Modular Products: Smartphone Design from a Circular Economy Perspective

Karsten Schischke*[1], Marina Proske[1], Nils F. Nissen[1], Klaus-Dieter Lang[1,2]

[1] Fraunhofer IZM, Berlin, Germany
[2] Technische Universität Berlin, Berlin, Germany

* Corresponding Author, karsten.schischke@izm.fraunhofer.de, +49 30 464 03 156

Abstract

Currently a range of modular smartphones is emerging, including the Fairphone 2, Puzzlephone, Google's Project ARA, RePhone, LG's G5 and others. In an industry of perceived short product cycles a modular design concept might become crucial for longer product lifetimes. The paper provides an overview on latest product developments and assesses these against environmental criteria, including longevity, durability, upgradeability, repairability and Design for Recycling and Reuse.

Modular product design however is not necessarily the most sustainable design option. Modularity first of all means inevitably more material consumption, as additional sub-housing and universal connectors are required, partly also a larger total product volume to allow for incorporation of the maximum potential configuration and anticipated future technologies. This has to pay off through a significantly longer use of individual devices and modules. It depends furthermore on the user, if the intended replacement of broken modules by new ones helps to keep whole devices in use much longer or if the user just replaces individual modules much more frequently to keep pace with latest technology features.

1 Introduction

Looking at Life Cycle Assessments of smartphones unveils, that production is dominating the life cycle impacts and that (even optimal) recycling can yield only marginal credits. Apple states for the iPhone SE a total carbon footprint of 75 kg CO_2-eq., thereof 82% allocated to the cradle-to-gate production of the phone alone [1]. No credits for recycling are stated, but it can be assumed, that even optimal material recycling a carbon footprint credit equalling at best 10-20% of the production impacts can be achieved. Under these conditions a long product and component use time seems to be the most sustainable way of smartphone usage.

In 2013 tablet computers have been disassembled at Fraunhofer labs to assess the dismantling features of mobile devices [2]. According to these analyses the material content of tablet computers sold worldwide in 2013 includes 20,000 tonnes of Li-ion batteries with a significant content of cobalt, 10,000 tonnes aluminium, but also a total of 2,000 tonnes magnesium [3].

Figure 1: Internal design of tablet computers [4]

One of the major findings of the Fraunhofer disassembly study, which was co-financed by the Green Electronics Council, was the distinction of two main tablet archetypes: Those with aluminium housing and those with a plastics housing, which usually achieve the required stiffness by an internal magnesium frame. About 5,000 tonnes of high-grade printed circuit boards made it into the roughly 200 million tablets sold worldwide in 2013. Keeping these materials in use for long and recycling a major share thereof at high material recovery rates is challenging. Although a general trend can be observed, that tablets are difficult to recycle, there are also some promising design options found among individual brands. The aspect of modularity has been found not to have been considered at all among the disassembled tablets. Best case in terms of modularity is a removable battery, accessible from the backside of a tablet, as found in two of the models [2].

Comparison of the internal structure of tablets however unveils, that tablets are already arranged in modules, as shown on the example of two typical tablets in figure 1: Display (removed), shell / back cover, electronics and battery are all clearly distinct parts of a tablet – but extremely connected through screws, clips, cables, connectors, adhesive, solder or otherwise. A similar assembly structure is found in smartphones as well.

2 Modularity

The term "modularity" has to be defined before discussing environmental impacts. From a product architecture perspective, modularity can be discussed on several levels. From a circular economy perspective, modularity shall be understood in this research as a potential contributor to resource efficiency.

2.1 Definition

Modules in a modular product are structurally independent elements or sub-assemblies with clearly defined interfaces [5]. Interfaces are non-permanent interconnections.

"Modularity" starts with an easily removable battery (example for a sub-assembly with a clearly defined interface) and mono-material back cover (example for a structurally independent element) as seen in the first generation Fairphone and other devices on the market. The next level is a platform, which allows the manufacturer to ship individually configured units. The RePhone follows such a design philosophy, and allows professional and semi-professional developers to configure a smartphone. Among tablets the Click ARM can serve as an example for such a platform, where in particular the mainboard can accommodate various electronics modules (see Figure 2).

photo by courtesy of imasD

Figure 2: Inner frame of the Click ARM tablet with mainboard and attached modules

Next, modularity can mean, that the user can replace easily some key subassemblies (or modules) when a repair is needed or more powerful components are wanted. Examples are the Fairphone 2, where the housing has to be opened to access individual building blocks of the smartphone (see Figure 3), the Puzzlephone, which will be made of only three modules (Figure 4), the battery, the display and the main electronics part, all connected through a standardized interface [6], or the Google ARA project, inspired by the earlier Phonebloks concept [7], where numerous modules can be attached to an endo skeleton. The Google ARA concept however has been revised recently and has little in common now with the initial extremely modular approach.

photo by courtesy of Fairphone B.V.,
Attribution-NonCommercial-ShareAlike CC BY-NC-SA

Figure 3: Fairphone 2, disassembled

Actually, the Fairphone 2 seems to have solved one of the main technical contradictions found in Fraunhofer's disassembly study: The Fairphone 2, according to information by Fairphone [8], features a high level of ruggedness and is at the same time easy to open and repair. Usually those devices, which are very robust also withstand mechanical force to open them for recycling.

Some of the aforementioned concepts also allow for a shared product platform and cascade reuse of modules in other applications after first life, such as microcomputers and home automation devices.

The development of smart modular devices and of the Puzzlephone in particular is currently researched in the Horizon 2020 project sustainablySMART, [9].

Based on these examples, modularity can be distinguished as listed in Table 1. Given the environmental life cycle profile explained above, these levels also represent a kind of environmental hierarchy, material modularity being the lowest level of environmental improvements and corresponding to the traditional Design for Recycling approach. Add-on modularity is rather a convenience aspect only, as only peripheral functionalities are added or exchanged, the lifetime of the core parts is not assumed to change through add-on modules.

❶ The *Brain* contains critical electronics: the CPU, GPU, RAM, memory, and cameras.

❷ The *Spine* is the structure: the high-res display. Core spine elements will be available in a variety of sizes and materials.

❸ The *Heart* contains the battery: it will be the enabler of secondary electronics and features chosen by the user.

photo by courtesy of Circular Devices Oy

Figure 4: Puzzlephone

Modularity level	**Characteristics**	**Conventional environmental design strategy**	**Examples of mobile devices** (design studies, development projects, and products)
Add-on modularity	Range of peripheral functionalities can be attached to a given core (display-CPU unit)	Not applicable	Google ARA (2016), LG G5, Thuraya's SatSleeve for iPhones to enable satellite communication and other third party extensions to smartphones
Material modularity	Some materials, such as covers and batteries can be easily separated	Design for recycling	Fairphone 1 and several other conventional smartphones
Platform modularity	Product can be configured for a range of individual specs, configuration requires a basic technical knowledge	Potentially Design for Repair / Refurbishment / Reuse depending on interconnect technology	Click ARM tablet, RePhone
Repair modularity	Key components can be easily exchanged	Design for Repair / Refurbishment / Reuse	Fairphone 2
Mix & match modularity	Range of specs for all modules, upgradeable, joint backbone and/or standardized module interfaces, ultimately hot-swapping is an option, maximum flexibility; includes repair modularity	Not applicable	Phonebloks, Google ARA (2015), PuzzlePhone

Table 1: Definition of modularity levels

A product can incorporate several of the above stated modularity strategies. This becomes evident, when looking at any laptop or PC with CPU socket, DIMM memory socket, graphics card PCI slot: material modularity (PC housing), platform modularity, repair modularity, mix & match modularity are all found in these designs, but hardly yet in tablets or smartphones due to shrunk form factors. Or in other words: The art of modularity for smartphones is to squeeze the modularity of PCs into the size of a palm.

2.2 Environmental considerations

Modular product design however is not necessarily the most sustainable design option. Modularity first of all means inevitably more material consumption, as additional sub-housing and universal connectors are required, partly also a larger total product volume to allow for incorporation of the maximum potential configuration and anticipated future technologies, see the design of the Click ARM mainboard, which requires a larger substrate footprint than a board, which is designed for only one distinct configuration. This has to pay off through a significantly longer use of individual devices and modules.

Modules require connectors: In the case of Google ARA ("spiral 2") the connector pads on the endo skeleton were supposed to be copper with a 30 µm gold finish [10], which significantly influences the environmental impacts in production. Mechanical fixation was meant to be realised through magnets [11]: On the endo side NdFeB permanent magnets and Alnico magnets (containing 5–24% Co) with a coil to switch on/off magnetic force of the endo were foreseen, and on the module side a Hiperco-50 alloy insert (48.75% Cobalt). This solution is now obsolete, but still demonstrates, how modular design first of all can increase the consumption of some critical raw materials. Also the Fairphone 2 uses additional gold connectors to connect the modules, quantification of this effect in terms of a Life Cycle Assessment is still pending.

It depends furthermore on the user, if the intended replacement of broken modules by new ones helps to keep whole devices in use much longer or if the user just replaces individual modules much more frequently to keep pace with latest technology features. Mix & match modularity bears the risk of a significant rebound effect.

Evidence from market surveys shows, that only a limited number of product replacements, i.e. short product lifetimes, are due to technical failures and much more frequently users tend to see tablets and smartphones as a status symbol, and as such owing latest generation devices is important to many. In the case of modular smartphones only the coming road tests will show, how use and consumption patterns actually will be influenced through such a disruptive technology change.

3 Design for a Circular Economy

The Ellen MacArthur Foundation defines the circular economy as follows [12]: "A circular economy is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." The term "highest utility and value" for modern IT means keeping it functional, not breaking it down into materials only.

A modular design has to be matched with circular economy principles to reap the full resource saving potential.

The concept of the Circular Economy is illustrated by the butterfly diagram of the Ellen MacArthur Foundation. The technical materials wing of this diagram is adapted in Figure 5 to illustrate the various design approaches in support of a circular economy.

Although the circular economy discussion frequently focusses on recycling, this should not be the top priority. Actually recycling "is a radical value reducer" [13]. For high-tech products the first three inner cycles of maintenance, reuse/redistribute und refurbish/remanufacture are almost similarly important, i.e. sustainable. Recycling is better than combustion or landfilling, but a lot of invested resources and energy is inevitably lost in such a cycle.

Bakker et al. [13] define six product design strategies for circular business models:

- #1 Attachment & Trust
- #2 Durability
- #3 Standardization & Compatibility
- #4 Ease of Maintenance & Repair
- #5 Upgradability & Adaptability
- #6 Dis- & Reassembly

For different products these design strategies are not equally important and they can be implemented in very different ways. For smartphones, and the approach of a modular product in particular, these design strategies can be described as follows, citations taken from Bakker et al. [13].

3.1 Attachment & Trust

Users are supposed to develop a certain bond with the objects they use. The designer however has not full control over attachment and trust, and context and user psychology are important factors which hardly can be predicted. A trigger to discontinue the use of a product is frequently a kind of disturbing change, “such as a noise, a dent, a stiff hinge or similar”. Affordability of a new product is also an aspect of attachment. Bakker et al. describe smartphones as “handheld extension of individual preoccupations”. Smartphones are highly personalized devices, characterized by apps, sounds, and content. Bakker et al. state for smartphones, that “the object as such doesn’t really matter all that much, as long as you can find it. You won’t replace it as long as you can trust it to sufficiently recharge.” This statement might be worthwhile to be challenged, as several surveys indicate, that a defect battery or a reduced battery capacity is not the dominating factor to replace a smartphone. Also brand image in the smartphone business seems to be much more relevant, than Bakker’s statement implies. For a modular design this means, that modularity should enhance attachment and trust. Attachment could be achieved through personalizing a device: Modules make it unique. The first Google ARA approaches strongly supported such an attachment philosophy by suggesting very individual designs of modules.

An important facilitator for attachment is open source: Having extended control also over the software and the operating system in particular, being able to adapt and adjust functionalities of modules or even to create own modules is highly relevant for some users. This open source aspect has been important for the Phonebloks idea right from the beginning.

Trust also has to do with believing in a long lifetime: In the case of smartphones the assumption of a low product quality and short lifetime by the consumer leads to a lower willingness to repair and a shorter usetime [14].

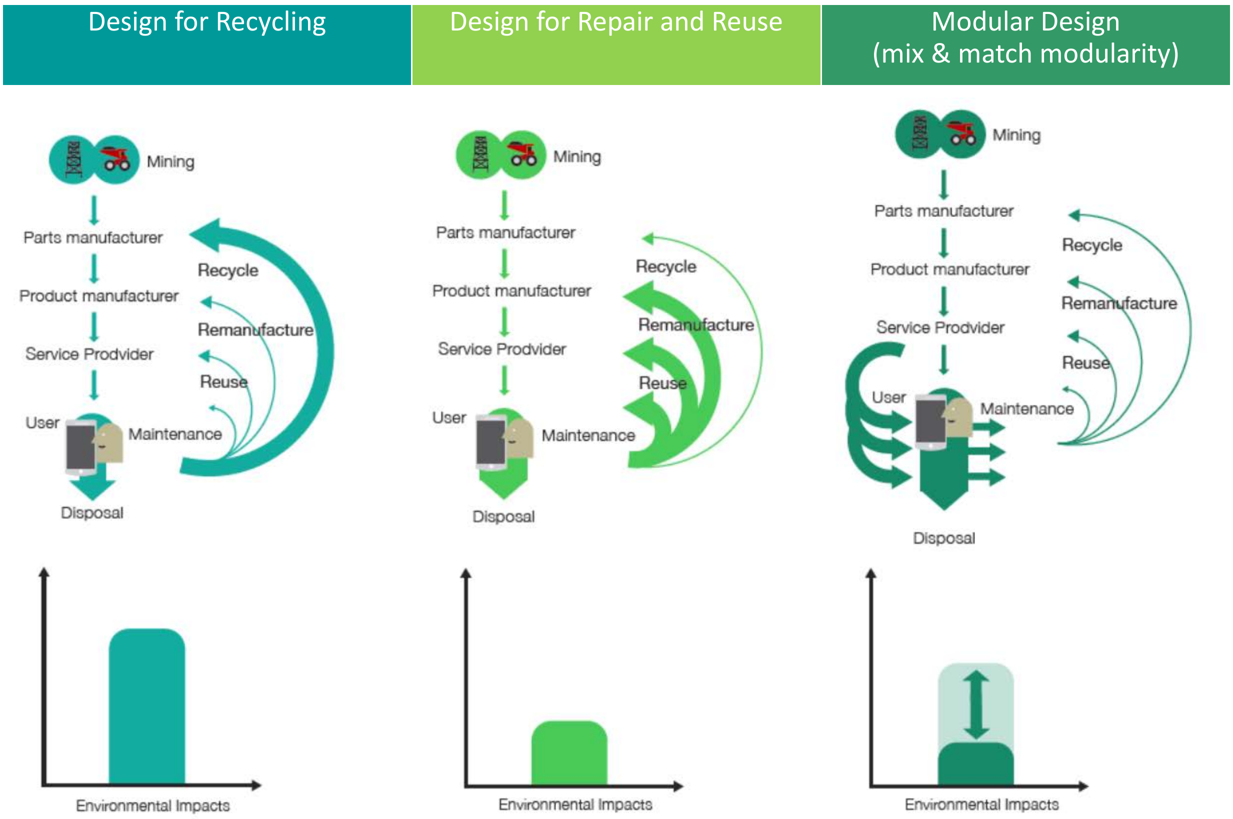

Figure 5: Design approaches for a circular economy

3.2 Durability

Design for Durability is based on defining optimum product reliability, which is a technical aspect. A product’s durability – or longevity - and the optimum reliability should be aligned with the economic and stylistic lifespan, i.e. designing a product for a longer lifespan than what is likely to be achievable due to other lifetime constraints is not necessarily required. Durability is about testing a product against assumptions about how the product is going to be used. This is also about imagination, what could happen to a product throughout its lifetime and about establishing mission profiles. This first aspect of durability is per-

ISBN 978-3-00-053763-9

ceived to be rather an argument against modularity, as additional interfaces and connectors are typically weak spots in terms of reliability. The mechanical flexibility of some module connector designs however can be also more reliable than a rigid connection technology.

Bakker et al. point out, that technical reliability is key, but that also reliability perception plays a role as well, explained on the example of printers: Users tend to accept occasional paper jams they themselves can fix within seconds over less frequent paper jams, which require external service staff to fix it and result in longer standstill times. Translating this finding to modular smartphones means that enabling Do-it-yourself repair through modularity contributes to durability.

Repairability will however not yield a tremendous breakthrough for smartphone lifetime: A better performance of a new phone and contracts, featuring frequently new phones are the dominating reasons to go for a new smartphone. Device defects or a weak battery are next, but not the most important reasons [15].

3.3 Standardization & Compatibility

Following certain standards is meant to result in compatibility. When products are connected to other parts, devices or systems it becomes evident, that lifecycles in most cases are not synchronized. An example are standardized power supplies for mobile phones: USB charging through Micro USB-B connectors became a standard through EN 62684:2010 [16], but with the introduction of the USB Type-C standard for higher data transfer rates and higher power transmission the industries' commitment for universal power supplies is obsolete. However, the USB standards have longer lifecycles than smartphones, and compatibility of chargers over several device generations is a good example of resource efficiency through compatibility.

The related business model might rely on applying standards or – if a company is in the right position – to set standards. Compatibility refers to both, hardware and software.

Compatibility is key for platform modularity and mix & match modularity. Several modular phone concepts rely on proprietary standards, such as Google ARA, RePhone and Puzzlephone, but there is no initiative yet to standardize interfaces across different modular phones. Google and Circular Devices, the compony behind Puzzlephone, however follow a business concept, where the specification of the interfaces is supposed to be published, allowing third parties to join the ecosystem and to develop customized compatible modules.

3.4 Ease of Maintenance & Repair

Design for ease of maintenance and repair is a complex task, as it has to address several players in a product life cycle, which is the original manufacturer, service providers and users. Actually a key question is who is supposed to care for maintenance and repair, as design decisions have to be made differently. The better the user is enabled to maintain and repair the product the higher is the chance that this leads to an optimized product lifetime. Ease of maintenance and repair means also easily exchangeable parts. Design for maintenance and repair in particular pays off, when the business model is built on providing a service instead of selling a product and if product ownership remains with the supplier. This business concept is implemented broadly in the business to business domain but much less for consumer products. Ease of maintenance and repair also requires solid knowledge about the parts, which require typically maintenance and repair. Only then design can address these aspects properly.

Smartphone displays are a typical part, which frequently requires repair due to accidental damage and therefore displays are a priority candidate for being modularized. As it is typically the front glass, which breaks, but not the display module as such, a non-permanent fixation of front glass and display module is the next level of repair enabling modularization.

3.5 Upgradability & Adaptability

Adaptation includes addressing different functions by part exchange. Upgradability is much more challenging and less common, as it has to anticipate future technology developments and how the product can be changed to reap these future possibilities: "The further design ideas are projected into the future, the larger the uncertainty becomes". Design for upgradability and adaptability requires a scenario that is projected well into the future. The scenario of change can be divided into functional levels, some of which will change very slowly.

Adaptability through a modular concept might have an adverse sustainability effect, namely that the adaptability just makes it too easy and comfortable to exchange modules, which might increase the amount of waste instead of slowing down the technology throughput of the technosphere.

On the other hand, smartphone users are used to seize the potential of ever increasing performance: A survey in Austria showed, that the main reasons to replace a mobile phone are the limited operability (31,4%), the better performance of a new one (22,8%), and that the old phone did not match with the individual requirements anymore (22,0%) [14]. User expectations grow, performance of a modular smartphone should do as well.

Environmentally speaking it sounds simple: The product shall meet the users' performance requirements. Oversizing right from the beginning means an extensive environmental footprint for features, which are not used. An example is storage: Memory contributes very significantly to the production related environmental impacts of smartphones. Less memory capacity means lower impact. Limited storage on the other hand might mean a relevant limitation to performance for a user at a certain point of time, letting him consider a replacement of the smartphone. Modular storage upgrade, i.e. extension, for which there is already a kind of modular solution (microSD card slots as seen in the Fairphone but also several conventional smartphones), allows for performance upgrades, when it is needed. Even only shifting the production of memory components into the future through a modular approach is an environmental advantage: Semiconductor technology progresses rapidly and same memory capacity can be produced with lower environmental impacts, if latest technology is used.

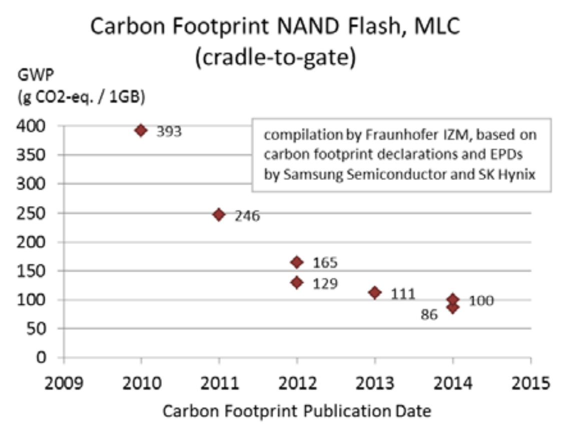

Figure 6: Carbon footprint of NAND Flash memory semiconductors (typically BGA packages)

Figure 6 depicts the carbon footprint of NAND Flash production (cradle-to-gate) compiled from product declarations of leading memory manufacturers: NAND Flash produced in 2010 (date of publication of the declaration) in 40nm technology had a carbon footprint of almost 400 g CO2-eq. per Gigabite storage capacity. This figure dropped below 100 g CO2-eq. per GB in 2014 with 10nm technology.

3.6 Dis- & Reassembly

To ease disassembly as an eco-design measure typically targets at recycling processes, whatever these might be, although typically a manual disassembly is understood to be the main targeted approach for end of life. The connection of disassembly with reassembly adds an additional perspective to design, as it requires a non-destructive disassembly and the possibility to put together the whole product from pieces. Reassembly is important for the three strategies compatibility, maintenance and repair, upgrading and adaptation, but may also include assembly with components of other products to become something different. To ease and speed up the process of disassembly and reassembly is one of the main assets of modular product design.

4 Modularity as Enabler for a Circular Economy

Comparing the various levels of modularity with the design strategies described by Bakker et al. unveils how well modular design fits into the concept of a circular economy (Table 2): It is evident that material modularity of smartphones is not a perfect match for a circular economy. Add-on modularity has some circular economy elements, but no obvious correlation to many of the strategies. Platform modularity, repair modularity, and mix & match modularity all have a correlation with (almost) all design strategies. It should be however noted, that every field of this matrix still leaves room for manoeuvre: Explained on the example of platform modularity and the design strategy standardization and compatibility it might be the case, that the technology platform is only compatible with the modules of one manufacturer – or with modules from many, compatibility might be given only for one product generation – or across many generations. The latter in both cases presumably is the better enabler for a circular economy.

Furthermore, this correspondence between modularity and circular economy design strategies does not mean, that a non-modular smartphone is in contradiction to a circular economy. This aspect just has not been analysed in this paper, and an everlasting "mono-block smartphone", which can be software upgraded over a long period of time of course could very well fit into the concept of a circular economy.

5 Acknowledgement

The project sustainablySMART has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 680640.

		Design for Circular Economy strategies					
	Matrix legend: o : no relevant correlation + : positive correlation ++ : very strong correlation	#1 Attachment & Trust	#2 Durability	#3 Standardization & Compatibility	#4 Ease of Maintenance & Repair	#5 Upgradability & Adaptability	#6 Dis- & Reassembly
Modularity level	**Add-on modularity**	++	o	+	o	+	o
	Material modularity	o	o	o	o	o	++
	Platform modularity	+	+	+	+	+	+
	Repair modularity	++ (1)	+	+	+	o	++
	Mix & match modularity	++	+	+	+	++	++

(1) assuming attachment to a self-repaired device is significantly increased

Table 2: Matching modularity levels with Design for Circular Economy strategies

6 Literature

[1] Apple Inc.: iPhone SE - Environmental Report, March 2016

[2] K. Schischke, L. Stobbe, S. Scheiber, M. Oerter, T. Nowak, A. Schlösser, H. Riedel, N. F. Nissen: Disassembly Analysis of Slates: Design for Repair and Recycling Evaluation, Berlin, 2013

[3] K. Schischke, N. F. Nissen, L. Stobbe, M. Oerter, S. Scheiber, A. Schlösser, G. Dimitrova, P. Genz, K.-D. Lang: Ansätze zur stofflichen Verwertung von Tablets aus Sicht des Produktdesigns, Recycling und Rohstoffe, Band 7, ISBN 9783944310091, Neuruppin, TK Verlag, 2014

[4] K. Schischke: Product design for the efficient use of critical materials - The case of mobile information technology devices, ESM workshop at World Resources Forum, Davos, Switzerland, 12-14 October 2015

[5] M. Kashkoush, H. El Maraghy: Optimum Overall Product Modularity, 6th CIRP Conference on Assembly Technologies and Systems (CATS)Procedia CIRP 44 (2016) 55 – 60

[6] T. Jokinen: PuzzlePhone – Design to last, Emerging Green Conference, Portland, OR, USA, 21 September 2015

[7] D. Hakkens: Phonebloks, https://phonebloks.com/

[8] O. Hebert: The architecture of the Fairphone 2: Designing a competitive device that embodies our values, June 16, 2015, www.fairphone.com

[9] M. Regenfelder, K. Schischke, S. Ebelt, A. P. Slowak: Achieving 'Sustainable Smart Mobile Devices Lifecycles Through Advanced Re-design, Reliability, and Re-use and Remanufacturing Technology', 8th International Scientific Conference MOTSP2016 - Management of Technology, Step to Sustainable Production, Porec, Istria, Croatia, 1-3 June 2016

[10] Project Ara - Module Developers Kit (MDK), Release 0.21 (alpha), March 3, 2015

[11] A. Knaian, D. Yeh: MDK Overview, Project Ara Developers Conference 2015, Mountain View

[12] Ellen MacArthur Foundation, https://www.ellenmacarthurfoundation.org/circular-economy, retrieved: August 1, 2016

[13] C. Bakker, M. den Hollander, E. van Hinte, Y. Zljstra: Products That Last – Product Design for Circular Business Models, TU Delft Library, 2014

[14] H. Wieser, N. Tröger: Die Nutzungsdauer und Obsoleszenz von Gebrauchsgütern im Zeitalter der Beschleunigung – Eine empirische Untersuchung in österreichischen Haushalten, Vienna, 2015

[15] Stiftung Warentest: Schon kaputt?, test, September 2013

[16] EN 62684:2010, Interoperability specifications of common EPS for use with data-enabled mobile telephones