DESIGNING FOR A CIRCULAR ECONOMY

The conceptual design of a circular mobile device
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Summary

E-waste, price volatility of resources and the constant increase of the middle class world population expecting the same 'high quality' life standards have (amongst other) made some companies consider their options. In the reports of the Ellen MacArthur Foundation (EMF), one aspect of the circular economy (CE) model aims at decoupling sales revenues from material input using a restorative industrial economy by intention and design. In contrast to the current model, products are designed for maintenance, reuse, refurbishment, remanufactured and/or recycling.

Along with a shift from current linear business practices, the way products are designed should change considerably to fit into a CE. The development of products thought to intentionally reuse the totality of the materials and reclaim the embedded value in end-of-use products in the biosphere and/or technosphere is crucial.

In this Circular Economy Innovation Project, the manner in which circular thinking could be integrated in the first stages of product development is explored for the case of mobile phones. A circular design framework of useful tools and methods from various schools of thoughts coupled with a list of circular design guidelines is proposed. The conceptual design of a circular mobile phone on a short term and on a long term is developed to test this framework.

A theoretical design framework was drafted sourcing inspiration from literature on CE, comparable schools of thoughts and other research fields.

Several tools and methods from Biomimicry, Cradle-to-Cradle (C2C) and Industrial Ecology - namely Design Spiral, Life’s Principles, AskNature, Vision, Roadmap, ABC X categorisation, C2C Certification, Life Cycle Assessment (LCA) - are underlined to be used in circular product development.

Since no concrete design guidelines were found for the development of circular products at the time of the case study, various design guidelines are gathered from literature on inter alia design for disassembly, design for maintenance, design for refurbishment, design for remanufacture and design for recycling. These are combined and organised in five categories: Product Structure, Components, Materials, Joints and Accessories.

Current mobile phone designs are assessed so as to identify inconsistencies with respect to circularity and to define components to prioritise based on price, level of repairability, lifetime, maturity and risks. The correct strategy to apply needs to be selected. These components are mainly the display assembly (both the screen and the glasspanel), the computer processing unit (CPU), the memory chip, the battery and the accelerometer. The ABC X categorisation can be borrowed from C2C to evaluate and visualise the risks linked to the materials throughout the product’s lifecycle.

First, a mobile device is designed for an advanced scenario.

Various opportunities for circular systems and products can be seized. Public procurement and business to business (B2B) are interesting targets for the introduction of circular devices and business models (as compared to consumer customers). By offering a lease-like programme, users can have access to personalised performances and upgrade products to meet these performance requirements during their contract period with a mobile network operator. A vision is drawn for the ideal circular design implementing key circular characteristics such as built to last, easy to disassemble and upgradeable components.

Ideas are generated using the Design Spiral and according to various Life Principles. AskNature is consulted to emulate solutions for our human challenges based on solutions found in nature. The best ideas are combined into several concepts which are in turn evaluated keeping the C2C certification criteria into account. Based on disassembly possibilities, upgradability, lifetime, risks and costs,
the circularity of the concepts can be assessed and a final concept is selected.

**BlackbOx** - the final concept for the advanced scenario - has standardised 3D printed components, durable and self-healing materials, and is completely recycled and recyclable. Active disassembly techniques have been integrated to ensure an efficient, effective and profitable treatment process.

A *roadmap* describing the steps from the current situation to this desired situation is generated detailing the system and the product characteristics for each milestone. The first milestone focusses on the low hanging fruits. The second and third ones are concentrating on making the most important components circular. In an advanced scenario (fourth milestone), all components are becoming circular. Finally in a truly circular economy (fifth milestone), the whole system and product are designed to create no waste.

Based on this roadmap, several *solutions that could be applied on a short term in the transition scenario towards circularity* are studied. Current commercially available solutions that have been proven could be used as a starting point for the product design. The 29 design guidelines might be helpful at this stage of the product development.

A second product - **Poppy** - is developed for the first milestone to embody the previously formulated characteristics and assess the proposed design framework again. It could be in use by employees in the public and private sector within a period of two years. The aim of this product development is to decrease costs on maintenance and refurbishment operations and lower the barriers for customers to hand in their old devices. The ratio between the labour needed to retrieve components and the value of the involved components and materials had to be improved. The designed mobile phone has a durable and minimalistic design suitable for the professional users. All the components can be easily accessed without damaging other components in the process as both the front and the back can be detached individually. The components to be prioritised are standardised and interchangeable between generations of the components. The solutions are derived from solutions in commercially available products. As a result, these can be more easily disassembled thus more simply repaired, upgraded, refurbished, remanufactured and recycled.

The two conceptual product development processes have enabled to evaluate the proposed circular design framework. An *optimised proposal* can be used as a base for further development and will need additional testing by other designers for the design of a circular mobile phone.

To *apply this design framework to more generic product development* considerable iterations will on top of this be required as the tools and guidelines may from time to time be too product specific.
Abbreviations

AD: Active Disassembly
B2B: Business to Business
C2C: Cradle-to-Cradle
CE: Circular Economy
CEIP: Circular Economy Innovation Project
CPU: Computer Processing Unit
DfD: Design for Disassembly
EEE: Electrical and Electronic Equipment
EMF: Ellen MacArthur Foundation
EoL: End of Life
IDE: Industrial Design Engineering
LCA: Life Cycle Assessment
RoHS: Restriction of Hazardous Substances
SMF: Schmidt-MacArthur Fellowship
TU Delft: Technical University Delft
WEEE: Waste Electrical and Electronic Equipment
Along with a shift from current linear business practices, the manner in which products are designed should change considerably to fit into a Circular Economy (CE). The development of products thought to intentionally make a regenerative use of resources in the biosphere and/or technosphere is crucial. But how can circular thinking be incorporated in product design?

The way Circular Economy could be integrated in the first stages of product development is explored in this study. The research focuses on the case study of the conceptual design of a mobile device in a CE. A design framework of useful tools and methods from various schools of thoughts will be proposed and a set of substantial circular design guidelines will be formulated.

This research is the result of a Circular Economy Innovation Project (CEIP) for the Schmidt-MacArthur Fellowship (SMF). The Schmidt-MacArthur Fellowship is an international programme for postgraduate students on creative and innovative thinking around Circular Economy. It takes on a pluri-disciplinary approach gathering input from business, engineering and design. The CEIP is a unique piece of postgraduate work aiming at contributing to the acceleration of the transition to a CE.

The case study was carried out as a graduation project of the Master ‘Integrated Product Design’ at the faculty of Industrial Design Engineering (IDE) at the Technical University of Delft (TU Delft) and was done in collaboration with Vodafone - a recent CE100\(^1\) member. David Peck - assistant professor in the department of Design Engineering and more specifically Reliability and Durability - tutored this CEIP as well as the graduation project.

The TU Delft is the largest and oldest public technical university in the Netherlands. With over 40 years of existence, IDE has established itself as one of the leading design programmes in the world. The study is multidisciplinary: students learn about a broad scale of essential disciplines for product development such as design, engineering, ergonomics, marketing & consumer behaviour, and sustainability.

The mobile network operator Vodafone intends to improve livelihoods and quality of life of customers by offering a broad range of products equipped with its mobile network. Searching for new innovations for more than 400 million customers, the company is keen to integrate circular thinking into its practices and wants to seize the opportunities circular business models can offer.

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\(^1\) International platform initiated by the EMF for companies and regions on circular thinking

### Problem Definition

Once the CE model has been adopted by a company and a system has been generated around a specific product, this same product will have to be designed and engineered to make a regenerative use of resources.

The Ellen MacArthur Foundation (EMF) - that developed and delivered the SMF programme - has been working on the acceleration of the transition to a CE. Until now, the published reports and books have mostly been approaching CE from a business and strategic perspective. No concrete circular design tools or guidelines have been found as such in literature.

Designers and engineers eager to integrate circular thinking into their practices will need a relevant design framework to lead them through research & product development.

### Scope And Research Objective

Considering the complexity and scale of the problem highlighted, the case study was selected to be utilised as a source of insights on circular product development.

Due to time restrictions and the limited scope of the graduation project, the integration of circular thinking in the design of a circular mobile device was only done for the first stages of the product development. The first stages of the process are defined as Fuzzy Front End, ideation and conceptualisation according to theory from Buijs & Valkenburg and Roozenburg & Eekels as shown in Figure 1. [1], [2]

The Fuzzy Front End is however briefly touched upon (here again because of time restrictions) in the case study and would need further research before formulating a design brief in practice. The result of the project was the conceptual design of a potentially circular mobile device. It will thus need more detailing before being sent to manufacture.
INTRODUCTION

As a result, this research aspires to unravel what these designers and engineers could use as a design framework in the first stages of product design. This objective is translated in the main research question.

Main research question
How could circular thinking be applied in the first stages of product development?

So as to clearly delineate the scope of the project, the main research was divided in three sub-research questions to be answered:

S-RQ1: What inspiration can be drawn from current knowledge on CE, comparable schools of thoughts and research fields?

S-RQ2: What criteria could be used to assess the circularity of a design?

S-RQ3: To what extent is the proposed framework supporting the development of a circular mobile device?

Relevance Study

In the context of our current linear economy, the benefits of a circular mobile device may not yet seem financially interesting for designers and adjacent stakeholders. Integrating circular thinking into practice in product development is nevertheless essential for multiple reasons:

• The rise of prosperity in developing countries resulting in a growth of the middle class coupled with an increasing world population have intensified global competition for certain resources. This pressure on resources is translated in the increased and volatile material prices.

[3] To address this, a new strategy is needed. As Walter Stahel noted: “Today’s goods in the market are the resources of tomorrow at yesterday’s resource prices” [4] Acknowledging the embedded value of products and acting upon it could enable businesses to get around this issue.

• Coupled with the price volatility of materials, the competition for resources also leads to additional pressure on the environment.

[5] Opening up new sources of supply generally involves more energy intensive mining and refining, more greenhouse gas emissions and higher water demands. Raw material shortage was seen as a risk for 80% of chief executives of manufacturing companies in 2012.[6]

• Regulations on this topic are prospected to become more severe and challenging in the near future as governments are aware of the risks. Designers and engineers should be armed to overcome these difficulties.

• Electrical and Electronic Equipment (EEE) waste is generally complex as assemblies of components do not easily lend themselves to for example repair or recycling.[7] Designers need to be aware of their responsibility on the life cycle of EEE products. They need to acknowledge the fact that their products will ultimately fail or be made redundant and end up in landfills (or as air pollution after energy recovery) if no conscious actions are undertaken.[8] Designers are becoming more and more sensitive to this issue; however, are not perceiving the urgency nor possess knowledge of fundamental concepts enabling to design for a CE yet.[9]

• Manufacturers do not identify the full embedded material and economic value of the devices. Today’s mobile phone may represent one of the most valuable products in terms of volume and mass currently found in great amounts in our waste streams.[10] With gold concentrations equal to 300g/T for mobile phone handsets, “urban mines” are significantly richer than traditional primary ores.[11] These concentrations are nearly 200 times larger than those for instance found in South African gold mines. [12] The embedded value of these products does not only come from their material
Numerous synergy opportunities within the telecommunication sector and beyond are left untouched. Components from one discarded product could potentially be repurposed into another product. Designers and engineers in every domain should be made aware of all these interesting chances.

Methodology

The CEIP report communicates the process and outcomes of the research on a circular design framework for the conceptual product development of a mobile phone. The main objective of this study is to define a way of how circular thinking could be applied in the first stages of product design (main research question).

The project and report are structured as shown in Figure 2.

This project is developed using insights gained during sessions of the SMF Summer School, the Fellowship webinars, the Circular Economy executive education introductory course and the experience at the TU Delft and at Vodafone.

Theoretical Design Framework

The current circular theoretical design framework will first be explored. Inspiration will be drawn from current knowledge on CE, comparable schools of thoughts and research fields (S-RQ1). The study will be performed sourcing information from literature, field research and internal documents from Vodafone.

Various schools of thoughts and research fields comparable to CE in terms of objectives and models will be consulted in order to find out more on design tools and guidelines that could potentially be useful in the design for the case study. This will be based more specifically on strategies like Industrial Ecology, Cradle-to-Cradle and Biomimicry, and design guidelines from literature on the fields of design for maintenance, reuse, refurbishment, remanufacturing, recycling, disassembly and reliability.

A proposal for tools and methods to use during the first stages of circular product development is made based on this analysis. Draft design guidelines for the circular product development will finally be formulated.

The proposed theoretical design framework content is composed in accordance with ‘relevance to the CE theory’ and ‘compatibility with prior design knowledge’. ‘Relevance’ denotes how well a tool/method/design guideline meets the user’s (the designer) need for guidance in the conceptual design of a mobile device in the context of a CE. ‘Compatibility’ designates how easily the user can utilise the framework with his/her conventional design background. The design strategies, methods, tools and guidelines taught at the faculty of IDE will be used as a reference.

Case study

The graduation project - used as a case study - aimed at developing a mobile device² for a circular economy in collaboration with Vodafone. It was fore mostly focussing on the conceptual design of a mobile phone contributing to a transition towards circularity.

The project was divided in two parts: (1) the study of the CE theory and the telecommunication industry and (2) a practical part in which this knowledge is applied to the design of a more circular mobile device.

Only the second part will be used as a case study as it will enable to assess the proposed theoretical design framework. Detailed results of this research can be found in the graduation thesis on the TU Delft Repository. Bearing the current and future limitations and opportunities in mind, this document reports on how to be ahead of the curve and create a beneficial disruptive system and product in the European mobile device market.

Utilising insights from the first part of the project, the two mobile devices were designed in order to be a viable consumer product that can go through the different loops of the CE model. The analysis of the case study is meant to define criteria that could be used to assess the circularity of a design (S-RQ2) and lay grounds for a reflection on the tools and guidelines required to design a product integrating circular thinking.

Information on the exact methodology followed to develop the mobile device will be given later in this report.

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² The term ‘mobile device’ was originally intentionally left broad as the future of these products and their shape are quite unpredictable
Chapter 1
Introduction

Chapter 2
Theoretical Design Framework

Sub - Research Question 1
What inspiration can be drawn from current design knowledge on CE, comparable schools of thoughts and research fields?

Chapter 3
Case Study

Sub - Research Question 2
What criteria could be used to assess the circularity of a design?

Chapter 4
Results

Sub - Research Question 3
To what extent is the proposed framework supporting the development of a circular mobile device?

Chapter 5
Conclusion

Research Question
How could circular thinking be applied in the first stages of product development?

Chapter 6
Discussion and Recommendations
The proposed theoretical design framework will be tested utilising the design process of the mobile device and the intended performance of the final concept selected.

Literature, field research and interviews with relevant stakeholders are used as input to validate and warrant the viability of the results. Throughout this report, the theory used on CE throughout this report is in line with the Ellen MacArthur Foundation.

**Results**

The product developments will have unravelled multiple challenges and opportunities for the application of CE in design.

A reflection on the tools and methods applied during the product development will be made so as to emphasize what designers and engineers could use when wanting to integrate circular thinking. The relevance and compatibility will be evaluated again considering the experience gained throughout the design process. Final recommendations will be made on which tools and methods to prefer and where to look for and at in a broader scope of strategies.

The draft guidelines will in addition be assessed on the same two criteria. The insights gotten during the design process will be turned into a set of guidelines for industrial design engineers working on the development of mobile telecommunication devices. Designers at Vodafone will be consulted to evaluate the formulated set of guidelines. The last sub-research question - To what extent is the proposed framework supporting the development of a circular mobile device? (S-RQ3) - will thus be answered.

The applicability of this theoretical design framework to generic product development will finally be discussed. It will be measured considering the extent of the specificity of the selection of the tools and methods based on the case study and the specificity of the formulated design guidelines.
Chapter 2 - Theoretical Design Framework

Current products are designed with little or no care for maintenance, reuse, refurbishment, remanufacture and recycling.[7] To develop systems and products for a CE, designers and engineers should have access to tools, methods and design guidelines to apply circular thinking.

First a definition of what circular thinking could mean in the context of the telecommunication industry will be explored.

Multiple tools, methods and design guidelines could be interesting when designing a mobile device for a circular economy. The EMF established a few pointers in their reports with respect to the power of circles.[15], [16] As no circular design framework was found, tools, methods and design guidelines from schools of thoughts comparable to CE coupled with other interesting design-centered techniques and research fields could be used to fill this gap.

The first sub-research question will thus be answered in this section of the report.

Sub - Research Question 1
What inspiration can be drawn from current knowledge on CE, comparable schools of thoughts and research fields?

Circular thinking in the telecommunication industry

Considering CE literature, the developed mobile device will be engineered to fit in the model adapted from the circular economy model as illustrated in Figure 3.

Resulting from an analysis of the telecommunication industry and the CE theory in the first part of the graduation project, the mobile device will exclusively be utilised in public procurement and enterprises. On top of this, the mobile device will not be owned by the customer; the employer will pay for its performance. According to literature and expert meetings, this will enable to eliminate a considerable amount of challenges (such as product attachment).

Structural changes in the infrastructure around the manufacture and distribution of mobile devices will be essential. Considerable resistance of these stakeholders will have to be overcome.3

As the CE model entails, the mobile device will have to be designed to be easily repaired, reused, refurbished, remanufactured and recycled. This includes the development of a corresponding product anatomy - a combination of the assembly and sub-assemblies, the organisation of the components and the individual components.

The meaning of maintenance, reuse, refurbishment, remanufacture and recycling and the subtleties differentiating the cycles from each other are identified in Table 1.

The Ellen MacArthur Foundation generates several principles to take into account while designing for a CE. Their publications mention four ways to increase material productivity and generate opportunities in contrast to linear product design and material use (see Figure 4).[15]

- When looking at the CE model, tighter circles (the less the device will need to be iterated in repair, reuse, remanufacturing and refurbishment phases, the fastest it comes back to a user) have higher potential savings in for example material, labour, energy and capital embedded, and the linked externalities (think of greenhouse gas emissions, soil and water pollution).

3 Consult the TU Delft repository for the graduation thesis report for more information on the system approach.
The number of successive cycles for each phase should be maximised as much as possible in order to get the most out of the phases. The usage phase of the product could be elongated by enabling simple and cheap maintenance. More durable products would be in turn beneficial for reuse and remanufacture as they will not need to repair so much to bring products to their original state (less operations mean more money saved).

CE promotes cascaded use: diversifying reuse across value chains. Components can as a result be reused not only in the original sector of use but also in other industries for instance in GPS devices or dongles. This will substitute an inflow of virgin materials.
• **Maintaining uncontaminated material flows** through design is essential to preserve the quality of the technical nutrients. At the end-of-life of the device, all materials should be allowed to be separated correctly so as to follow their respective material recycling flow.

According to the EMF and McKinsey & Company, circular designs can be made by improving material selection and product design. This is said to be done by standardising components and/or making them modular, designing purer material flows, and designing for easier disassembly.[15]

**Lessons From Various Schools Of Thoughts**

The general concept of CE has inherent origins and cannot be pinpointed to one specific author or date. Multiple schools of thoughts have been using insights from living systems and have been refined throughout time. Lessons from these various schools of thoughts could be learnt when it comes to their design approach and tools.

**Industrial Ecology**

Industrial ecology (IE) studies material and energy flows through industrial systems and concentrates on the actors within industrial ecosystems. This approach purposes to create closed-loop processes in which ‘waste’ is used as an input.

Graedel and Allenby defined IE as ‘the means by which humanity can deliberately approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them.’. The interdisciplinary aspect of the field is an important lesson to implement during the development of a product and system for a CE.[17],[18]

Various tools used in the field of Industrial Ecology could be useful during the design of a device. Conducting a Life Cycle Assessment (LCA) — technique evaluating the environmental impact of products — could enable the designer to be aware of the entire life cycle of the product and think ahead during the product development. The LCA is the most prominent (evaluation) technique used in practice. An International Standard describes the framework and principles of the tool.[19] LCA analyses the environmental impact throughout the life cycle of the product. The main objectives of the technique are to enable (1) to identify the possible improvements in environmental aspects at different stages of the lifecycle; (2) to support industries, governments and non-governmental organisations in decision-making; (3) to assist in the selection of appropriate environmental performance indicators; and (4) help with the correct marketing of the products.[19]

The phases of an LCA are as follows:

![Figure 5 - Phases of an LCA (source: ISO 14040-2006)](image)

The danger with using this technique is that it was originally designed for a linear life cycle and may not be appropriate for product design in a circular context. LCA is namely also a major part of Ecodesign. The design strategy stands for the deliberate design of a product aimed at lowering its environmental impact during its complete life cycle without concessions on other important product criteria.[20] This approach is seen as a key to sustainable and improved products.[21] Motivated by the growing acknowledgement of the corporate responsibility in the impact of global warming and increase in CO₂ emissions, companies are considering their options in designing more environmental friendly. While the focus was first on “end-of-pipe” solutions - targeting the reduction of the amount of harmful emissions from production plants - organisations are currently looking at the environment in a broader sense.[20]

On top of this, design guidelines from Design for Environment and product life extension could be used (see next section).

According to Reid Lifset, IE and CE are for approximately 85% similar to each other. IE has however a more scientifically driven approach as opposed to CE. Since the late 80s, an active scientific community has been growing fast across the planet, giving IE a strong and dynamic position within the international scientific community. Years of research
and knowledge sharing in the area can drastically benefit the development of circular economy.

**Regenerative Design**

In the late 1970s, the American professor John T. Lyle developed the concept in which systems could, as in nature, be arranged in a regenerative fashion. Processes could renew themselves or generate energy sources and materials they could in turn consume.[22]

No specific design tools and methods to be used were found.

**Performance Economy**

Walter Stahel has throughout his work emphasized the importance of selling services as opposed to products. His Product-Life Institute in Switzerland is a rational sustainability think tank with four distinct goals: product-life extension, long-life goods, reconditioning activities, and waste prevention.[4], [23]

No concrete design tools could be found from a performance economy angle.

The business model is here of utter importance. As Stahel stated: ‘the performance economy takes the principles of the circular economy to the extreme, where we no longer buy goods but simply services.’. In a CE, products do not have to be owned by companies per definition.[24]

**Cradle to Cradle**

In this design philosophy, developed by chemist Michael Braungart and architect Bill McDonough, materials implemented in industrial and commercial processes should be considered as biological or technical nutrients, like CE. Also comparable to CE, the concept focuses on effectiveness rather than efficiency. Cradle to Cradle (C2C) aims at creating a positive impact on fauna and flora (including humans) in contrast to the current design concentrating on reducing negative impact. Principles include ‘waste is food’, ‘use solar income’ and ‘celebrate diversity’. [25]–[28]

Various design tools could be lend from Cradle to Cradle to develop a circular product. The idea of creating an idealistic Vision and generating a Roadmap with steps to take to achieve the ultimate goal could be attractive for circular product development. The vision for the redesign must be described using inspirational goals, stating the enhancements in functionality and benefits. The redesign will probably not be implemented immediately due to the needed technology or infrastructure. Therefore, the intended path can be visualised using a roadmap with milestones finishing at the ideal (a truly sustainable product) situation.

In addition, the list of criteria from the C2C Certification programme could be utilised to assess the impact of the designed product.[29] An EPEA certification can be obtained on different levels (basic, bronze, silver, gold and platinum) depending on the standards of the C2C certified product design. Its criteria can be used as an evaluation tool for ideas and concepts. The different categories of standards to comply with are: Material Health, Material Reutilisation, Renewable energy and Carbon Management, Water Stewardship and Social Fairness. An example of the standards for a Platinum certified product are given in Figure 6.

![Figure 6 - EPEA certification example (source: EPEA)](source: EPEA)

In terms of materials, the ABC X Categorisation and Banned Materials/Positive Lists would be beneficial during the selection of materials able to stream through the different cycles of the model. [30], [31] The biological and technical cycles of the product should be defined and the materials should be inventorised. The impact level of harmful contaminants should be assessed and visualised using an ABC-X Categorisation. X-materials are considered as not acceptable according to C2C standards due to teratogenic, mutagenic and carcinogenic properties (i.e. PVC, Cadmium, Lead or Chlorine) and need to be phased out of the product using alternative materials. The P list (or Positive List) is a set of substances that are defined as safe to use for humans and nature. Different gradients are given from Tolerable (C) to Optimising (B) and Optimal (A) as visualised in Figure 7.
In the CE context, the idea of designing solutions beneficial for the user and system would seem too idealistic. While the concept is quite inspirational, current businesses appear to not yet be thinking that far ahead.

In the early days of the strategy, criticism has been expressed on the Certification programme and the commercialisation of the strategy due to the fact that it would prevent the model to grow. In contrary to C2C’s approach, the EMF does not want CE to be a label or certification.[32]

**Biomimicry**

Nature is the result of thousands of years of engineering and offers a broad scale of solutions adaptable to human problems. Janine Benyus, author of ‘Biomimicry: Innovation Inspired by Nature’, describes biomimicry as the study of nature’s best ideas and translates these to human design issues. [33]

Biomimicry 3.8 is providing interesting hands on design methods and tools to apply and broaden the users’ minds on natural systems and their workings. The general approach is to go through the Design Spiral, select relevant Life’s Principles that are not met by the current design, distill and translate the design function of the product development, get inspired by looking into the AskNature database and finally emulate this all into one design to be tested. Design and Nature are here on the foreground leaving business models a bit aside in comparison to CE.[34], [35]

The Design Spiral embodies a concrete roadmap to designs inspired by nature (see Figure 8). Five different steps are described in order to apply concepts from nature into human-made products and systems. This method can be used from the concept generation stage to the detailed design stage. It is comparable to the usual design process but expands the design brief by integrating biological processes.[36]

![Figure 7 - ABC-X Categorisation (source: EPEA)](image)

Figure 7 - ABC-X Categorisation (source: EPEA)

![Figure 8 - Design Spiral](image)

Figure 8 - Design Spiral

Life’s Principles - design lessons from nature - could also be used to learn from living organisms and systems (Figure 9). 6 Life’s Principles and their detailing represent overarching patterns found in nature and could be used as a recipe to incorporate nature’s solutions in human design.

The AskNature website is a database gathering inspiration for the biomimicry community.[37] It shows examples from nature and products or researches based on biomimicry principles and could be a very interesting resource for idea generation. The website gives the world’s most comprehensive catalogue of nature’s solutions by function to be emulated to solve human design challenges in a sustainable manner. By finishing the sentence “How does nature...” by for example ‘regulate temperature’ or ‘maximise resilience’, various solutions can be explored.
Blue Economy

As the Blue Economy manifesto affirms “using the resources available in cascading system (...) the waste of one product becomes the input to create a new cash flow.” Started by Gunter Pauli - a Belgian businessman and former Ecover CEO - the Blue Economy is an open-source initiative with a report compiling practical case studies. This report emphasizes examples of profitable South-South collaborations and a hands-on approach.[38], [39] CE has a broader scope and aspires to create collaborations around the world not restricted by hemispheres.

Around hundred cases have been published on the Blue Economy and thirty interesting principles have been developed to guide entrepreneurs. Unfortunately, these cannot explicitly be used as guidelines for the development of a product focussing on technical nutrients.

Permaculture

As the Australian ecologists Bill Mollison and David Holmgren defined the term in the late 1970s, a permaculture is ‘the conscious design and maintenance of agriculturally productive ecosystems, which have the diversity, stability and resilience of natural ecosystems’.

These last two approaches were added to the list in the second EMF report.[15], [16] They are both concentrating on the biological side of the CE model.

The principles of permaculture are summarised in the ‘Permaculture Flower’. [40] Even though inspiration could be drawn from this flower, no concrete design tools were find.
CHAPTER 2

A distinction between the different focuses of the schools of thoughts can be noticed. While CE and for example performance economy are foremost concentrating on the business model and system, others are looking more into the design aspect and/or environmental impact of systems and products.

The lists of schools of thoughts in the two EMF reports are meant to be illustrative and not comprehensive. [41] While several of them were described in the publications, others that might have the same origins are not mentioned.

For instance, The Natural Step, although early in the field, is not named. The outline is based on a metaphor of a funnel standing for the systematic degradation of the ecosystem’s function’s and biodiversity which prohibits its ability to sustain society.[42], [43] It is intentionally not described in the reports because of the specific focus on environmental sustainability rather than on economic models (which would go against the framework used in the reports). The theory is said to imply zero growth in the physical scale of economies and businesses.[44]

For these same reasons, Natural Capitalism, Factor 4 and Factor 10 have not been covered in the reports.[45]–[47] Looking more into the business perspective, several frameworks such as that of the collaborative economy or gift economy could be mentioned, to name a few.

These other schools of thoughts could in the future be consulted in order to unravel other design approaches, tools and guidelines.

Valuable tools and methods from multiple schools of thoughts could be relevant and compatible with the user’s design background in the first stages of circular product development are: the Design Spiral, Life’s Principles, AskNature, Vision and Roadmap, ABC X categorisation, criteria from the C2C Certification and LCA.

These tools and methods are not all at the same level and cannot be used at the same time. The C2C Vision and Roadmap will be an asset at the start of the product development to set out a more concrete objective. The Design Spiral and Life’s Principles will be very interesting to use in a second movement. AskNature could be valuable to gain inspiration to emulate these methods into the design. The ABC X categorisation will be of essence when detailing the materials to be incorporated in the product concept. LCA and C2C certification criteria could be kept into account throughout the early stages of the design process, but do not strictly have to followed as the development is still quite conceptual. Evaluating at this point will reflect a distorted image of the product being designed as not all aspects of the product have been thought through in detail.

Lessons From Various Fields Of Study

Various fields of study with objectives, model and principles to some extent comparable to CE have been considerably studied in the past years or even decennia’s. Their design guidelines might be borrowed for the development of a circular product.

Design for Product Life Extension, Design for Maintenance, Design for Re-use, Design for Remanufacturing, Design for Recycling, Design for Disassembly and Design for Reliability all have undeniable links to CE theory. The research is limited to these 9 fields of study as these seemed to be the most relevant and significantly developed at the time of the study.

• Design for Product Life Extension

Product Life Extension is meant to maintain product integrity. The product has to stay as close to its original state over time and suppress perceived reasons for obsolescence. Canny Bakker and Marcel den Hollander have identified 6 design strategies for longer lasting products in a circular economy by clustering results of existing research and conducting new analyses of companies and longer-lasting products. These are said to prevent or at least postpone perceived product obsolescence and include: Design for Product Attachment and Trust, Design for Product Durability, Design for Standardization & Compatibility, Design for Ease of maintenance and Repair, Design for Upgradability & Adaptability and Design for Dis- and Reassembly. [48]

Bakker et al. however note that for most products categories, “tailored product life extension approaches will be needed depending on product characteristics such as lifespan, technological maturity and resource intensity, and business constraints such as market competitiveness and regulations.” [49] For the case of laptops analysed in their article, designing the product to last for at least 7 years is considered economical suicide; remanufacturing and recycling seem to be more consistent.

• Design for Maintenance

Design for Maintenance is also referred to as Design for Maintainability or Repairability in literature. Gits defined maintenance as “the total of activities...
required to retain the systems in, or restore them to the state necessary for fulfilment of the production function".[50] The core aim of the technique is to ensure the designed product can be repaired throughout its lifecycle at reasonable costs and without too much difficulties.[51]

Several researchers have generated fundamental principles to take into account. Key elements are: (1) accessibility, (2) interchangeability (and standardisation) of parts, (3) straightforward failure diagnostics and isolation of the failure, (4) safety of the repairer, and (5) ease of final adjustments (preferably compatible with robots for removal). [51]–[53]

- **Design for Re-use**

The European Parliament and the Council of European Union state “‘Reuse’ means any operation by which a product or its components, having reached the end of their first use, are used for the same purpose for which they were conceived, including the continued use of a product which is returned to a collection point, distributor, recycler or manufacturer, as well as reuse of a product following refurbishment”. In regulations, this term is strongly associated to the Ecodesign Directive and thus eco-efficiency.

Nevertheless, According to Hoffmann et al., re-use activities are influenced by easy disassembly and repair of sub-assemblies or devices. As a result, Design for Maintenance and Design for Disassembly are essential for the creation of a product built for re-use.[54] The importance of Design for Disassembly for Re-use is also underlined by Fabian Watelet in his research on the re-use of EEE consumer products. [55]

- **Design for Refurbishment**

The purpose of refurbishment is to return product in adequate working conditions and original aesthetics. [56], [57]

Concrete guidelines were not find on this specific stage of the lifecycle of the product. However, the activities performed for the refurbishment of the product are comparable to the first steps of remanufacturing.

- **Design for Remanufacturing**

Different operations are done during the remanufacturing of the device: the product should first be inspected, then disassembled, the components will be cleaned, stored and remediated, after which a product will be reassembled and tested.[58]

Ijomah has developed several guidelines to allow for all the different operations of remanufacturing. [56], [59] According to Nasr and Thurston, special care should be put in disassembly techniques, design with an eye on multiple life-cycles, modular design and take-back decision support.[60]

Products designed for remanufacturing are required to be designed for disassembly while ensuring there are no damages that could affect the functional performance or aesthetics of the products.[61]

- **Design for Recycling**

Manual disassembly of hazardous or very valuable parts has been done since the early nineties in recycling plants.[61] When the majority of the components has been disassembled, residual parts may still contain over one material.[62] Recycling aims at separating these from each other, using various automated methods after shredding the parts.

Going deeper than the value of the handsets themselves, not only components, but also the individual materials should be allowed to be disassembled from the assembly. The materials, complexity of the structure and the interactions inside of the product are defined by the product’s design. The quality of the recycling stream is itself defined by the possibility of separating materials from each other.[62] Considerable research has been done in this area and a number of guidelines formulated need to be followed to facilitate an appropriate process.

- **Design for Disassembly**

Disassembling the devices is one of the most important challenges to overcome in order to improve their end-of-use and end-of-life.[7] Current design practices such as the overuse of adhesives and surface coatings or integrated designs are the main cause. Products are not thought to be easily taken apart and separating the totality of the parts into non-contaminated groups of materials is near to impossible.

Opening up and disassembling a product easily has great value for both the customer and the manufacturer. The customer can be in control and extend the life of the device by repairing it or upgrading it. As for manufacturers, upgrading products and making them repairable enables them to keep customers. Instead of disposing the obsolete device for possibly a competitor’s product, the customer can upgrade or repair utilising the manufacturer’s own parts; maintaining the customer relationship. Material and energy costs can additionally be saved by reusing or remanufacturing the components their customers do not need anymore.[63]

Design for Disassembly aims at designing products for dismantle during various stages of their lifespan.
CHAPTER 2

Materials used, components and sub-assemblies are optimised to allow for maintenance, reuse, refurbishment, remanufacture and recycling. The term 'disassembly' however has a different meaning depending on the stage it is being done in. For example, disassembling a specific part of a product for repair requires careful removal of components to outlaw damages. Whereas during the disassembly of a product for recycling, parts can be separated with considerable force inducing breakage. Successful DfD is dictated by the application of three fundamental disciplines: (1) design of components and the product architecture; (2) selection and use of materials; and (3) the selection and use of joints, connectors and fasteners.[8]

The disassembly of EEE products can be either done manually, semi-automated or fully automated. Manual labour is done to unfasten components by hand using tools in a non-destructive fashion for further reuse. The process is precise, however as it is labour intensive and complex, it is expensive and requires trained staff.[64] Taking into account economic considerations. On this basis, it embeds all relevant cost elements to be included in the decision-making process, such as recovered materials and (depreciated Automated disassembly is prone to damage components, however the expenses are smaller and larger numbers of products can be disassembled in the same timeframe.[65]

For a profitable remanufacturing and recycling process of telecommunication and other hand-held electronic or electrical appliances, high financial efficiencies are crucial during their disassembly.[61] Manual disassembly is said to obstruct this.

Active disassembly (AD) is a developing technology aimed at disassembling product easily by triggering smart materials. AD aspires to optimise the reuse of components by releasing them in a hierarchical, controlled and non-destructive manner.[9], [56], [61], [63] This could be an interesting technology to use in automated disassembly.

In spite of decennia of research, DfD knowledge and guidelines are not well spread amongst designers. [14] This could be explained by the fact that the design briefs are not yet implementing EoL as a core priority (due to linear thinking), limiting the need for insights on the topic. On top of this, DfD does not seem to have an important place in the education of designers.

Implementing DfD into the design specifications would allow for suiting components and overall product organisation for maintenance, re-use, refurbishment or recycling.[66]

Specifically thinking of mobile phones, components that are more likely to break down during the life time of the product will have to be the most accessible to enable repair. For the current handsets, the screens and battery are the most recurring repairs required. Other components that need to be replaced for re-use and refurbishment will also need to be accessible. These could however be more difficult to get to than those needing maintenance.

As experienced during the teardown labs, several features are affecting the disassembly process: product structure, material mechanical properties, joints, characteristics of components for disassembly and disassembly conditions. To assess the product structure and the ease of disassembly, a reverse fishbone by Ishii and Lee [67] could be used. The reverse fishbone diagram graphically makes a difference between sequence dependent and independent disassembly.

In Figure 23 - Two types of Reverse Fishbones (source: Ishii and Lee)

Sequence independence is preferred as it enables overhead operations to be divided among parts and allows multiple components to be separated from the body or ignored without any repercussions on other parts.[67]

Whilst vehicle dismantling and recycling is considerably mature and reflected in various features of vehicle design, EEE do not yet lend themselves as 'easily' to reuse and recycling due to their complex assemblies.[8] To decrease the degree of complexity of the product, modular design could be used.[68]

Modular design principles within design for disassembly techniques enable a considerable flexibility and ease during product development, ease of product updates, component economies of scale, enhanced product variety and reduced order lead-time.[69]–[71] Modularity affects serviceability and recyclability when it comes to disassembly, repair, and reprocessing.[72]

The objective of modularity is different from interchangeability or reconfiguration of parts, but
rather to group all attributes with similar “life cycle processes into a single module and decouple them from all other attributes and life-cycle processes”. [71] Design for upgradability and adaptability offering future expansion and modification is also seen as an important way to counter systemic obsolescence.[48]

- **Design for Reliability**

The Advisory Group on Reliability of Electronic Equipment defined reliability as “the probability of a product performing without failure a specified function under given conditions for a given period of time”. Four factors are of importance: probability, specified function, designated environment, and length of time.

Ireson and Coombs generated several guidelines for Design for Reliability: (1) simplicity, (2) use of proven components and preferred designs, (3) stress and strength design, (4) redundancy, (5) local environment control, (6) identification and elimination of critical failure modes, (7) detection of impending failures, (8) preventive maintenance, (9) tolerance evaluation, and (10) human engineering.[73]

- **Conclusion**

The key for obtaining the best possible reins for circular product development would be to combine all relevant guidelines without bending the core purpose of each source. Each strategy has been used and validated in a defined context for a defined purpose. Special care should thus be put in the shaping of an hybrid. The shaped combined design guidelines should be used and validated in the new context.[74]

Specifically looking at the to-be designed circular mobile device, a list of draft guidelines has been compiled in Table 2.

The drafted guidelines are adapted from literature on Circular Economy, DfX and developments in joining technologies, sourcing guidelines from researchers such as Bogue, Ijomah, Chiodo and Boothroyd. The exact sources are mentioned next to each guideline. The independent lists of principles for the studied design techniques can be found in Appendix I.

The guidelines are not all separate; some are dependent on each other.

The list could to some extent be used for other types of products, however the selection of guidelines from the aforementioned design techniques was specifically made for the to-be-designed product. A distinction is made between guidelines for the product structure, those specific to components, those for materials, joints and finally accessories.
<table>
<thead>
<tr>
<th>Major parts</th>
<th>Components</th>
<th>Price</th>
<th>Repairability</th>
<th>Lifetime</th>
<th>Maturity</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casing</td>
<td>Clicked to the back casing. Score 1</td>
<td></td>
<td>Most prone to aesthetic deterioration</td>
<td>Technically mature, except for dimensions and design (influenced by screen size)</td>
<td>Can contain hazardous compounds</td>
<td></td>
</tr>
<tr>
<td>Display Assembly</td>
<td>Screen</td>
<td>+++</td>
<td>Fused to the touch panel, connected to the printed circuit board (PCB) with ribbon cable click system. Score 3</td>
<td>LCD screens (most used screen technology) lasts for almost 7 years</td>
<td>Resolution is mature. Size keeps increasing. Other innovations on display technologies are coming. The technology could be considered mature for customers that do not want fancy iconic innovations.</td>
<td>Contains indium, yttrium, cerium, europium (CRM). Contains hazardous compounds</td>
</tr>
<tr>
<td>Touch panel</td>
<td>++</td>
<td></td>
<td>Fused to the screen, connected to the PCB with ribbon cable click system. Score 3</td>
<td>Most break sensitive component (due to user dropping the device for example)</td>
<td>Resolution is mature. Size keeps increasing. Other innovations on display technologies are coming. The technology could be considered mature for customers that do not want fancy iconic innovations.</td>
<td></td>
</tr>
<tr>
<td>Circuit Board Assembly</td>
<td>Printed Circuit Board</td>
<td></td>
<td>Connected to the display assembly by multiple screws or adhesive, in case of two PCB components these are connected with a wire clicked on the board and ribbon cable. Score 2</td>
<td>-</td>
<td>Mature technology. Shape within the device may vary (one plate vs 2 connected plates constructed around the battery</td>
<td>Assembly contains tin, zinc, tungsten, palladium, tantalum and gallium (CRM) the conductive paths are made from copper, silver or gold depending on estimated lifespan. Assembly also contains hazardous compounds</td>
</tr>
<tr>
<td>CPU</td>
<td>Soldered on the PCB, covered by EMI shield. Score 3</td>
<td>+++</td>
<td>Up to 9 years. Signal timing across the chip can slowly degrade</td>
<td>Most technically upgraded part</td>
<td>Gallium (CRM)</td>
<td></td>
</tr>
<tr>
<td>Memory Chips</td>
<td>Soldered on the PCB, covered by EMI shield. Score 3</td>
<td>+++</td>
<td>Depending on the technology used - near to infinite lifetime</td>
<td>Most technically upgraded part. However hardware upgrades may in the future be replaced by software (cloud) update</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(nano or micro) SIM Cassette</td>
<td>Soldered on the PCB. Score 3</td>
<td></td>
<td>-</td>
<td>Unchanged part over time (standardization (micro) SIM)</td>
<td>RE (neodymium, praseodymium and dysprosium) (CRM)</td>
<td></td>
</tr>
<tr>
<td>Speaker</td>
<td>Adhered to the casing and connector is soldered on the PCB. Score 3</td>
<td></td>
<td>-</td>
<td>Slight technical improvements, could be considered mature</td>
<td>RE (neodymium, praseodymium and dysprosium) (CRM)</td>
<td></td>
</tr>
<tr>
<td>Microphone</td>
<td>Soldered on the PCB. Score 3</td>
<td></td>
<td>-</td>
<td>Slight technical improvements, could be considered mature</td>
<td>RE (neodymium, praseodymium and dysprosium) (CRM)</td>
<td></td>
</tr>
<tr>
<td>Main (and front) Camera</td>
<td>Ribbon wire clicked on the PCB, can be adhered to be kept in place. Score 2</td>
<td>+++(+)</td>
<td>-</td>
<td>Constant technical imaging quality improvements</td>
<td>RE (lanthanum) (CRM)</td>
<td></td>
</tr>
</tbody>
</table>
## Theoretical Design Framework

### Flash (magnified LED)
- Ribbon wire clicked on the PCB or soldered on the PCB, can be adhered to be kept in place. Score 2

### Image Sensors
- Soldered on PCB. Score 3
- Constant technical imaging quality improvements

### Vibrator
- Soldered on PCB. Score 3
- Mature

### Accelerometer ++
- Soldered on PCB, covered by EMI shield. Score 3
- Slight technical improvements

### Calling Antenna
- Soldered on PCB, covered by EMI shield. Score 3
- Slight technical improvements

### WiFi Antenna
- Soldered on PCB, covered by EMI shield. Score 3
- Slight technical improvements

### RF Antenna +
- Soldered on PCB, covered by EMI shield. Score 3
- Slight technical improvements

### GPS
- Soldered on PCB, covered by EMI shield. Score 3
- Slight technical improvements

### Compass
- Soldered on PCB, covered by EMI shield. Score 3
- Slight technical improvements

### Jack
- Soldered on PCB. Score 3
- Mature standard part

### Battery Connector
- Soldered on PCB. Score 3
- Mature

### Protruding Buttons
- Mechanical fit and connector is soldered on PCB. Score 2
- Mature, might change shape

### Battery +
- Integrated in design, kept in place by rear casing assembly. Score 2
- Quite similar. Power requirements and dimensions may vary
- Contains cobalt and lithium (CRM), also contains hazardous compounds

### Table 2- Draft Guidelines for the design of a circular mobile device

<table>
<thead>
<tr>
<th>Major parts</th>
<th>Components</th>
<th>Price</th>
<th>Repairability</th>
<th>Lifetime</th>
<th>Maturity</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>(+)</td>
<td></td>
<td>Ribbon wire clicked on the PCB or soldered on the PCB, can be adhered to be kept in place. Score 2</td>
<td></td>
<td>Mature</td>
<td>Indium (CRM)</td>
</tr>
<tr>
<td>Image Sensors</td>
<td></td>
<td></td>
<td>Soldered on PCB. Score 3</td>
<td></td>
<td>Constant technical imaging quality improvements</td>
<td></td>
</tr>
<tr>
<td>Vibrator</td>
<td></td>
<td></td>
<td>Soldered on PCB. Score 3</td>
<td></td>
<td>Mature</td>
<td></td>
</tr>
<tr>
<td>Accelerometer ++</td>
<td></td>
<td></td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td></td>
<td>Slight technical improvements</td>
<td></td>
</tr>
<tr>
<td>Calling Antenna</td>
<td></td>
<td></td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td></td>
<td>Slight technical improvements</td>
<td></td>
</tr>
<tr>
<td>WiFi Antenna</td>
<td></td>
<td></td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td></td>
<td>Slight technical improvements</td>
<td></td>
</tr>
<tr>
<td>RF Antenna +</td>
<td></td>
<td></td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td></td>
<td>Slight technical improvements</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td></td>
<td></td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td></td>
<td>Slight technical improvements</td>
<td></td>
</tr>
<tr>
<td>Compass</td>
<td></td>
<td></td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td></td>
<td>Slight technical improvements</td>
<td></td>
</tr>
<tr>
<td>Jack</td>
<td></td>
<td></td>
<td>Soldered on PCB. Score 3</td>
<td></td>
<td>Mature standard part</td>
<td></td>
</tr>
<tr>
<td>Battery Connector</td>
<td></td>
<td></td>
<td>Soldered on PCB. Score 3</td>
<td></td>
<td>Mature</td>
<td></td>
</tr>
<tr>
<td>Protruding Buttons</td>
<td></td>
<td></td>
<td>Mechanical fit and connector is soldered on PCB. Score 2</td>
<td></td>
<td>Mature, might change shape</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>+</td>
<td></td>
<td>Integrated in design, kept in place by rear casing assembly. Score 2</td>
<td></td>
<td>Quite similar. Power requirements and dimensions may vary</td>
<td>Contains cobalt and lithium (CRM), also contains hazardous compounds</td>
</tr>
</tbody>
</table>

1. Kyle Wiens (CEO from iFixit and Duzoki), dr.ir. Hans Goosen (assistant professor at the department of Precision and Microsystems Engineering at the TU Delft), designers and engineers at Vodafone
2. The financial value of the parts may decrease over time. An exact breakdown of the costs remains unknown as an overview was not found. This requires further research.
3. The processing units are an assembly of transistors known for their degradation mechanisms (for example gate-oxide breakdown and hot-electron effects)
4. According to calculations a 32GB external SSD storage could have a lifetime of 2366 years
Chapter 3 - Case Study: The Development Of A Mobile Device For A Circular Economy

The analysis of a case study on the development of a mobile device for a circular economy will enable the assessment of the theoretical framework proposed in the previous chapter. The second sub-research question will be answered in this chapter.

Sub - Research Question 2
What criteria could be used to assess the circularity of a design?

Background

The case study originates from the graduation project for the master 'Integrated Product Design' at the IDE faculty of the TU Delft. The development of a mobile device for a circular economy was done over a period of half a year. The study was carried out within the Circular Economy Research Programme at Vodafone.

The development of a mobile device for a circular economy has in particular been chosen because of the urgency of the problems linked to their production and due to the considerable opportunities that could be seized in this industry.

Because of fast changing trends, technological improvements and fixed duration subscriptions, mobile devices tend to have a rather short life span. In mature markets (Japan, North America and Western Europe), the average usage time is down to less than two years. Simultaneously, this sector is eager to experience exponential growth in emerging markets. Over time, this only increases the amount of mobile phones produced and disposed of. With a rate of less than 10%, mobile devices are scoring far under average collection rates in comparison to other electronic appliances such as computers and TVs. Additionally, from this portion of collected mobile devices, only 10% is recycled and 65% is reused.

Paradoxically, the resources and components discarded and considered as waste still embed substantial value. The mobile devices are indeed full of valuable materials such as silver, gold and rare earth metals. In Europe, 160 million devices not being collected for recycling represent a material loss of up to 500 million dollars annually. Apart from having to comply with legal requirements such as Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) legislations, applying CE principles could for one diminish production costs or increase technical efficiency.

Process towards the design of mobile device for a circular economy

The project was divided in two parts: the study of the CE theory and the telecommunication industry and a practical part where this knowledge is applied to the design of a more circular mobile device.

Part 1

In part 1, to grasp the essence of CE and discover the interesting directions the development of a circular mobile device could take, a holistic approach was required. The current lifecycle of mobile devices, the theory of the circular economy and its implications in the telecommunication industry were studied. The study was carried out sourcing information from a thorough literature research coupled with field research, interviews of various stakeholders involved and practical sessions (such as teardown sessions).

The following research questions were investigated in this first phase of the project:

- RQ: What are the characteristics of a mobile device in a circular economy?
- S-RQ1: Why hasn’t a circular mobile device been developed to this day?
- S-RQ2: What opportunities do circular mobile devices offer the sector?

The current linear consumption situation of the sector was analysed in order to identify challenges and opportunities to the implementation of circular economy principles.

Multiple threats to the application of circular thinking exist with respect to society & customers, design, manufacturing, End of Life and economics. For example, the complexity of the map of stakeholders, the complexity of the composition of current mobile phones, the lack of knowledge on the topic throughout the value chain, customer behaviour and confidentiality issues might stand in the way of circularity.
Various opportunities for circular systems and products can be seized. Public procurement and B2B can be seen as interesting targets for the introduction of circular devices and business models (as compared to consumer customers). By offering a lease-like programme, users can have access to personalised performances and upgrade products to meet these performance requirements during their contract period with a mobile network operator. Collaboration cross cycles and sectors will be essential for the success of this model.

An analysis of design tools, methods and guidelines from various schools of thought and fields of research was done to get some guidance through the design process (as described in Chapter 2). The most relevant and compatible ones were selected to be used during the case study.

The drafted guidelines, challenges and opportunities were translated into concrete characteristics for a desired circular future product in the mobile telecommunication industry.

The future customers will pay for the performance of their device instead of owning it for a few years. The product development was set to be focussed on public procurement and enterprise as a target group. This group was carefully selected assuming it would eliminate various psychological barriers linked to product attachment and to avoid dealing with trend-sensitiveness. A corresponding system was adapted to fulfil the needs of the customer and that of the other stakeholders involved in the production and services around mobile devices.

Part 2

In part 2, using the insights gained in the first part of the project, the aim was to design a viable consumer product that could go through the different loops of the CE model. Going through this design process would allow for the evaluation of the tools and design guidelines proposed.

The design process followed for the product development is based on the different stages identified by Buijs and Valkenburg [1] combined with those of Roozenburg and Eekels [2] (as seen in Figure 2). It was nevertheless be forced to stop before the end of the complete product development due to the scope and time limit of the graduation project.

Based on literature, key circular characteristics have been identified for the case of a circular mobile device:

- built to last
- easy to disassemble
- modular parts
- standardised components and joints
- upgradeable components
- materials cycle through the various CE circles (‘waste’ is used as input)
- uncontaminated material flows
- tight CE circles are preferred throughout the life of the product

Using amongst others C2C idealistic vision, the Design Spiral and the Life Principles of ‘adapt to changing conditions’ and ‘integrate development with growth’, ideas were developed for this circular product. Some inspiration was drawn from nature (by consulting AskNature) for several ideas. The best ideas were selected and compiled into 8 concepts and variants. Finally, one concept was selected to be further developed. As explained in the previous chapter, active disassembly was also integrated into the design.

4 consult graduation thesis for more information
Originally only one single mobile device for a circular economy would be designed. However, during the project, the assignment was altered. The time scale within which the mobile device would potentially be in use was shortened by the company. Note that the conception of long term and short term can drastically be different depending on the stakeholder. In terms of technological improvements and design trends for mobile device, looking one year into the future is already quite long term. As a result, the first product designed at this stage - thought to be technically and operationally feasible in around 10 years - was defined as a device for an advanced scenario.

This conceptual design was used as a way to backcast a roadmap (combined with the idealistic vision and roadmap from Cradle-to-Cradle). The necessary system and product steps enabling the realisation of the future vision - the transition towards circularity - were identified as milestones in various time frames. The feasibility of these milestones were assessed using the knowledge from experts in the industry within and beyond Vodafone.

The first milestone was defined as a mobile phone designed to seize low hanging fruits. It could be in use by employees in the public and private sector within a period of two years. Vodafone was eager to find out how to embody this milestone in practice. Therefore, this product was designed in a second movement.

The designs of the mobile device were evaluated using the draft guidelines. The expertise from professionals was inquired to estimate the feasibility of the concept developed. Special attention was put in the selection and use of materials, the components design and product architecture, and the selection and use of fasteners. Special care was also be put in the product service system around this object.

Literature, field research and interviews with relevant stakeholders were used as input to validate and warrant the viability of the results. The theory used on CE throughout this report is in line with the Ellen MacArthur Foundation.

Detailed results of this research can be found in the graduation thesis on the TU Delft Repository. Bearing the current and future limitations and opportunities in mind, this document reports on how to be ahead of the curve and create a beneficial disruptive system and product in the European mobile device market.

Analysis of current mobile device designs

Current mobile devices are not thought to fit in a CE. Multiple challenges standing in the way of the integration of CE in these products are identified in the graduation thesis.

In order to seize the four opportunities mentioned by the EMF, the multiple use of products and components without producing material waste will be required during any of the stages. Therefore, the complex interconnectivity between the various entities in the product life cycle should be well-understood. The average structure of a mobile phone is visualised in Figure 12.

Today’s mobile devices are intricate assemblies and sub-assemblies of over 200 components. They are composed of more than 40 different elements. The phones are made of approximately 25% of metals, up to 50% of plastics, 15% glass and ceramics, and a combination of a multitude of materials in very small percentages.

To make this product circular, current issues to be tackled must be pinpointed. Using insights gained during the teardowns of current mobile phones and information made available by manufacturers and repairers, the structure of a current handset, the different components used, their price, ease of disassembly, lifetime, maturity and risks are summarized in Table 3.

The embedded value of the components used in the mobile phones can be analysed by looking at the price combined with repurposing potential (linked to maturity). The ease of regaining this value is described by assigning a disassembly score to each major component. Finally, the importance of recovering the value is defined acknowledging the lifetime, maturity and risks (engendered by the use of specific chemical compounds) bound to each component.
Figure 12 - Simplified Structure of a current Mobile Device
LEGEND

**Price**
The indicated price is the price per new spare part (direct costs of the components from the supplier). Data is based on numbers from Gartner [79] and Nomura [80].

The following code is used: + stands for a price above 5 euros, ++ stands for a price above 10 euros and +++ stands for a price above 15 euros. When the space is left empty, the price of the component is very low.

**Disassembly score**
An individual disassembly score has been given to each major component in order to assess their accessibility within the product architecture and the ease of separating bonding techniques used in the (sub-)assembly. The information is based on teardown manuals, online disassembly guides and teardown labs described afore. 1 is the highest score awarded (easiest to repair), 3 the lowest. An average was calculated from the substitution of the component disassembly scores. The scores are relative to each other. Only the major components identified were taken into account.

The score chart is as follows:

<table>
<thead>
<tr>
<th>Major parts</th>
<th>Components</th>
<th>Highest score (1)</th>
<th>Average score (2)</th>
<th>Lowest score (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Casing</strong></td>
<td>Front and back casing clicked into each other and easily removed without too much prying with a common tool.</td>
<td>Front and back casing clicked into each other and can be removed with a little bit of prying.</td>
<td>Very difficult to access. Requires multiple non standard tools to access. Requires to separate other major components and potentially causing damages.</td>
<td></td>
</tr>
<tr>
<td><strong>Display Assembly</strong></td>
<td>Not fused to the front glass nor the rest of the product. It can be replaced individually thanks to a simple clicking system.</td>
<td>Not fused to the front glass nor the rest of the product. It can be replaced individually by unscrewing the component</td>
<td>Fused to the front glass and permanently glued onto the product with strong adhesive. The component damage easily.</td>
<td></td>
</tr>
<tr>
<td><strong>Front glass</strong></td>
<td>Not fused to the screen nor the rest of the assembly. It can be replaced individually thanks to a simple clicking system.</td>
<td>Not fused to the screen nor the rest of the assembly. It can be replaced individually as it is screwed using standard screws</td>
<td>Fused to the screen and permanently glued onto the product with strong adhesive. The component damage easily.</td>
<td></td>
</tr>
<tr>
<td><strong>Circuit Board Assembly</strong></td>
<td>Clicked onto the product. Very accessible without damaging other components.</td>
<td>Connected to the display assembly by multiple screws or adhesive, in case of two PCB components these are connected with a wire clicked on the board and ribbon cable.</td>
<td>Very difficult to access. Requires multiple non standard tools to access. Requires to separate other major components and potentially causing damages.</td>
<td></td>
</tr>
<tr>
<td><strong>Components onto the Circuit Board</strong></td>
<td>Mechanically fit onto the PCB requiring common tools to take apart</td>
<td>Mechanically fit onto the PCB requiring special tools to take apart</td>
<td>Soldered onto the PCB requiring specific tools and skills to take apart. Extra adhesives ensure all the components are not moving. In some cases covered by an EMI shield</td>
<td></td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td>Can be removed in seconds without any tool</td>
<td>Integrated in design, making it less easy to access, kept in place by rear casing assembly. Can be disassembled using common tools</td>
<td>Very difficult to access. Requires to separate other major components. Retrieving it can potentially cause damages (E.g. adhered to midframe)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - Disassembly score chart per major component
<table>
<thead>
<tr>
<th>Major parts</th>
<th>Components</th>
<th>Price</th>
<th>Disassembly Score</th>
<th>Lifetime</th>
<th>Maturity</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casing</td>
<td>Clicked to the backcasing. Score 1</td>
<td>Most prone to aesthetic deterioration</td>
<td>Technically mature, except for dimensions and design (influenced by screen size)</td>
<td>Can contain hazardous compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Display Assembly</td>
<td>Screen Fused to the touch panel, connected to the printed circuit board (PCB) with ribbon cable click system. Score 3</td>
<td>LCD screens (most used screen technology) lasts for almost 7 years</td>
<td>Resolution is mature. Size keeps increasing. Other innovations on display technologies are coming. The technology could be considered mature for customers that do not want fancy iconic innovations.</td>
<td>Contains indium, yttrium, cerium, europium (CRM). Contains hazardous compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Touch panel</td>
<td>Fused to the screen, connected to the PCB with ribbon cable click system. Score 3</td>
<td>Most break sensitive component (due to user dropping the device for example)</td>
<td>Resolution is mature. Size keeps increasing. Other innovations on display technologies are coming. The technology could be considered mature for customers that do not want fancy iconic innovations.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circuit Board Assembly</td>
<td>Printed Circuit Board Connected to the display assembly by multiple screws or adhesive, in case of two PCB components these are connected with a wire clicked on the board and ribbon cable. Score 2</td>
<td>-</td>
<td>Mature technology. Shape within the device may vary (one plate vs 2 connected plates constructed around the battery)</td>
<td>Assembly contains tin, zinc, tungsten, palladium, tantalum and gallium (CRM). The conductive paths are made from copper, silver or gold depending on estimated lifespan. Assembly also contains hazardous compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>Soldered on the PCB, covered by EMI shield. Score 3</td>
<td>Up to 9 years. Signal timing across the chip can slowly degrade</td>
<td>Most technically upgraded part</td>
<td>Gallium (CRM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Memory Chips</td>
<td>Soldered on the PCB, covered by EMI shield. Score 3</td>
<td>Depending on the technology used - near to infinite lifetime *</td>
<td>Most technically upgraded part. Might shift to clouds though.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(nano or micro) SIM Cassette</td>
<td>Soldered on the PCB. Score 3</td>
<td>-</td>
<td>Relatively quite constant (standardization (micro) SIM)</td>
<td>RE (neodymium, praseodymium and dysprosium) (CRM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speaker</td>
<td>Adhered to the casing and connector is soldered on the PCB. Score 3</td>
<td>-</td>
<td>Slight technical improvements, could be considered mature</td>
<td>RE (neodymium, praseodymium and dysprosium) (CRM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microphone</td>
<td>Soldered on the PCB. Score 3</td>
<td>-</td>
<td>Slight technical improvements, could be considered mature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major parts</td>
<td>Components</td>
<td>Price</td>
<td>Repairability</td>
<td>Lifetime</td>
<td>Maturity</td>
<td>Risk</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------</td>
<td>--------</td>
<td>---------------------------</td>
<td>------------</td>
<td>----------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Flash (magnified</td>
<td>Ribbon wire clicked</td>
<td>+</td>
<td>-</td>
<td>Mature</td>
<td>Indium (CRM)</td>
<td></td>
</tr>
<tr>
<td>LED)</td>
<td>on the PCB or soldered on the PCB, can be adhered to be kept in place. Score 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image Sensors</td>
<td>Soldered on PCB.</td>
<td>++</td>
<td>-</td>
<td>Constant technical imaging quality improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Score 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrator</td>
<td>Soldered on PCB.</td>
<td>+</td>
<td>-</td>
<td>Mature</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Score 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerometer</td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td>++</td>
<td>-</td>
<td>Slight technical improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calling Antenna</td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td>++</td>
<td>-</td>
<td>Slight technical improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WiFi Antenna</td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td>++</td>
<td>-</td>
<td>Slight technical improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Antenna</td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td>++</td>
<td>-</td>
<td>Slight technical improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td>++</td>
<td>-</td>
<td>Slight technical improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compass</td>
<td>Soldered on PCB, covered by EMI shield. Score 3</td>
<td>++</td>
<td>-</td>
<td>Slight technical improvements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jack</td>
<td>Soldered on PCB.</td>
<td>++</td>
<td>-</td>
<td>Mature</td>
<td></td>
<td>Standard part</td>
</tr>
<tr>
<td>Battery Connector</td>
<td>Soldered on PCB.</td>
<td>++</td>
<td>-</td>
<td>Mature</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Score 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protruding Buttons</td>
<td>Mechanical fit and connector is soldered on PCB. Score 2</td>
<td>++</td>
<td>-</td>
<td>Mature, might change shape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>Integrated in design, kept in place by rear casing assembly. Score 2</td>
<td>++</td>
<td>1,5 years in average, depending on technology and use, performance degrades the fastest in time as compared to other component, one of the component most prone to failure</td>
<td>Quite similar. Power requirements and dimensions may vary</td>
<td></td>
<td>Contains cobalt and lithium (CRM), also contains hazardous compounds</td>
</tr>
</tbody>
</table>

Table 3 - Structure of a current handset, different components used, their price, ease of disassembly, lifetime, maturity and risks
According to the C2C Institute and the Rijksoverheid, the materials (present in quantities higher than 5%) in today’s average mobile phone can be categorised as follows (see Figure 13).

Looking at this previous table, some inconsistencies can be found in the current design of the mobile phones.

- First, the criticality of a material used is not translated in the price of the component (see the speaker or microphone). This could be explained by the fact that merely very small amounts of the materials are present in the parts.

- On top of this, the component that is the most sensitive to break during usage (the touchpanel) is inseparable from one of the most expensive parts of the product (the display). Since the two components will need to be replaced in case of break, the costs of the repair seem unnecessarily high.

- The CPU and Memory chips are the most prone to technical improvements (one of the most prominent reasons for the purchase of new mobile phone). These are two very expensive components that are soldered onto the PCB plus covered by EMI shields and thus difficult to separate from the assembly for a potential upgrade.

- The accelerometer slightly improves in time but is an expensive part of the product that cannot be recovered easily from the assembly. This is caused by the fact that it is here again soldered onto the PCB and covered by EMI shields.

- Finally, the battery contains a large amount of hazardous compounds and some critical raw materials, and it also degrades over time. Unfortunately for recycling and maintenance, the component is generally integrated in the design of the product and difficult to retrieve from the assembly.

These inconsistencies should be taken into account and remediated in the future development of a circular mobile device.

**Design of a mobile device for an advanced circular scenario**

After analysing the current designs of mobile phones and prioritising the components to be made circular, the product development can be initiated.

**Vision for a circular mobile phone**

Based on opportunities and challenges underlined in prior research in the first part of the graduation project, a system was developed around the product. To enable this system to function successfully, various iterations in the hardware and software of the product are necessary.

**Hardware**

In terms of hardware, the product should be built to last, be easy to disassemble, have standardised components and joints, have upgradeable components, and materials should be specially selected to cycle properly.
CHAPTER 3

Building to last will be an important principle for the mobile device's design. All components should be durable during the products' lifespan but also that of the next generations of product. As the product will remain in a controlled environment, higher quality materials can be selected for the product design.

As discussed earlier, DfD is vital to enable the product to go through the different cycles of the CE model. The ratio between the value of the reclaimed product, component or material and the required labour to retrieve it could be improved by the use of different joints enabling disassembly.[16]

Components that have the highest value, that are considered mature and contain critical raw materials have the most commercial potential and should be made circular as soon as possible. Those that also cannot be repaired easily will need special care and will have to be prioritised. According to earlier analysis, components to prioritise are the display assembly, CPU, memory chip, camera, accelerometer and battery.

In order to make the treatment even more economically and technically feasible, standardised components and joints across models and possibly brands are of high importance. This process could be strengthened by the use of semi-automated and pre-sorting systems.

Once components and joints are standardised and the design is built to last and simple to disassemble, the product components could be easily upgraded. To facilitate this, components should be engineered so as to only reduce in size while having the same connections to the circuit board or other components.

In order for the product to stream through the various circles of the CE model, materials (and their assembly) should be selected carefully. These should ideally all be recyclable and even recycled.

Software

To lower the psychological barrier before return, the product should be equipped with software erasing all the personal data. The user should be able to access and command it. Ideally, the customer should be able to retrieve all his/her personal information by taking out all the memory hardware components containing all his/her data. The unused mobile phone will then be deprived of all the personal information of the previous user. In addition, the customer would be able to transfer all data to his/her new device.

In terms of software, a standardised state of the art diagnosis software should be installed on every device so as to enable a fast analysis of the remaining value in products and selecting a path accordingly.

Idea generation

After defining the PSS and the vision for a circular mobile device, the next steps of product development can now be taken.

Several features are crucial for the average use of the target group and will have to be included in the design: calling, texting, instant messaging, emailing, browsing, the use of GPS and the generation of WiFi hotspots should be enabled by the designed product.

Next to the design guidelines drafted earlier, other techniques such as a collage were used to come up to new ideas.

A collection of disassembly ideas was generated based on the previous findings and literature from Duflou et al. [86] and Chiodo & Jones [65] in Table 5.

| Mechanical | Mechanical force, Pneumatic, Ultrasound, Pressure, Vibrations |
| Thermal | Heat, Cold |
| Chemical | Soluble, Biodegradable |
| Electro-magnetic | Electromagnet, Ultraviolet light |
| Electrical | Piezoelectric, Hotwire |

Table 5 - Disassembly techniques

Conceptualisation

The generated ideas were evaluated based on their technical development level and the guidelines listed in the previous chapter. The ideas were judged on first hand using theory from literature when possible and in a second movement quickly and intuitively. Positive and negative features were listed for each idea (using the Itemised Response Method [87]). All the different ideas were combined together into various concepts.

Eight concepts and variants were compiled so as to fulfill as much requirements and wishes as possible. Emphasis has been put on the structure and engineering of the device rather than on the aesthetics of the product. The concepts generated can be seen in Figure 13.
LEGO
building blocks, component clicked into the body, connecting onto a special PCB, polishable cosmetic components, soluble joints

Shake it Magneto
near to indestructible materials, magnets as joints, human powered

Zipper
UV light triggered disassembly, cleans inside office air

Tetris
disassembly done by putting a pin through on the top, modules organized inside

DIY
self healing materials, hotwire and active disassembly using pressure

Bubble Gum
Elastic casing holds product parts together, wireless charging battery, heat-triggered disassembly

Grow your Device
inspired on nature, 3D printable biodegradable material, conductive surgical joints based on mussel glue

Puzzle
disassembly done only by snap fits, modules are connected to each other and fixed on the rear panel of the device

Figure 13 - Concepts for the envisioned circular design
As we cannot yet imagine the shape of the future generation of telecommunication devices in over two years, the current conventional phone shape was used as object to attach the various systems and disassembly methods to. These techniques would however be adaptable to innovative turns the telecommunication industry may take in a few years.

**Final Conceptual Design - BlackbOx**

So as to come to one final concept, all the concepts and variants were analysed and evaluated. Further information on the evaluation of the concepts can be found in the Appendix XII.

Previous concepts have been combined into a single concept in order to reorganise the best solutions together - the BlackbOx as illustrated in Figure 14.

The name of the concept comes from the shape and colour of the product combined with the analogy of a mysterious device constructed with defined performance characteristics but unknown means of operation to the viewer. The letter ‘o’ is highlighted to underline the circular properties of the device. The shape of the device is very rectangular to contrast with its insides that enable the components and materials embedded to flow through various CE circles.

As stated before, the circular product should be built to last, be easy to disassemble, have standardised components and joints, have upgradeable components, and materials should be specially selected to cycle properly.

Research shows a circular product and system would not be introduced in at least ten years. The technologies used are therefore selected to be fully commercially available and proved reliable around this period.

This concept should not be seen as a future end result (nobody knows what the future shape of telecommunication devices will be), but rather a conceptual goal (just like Moore’s Law was).
Specifications

- withstands water and dust
- 3D printed and standardised components
- use of modular components thanks to a flexible PCB and retraceable conductive tracks

Materials:

- durable
- self healing when possible, exterior components are polishable
- recycled and recyclable
- conflict free minerals
- surface cleans the air (inspired on Cradle to Cradle principles) increasing the productivity of the user and his surrounding colleagues
- built with less than five polymers (inspired by Biomimicry), mechanical properties are modified by applying structure

Energy source:

wireless power assuming it will be more efficient, effective and widely publicly spread (for example in public spaces as wireless charging), no charging connector is required

Closed hardware disassembly (see Figure 15):

- built from the inside out
- hot wire required to open the device
- manual disassembly of all important components enabled by snap fits
- automated disassembly of all components using heat (assumed to be one of the first disassembly techniques to attain commercial viability [155]. If possible within the time restriction, pressure triggered disassembly would be particularly interesting for closed hardware disassembly due to the specific tools required)
Figure 15 - Exploded view of BlackbOx

Influence of heat on snapfits - detail of the electronic components on the PCB

Temperature rises and the state of the hotwire changes to release the part.

Solid state of the hotwire at Tg

Liquid state of the hotwire at Tm

Hotwire is applied and the part is assembled

Electricity is applied on the hotwire

Camera

Rear casing made from durable material

CPU & memory chips

Battery wireless charging

Influence of heat on snapfits - detail of the rear casing

Snapfit

Tg

Tm

Temperature rise

Screen clicked onto the glass panel

Touch panel
Design of a mobile device for a transition towards circular economy

As explained earlier, the time scale within which the mobile device would potentially be in use was altered by the company. The first product designed is used as a device for an advanced scenario for further reference.

Roadmap

By implementing a circular strategy, the mobile network operator could drive internal and external innovation and could be the facilitator - the middle man - bringing companies together and creating synergy. Zooming out, a regenerative system would enable to control resources and enable a more controlled recycling of the devices, thus tremendously lower resource associated risks, improve net benefit and decrease the environmental impact of the industry.\[14\]

Using all the gained insights and the formulated objectives, a roadmap was compiled to show the steps required from a system and product point of view for mobile network operators in general (see Figure 16). The map illustrates briefly how a transition from the status quo can be done to a circular scenario by passing through a transition phase and an advanced scenario.

Along the roadmap, the circular qualities of the product and system will grow from the status quo to a circular scenario. As a result, the number of accessible and easy to disassemble components that can be repaired, refurbished, remanufactured and/or recycled will be increasing.

Figure 16 - Roadmap towards circular designs
CHAPTER 3

Idea generation

The aim of this product development was to decrease costs on maintenance and refurbishment operations and lower the barriers for customers to hand in their old devices. The ratio between the labour needed to retrieve components and the value of the involved components and materials had to be improved.

Based on a brief customer research, several features were defined as crucial for the average use of the target group - B2B and public procurement. These include: calling, texting, instant messaging, emailing, browsing, the use of GPS and the generation of WiFi hotspots.

A set of requirements was created as a base for the design process.

As pointed out earlier, diverse components of current mobile phone designs had to be made more circular immediately; namely, the screen and touch panel, the CPU, the memory chip, the camera, accelerometer and the battery.

Some of the joining techniques described in the previous section are for the majority still too young in their development and are thus not yet commercially viable. Therefore, less innovative solutions should be preferred for the first milestone.

Some state of the art alternatives more suitable for disassembly and already applied in other products (as illustrated in Figure 17) could thus be used when suitable.

![Figure 17 - Overview of alternative joining techniques in electronic devices for (from left-to-right) a display assembly in an iPad joined to the body using snap fits, LCD screen in a Motorola phone is disassembled using snap fits, memory chips clicked into the motherboard of a desktop computer, CPU clicked onto the motherboard of an HP computer, non-integrated battery in a Motorola phone and a camera clicked onto a motherboard in a mobile phone (source: iFixit & HP)](image17)

Other possible joints such as snap fits can be used in the design to enable an easy and fast disassembly. Most important types of snap fits are: cantilever, U-shaped cantilever and L-shaped cantilever (Figure 18).[86], [87]

![Figure 18 - Different types of snap fits and different kinds of designs for disassembly](image18)

The shown alternative solutions have all been commercially launched, thus showing the viability of the joining technique in the supply chain. This implies that these solutions could already be applied and are economically and technically feasible in Vodafone’s mobile phones today.

In order to generate more ideas, the C2C idealistic vision, the Design Spiral, Life’s Principles (same as during the advanced scenario) and the AskNature database were used.

Conceptualisation

Various proven solutions and some more advanced ones were combined into a selection of concepts as visualised in Figure 19.

In order to choose an adequate concept to further develop, the advantages and disadvantages were weighted per concept (see Appendix II). Looking at the total scores, the third concept had to be improved using solutions from the other concepts and was further detailed.
LCA and the C2C certification criteria were taken into account while designing and fore mostly when selecting the best solutions. During the detailing of the materials of the conceptual design, the ABC X categorisation was consulted.

<table>
<thead>
<tr>
<th>CONCEPT 1</th>
<th>CONCEPT 2</th>
<th>CONCEPT 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>casing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>display assembly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>processor &amp; memory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>camera &amp; speaker</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rear casing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 19 - Designed concepts for the first step to a circular mobile phone](image)

**Prototyping and testing**

So as to prove the improved concept, prototypes were built to test the working principle (Figure 20). A digital 3D model of the components was made using SolidWorks. The housing of the product was 3D printed and components used in current designs were integrated in the prototypes.

Using trial and error, the best set of solutions are developed into one final concept.

![Figure 20 - Prototypes and testing](image)
CHAPTER 3

Final conceptual design - Poppy

Figure 21 - Final conceptual design Poppy

Specifications

Design:
• Business-like and minimalistic
• Use of modular building blocks and standardised components for the display assembly, the battery, the CPU and the memory chips (most of the ‘to prioritise’ components)

Software changes:
• Failure diagnostic
• Data wipe application
• Energy efficiency
• Programmed to work fast across several mobile phone generations

Materials:
• Durable (rhino shield, d3o, sapphire glass)
• Recyclable for over 40%
• Efforts for use of conflict free minerals
• Indicate element symbol on each component
• The surface of the PCBs is soluble, making it possible to eliminate all the solders and retrieve all the soldered components

Open hardware disassembly:
• Built from the inside out
• Manual disassembly of most prioritised components enabled by snap fits
• Automated disassembly similar to current models
Bright poppies grow in conditions of disturbed earth throughout Western Europe. The name Poppy was chosen to refer to the product’s ability to disrupt the current linear consumption model and to ‘pop’ open.

Structure, Components & Materials

The structure of the product and the used materials are shown in the exploded view in Figure 22.

Figure 22 - Exploded View of the concept

Materials and the designed shape of the structure have been selected for their durable mechanical properties and environmental impact using the materials and processes database CES EduPack by Granta Design. Nevertheless, a list of banned materials compiled by the C2C Institute was used during the selection of the materials. Other lists from different instances were also analysed. Further specifications of the materials is required to evaluate the exact impact of the embedded substances.

The product can be disassembled from both the bottom (rear casing) and the top (display) without unnecessarily having to separate other components and potentially damage them.

Specific materials have been implemented in the design so as to enhance the performance and aesthetics durability of the parts. The middle frame of the housing is for example covered with d3o, a specially engineered rubber like material absorbing shocks when the phone is dropped. On top of this,
the shape of the frame ensures that when the phone falls onto a flat surface, the display assembly does not interact directly with it and therefore will not break easily.

The touch panel and rear casing are in addition covered with a Rhino shield effectively protecting it from scratches and shocks (withstanding hammer strikes).

The materials will be easily identified thanks to the engravings of the corresponding material on each component (Figure 23).

![Image](image.png)

**Figure 23 - Detail of the outer shell of the frame showing the embedded material identification**

According to Hoffmann et al., the smallest labels on chips should be larger than 3 pt and should have a high contrast to the chip’s colour.[54]

Materials were selected using the original requirements (i.e. be recyclable) coupled with the mechanical properties (such as specific elongation for the snap fits) needed to fulfill the correct functioning of the designed product. According to BASF, thermoplastics are perfect candidates for snapfits as they are highly flexible, have a relatively high elongation, low coefficient of friction but can also be combined with strength and stiffness.[87]

**Disassembly**

As analysis shown, the product should be designed for disassembly in order to enable the correct treatment of the product. Different levels of disassembly are required throughout the lifetime of the device: (1) for common repairs and upgrades; (2) for all repairs and upgrades; and finally, (3) for recycling. The first level needs to be the most accessible, fastest and easiest one (containing the previously prioritised components). Levels 1 & 2 will allow for outstanding maintenance and refurbishment capability. The third still needs to be simple and must not require a large amount of tools to separate the components/materials.

Level 1 components can be easily separated from the body of the mobile phone thanks to clicking systems. These components count: the display assembly (connected to the body), the LCD & front panel, the camera, the rear casing (onto the body) and the PCB’s & battery (onto the rear casing). The processor and memory components are supposed to be in this category but will have to be screwed onto the PCB instead of soldered to ensure the reliability and durability of the joint.[90] The frame pushing the parts on the PCB and keeping them in place are also used as EMI shields. Special care should be put in the implementation phase of these frames (keeping potential heat transfers issues and tolerances in mind).

Level 2 components are at this point of time still soldered onto the PCB’s. These will require more labour and energy input to disassemble. During recycling, the separation of these parts from the PCB will become easier as the layer on which solders have been placed could be dissolved in water. As such, the components can be retrieved.

Level 3 parts will have to be chemically taken apart to retrieve pure streams of materials during the recycling phase.

In comparison to current designs built from the back to the front or front to the back (like the HTC One for example), this concept should be designed from the inside-out to enhance access.

The reverse fishbone diagram by Ishii and Lee [67] graphically makes a difference between sequence dependent and independent disassembly. The total disassembly of the product can be done as illustrated in Figure 24.
The total disassembly time of the whole product can be calculated using the equation from Ishii, Eubanks and DiMarco: [91]

$$D_s = \sum_{i=1}^{1} C_i + \sum_{j=0}^{m} (f_n \times F_j) + \sum_{k=0}^{n} (p_n \times P_k)$$

where:
- $D_s$ = system disassembly cost
- $C_i$ = time to remove component
- $F_j$ = time to remove fastener
- $P_k$ = time to remove or undo process
- $f_{nj}$ = number of fastener associated with one link
- $p_n$ = number of process points associated with one link
- $l$ = total number of components in system
- $m$ = total number of links with fasteners
- $n$ = total number of links with fastening processes

According to this equation and the Philips DFA manual [92], the total disassembly time of all the major components will take less than 8 minutes. In comparison to the tear-downs done earlier, this is at least more than 4 times less time than the average disassemblies done.

Comparative study of current designs, the design for a transition towards circularity and an advanced scenario

A large portion of the requirements defined in the case study cannot be evaluated at this stage of the product development. Nonetheless, the concept is carefully designed to meet requirements with respect to the product architecture, components, materials and joints (as the draft design guidelines emphasized these). The numbers of standard tools required was however not met: prying tools as well...
as a phillips screwdriver and soldering iron will be required (one extra tool). The soldering iron will nevertheless not be needed for common repairs.

Nearly all of the to prioritise components were made more circular by making them easier to repair, re-use, refurbish, remanufacture and/or recycle (with the exception of the accelerometer).

The first milestone mobile phones and current designs are compared in Table 4. The assessment is based on 5 criteria derived from the CE characteristics defined for the development of a circular mobile device. Disassembly level, upgradability potential, lifetime, risk management and costs were considered relevant enough to assess the level of circularity of the final design (nearly the same as used in Table 3).

Even though the product detailing between the design of current mobile phones and the Poppy concept differs, it is clear that some improvements have been made with respect to design and disassembly, upgradability, lifetime, risk management and costs.

Several developments are required in the future to take the concept to the next level. The concept should be detailed further and the product & components should be entirely embodied. All the OEM & ODM parts should be defined. ODM parts should be developed in collaboration with the platform’s partners so as to optimise the repurposing of the components during the life of the product. The formulated guidelines and requirements should be used for these future phases. More time should be put in the compliance of the product with legislation.

The objective is however to maintain this level of performance when it comes to the 5 criteria described.
<table>
<thead>
<tr>
<th>Current mobile phone designs</th>
<th>First milestone mobile phone concept</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Disassembly</strong></td>
<td>Five of the most problematic components (display, touchpanel, CPU, memory chip, and battery) are designed for disassembly. This requires standard tools and could be done simply and fast by hand. The accelerometer remains an issue. The entire product can still not completely be disassembled. Manual disassembly is made easier nonetheless automated disassembly is not yet enhanced.</td>
</tr>
<tr>
<td>Barely taken into account in the design. Problematic: slow, costly, can require specific tools, incomplete disassembly of components for both manual and automated disassembly.</td>
<td></td>
</tr>
<tr>
<td><strong>Upgradability</strong></td>
<td>Display, touchpanel, CPU, memory chip, and battery can be upgraded by standardised components.</td>
</tr>
<tr>
<td>No hardware upgrade is possible - necessitates the purchase of an entire new phone</td>
<td></td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>At least 7 years. Customers can now upgrade the device and are paying for its performance, meaning the product will not be disposed of before the end of the calculated life as a product (components have the potential to be repurposed depending on their (longer) lifetime).</td>
</tr>
<tr>
<td>Potentially up to 10 years, but customers dispose of them after two years in average</td>
<td></td>
</tr>
<tr>
<td><strong>Risks</strong></td>
<td>Some of the joining techniques used are commercially available, yet they have not all been used in mobile phones.</td>
</tr>
<tr>
<td>Considerable amount of components are hazardous and contain CRM. The risk is emphasized by the fact that the disassembly is difficult, hence the embedded value cannot be retrieved.</td>
<td>Components will probably still be composed of hazardous compounds and still contain CRM. Nevertheless, since the disassembly of major parts is simplified, the value can be extracted more easily.</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>The production costs can only be calculated when the concept is more detailed and the origin of all components is defined.</td>
</tr>
<tr>
<td>Production costs varying up to around 200 dollars for an iPhone 5S for example.[165]</td>
<td>Since the customers pay for performance, the mobile network operator will ensure the product can always be used optimally. The smart engineering of the mobile phone will enable a simple and fast disassembly. Thus the costs of occasional repairs/ upgrades will be covered by the contract.</td>
</tr>
<tr>
<td>Important costs for the customer when a component breaks outside of the warranty. Complex product structure and disassembly raises the time required for repairs</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4 - Comparison of current mobile phones and the design of the first milestone*
Chapter 4 - Results

Useful Tools and Methods for the Case Study

An evaluation of the tools and methods proposed is detailed in Table 5.

The most relevant and easy to use tools and methods experienced were AskNature (in combination with the Design Spiral), the ivision and the roadmap.

C2C Certification criteria and LCA were more difficult to apply in the design process. It was however used during the selection of the ideas to further develop for conceptualisation. These will probably be more useful when evaluating the final result.

Design Guidelines Adapted To The Case Study

Previously, based on literature, a list of guidelines for the design of mobile devices in a circular economy was drafted. The list is composed of 5 different categories of guides: Product Structure, Components, Materials, Joints and Accessories.

Throughout the design process, insights were gained on which design tools and guidelines were useful or not for the appropriate development of a transition towards circularity or circular product. The guidelines were all evaluated individually using the insights gained during the design process and the feedback of experts at Vodafone (see Appendix III).

An improved version of this list is compiled to be used and validated by other mobile device designers and engineers. Tools enabling the application of these guidelines will be mentioned when needed.

Sub-research question 3
To what extent is the proposed framework supporting the development of a circular mobile device?

The evaluation of this experience with the proposed theoretical framework is based on two criteria: relevance and compatibility with prior design knowledge of the designer.

Relevance is linked to the importance the entity had for the development of a circular product when it comes to regenerative design and thinking in systems. The appropriateness of the proposed framework within the context of product development will also be evaluated.

The compatibility with prior design knowledge of the user will also be evaluated using the designer’s experience with the tools, methods and design guidelines. As mentioned in the first chapter, ‘Compatibility’ designates how easily the user can utilise the framework with his/her conventional design background. The design strategies, methods, tools and guidelines taught at the faculty of IDE will be used as a reference. The amount of prior knowledge required on the use of such techniques as well as on the topic of CE and sustainable development will be weighed.

Finally, the applicability of this design framework to generic product design is discussed.

The product development has enabled to experience the use of several tools and methods, and the application of the draft design guidelines.

The proposed theoretical design framework can as a result be assessed answering the third sub-research question.
<table>
<thead>
<tr>
<th>Tools and methods proposed</th>
<th>Used during the design process</th>
<th>Relevance to circular conceptual design</th>
<th>Compatibility with prior design knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Spiral</td>
<td>Was used in parallel with the Life’s Principles and AskNature</td>
<td>Enabled to make a coherent and comprehensive use of the Life’s Principles and AskNature. It served as inspiration for the idea generation</td>
<td>The steps to use are quite simple and easy to grasp whatever the prior knowledge of the designer. It resembled the general design process</td>
</tr>
<tr>
<td>Life’s Principles</td>
<td>Two Life Principles were used: ‘adapt to changing conditions’ and ‘integrate development with growth’</td>
<td>The link between the product to be designed and nature was easier to grasp when considering which Life’s Principle to use (needs the support of the Design Spiral though)</td>
<td>The Life’s Principles and their relevance in conceptual design are difficult to understand without basic understanding of the method.</td>
</tr>
<tr>
<td>AskNature</td>
<td>Enabled to find innovative solutions to problems such as “How does nature... heal” finding self-repairing materials for the surface of the product</td>
<td>Opened the user’s eyes on the possibilities and ingenuity of species in nature. Very inspiring. Resulted in a few ideas inspired by nature</td>
<td>The database is very intuitive. The articles on the solutions/products/researches are quite interesting and can be directly emulated with ease</td>
</tr>
<tr>
<td>Vision</td>
<td>An idealistic vision was formulated by listing all the circular characteristics the product should have</td>
<td>Having a future vision to work towards was very inspiring and beneficial for the design as it stimulated to think beyond current practices and explore unknown grounds.</td>
<td>The concept is simple to understand but could be counter-intuitive for pragmatic designers</td>
</tr>
<tr>
<td>Roadmap</td>
<td>During the first product design, a roadmap did not seem to be needed. However, after re-identifying this product as an advanced scenario, a roadmap was backcasted</td>
<td>Identifying the steps towards circularity was very helpful to assess what type of solutions had to be integrated into the design of the first step towards circularity.</td>
<td>Backcasting is not a method that is broadly known. Knowing what the final goal was (the vision) enabled to easily make a roadmap though. The theory behind the roadmap is easy to get a grip on without any prior knowledge</td>
</tr>
<tr>
<td>ABC X categorisation</td>
<td>Used to analyse current mobile phones</td>
<td>Made it possible to gain an overview of the risks linked to materials. Not concretely usable as it is during the conceptual design of a product. Not all the properties of the materials implemented in components such as the screen etc were not known and thus could not be evaluated at this point</td>
<td>The use of the categorisation is intuitive and does not require any prior knowledge (as long as data can be found for each material)</td>
</tr>
<tr>
<td>C2C Certification</td>
<td>Was taken into account during the design but was not used explicitly</td>
<td>Not concretely usable as it is during the conceptual design of a product. It can nevertheless help in selecting ideas or concepts to further develop</td>
<td>Prior knowledge in sustainable development and Cradle to Cradle is needed to fully understand the criteria</td>
</tr>
<tr>
<td>LCA</td>
<td>The conception of the life cycle and the environmental impact at each stage was kept in mind</td>
<td>Not concretely usable as it is during the conceptual design of a product. It can nevertheless help in selecting ideas or concepts to further develop. The environmental impact of the stages cannot really be evaluated at this point of the design process</td>
<td>Performing an LCA is considerably intricate for people that are not familiar with the tool or even Ecodesign. Some training will be required before using it.</td>
</tr>
</tbody>
</table>

Table 5 - Evaluation of the tools and methods proposed
**Product structure**

Product structure stands for the architecture of the product, the organisation of the components within an assembly. The main objective of the structure of the product is to ensure a simple disassembly procedure and enhance the upgradability of the components while maintaining reliability.

1. **Minimise the number of components used in an assembly**

   By lowering the number of components to disassemble, the labour time and costs of the disassembly and potentially environmental impact (less energy, less materials, less emissions etc during production) are reduced.

   Redundant components should be removed from the design as much as possible. This can be done by integrating parts or through system re-design.

   Only apply this guideline when the elimination of the component(s) does not alter the proper functioning of the device, nor the accessibility of parts or the manufacturing of the product. A balance should be found keeping expenses and environmental impact in mind.

2. **Make designs as modular as possible**

   Components of the mobile device can be clustered into functions. Each function can be embodied in a different building block, a module. Several modules can be used in mobile phones: Casing, Display, Power supply, Speed, Storage, Connectivity, Sound, Imagery and Location. This could facilitates the replacement or upgrade of specific entities of the product.

   However, it is important to note that current mobile phones have over 200 components packed in one small and compact assembly. Therefore, dividing their components into a few modules would only potentially create more waste, displace the disassembly issue on the PCB and augment the volume of the device. Other issues could be linked to the speed of the electrical impulses between components if the path is cut by another joint.

   As a result, the modularity of complex products such as mobile phones has to be handled carefully.

3. **Good accessibility of parts**

   This would maintain a low disassembly time, to disassemble without damaging (other) components and to ensure parts can be easily cleaned for refurbishment. Components should be easy and fast to access with tools or by hand (depending on manual or automated disassembly).

   Make components with highest value easiest to access. Circularity will not be obtained overnight. To ease the transition to a circular model, a prioritisation of components is needed to optimise return on investment at the start of the roadmap.

   When considering price, repairability, lifetime, maturity and risks linked to components, the ones to prioritise are: the touchscreen, display, CPU, memory chips, battery and the accelerometer.

4. **Hazardous components should be easy to remove**

   The fast removal of hazardous compounds from the stream of materials is required for an effective and safe recycling. These will finally not contaminate the recycled material stream. These components should be removable via handpicking before shredding. A health and safety dimension should be noted: as the majority of disposed mobile phones are today ending up in third world countries where they will be manually disassembled for recycling.

   A list of hazardous compounds can be found on different platforms. Components prone to be composed of such materials are the casing, the screen, the circuit board and the battery. These components should not be permanently fixed (glued, welded and enclosed solutions) to the assembly.

5. **Ensure resistance to dirt accumulation**

   Dirt can damage the appearance and functioning of the device and requires cleaning (which takes time and energy and increases costs). This could be taken care of by designing the product smartly so that dirt does not have the chance to build up. Consequently, avoid sharp edges and thresholds attracting dirt such as holes.

6. **Design parts for a stable disassembly**

   The parts to be manipulated by hands during disassembly should be intentionally designed to have an even surface to be held on a table for example or give enough grip to be properly held in hands. This would enable a faster and thus more cost efficient manual disassembly.
7. Strive for designs allowing for an automated disassembly

As a result, fast and less expensive disassembly could be operated. Active disassembly technologies will be further developed and researched in the coming years and would be interesting to apply in this context.

Components

Zooming into the next level of the assembly, components should be carefully designed (and/or selected) to allow the success of the implementation of the key characteristics of the product.

8. Optimise component standardisation

Standardisation facilitates replacement and repair (parts supply), enables cross-product remanufacturing and simpler dismantling processes (as it is easier to understand the assembly). Collaboration is needed so as to standardise family of components throughout generations. The dimensions and joints location should remain similar throughout time.

9. Only use durable components that are built to last

The components should withstand as much of the (mis)use of the product and should resist the repetitive disassembly and reassembly. This means the mechanical properties of the components and the materials used should be carefully selected for their application.

This is needed to extend the product’s cycles, especially for components destined for reuse. Nonetheless, special attention needs to be put in finding a balance between the durability of the components and their (financial and environmental) costs. Design strategies developed by Conny Bakker and Marcel Hollander could be used. [48]

10. Minimise length of wires and cables

The length of wires and cables is important as flexible elements are slower to remove then rigid ones. Reducing the length will speed up the process. This should however not restrict the functioning of the product or limit the durability of the components.

11. Avoid non-irreversible contamination of components

Contaminations can occur when a component is covered with a surface coating or paint. This is required to ensure an uncontaminated and thus valuable stream of materials at the recycling stage.

When a coating is required for durability reasons, special measures should be taken: (1) dry paint should be a maximum of 2% of the component’s weight, (2) low volatile organic compound, electrostatic or UV cure paint should be selected, (3) the to be painted components should not be made of PS, a PS-ABS mix, HDPE, PVC, nor PP and should weigh more than 90 grams. [96]

Materials

On an even deeper level of the assembly, attention should be put in the selection of the materials used in the components. These materials should allow the use of the waste of the product as a resource for another process/product, or even use waste as a resource itself. The streaming through the different cycles of the CE model should be made possible.

12. Prefer pure material parts

The stream of materials should be uncontaminated during the recycling phase. By preferring pure material parts, this process is simplified and the need for disassembly and sorting is reduced. When not possible for functionalities and durability reasons, make the used materials easy to separate.

13. Select recyclable materials

This would minimise leakages to landfill and energy recovery, and increase the EoL value of the product. Recyclable materials can be found in the database CES EduPack. The selection of the materials should be done in collaboration with recycling companies. The infrastructures will at first not be very developed for all different kinds of materials. Prefer materials with high recyclability rates (while baring durability and reliability into account).

14. Select recycled materials

At the start of the roadmap, it is possible that not all materials adequate for the design are available
in a recycled form or at least not in a required way (i.e. to get the recylcates long distances should be bridged which would drastically increase the environmental impact and costs of the product). Beware of the required infrastructures and their location.

Creating a steady demand for recycled materials would enable to stimulate the market for recylcates.

15. Materials from components to be reused should withstand cleaning processes

This specific guideline is needed so as to ensure no damages occur during the refurbishment and remanufacturing of components. The resistance of materials for specific chemicals should as a result be studied when the component has the potential to be cleaned during its lifecycle.

16. Make materials identifiable

Accurate identification and sorting increases the recyclate's quality and value.

The identification markers should not be contaminating the material streams. Avoid labels and prefer techniques such as moulding, etching or lasering.

17. Ensure that materials that cannot be separated are compatible (including the joints)

This would limit the potential damage to parts during disassembly making the component ill-fit for repurposing.

The compatibility of materials can be evaluated using diverse tables (for example [97]).

18. Aim to go beyond legislation when it comes to the restriction of the use of toxic or hazardous materials

A circular product has to be engineered to last and go through cycles for a very long time. It is not only important to decrease the environmental, health and safety impact of the device. After a few years of use, new limitations are prospected to be installeld by the government. Refurbished products will thus have to comply with the new regulations. On top of this, recycling restricted materials will create no profit margin in the future. An indication of the substances that could be regulated by legislation in the future can be found in the CARACAL list.

For a list of compounds to currently avoid various databases can be used:[31], [90] Materials from the P list compiled by the C2C Institute could be preferred to be sure the compounds used are 'clean'.

19. Minimise the number of material types used

The resource quest and recycling process will in this case be less intricate and costly in order to retrieve very small portions of substances. This should however not work against the proper functioning of the product or durability aspects.

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The resource quest and recycling process will in this case be less intricate and costly in order to retrieve very small portions of substances. This should however not work against the proper functioning of the product or durability aspects.

Joints

The connections between the different components keeping the assembly together and in place can be designed using several guidelines. Here again, the aim is to ease the disassembly process and make the product as durable as possible.

20. Strive for an improvement of the ratio between the labour required to retrieve a component/sub-assembly and the value of these parts

Do not permanently fix valuable components onto the body of the product. Prefer clicking systems and snap fits over adhesives, welds and integrated solutions.

Valuable and high risk components such as the touchpanel and the LCD screen should be prioritised in this process. Components (such as the battery) containing hazardous compounds and critical raw materials should in no situation be permanently fixed.

21. Disassembly must be performed using simple and standard tools

This would reduce disassembly time and performance and tooling costs.

Standard tools such as Phillips screwdrivers or plastic opening tools could be used. If screws are implemented in the design, very specific screws should be avoided.

Preferably manual disassemby could be even done without any tools.
22. **Minimise the number and types of joints**

By minimising the number and types of joints, the disassembly time and costs are decreased.

A distinction can be made between different manners to join components: fasteners (snapfit, bolt, buckle, staple, threaded fasteners such as screws, zipper and so on), adhesives (solvent bonding, flexible fasteners or rigid fasteners), mechanical welding and thermal welding. Two materials can also be joined by shaping the components and manufacturing two (or more) materials together (moulding, casting, fusing, etc).

23. **Do not mould or fuse various incompatible types of materials together**

The materials will in this case be very difficult to isolate from each other and will as a result contaminate the stream of resources at the end of the cycles.

24. **Prioritise snapfits over fasteners, fasteners over adhesives**

Use snapfits where possible to eliminate the need for fasteners. Consider work-hardening, fracture, fatigue failure and general wear when designing snap fits. If snapfits cannot be used, use fasteners rather than adhesives so that components can be more easily separated.

This should be done without compromising the structural qualities of the assembly by using too few or inadequate joints.

25. **Make joints visible and accessible and emphasize non obvious joints**

The logical structure speeds up the disassembly and training processes. Several use cues such as colours, symbols, notches etc. Lables should here again be avoided.

26. **Standardise the joints used**

Standardisation decreases the complexity of the assembly and number of tools required for disassembly. Standardisation facilitates replacement and repair (parts supply), enables cross-product remanufacturing and simpler dismantling processes (as it is easier to understand assembly).

Collaboration is needed so as to standardise family of components throughout generations.

27. **Consider the use of active disassembly**

Active disassembly is a technical process enabling the mechanical self-disassembly of products by using smart materials. These materials are all engineered to react in a pre-determined manner controlled by external stimuli.[65]

Active disassembly techniques (described in chapter 3) should be considered in the future.

28. **Apply previous guidelines to all provided accessories**

29. **Minimise the need for different chargers or accessories across product families**

Dematerialisation would decrease the environmental impact of the product and system. One same charger could be used for multiple purposes while requiring little to no modifications. Several small EEE can already be charged with the same type of charger.
Applicability To Generic Product Developments

The theoretical design framework was selected and detailed while keeping the product category of the case study in mind. It can however to some extent be used for the development of more generic products.

All the tools and methods borrowed from Biomimicry, Cradle-to-Cradle and Industrial Ecology are already quite generic and can be used in all types of product developments. Their applicability will however depend on the stage of the product development. In the case study, only the first steps of product development were followed in order to come up with a final concept for circular mobile phones.

The design guidelines were nevertheless specifically selected for the case study. Mobile devices, just like other EEE such as laptops, are subject to dynamic market conditions driving technological development and innovation in contrast to for example fridges. Strategies need to be adapted according to the industry of choice. A fridge can easily be designed to last for 20 years. Nonetheless, making a laptop last for over 7 years is regarded as economical suicide. Therefore, in this industry, the ability of the product to be upgraded, refurbished, remanufactured and recycling should be preferred over product life extension. This consideration must be done for each type of product to be designed.

The applicability of the design guidelines formulated is detailed in Table 8.

The majority of the design guidelines can to some extent be applicable to generic product development. Note that a balance must be found between reliability and ease of disassembly depending on the type of product designed. Other design guidelines from the fields of research mentionned could be added to the list.
<table>
<thead>
<tr>
<th>Design guidelines proposed</th>
<th>Specific to the development of a mobile device</th>
<th>Specific to the development of EEE</th>
<th>Applicable to other product developments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Minimise the number of components used in an assembly</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>2. Make designs as modular as possible</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>3. Good accessibility of parts</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>4. Hazardous components should be easy to remove</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>5. Ensure resistance to dirt accumulation</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>6. Design parts for a stable disassembly</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>7. Strive for designs allowing for an automated disassembly</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>8. Optimise component standardisation</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>9. Only use durable components that are built to last</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>10. Minimise length of wires and cables</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>11. Avoid non-reversible contamination of components</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>12. Prefer pure-material parts</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>13. Select recyclable materials</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>14. Select recycled materials</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>15. Materials from components to be reused should withstand cleaning processes</td>
<td></td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>16. Make materials identifiable</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>17. Ensure that materials that cannot be separated are compatible (including the joints)</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>18. Aim to go beyond legislation when it comes to the restriction of the use of toxic or hazardous materials</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>19. Minimise the number of material types used</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>20. Strive for an improvement of the ratio between the labour required to retrieve a component/sub-assembly and the value of these parts</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>21. Disassembly must be performed using simple and standard tools</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>22. Minimise the number and types of joints</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>23. Do not mould or fuse various incompatible types of materials together</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>24. Prioritise snapfits over fasteners, fasteners over adhesives</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>25. Make joints visible and accessible and emphasize non obvious joints</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>26. Standardise the joints used</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>27. Consider the use of active disassembly</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>28. Apply previous guidelines to all provided accessories</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>29. Minimise the need for different chargers or accessories across product families</td>
<td></td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Table 8 - Applicability of the design guidelines proposed
Chapter 5 - Conclusion

In the context of the Schmidt-MacArthur Fellowship, a design framework needed for the development of a circular mobile phone explored in this Circular Economy Innovation Project. Indeed, as the current publications on CE are foremost focusing on the business side of the strategy, designers and engineers are left in the dark when it comes to applying circular thinking in practice.

The main research question - How could circular thinking be applied in the first stages of product development? - was unravelled in this study. A graduation project on the development of a mobile device for a circular economy in collaboration with Vodafone was utilised as a case study to test and validate a proposed design framework.

The framework was drafted sourcing inspiration from literature on CE, comparable schools of thoughts and other research fields (sub-research question 1). Several tools and methods from Biomimicry, Cradle-to-Cradle and Industrial Ecology - namely Design Spiral, Life’s Principles, AskNature, Vision, Roadmap, ABC X categorisation, C2C Certification and LCA - were underlined to be used in circular product development. Keeping the case study in mind, design guidelines were generated based on guidelines on Design for Maintenance, Design for Reuse, Design for Refurbishment, Design for Remanufacture, Design for Recycling, Design for Disassembly and Design for Reliability. The guidelines were clustered in five different categories: product architecture, components, materials, joints and accessories. This categorisation was based on the level of focus: first looking at the structure of the product as a whole, then zooming into the parts composing the whole and finally zooming in more into the constituents of these parts.

The application of the proposed design framework was analysed by dissecting the process and outcomes of the case study. In the graduation project, the system around the to be designed product was defined based on literature on interesting circular business models, but also various schools of thoughts and fields of research. The theoretical design framework served as a starting point for the product development. It was later translated into CE product characteristics that would enable the designed mobile device to cycle in the projected system. While the product development started by focussing on an advanced circular scenario, it quickly became clear that the mobile network operator was more keen to unravel what it would mean for products to become circular in a shorter term. As a result, building onto the design of an advanced scenario, a roadmap was backcasted identifying the various steps to be taken towards circularity. Ideas and concepts for a first step - achievable within two years - were developed using state of the art commercially available EEE technologies. The most viable and technically feasible solutions within the time frame were bundled into one final concept.

The new design was finally assessed on circularity and compared to the current mobile device designs. Disassembly possibilities, upgradability, lifetime, risks and costs were used as criteria to evaluate how circular the design was (S-RQ2). Considerable improvements were made in the regeneration of resources, however a significant amount of research and development will be required to take it to the next level.

Considering these improvements, the proposed theoretical design framework seemed to be supporting the circular product development (S-RQ3). The framework was evaluated on relevance and compatibility with the user’s prior knowledge based on the insights gained throughout the design process of the case study.

Multiple tools and methods, such as AskNature (in combination with Design Spiral), the vision and the roadmap, were found useful during the conceptual design of the mobile device for a circular economy. The draft design guidelines were also evaluated making use of this experience. At the end, 29 design guidelines were detailed for this case study. Several changes were made to the guidelines making them clearer and more relevant for the user. The categories reorganised according to their priorities. This set of guidelines could to some extent be used for product developments beyond the scope of mobile devices.

The drafted design framework could therefore be used to apply circular thinking in the first stages of product development. (RQ) After analysing the design framework used, the following steps could be taken to design this type of product:

- Start with analysing the current design of mobile phones. Research the life cycle of the product: which materials are used, production, user phase and end of life while minding the whole system around it. Define for which side of the CE model you like to design the product.
- Study the architecture of the product by taking various models apart and looking at (dis)assembly manuals. Assess the major components to start with. At this level, evaluate
the components’ price, level of repairability, lifetime, maturity and risks when it comes to criticality and hazard. Try to critically categorise all the materials using the ABC-X categorisation. Identify the inconsistencies and prioritise components to be made circular as soon as possible.

• Develop a vision for the ideal circular design of the mobile phone to be reached in for example 15 years (depending on what potentially could be realistic).

• Develop a roadmap starting from the status quo situation working towards circularity as defined by the vision. Take both system and product design into account.

• Based on this roadmap, explore several solutions for on a short term or a longer term in the transition scenario towards circularity. In this industry 2 years will seem long term but will in the scope of the whole system in infrastructure be quite short term. Commercially available solutions that have been proven could be used to begin the product design. On a longer term, the shape of the product will be difficult to prospect. Nevertheless, the focus could at this point less lay on the aesthetics of the product and more on the structure, joints, components and materials. Disassembly technologies currently being developed could be interesting to explore for this scenario.

• The 29 design guidelines could be helpful at this stage of the product development.

• Ideas could be generated using the Design Spiral and according to various Life Principles. AskNature could be consulted to emulate solutions for our human challenges based on solutions found in nature.

• Develop various concepts combining the best solutions in terms of feasibility for the targeted point in time, innovation and requirements of the client.

• Evaluate these concepts (keeping the C2C certification criteria into account) and select the best one to further develop into a final concept.

This proposal could be used as a base for further development and testing by designers. Nevertheless, some iterations will have to be done in the design guidelines that are from time to time too product specific.
Based on literature, practical activities and several interviews of stakeholders and experts, a CE roadmap, two product developments and a circular design framework for circular mobile phone designers were generated. In this final chapter, the results of the study will be evaluated and its shortcomings will be explored. Building up on this, required future research and recommendations will be given.

Research

When it comes to the research conducted, the influence of the background of the researcher, the terminology and model used, the range of fields for the application of CE, the accuracy and validity of data, and shortcoming in the areas integrated in the system and product development can be discussed.

The study and results were restricted by the researcher’s background in industrial design engineering and limited knowledge on industrial ecology. This may have impacted the interpretation of literature and narrowed the applicability of the results in other fields/industries.

The terminology used throughout this report was in line with that of the Ellen MacArthur Foundation and McKinsey & Company in the CE reports. The reader must note that a multitude of definitions exist for terms such as ‘circular’ and ‘refurbishment’. ‘Re-use’ for example has over 16 different official definitions.

Additionally, the model embodying the strategy of Circular Economy and used throughout this project, was also sourced from this same reports. Nevertheless, here again, several other circular models have been published. In addition, the value of different components used in mobile phones was considered constant in time in case the component would not degrade during usage. This assumption is debatable. No data was found confirming nor denying this.

The range of fields in which CE concepts have been applied are still limited. Scientific literature on the subject as defined by the EMF is narrow. Therefore, literature on specific topics studied independently from the system (i.e. re-use, remanufacture or disassembly) was used in the research. The applicability of these studies in combination with each other in one same system could be debatable.

The accuracy and validity throughout time of the data used for materials and components could be arguable. For instance, the criticality of materials varies according to geological and technical availability. The list of CRM is updated every 5 years and changes due to for example societal changes or technical improvements. Critical materials of today motivating stakeholders to shift to more sustainable practices to minimise risks and losses might not be critical anymore tomorrow. Depending on the scale of these changes, iterations would put a spanner in the application of circular thinking on a long term based on risk assessment. Moreover, the study and selection of the critical compounds is based upon various assumptions and has its own limitations.

In addition, the value of different components used in mobile phones was considered constant in time in case the component would not degrade during usage. This assumption is debatable. No data was found confirming nor denying this. The value of the components could be decreasing even if technically speaking they are not lowering in quality over time. Moreover, the simplification of the models and maps is restricting the accuracy of the results. Due to the time limitations of this project, multiple assumptions and simplifications had to be made potentially limiting the validity of the results. The design guidelines should for example take reliability more into account. A balance should be found between the ease of disassembly and the level of reliability of the product. More expertise and time will be required to establish this.

As the focus of this project laid on the first stages of the development of a circular product some areas have just been briefly explored. As a result, the business component of the system requires further
DISCUSSION AND RECOMMENDATIONS

research and improvement. The circular business canvas as being developed by Bas Mentink in his graduation thesis at the TU Delft could potentially be used.

Additionally, customers and their inclination to use circular services and products will need a more extensive study. Recommendations for research on this area is given in the following section on the target group.

Products

Considering the products designed, their status, the open and closed hardware options, modularity from the outside, the extent of the challenge, the DFX strategies and guidelines, and the use and validity of the guidelines will be discussed.

The concepts designed are proposals meant as a starting point for discussions on the implementation of circular characteristics into current mobile devices. Multiple points will have to be explored further. As an example, the disassembly solutions used in the concepts were selected based on current forecasts and several expert opinions. These forecasts can be iterated within a few months due to new research findings, meaning other solutions could be preferred over the ones selected in this project.

No real affinity was expressed on the notion of open and close hardware for the designed system and product for B2B and public procurement. Designing for the broader public would nevertheless require a more thought-through consideration of the two options. Several mobile device manufacturers have expressed their preference for one or the other. [102], [103] Both types of hardware disassembly could be beneficial from an environmental point of view. The preference might depend on the aimed user experience.

Modularity from the outside – using external parts and plug them into other devices to access a specific feature – was briefly mentioned but not investigated. All the functions of a mobile phone could be staked into a chip that the customer can carry around and plug into devices on its way to work or at work to send or receive texts.

Dematerialisation is a concept that has also not been discussed as such in this study. More research could be conducted on this topic to unravel opportunities of such modular blocks.

Several experts consulted have expressed their concern as to the extent of the challenge of making such a compactly engineered product more circular. This is due to the size of the components and joints coupled with the little play and tolerances allowed for the proper functioning of the product. Tablets would seem to have a lower threshold and their structure could lend itself more easily to modularity.

Multiple DFX strategies and guidelines have been analysed and used to design the two circular mobile devices. A large number of such strategies (i.e. ‘Design for Assembly’ or ‘Design for Quality’ [105] have however been left unexplored because of the scope and time limit of this project. More research should be done on these various DFX’s as others could be of interest for the development of circular guidelines and products.

On top of this, according to Hoffmann et al.[54], the design guidelines for disassembly are yet focusing too much on manual disassembly and are thus too general for automatic disassembly activities. With the development and commercialisation of more profitable automatic disassembly techniques, DfD guidelines and the CE guidelines mentioned in this research will need to be altered.

The use and validity of the formulated design framework can be tempered by the prior knowledge of the researcher on sustainable product development and the theory behind CE. Most design teams have no extensive background and experience in sustainable innovation or circular economy yet. In order to validate the guidelines, these should be tested by designers in practice during case studies.

Target group

Four main limits can be pointed out with respect to the choice of the target group, their implication in the design process and the possible application of the results to other types of users.

Several issues will have to be tackled before a green light can be given to the official targeting of public procurement. Public procurements rules have been established at a European level [106], thus quite homogeneous in this market, nonetheless the application may differ from country to country.
CHAPTER 6

Looking at the Netherlands, a fragmentation is required between landline contracts, mobile network and mobile handset procurement to outlaw monopoly problems. The exact implications of these topics have not been touched upon in this study and will require more research in the future to bring the designed system and product to fruition.

Direct contact with the B2B and public procurement employees was narrow. The selection of the target group was based on a literature research, internal data from Vodafone and the opinion of various stakeholders. These sources were also used during the two product developments.

Responses to a short questionnaire on the mobile phone features used were gathered from a very small group of respondents and the context of the work placement in the Vodafone Campus might give a tinted view of mobile phone use in a professional context. The interpretation of the results should therefore be done with awareness of the limitations of the study.

Customer behaviour will require further study to allow for the implementation and acceptance of circular products by users. Special attention should be put in customer’s perception of leased and refurbished devices. Would they be less careful with these types of product? Would the durability of the product be hindered?

It has been suggested that a circular system and product designs for B2B and public procurement could be applied to the design of circular mobile devices for a broader public later in time. The validity of these results is nonetheless undermined by inherent differences between business customers and private customers. Various iterations will be required in terms of approach of the system application and design of the product. The extent to how much customer behaviour varies between these two contexts should be thoroughly researched to create a better understanding for the design of an adapted system and product.

Moreover, the customer experience has not been developed. Other components of the product such as circular software for example should be thought through.

Sustainability

Aspects of sustainability in terms of the model used and the designed system and product can be put up for discussion.

CE is intentionally not explicitly associated to the term “sustainability” in either EMF publications nor communication with the foundation. Even though the CE model has undeniable links with environmental performance, this is not frequently emphasized for semantics reasons. This performance improvement has nevertheless yet to be proved.

Issues have been raised by several researchers with respect to the lack of quantitative analysis for some of the strategies resembling CE. Some important factors in a circular strategy, such as life span extension of appliances, are very complex to benchmark. Many designers therefore might prefer to focus on measurable aspects like energy use, material environmental impact or material reduction. Finding a balance between durability and recyclability for instance will be challenging. The EMF could support designers during product development by elaborating tools to enable for benchmarking and assist them in considering options.

According to Lifset and Lindqvist, leasing products does not automatically improve EoL management of the leased products. The authors underline the importance of designing a product not only for durability, but also keep an eye on recycling and the disposal of the products. Since this has been done throughout the product development, it might seem that the environmental impact of the designed device would be reduced.

In this project, the product designs have been researched in terms of structure, components, joints and materials having an impact on the end-of-life stage. This could improve environmental performance, however the major losses are not only at the EoL. According to Thomas, 98% of all resources end up in waste within just six months. This does not only occur at the EoL of the product, but also during its production and distribution. As a result, to take this research to the next level, the whole life cycle of the product should be taken into account. The packaging of the product should for instance also be thought through. The exact production steps should be detailed ruling out as much leakages and losses as possible.
This research mostly focussed on the technical side of the CE model and not the biological one. However, it is not clear which options are more sustainable at the end. Can human made ‘natural’ materials be as sustainable as nature designed it? What kind of materials should be preferred?

Ijomah et al. [56] identified profitability as the most important motivation paramount to organisations’ existence. In the remanufacture case study in this article, the OEM finally opted for a non-remanufacturable design due to its higher profitability and superior environmental performance during some parts of the life cycle.

Although brought up by nearly all the DfX methods and mentioned as one of the key factors to enable circularity, using DfD techniques does not automatically mean the designed product is going to be more sustainable. Bad decisions can still be made at a material level and the durability & reliability of the device is not guaranteed, making the product’s environmental impact possibly larger. The same is true with the individual analysis of CE cycles.


[41] Personal communication with Ken Webster. 2013.


[74] Personal communication with Leon Williams. 2013.


[78] Vodafone, Internal Documents.


[92] Personal communication with Hans Goossen.


[102] Personal communication with employee A. 2013.


[104] Personal communication with employee B. 2013.


[107] Personal communication with Ellen MacArthur, Ken Webster and Jo Miller from the Ellen MacArthur Foundation.” 2013.


Appendix I

Independent list of principles of various design techniques

1. Principles from R. Bogue

<table>
<thead>
<tr>
<th>Factors affecting the disassembly process</th>
<th>Guides to improve disassembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product structure</td>
<td>Create a modular design</td>
</tr>
<tr>
<td></td>
<td>Minimise the component count</td>
</tr>
<tr>
<td></td>
<td>Optimise component standardisation</td>
</tr>
<tr>
<td></td>
<td>Minimise product variants</td>
</tr>
<tr>
<td>Materials</td>
<td>Minimise the use of different materials</td>
</tr>
<tr>
<td></td>
<td>Use recyclable materials</td>
</tr>
<tr>
<td>Fasteners, joints and connections</td>
<td>Minimise the number of joints and connections</td>
</tr>
<tr>
<td></td>
<td>Make joints visible and accessible, eliminate hidden joints</td>
</tr>
<tr>
<td></td>
<td>Use joints that are easy to disassemble</td>
</tr>
<tr>
<td></td>
<td>Mark non-obvious joints</td>
</tr>
<tr>
<td></td>
<td>Use fasteners rather than adhesives</td>
</tr>
<tr>
<td>Characteristics of components for disassembly</td>
<td>Good accessibility</td>
</tr>
<tr>
<td>Disassembly conditions</td>
<td>Design for automated disassembly</td>
</tr>
<tr>
<td></td>
<td>Eliminate the need for specialised disassembly procedures</td>
</tr>
<tr>
<td></td>
<td>DFD with simple and standard tools</td>
</tr>
</tbody>
</table>

2. Principles from G. Boothroyd and L. Alting

- Use compatible materials
- Use recyclable materials including bonding aspects
- Minimize material count, using the least number of different polymers
- Minimize assembly operations
- Design for easy separation, handling and cleaning
- Simplify potential uses/users of products and parts
- Use two-way snap fits/break points on snap fits
- Provide standard, easy identification for all materials (molded-in material name or logo)
- Identify separation or cut points
- Use molded-in material name in multiple locations to accommodate cut points
- Avoid secondary finishing operations such as painting, plating, coating and so forth
- Avoid toxic materials/foams, blowing agents (CFC’s), heavy metals and so forth
- Minimize waste in production, for example by incorporating material handling programs to lower the cost of manufacturing
- Understand side effects of processes and equipment emissions, such as paint vapor and abusive molding
- Avoid inserts
<table>
<thead>
<tr>
<th>Design for Disassembly Guidelines</th>
<th>Maintenance</th>
<th>Remanufacturing</th>
<th>Materials-recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHASE I: DRAFT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear and unified disassembly direction</td>
<td>B</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Sandwich structure with central joining elements</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Base part product structure</td>
<td>B</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Standardized assembly groups for variants</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Avoid non-rigid parts</td>
<td>C</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td><strong>PHASE II: DESIGN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration of parts</td>
<td>B</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Include nominal breakpoints</td>
<td>B</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Operating spots for destroying separation tools</td>
<td>B</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Minimize number of joining elements</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Use joining elements that are detachable or easy to destroy</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Parts should be easy to pile or store to save room</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Non-ageing material combination</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Non-corrosive material combination</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Protect assembly groups from soiling or corrosion</td>
<td>A</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Design of parts for easy transport</td>
<td>C</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Limitation to number of different materials</td>
<td>B</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Integration of poisonous substances in closed units</td>
<td>A</td>
<td>C</td>
<td>X</td>
</tr>
<tr>
<td>Avoid turning operations for disassembly</td>
<td>C</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td><strong>PHASE III: SPECIFICATION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standardize parts for multiple use</td>
<td>B</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Standard and simple joining techniques</td>
<td>B</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Marking of central joining elements for disassembly</td>
<td>B</td>
<td>C</td>
<td>X</td>
</tr>
<tr>
<td>Open access and visibility at separation points</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Centre-elements on base parts</td>
<td>A</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Standard gripping spots near center of gravity</td>
<td>A</td>
<td>C</td>
<td>X</td>
</tr>
<tr>
<td>Enable simultaneous separation and disassembly</td>
<td>B</td>
<td>B</td>
<td>X</td>
</tr>
<tr>
<td>Avoid necessity for simultaneous disassembly at different joining elements</td>
<td>B</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>Use of parts with narrow tolerance</td>
<td>C</td>
<td>B</td>
<td>X</td>
</tr>
</tbody>
</table>

A: Very important  B: Important  C: Less important
3. Principles from: W. Ijomah and C. McMahon

<table>
<thead>
<tr>
<th>Process activities</th>
<th>Product/design characteristics</th>
<th>Assembly technique</th>
<th>Product structure</th>
<th>Environmental considerations/safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspect product</td>
<td>Use materials that will survive the inspection process</td>
<td>Use assembly techniques that allow easy access to inspection points Ensure that assembly methods and joint locations do not conceal product details</td>
<td>Structure to facilitate efficient and effective inspection</td>
<td>Use non-hazardous material</td>
</tr>
<tr>
<td></td>
<td>Clearly identify product material</td>
<td>Use assembly technique that will withstand the cleaning process but that will not allow disassembly without damage to components that have potential to be reused</td>
<td>Mark inspection points clearly Clearly identify product technical details, e.g. make, model and year of manufacture, etc.</td>
<td>Use environmentally friendly materials</td>
</tr>
<tr>
<td>Clean product</td>
<td>Use product materials that will survive the cleaning process Use durable materials for identification methods, e.g. avoid use of stickers as these may detach during cleaning Avoid materials that are difficult to clean, e.g. material with pitted surfaces Minimise number of different materials used in the product thus limiting use of variety of cleaning agents</td>
<td>Ensure easy access to all areas to be cleaned Ensure good resistance to dirt accumulation, e.g. avoid sharp edges and thresholds that may attract dirt Ensure ease of handling, e.g. reduce product unit weight where ever possible without limiting functionality or required durability</td>
<td>Avoid hazardous or banned cleaning agents</td>
<td>Use environmentally friendly cleaning agents</td>
</tr>
<tr>
<td></td>
<td>Use easy-clean material without cleaning residue For components destined for reuse ensure that their materials are sufficiently durable to survive disassembly Ensure that fasteners’ material are similar or compatible to that of base material thus limiting opportunity of damage to parts during disassembly</td>
<td>Use assembly methods that would allow disassembly without damage to components</td>
<td>Arrange components for ease of disassembly</td>
<td>Use environmentally friendly disassembly method and substances Consider design for disassembly techniques that would not prevent reassembly</td>
</tr>
<tr>
<td>Disassemble product</td>
<td>Use modular components thus reducing complexity of disassembly because types of assembly techniques are reduced</td>
<td>Reduce the total number of parts Reduce complexity of disassembly, for example by standardising fasteners</td>
<td>Use an environmentally friendly disassembly process should not require the use of hazardous substances</td>
<td>Disassembly process should not demand the use of hazardous substances</td>
</tr>
<tr>
<td>Process activities</td>
<td>Product/design characteristics</td>
<td>Environmental consideration/safety</td>
<td></td>
<td></td>
</tr>
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<td>--------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material Assembly technique</td>
<td>Product structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sort components</td>
<td>Identify components of similar materials Minimise the number of different materials used for parts thus facilitating component sorting Limit the number of material type per part to reduce sorting complexity Identify parts requiring similar cleaning or processing modes</td>
<td>Arrange components so that separation joints are easily accessible and easily identifiable Minimise the number of joints Reduce/eliminate redundant parts Simplify and standardise component fits Reduce/eliminate redundant parts thus limiting sorting time and expense Use reusable components Ensure that parts that can be remanufactured can be reconditioned or repaired or in the worst case scenario can be recycled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean components</td>
<td>Use material that would survive cleaning process Use components that all require or at least can be divided into groups that require similar cleaning agents and procedures E.g. limit the number of material types per part Identify components requiring similar cleaning procedures and agents</td>
<td>Use assembly methods that allow disassembly at least to the point that internal components can be accessed for cleaning Ensure that all parts to be cleaned are easily accessed Do not use banned cleaning chemicals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remanufacture/replace components</td>
<td>Use materials that are at least durable enough to survive the refurbishment process Use materials that do not prevent upgrade and rebuilding of the product</td>
<td>Use assembly methods that would allow disassembly at least to the point that internal components and sub-systems requiring it can be accessed Use assembly methods that do not prevent upgrade of product Ensure replacements for unremanufacturable components are at least recyclable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test components</td>
<td>Identify component material</td>
<td>Arrange components so that parts that are prone to damage are easily accessible Standardise parts Use environmentally friendly test procedures and methods Limit resource used in test, e.g. energy, electricity, water, etc. Structure to ensure ease in determining component condition Component structure should be such that testing is sequential in that it mirrors the order in which the product is assembled Minimise the disassembly level required to effectively test components Reduce test complexity Clearly identify component load limits, tolerances and adjustments Standardise tests</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 4. Principles from T. Dowie and M. Simon

<table>
<thead>
<tr>
<th>A. Materials</th>
<th>Reason for guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Minimise the number of different types of material.</td>
<td>Simplify the recycling process.</td>
</tr>
<tr>
<td>2. Make subassemblies and inseparably connected parts from the same or a compatible material.</td>
<td>Reduce the need for disassembly and sorting.</td>
</tr>
<tr>
<td>3. Mark all plastic and similar parts for ease of identification.</td>
<td>Many materials' value is increased by accurate identification and sorting.</td>
</tr>
<tr>
<td>4. Use materials which can be recycled</td>
<td>Minimise waste. Increase the end-of-life value of the product.</td>
</tr>
<tr>
<td>5. Use recyclable materials.</td>
<td>Stimulate the market for recyclates.</td>
</tr>
<tr>
<td>6. Ensure compatibility of ink where printing is required on plastic parts.</td>
<td>Maintain maximum value of recovered material.</td>
</tr>
<tr>
<td>7. Eliminate incompatible labels on plastic parts.</td>
<td>Avoid costly label removal or sorting operations.</td>
</tr>
<tr>
<td>8. Hazardous parts should be clearly marked and easily removed.</td>
<td>Rapidly eliminate parts of negative value.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Fasteners &amp; Connections</th>
<th>Reason for guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. Minimise the number of fasteners</td>
<td>Most disassembly time is fastener removal.</td>
</tr>
<tr>
<td>10. Minimise the number of fastener removal tools needed</td>
<td>Tool changing costs time.</td>
</tr>
<tr>
<td>11. Fasteners should be easy to remove</td>
<td>Save time in disassembly.</td>
</tr>
<tr>
<td>12. Fastening points should be easy to access</td>
<td>Awkward movements slow down manual disassembly.</td>
</tr>
<tr>
<td>13. Snap-fits should be obviously located and able to be disassembled using standard tools</td>
<td>Special tools may not be identified or available.</td>
</tr>
<tr>
<td>14. Try to use fasteners of material compatible with the parts connected</td>
<td>Enables disassembly operations to be avoided.</td>
</tr>
<tr>
<td>15. If two parts cannot be compatible make them easy to separate</td>
<td></td>
</tr>
<tr>
<td>16. Eliminate adhesives unless compatible with both parts joined</td>
<td>Many adhesives cause contamination of materials.</td>
</tr>
<tr>
<td>17. Minimise the number and length of interconnecting wires or cables used</td>
<td>Flexible elements slow to remove; copper contaminates steel, etc.</td>
</tr>
<tr>
<td>18. Connections can be designed to break as an alternative to removing fasteners</td>
<td>Fracture is a fast disassembly operation.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Product Structure</th>
<th>Reason for guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>19. Minimise the number of parts.</td>
<td>Reduce disassembly.</td>
</tr>
<tr>
<td>20. Make designs as modular as possible, with separation of functions.</td>
<td>Allows options of service, upgrade or recycle.</td>
</tr>
<tr>
<td>21. Locate unrecyclable parts in one area which can be quickly removed and discarded.</td>
<td>Speeds disassembly - see no 8.</td>
</tr>
<tr>
<td>22. Locate parts with the highest value in easily accessible places.</td>
<td>Enables partial disassembly for optimum return.</td>
</tr>
<tr>
<td>24. Avoid moulded-in metal inserts or reinforcements in plastic parts.</td>
<td>Creates the need for shredding and separation.</td>
</tr>
<tr>
<td>25. Access and break points should be made obvious.</td>
<td>Logical structure speeds disassembly and training.</td>
</tr>
</tbody>
</table>
5. Principles from J. Chiodo

Component Design & Product Architecture

Design for Disassembly through component design and product architecture shares many of the principles used in design for assembly. Designers should:

• Minimise the number of components used in an assembly, either by integrating parts or through system re-design
• Minimise the number of material types used in an assembly
• Separate working components into modular sub-assemblies
• Construct sub-assemblies in planes which do not affect the function of the components
• Avoid using laminates which require separation prior to re-use
• Avoid painting parts as only a small percentage of paint can contaminate and prevent an entire batch of plastic from being recycled.

Use of Fasteners

Fasteners play an integral part in the joining of components and subassemblies. Designers should:

• Minimise the number of fasteners used within an assembly.
• Minimise the types of fastener used within an assembly.
• Standardise the fasteners used.
• Not compromise the structural qualities of the assembly by using too few or inadequate fasteners.
• Use snap-fits where possible to eliminate the need for a fastener
• Consider work-hardening, fracture, fatigue failure and general wear when designing snap-fits.
• Consider the use of destructive fasteners or those incorporating ADSM technology.
### Appendix II

**Advantages and Disadvantages of the various concepts**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Solutions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Current cover</td>
<td>Familiar design for oem, customer and repairer, already tested and successful, no tools required</td>
<td>Requires the use of an inside structure for strength and stiffness</td>
</tr>
<tr>
<td></td>
<td>Frame parts for the LCD</td>
<td>Fast and easy disassembly, no tools required, cheap, keeps the lcd tightly to the front panel</td>
<td>Moving parts, can wear, add volume</td>
</tr>
<tr>
<td></td>
<td>PC memory clicking system for the chipsets</td>
<td>Modular solution, fast and easy disassembly, no tools required</td>
<td>Very voluminous, not yet used in, no manufacturer, combined with frame part (see above)</td>
</tr>
<tr>
<td></td>
<td>Integrated assembly, cliphold system</td>
<td>Adds strength and stiffness to the assembly, battery and sim can be placed in and removed easily without tools</td>
<td>Adds volume, extra material use, extra time required to access pcb and other internal parts, requires extra disassembly time, extra parts that could wear. Could be less reliable</td>
</tr>
<tr>
<td>2</td>
<td>Heat allowing for disassembly front panel and body of the product</td>
<td>Durable and secure joint, already widely used in the industry</td>
<td>Disassembly requires the use of a tool, takes time, could cause damages</td>
</tr>
<tr>
<td></td>
<td>Metallic frame and screws to hold LCD on front panel</td>
<td>Secure fitting of the lcd screen onto the front panel</td>
<td>Extra material, extra weight, increases volume, threads needed in the front panel</td>
</tr>
<tr>
<td></td>
<td>EMI shield/screws</td>
<td>Uses less material as it integrates multiple functions, partially already commercially launched</td>
<td>Requires a screwdriver, adds volume, thread is needed in the rear panel</td>
</tr>
<tr>
<td></td>
<td>Snap fits onto rear panel for pcb, battery and other components</td>
<td>Modular solution, fast and easy disassembly, no tools required</td>
<td>Moving parts, can wear, add volume</td>
</tr>
<tr>
<td>3</td>
<td>Clicking system for display assembly</td>
<td>Modular solution, fast and easy disassembly, no tools required</td>
<td>Prying for disassembly could cause damages, parts could wear, reliability unknown</td>
</tr>
<tr>
<td></td>
<td>Snap fits LCD/front panel</td>
<td>Fast and easy disassembly, no tools required, cheap, keeps the lcd tightly to the front panel</td>
<td>Parts could wear, reliability unknown</td>
</tr>
<tr>
<td></td>
<td>Hp Z1 lever system chipset</td>
<td>Already commercially launched, modular solution, fast and easy disassembly, no tools required</td>
<td>Requires more materials, augments volume, adds weight</td>
</tr>
<tr>
<td></td>
<td>Outer frame to put display and rear panel on each side, internal components screwed onto the outer frame</td>
<td>Components are accessible from both front and back, disassembly of one component does not require the total disassembly of the product thus potentially causing unnecessary damages to working pieces, could absorb all the forces without damaging the inside components</td>
<td>May be difficult to produce, moving parts could wear, screws add weight, require thread</td>
</tr>
</tbody>
</table>
Appendix III
Evaluation of the Design Guidelines

<table>
<thead>
<tr>
<th>Category</th>
<th>Drafted Design Guideline</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product structure</td>
<td>• Minimise the number of components used in an assembly can be done by integrating parts or through system re-design simplifies the disassembly process and restricts labour, energy, material and financial input. Can be applied when the elimination of components does not alter the proper functioning of the device, Reduces the labour time and costs of the disassembly, potentially reduces environmental impact (less energy, less materials, less emissions etc during production)</td>
<td>• Requires more details. What does ‘minimise’ mean? To what is it limited? When is it applicable? Integrating parts could make parts more difficult to manufacture or obstruct accessibility of other part. Where is the balance?</td>
</tr>
<tr>
<td></td>
<td>• Make designs as modular as possible (by separating functions) Facilitates replacement, upgrade and recycling of components</td>
<td>• Requires more details. Specify the meaning of ‘modular’ and ‘functions’ for EEE. How far can this be taken? Details are needed on how to facilitate it. Not clear how to do this.</td>
</tr>
<tr>
<td></td>
<td>• Optimise component standardisation Facilitates replacement and repair (parts supply), enables cross-product remanufacturing and simpler dismantling processes (as it is easier to understand assembly)</td>
<td>• The meaning of ‘good’ and ‘accessibility’ is unclear. For who and what for should it be made accessible?</td>
</tr>
<tr>
<td></td>
<td>• Good accessibility of parts in order to maintain a low disassembly time, to disassemble without damaging components and to ensure parts can be easily cleaned for refurbishment</td>
<td>• Precision is needed on the components with highest value. Explanation would be required as to why this is essential. Detail what type of components these could be.</td>
</tr>
<tr>
<td></td>
<td>• Make components with highest value easiest to access Optimum return</td>
<td>• Describe how stability can be achieved. Dirt accumulation has not been discussed, but could be quite important for the durability of the product.</td>
</tr>
<tr>
<td></td>
<td>• Hazardous components should be easy to remove Fast elimination of hazardous compounds from the stream of materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Design parts for a stable disassembly Faster manual disassembly</td>
<td></td>
</tr>
</tbody>
</table>
# APPENDICES

## Components

- **Non fragile parts**  
  To extend product durability, especially for components destined for reuse
- **Low weight parts**  
  Eases manual disassembly

- Minimise length of wires and cables  
  Flexible elements are slower to remove than rigid ones
- Avoid non-reversible contamination of components with for example surface coating

## Materials

- **Minimise the number of material types**  
  Simplifies recycling process
- **Prefer pure-material parts**  
  Simplifies recycling process, reduces need for disassembly and sorting. When not possible, make them easy to separate
- **Select recyclable materials**  
  Minimises leakages to landfill and energy recovery and increases EoL value of the product
- **Select recycled materials**  
  Stimulates market for recyclates

- **Materials from components to be reused should withstand cleaning process**  
  So as to ensure no damages occur during the refurbishment and remanufacturing of components
- **Eliminate the use of toxic or hazardous materials as much as possible**  
  Decreases environmental, health and safety impact
- **Make materials identifiable**  
  Accurate identification and sorting increases the material’s value
- **Ensure fastener’s material are compatible with that of the base material**  
  Limiting potential damage to parts during disassembly

- **Details are needed on the mechanical properties linked to fragility. How is this parameter measurable?**
- **Describe what low weight means. This is however going against the issue of (too) small concentrations of elements to enable for an effective and efficient recycling. [Okala]**  
  On top of this the weights are already very small in the product. This rule is thus quite redundant...
- **Detail on the length.**
- **Detail how. What if you really have to paint it for durability reasons?**

- **Also what type of material types should be favored? What is it depending on?**
- **Detail the meaning of purity**

- **Precise a database that can be used. What should be prioritised? Recyclable or recycled?**  
  Detail to prefer the highest recycling rates.
- **Precise a database that can be used.**  
  At the start of the roadmap, it is possible that not all materials adequate are available in a recycled form or at least not in a proper manner. Beware of the required infrastructures
- **Detail what constitutes the cleaning process.**

- **Where can a database be find of these toxic and hazardous materials?**  
  Add to prefer P list materials (C2C) and eliminate carcogenic compounds etc from the product design.
- **Describe what type of techniques could be used or are already used. But remember it should not contaminate the stream of materials (so no labels, but rather etching, moulding)**
- **Detail the meaning of compatibility.**
<table>
<thead>
<tr>
<th>Joints</th>
<th></th>
</tr>
</thead>
</table>
| • Disassembly must be performed using simple and standard tools  
  Reduces disassembly time and disassembly & tooling costs  
  • Minimise the number of joints  
  Without compromising the structural qualities of the assembly by using too few or inadequate joints.  
  Reduces the disassembly time tremendously and thus costs  
  • Make joints visible and accessible and emphasize non obvious joints  
  The logical structure speeds up the disassembly and training processes. Several use cues such as colours, symbols, notches etc  
  • Standardise the joints used  
  Decreases complexity of the assembly and number of tools required for disassembly  
  • Use snapfits where possible to eliminate the need for fastener  
  • Use fasteners rather than adhesives  
  Only in case adhesives are vital and snapfits are not possible to apply  
  Fasteners are less permanent and easier to tear down than adhesives  
  • Consider work-hardening, fracture, fatigue failure and general wear when designing snapfits  
  In order to increase durability of the product and components  
  • Consider the use of active disassembly | • The use of no tools should be emphasized. What types of tools could be used?  
  Automated disassembly should also be taken into account though.  
  • Requires more details. What does 'minimise' means? To what is it limited? When is it applicable? Add what the overall aim is:  
  minimise the time required to separate the product into parts. Plus design sub-assemblies so they are easily separated into fragments with different waste treatments. Should you also minimise the types of joints?  
  • Requires details.  
  • Needs more details.  
  • What type of snapfits? When is it possible? In conflict with the rule above.  
  • Why is this required exactly? Does not make sense after talking about fasteners. Use Bayern guidelines  
  • Describe active disassembly and databases that could be used for information |