km
PCB Production:									
Mainboard & Daughterboard	Guandong	Chonqing	operation, coal freight train, diesel	979	6.42070	0.1	0.64207	7.06277	0.00691
LCD Screen Production:									
Flexible Printed Circuit (2 pieces)	Shenzhen	Changsha	transport, aircraft, freight, intercontinental	642	0.88410	0.1	0.08841	0.97251	0.00062
LCD touch panel	Korea	Changsha	transport, aircraft, freight, intercontinental	1635	5.34570	0.1	0.53457	5.88027	0.00961
LCD glass	Japan	Changsha	transport, aircraft, freight, intercontinental	2532	28.57500	0.1	2.85750	31.43250	0.07959
Stainless Steel plate	Shenzhen	Changsha	transport, aircraft, freight, intercontinental	1082	9.74650	0.1	0.97465	10.72115	0.01160
LEDs	Philippine	Changsha	transport, aircraft, freight, intercontinental	1937	0.41000	1.94	0.79540	1.20540	0.00233
Assemblied LCD Screen	Changsha	Chonqing	transport, aircraft, freight	639	44.96130	0.1	4.49613	49.45743	0.03160
Battery Production:									
Battery	Guandong	Chonqing	transport, lorry 16-32t, EURO5	1614	38.59830	0.1	3.85983	42.45813	0.06853
Housing Production:									
Battery Cap	Shenzhen	Chonqing	transport, aircraft, freight	1082	24.90900	0.1	2.49090	27.39990	0.02965
Stainless Steel platewith holes	Shenzhen	Chonqing	transport, aircraft, freight	1082	20.16330	0.1	2.01633	22.17963	0.02400
Plastic housing	Korea	Shenzhen	transport, aircraft, freight, intercontinental	1990	11.12460	0.1	1.11246	12.23706	0.02435
Plastic housing	Shenzhen	Chonqing	transport, barge	1082	11.12460	0.1	1.11246	12.23706	0.01324
Camera, Earpiece, Speaker & Vibration Motor Production:									
Rear Camera	Jiangsu	Chonqing	transport, lorry 16-32t, EURO5	1417	0.15800	1.94	0.30652	0.46452	0.00066
Vibration Motor	Dongyang	Chonqing	transport, lorry 16-32t, EURO5	1633	0.71520	0.1	0.07152	0.78672	0.00128
Earpiece Speaker	Shenzhen	Chonqing	transport, lorry 16-32t, EURO5	1605	0.51430	0.1	0.05143	0.56573	0.00091
Camera	Zhejiang	Chonqing	transport, lorry 16-32t, EURO5	1613	0.91600	0.1	0.09160	1.00760	0.00163
Speaker	Shandong	Chonqing	transport, lorry 16-32t, EURO5	1631	1.32860	0.1	0.13286	1.46146	0.00238

Component	From	To	Transportation Type	Distance (km)	Component Weight (g)	Packaging Factor	Packaging Weight (g)	Total Weight (g)	t*km
Capacitor, Diode, Varistor & Transistor Production:									
Diodes	Shenzhen	Chonqing	transport, lorry 16-32t, EURO5	1082	0.00517	1.94	0.01002	0.01519	0.00002
Diodes	Jiangsu	Chonqing	transport, lorry 16-32t, EURO6	1417	0.36418	1.94	0.70651	1.07070	0.00152
Diodes	Sichuan	Chonqing	transport, lorry 16-32t, EURO7	318	0.09298	1.94	0.18039	0.27337	0.00009
Diodes	Shanghai	Chonqing	transport, lorry 16-32t, EURO8	1721	0.01291	1.94	0.02505	0.03797	0.00007
Diodes	Beijing	Chonqing	transport, lorry 16-32t, EURO9	1762	0.01550	1.94	0.03006	0.04556	0.00008
Capacitors from Jiangsu	Jiangsu	Chonqing	transport, lorry 16-32t, EURO5	1417	0.44510	1.94	0.86349	1.30859	0.00185
Tantalum Capacitor	Chengdu	Chonqing	transport, lorry 16-32t, EURO5	327	0.01700	1.94	0.03298	0.04998	0.00002
Diodes	Japan	Chonqing	transport, aircraft, freight, intercontinental	2532	0.01550	1.94	0.03006	0.04556	0.00012
Diodes	U.S.A	Chonqing	transport, aircraft, freight, intercontinental	12249	0.01033	1.94	0.02004	0.03037	0.00037
Transistors	Taiwan	Chonqing	transport, aircraft, freight, intercontinental	1572	0.01500	1.94	0.02910	0.04410	0.00007
Tantalum Capacitor	Chech Republic	Chengdu	transport, aircraft, freight, intercontinental	7618	0.01700	1.94	0.03298	0.04998	0.00038
Capacitors from Japan	Japan	Chonqing	transport, aircraft, freight, intercontinental	3036	0.01800	1.94	0.03492	0.05292	0.00016
SAW	Japan	Chonqing	transport, aircraft, freight, intercontinental	3036	0.04327	1.94	0.08394	0.12721	0.00039
Integrated Circuits Production:									
Integrated Circuits	Mainly from Taiwan	Chonqing	transport, aircraft, freight, intercontinental	1572	1.07400	1.94	2.08356	3.15756	0.00496
Other Components Production:									
simcard holders	Shenzen	Chonqing	transport, barge	1082	1.28900	0.1	0.12890	1.41790	0.00153
Metal parts covering PCB	Shenzen	Chonqing	transport, lorry 16-32t, EURO5	1082	3.93850	0.1	0.39385	4.33235	0.00469
Cable	Shenzen	Chonqing	transport, lorry 16-32t, EURO5	1082	0.18510	1.94	0.35909	0.54419	0.00059
Screws	Dongguan	Chonqing	transport, lorry 16-32t, EURO5	1523	0.22400	1.94	0.43456	0.65856	0.00100
Coils	Japan	Chonqing	transport, aircraft, freight, intercontinental	3036	0.06055	1.94	0.11747	0.17802	0.00054
Magnetic Bead	Japan	Chonqing	transport, aircraft, freight, intercontinental	3036	0.01700	1.94	0.03298	0.04998	0.00015
Packaging Production:									
User Guide	Beijing	Chonqing	transport, lorry 16-32t, EURO5	1762	68	0.1	6.80000	74.80000	0.13180
Cardboard	Chongqing	Chonqing	transport, lorry 16-32t, EURO5	100	54	0.1	5.40000	59.40000	0.00594

Appendix D. Results of the Contribution Analysis

Category	LCD	Battery	PCB	Camera, Ea	Capacitor, D	Housing	IC	Unit
Metal Depletion	0.36321	0.75176	0.6862	0.19558	0.10413	0.34833	0.47038	kg Fe-Eq
Climate Change	1.8538	0.25233	0.58954	0.17388	0.16488	0.43323	0.75991	kg CO2-Eq
Human Toxicity	1.2965	1.1122	1.1399	0.71903	0.23021	0.16398	3.4156	1,4-DCB-Eq

Category	Others	Packaging	Transportat	Production	Use	Recycling	Total	Unit
Metal Depletion	0.31397	0.0085204	0.01184222	3.99535778	0.032602	0.00268884	4.0425	kg Fe-Eq
Climate Change	0.09695	0.26185	2.726598	5.340102	7.9063	0.070809	16.044	kg CO2-Eq
Human Toxicity	0.49671	0.12672	0.0986232	9.8950768	3.9395	0.0280886	13.961	1,4-DCB-Eq

Appendix E. Data of the Scenarios

Processes	Metal Depletion (kg Fe-Eq)			
Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4
LCD Screen	1.089	0.726	0.726	0.363
Battery	2.256	3.007	2.260	2.260
PCB	2.058	1.372	0.686	0.343
Camera, Earpiece, Spea	0.588	0.391	0.244	0.147
Capacitor, Diode, Varist	0.312	0.208	0.104	0.052
Housing	1.044	0.697	0.348	0.174
Integrated Cir.	1.410	0.941	0.470	0.235
Others	0.942	0.628	0.314	0.157
Packaging	0.026	0.017	0.009	0.009
Assembly Act.	0.005	0.003	0.002	0.002
Transportation	0.035	0.029	0.021	0.021
Use	0.065	0.065	0.065	0.065
Recycling, Fairphone	0.003	0.002	0.001	0.001
Recycling, battery	0.005	0.007	0.005	0.005
TOTAL	**9.838**	**8.094**	**5.255**	**3.833**
Processes	**Climate Change (kg CO2-Eq)**			
Scenarios	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
LCD Screen	5.550	3.708	3.710	1.850
Battery	0.756	1.009	0.757	0.757
PCB	1.770	1.179	0.590	0.295
Camera, Earpiece, Spea	0.522	0.348	0.217	0.130
Capacitor, Diode, Varist	0.495	0.330	0.165	0.082
Housing	1.299	0.866	0.433	0.217
Integrated Cir.	2.280	1.520	0.760	0.380
Others	0.291	0.194	0.097	0.049
Packaging	0.786	0.524	0.262	0.262
Assembly Act.	1.515	1.010	0.505	0.505
Transportation	8.189	6.748	4.794	4.794
Use	15.810	15.813	15.810	15.810
Recycling, Fairphone	0.105	0.070	0.048	0.026
Recycling, battery	0.108	0.144	0.108	0.108
TOTAL	**39.475**	**33.462**	**28.256**	**25.265**
Processes	**Human Toxicity (kg 1,4-DCB-Eq)**			
Scenarios	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
LCD Screen	3.900	2.593	2.590	1.300
Battery	3.330	4.449	3.340	3.340
PCB	3.420	2.280	1.140	0.570
Camera, Earpiece, Spea	2.157	1.438	0.899	0.539
Capacitor, Diode, Varist	0.690	0.460	0.230	0.115
Housing	0.492	0.328	0.164	0.082
Integrated Cir.	10.260	6.831	3.420	1.710
Others	1.491	0.993	0.497	0.248
Packaging	0.381	0.253	0.127	0.127
Assembly Act.	0.246	0.164	0.082	0.082
Transportation	0.296	0.244	0.173	0.173
Use	7.866	7.879	7.880	7.880
Recycling, Fairphone	0.027	0.018	0.012	0.007
Recycling, battery	0.057	0.076	0.057	0.057
TOTAL	**34.614**	**28.007**	**20.612**	**16.230**

Appendix F. Fairphone User Questionnaire

Fairphone Spring 2014 Survey

Dear Fairphone Owners,

This survey is led by two research interns at Fairphone, who are doing internships related to their masters thesis projects at Delft University of Technology and Leiden University, Netherlands. There are three main parts in in the survey: 1) users' energy consumption, data usage and recycling behaviour for use in a Fairphone Life Cycle Assessment, 2) the current user experience of the Fairphone in order to improve the product, and 3) demographics to better understand the individuals in our community.

The data you will provide in this study will be treated anonymously. It will not be traceable and no personal data will be given away to other institutions. Enhanced security (SSL/HTTPS) is used for the survey.

The completion of the survey will take you approximately 10 minutes. There is no right or wrong answers, we are only interested in your own personal opinions.

We are really thankful that you support us in our research!

Sincerely,
Merve Güvendik (Delft/Leiden University), Youge Xiao (Delft University), and the Fairphone team

Contact: merve[at]fairphone.com

Universiteit Leiden

TU Delft Delft University of Technology

User Behavior Questions

This information will be used to improve the environmental impact of Fairphone.

***1. After a full charge, how long does your battery last on an average day?**

Please give your answer in hours:

2. Do you leave the charger in the outlet after removing the phone?

- Always
- Sometimes
- Never

Fairphone Spring 2014 Survey

3. On a typical day, about how many hours in total do you actively use your phone?

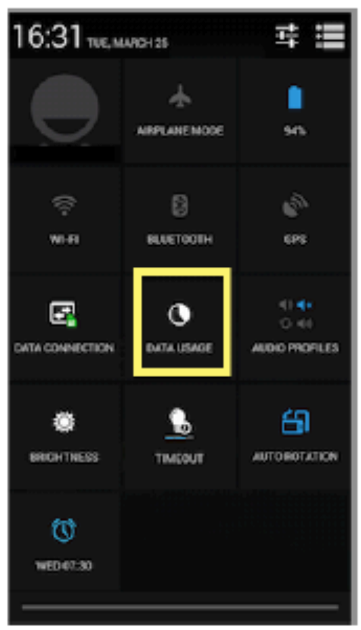
- 0-1 hour
- 1-2 hours
- 2-3 hours
- 3-4 hours
- 4-5 hours
- 5-6 hours
- 6-7 hours

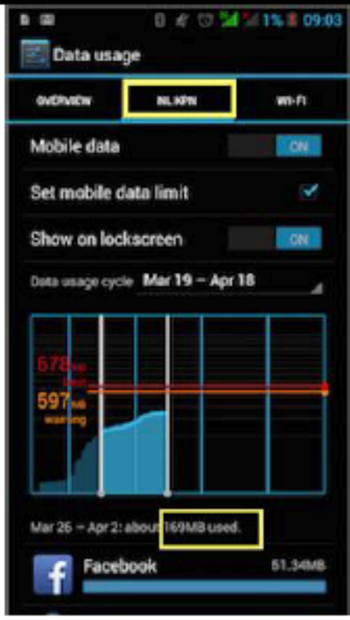
Other (please specify)

Mobile Data Usage

In this section, we will be asking you about your mobile data usage. Please pull-down the menu on your Fairphone and click on the button on the top right to see the screen pictured below.

When you click on "Data Usage", and then click on your mobile operator name, you will see how many MB of internet you used last week.



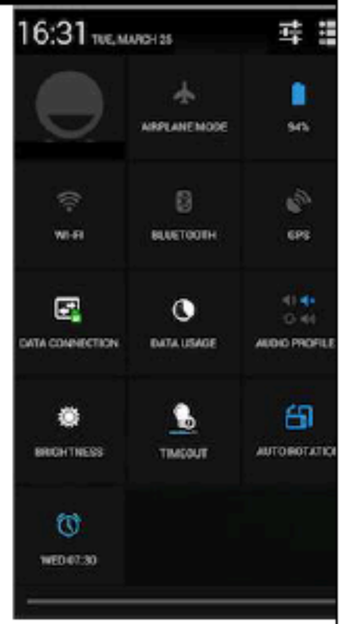


***4. How many MB of Internet did you use last week? (To check, please follow instructions at the top of the page.)**

Functions of Fairphone

If you use the pull-down menu and click on the button on the top right you get quick access to turn on/off a lot of different functions (see example screen below). In this section, we will be asking you how often you activate these options.

Fairphone Spring 2014 Survey



5. How long do you keep Wi-Fi on?

- All the time
- I keep it on during the day time, turn it off before sleeping
- Only at hotspots (Work, Home, Cafes...)
- Never
- I don't know

6. How long do you keep GPS on?

- All the time
- Only while traveling (using maps and similar application)
- Only while using other applications
- Never
- I don't know

7. Your phone uses Data Connection to send and receive data using your mobile operator's cellular network. How long do you keep Data Connection on (eg, 3G Internet)?

- All the time
- During day time I keep it on and I turn it off before sleeping
- Never
- I don't know

Fairphone Spring 2014 Survey

8. How long do you keep Bluetooth on?

- All the time
- Only when I need to connect it to other devices
- Never
- I don't know

Dual SIM usage

***9. Have you ever used the Dual SIM option?**

- Yes
- Never

***10. What is the main reason for you to use the dual SIM option?**

- Mostly while traveling
- Mostly to combine personal and work number
- Mostly to combine public and anonymous numbers
- Mostly to have two different tariffs or fees
- Mostly to keep your domestic/previous phone number if you live abroad
- None of the previous reasons

11. How many phones are you using right now?

- 1
- 2
- 3 or more

***12. How many phones were you using before ordering a Fairphone?**

- 1
- 2
- 3 or more

Your Previous Phone

These questions ask about your previous phone which you were using before the Fairphone.

Fairphone Spring 2014 Survey

***13. About your previous phone: What kind of phone did you use?**

- Smartphone (with an operating system that opens 3rd party applications)
- Feature Phone (without an operating system that opens 3rd party applications)
- Basic mobile phone (only capable of voice calling and text messaging)

14. About your previous phone: What was the operating system?

- IOS / Apple
- Android
- Windows Mobile
- Blackberry OS
- Symbian
- MeeGo
- Firefox OS

Other (please specify)

***15. About your previous phone: For how long did you use it? (in months)**

***16. About your previous phone: Was it still functioning when you received your Fairphone?**

- Yes
- No
- Partially (some repairable problems with screen, battery, etc)

Reason to buy the Fairphone

17. What was the main reason for you to buy a Fairphone?

- To upgrade to a smarter phone
- The idea of Fairphone was cool
- To support what Fairphone does
- I was bored with my old phone
- My previous phone was not sufficient for my needs

Other (please specify)

Fairphone Spring 2014 Survey

Reuse and recycling

*** 18. About your previous phone: What did you do with it when you received the Fairphone?**

- Still use it
- Gave it to someone
- Sold it to another person
- Sent it to take-back program of the phone producer
- Sent/dropped to Recovery Points (Telecommunication shop, others)
- Donated it for a non-profit campaign
- Throw it away
- Kept in personal storage at home

Other (please specify)

19. When you delivered your phone to the Recovery Point, can you share with us the value (monetary amount) of your phone? if you were not paid, please enter 0.

In Euro: