STRATEGIES FOR MORE CIRCULARITY IN THE LIFE CYCLE OF MOBILE INFORMATION TECHNOLOGY

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Abstract: The EU funded Horizon2020 project sustainablySMART develops technological and business innovations along the lifecycle of mobile information and communication technology devices with the aim to enhance circularity in this fast-paced and highly innovative sector. This includes aspects for enhanced end-of-life performance, re-use and remanufacturing design strategies as well as new automatic re-/de-manufacturing processes for improved resource efficiency.

1. INTRODUCTION

Mobile ICT products, such as smartphones and tablets, feature a significant environmental footprint (close to 11% of all ICT industry) whilst having a product life of few years only. Moreover, electronic devices incorporate a number of scarce and valuable natural resources in the manufacturing of their electr(on)ic components or battery unit. Out of those rare resources, several cannot be recovered efficiently and there is only a small credit regarding the environmental impact through material recycling.

Consequently, only keeping those products or components 'alive' allows continuous efficient use of the once invested natural resources and emitted greenhouse gases. This approach necessitates the introduction of a 'circular economy' or 'closed-loop economy', which subsumes approaches for keeping natural resources, materials, components and products in the industrial cycle beyond a first use phase. Loop-closing assumes efficient processes on materials recycling, reparability, refurbishment, reuse and remanufacturing and therefore requires an operational transformation at corporate level in order to create and capture additional value for the customer across the product lifecycle.

2. RESEARCH AND INNOVATION AGENDA

The target of more – and sustainable - circularity for ICT devices requires a comprehensive research agenda tackling numerous questions along the product life cycle in parallel. The research agenda of the project sustainablySMART illustrates the various technological approaches (Figure 1):

An effective circular economy approach for smart mobile devices prioritizes lifetime extension of products and components. This can be reached through a product design based on modularity. Modularity again can address several levels [1]:

(1) **Modularity on the printed circuit board level**: Individual PCB modules help to avoid board level repairs and might even allow to simplify the design of the mainboard, thus reducing the overall environmental impact of PCB production. Embedding technologies for compact modules [2] and reversible assembly technologies for the individual modules are essential to realize such a design. Such an internal modularity approach is easier to implement in an only moderately complex ICT product, such as a digital voice recorder and rather not in the first place in smartphones or similar devices where volume and assembly height restrictions limit the possibility of modularizing functions.

(2) **Modularity for DIY sub-assembly replacement**: The only smartphone intended to be opened by layman and where individual modules can be detached and replaced easily is the Fairphone 2. This lowers significantly

the barriers for repair and even allows potentially for upgrades as soon as performance-wise better modules become available. The Fairphone 2 as a case study is analysed more in detail below.

(3) **Modularity for customization of functionalities**: An open eco-system for smartphone modules would allow developers to create modules for specific applications, thus customizing the product much better for the needs of the user. Technically this calls for standardized interfaces. In parallel, modules connected through an open connector solution can be replaced easily, opening the door for repair, upgrade, reuse and repurposing. Such an approach is implemented with the PuzzleCompatible connector solution, which is demonstrated in sustainablySMART.

As long as product design of smart mobile devices does not fully embrace the concept of a Circular Design technological solutions are needed to address device-related challenges at end of (first) life:

(4) **Data privacy**: One major reason, why smartphones are kept in homes instead of being handed over to reuse are data privacy concerns and that sensitive data might be accessible for a second user. Reliable data erasure routines are therefore essential to stimulate reuse, but also collection for recycling.

(5) **Battery ageing**: Inevitably, batteries are subject to ageing over time. A thorough understanding of ageing processes and related to this a modelling of the battery State-of-Health allows for a better planning of device reuse.

End-of-(first)-life processes benefit from more efficient treatment processes:

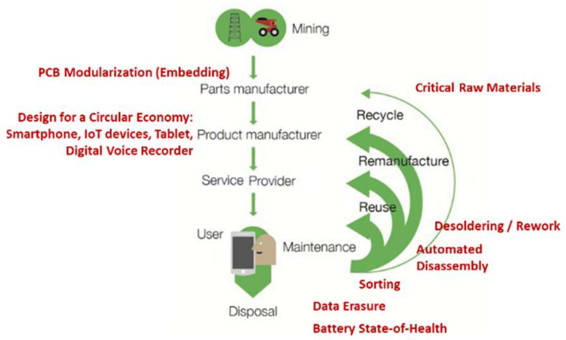
(6) **Smartphone sorting**: From a mixed stream of smartphones a rapid identification and sorting of reusable devices and those, which qualify for spare parts or reuse parts cannibalization vs. smartphones, which have to be channeled towards material recycling is essential for keeping costs of reuse low.

(7) **Collaborative Robotics for Disassembly**: Non-destructive smartphone disassembly for repair and components harvesting is a time consuming process. Some of the process steps can be accelerated, if the potential of collaborative robotics is properly implemented.

(8) **Desoldering and rework of semiconductor components**: Semiconductor packages qualify for reuse, as these are associated with particularly high environmental burden at the manufacturing stage. Desoldering and rework of BGA components is however an industrial process, which requires proper production environment, quality control, and skills.

Besides the technical work sustainablySMART deploys a business model perspective, involving the various players in the potential Circular Economy eco-system of mobile ICT devices. This does not result in one joint business model, but well targeted individual models, outlining the value proposition for each case individually. Some synergies between case studies are nevertheless existent.

Figure 1: Technical Circular Economy Research and Innovation along the Product Lifecycle of Mobile ICT



The following papers will go into details of the various research and innovation activities implemented by sustainablySMART. The following chapters of this paper will touch some highlights of other work done within the project.

3. CASE STUDY DISRUPTIVE SMARTPHONE DESIGN: FAIRPHONE 2

Fairphone B.V. launched the first modular smartphone in December 2015 embracing social aspects of a smartphone lifecycle, but also targeting at an extended product lifetime. The modular approach allows for DIY replacements, lowering the barrier for repairs.

Following modules are available as spare parts:

- Display module
- Battery
- Rear camera module

- Top module: Selfie camera, headset connector, noise-canceling microphone, LED, ambient light and proximity sensor
- Bottom module: speaker, vibration motor, USB connector and primary microphone
- Back cover

These user-accessible modules contain most of the electromechanical components of the device, which normally have shorter lifetime due to the interaction with the medium and the type of user profile.

Both, spare parts availability and information, how to repair a device are crucial for successful repairs. Although the exchange of modules of the Fairphone 2 is straight forward, repair guides have been published next to Fairphone's spare parts webstore. The repair instructions, compiled by iFixit, provide step by step guidance on how to disassemble and re-assemble the smartphone (see e.g. [3]).

The complexity of repairs is decreased significantly through this modular approach. **Figure 2** depicts the amount of fasteners required to be opened to replace the rear camera. Compared to the 1st generation Fairphone, which represented a more conventional smartphone design the complexity has been decreased significantly, but also in comparison to other smartphones the number of fasteners is much lower. It has to be noted however, that flagship phones tend to be designed dust and waterproof, which requires proper sealing of the device.

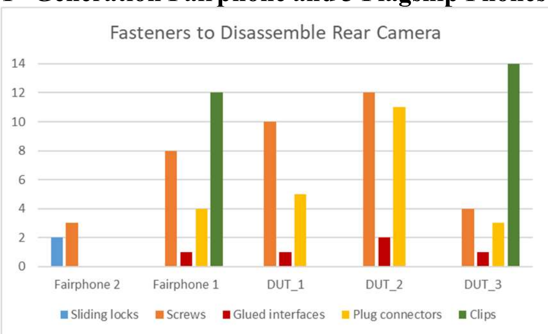


Figure 2: Fasteners to Disassemble the Rear Camera of the Fairphone 2 in comparison to the 1st Generation Fairphone and 3 Flagship Phones

The results of the Life Cycle Assessment [4] underpin the modular strategy: All those modules, which can be replaced and are available as spare parts have a moderate global warming impact only (see **Figure 3**), compared to the core module. However, a malfunction of any of these modules can potentially let the user replace the whole device by a new one. Being in the position to replace easily these modules helps to "keep alive" the high-impact core module longer.

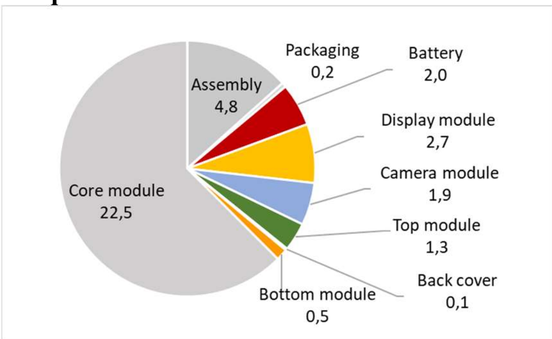


Figure 3: Global Warming Potential of Module Production, Assembly and Packaging of the Fairphone 2

These different modules will benefit the creation of new business models in the future and new diagnostics tools. Modules that are still usable can be harvested and reused for a fraction of the costs that are require with other product architectures. These have been researched during the course of the project as well.

4. CASE STUDY RECOVERY POTENTIAL FOR CRITICAL RAW MATERIALS: TANTALUM, TUNGSTEN, RARE EARTH ELEMENTS

Usually the Circular Economy debate is dominated by a strong focus on material recycling. Only in the last few years there is a better understanding of the importance of closing the inner circles of the Circular Economy instead of focusing on recycling only. Among smartphone devices however, there is a lot of research going on to harvest spice metals. There is no economically viable option yet, just to harvest components from end-of-life products for material recycling. The only operating processing line in this sense are the disassembly robots of Apple [5] taking apart iPhones, recovering potentially Aluminum, Rare Earth Elements, Tungsten, and Tantalum besides some other metals, which are also recycled in conventional processes. Such a disassembly robot, being highly relevant for resource savings, hardly pays for itself.

The idea of sustainablySMART is, that such metals can be recovered as a by-catch of the much more economically interesting recovery of reusable components. In a feasibility study the recovery potential for three critical raw materials, tantalum, gallium and tungsten has been analysed.

For the 3 target metals tantalum, gallium and tungsten Graedel et al. [6] state rather low end-of-life recycling rates, which is a sound argument for exploring alternative recycling approaches:

- Tantalum: <1% End-of-Life Recycling Rate
- Gallium: <1% End-of-Life Recycling Rate

- Tungsten: >10-25% End-of-Life Recycling Rate

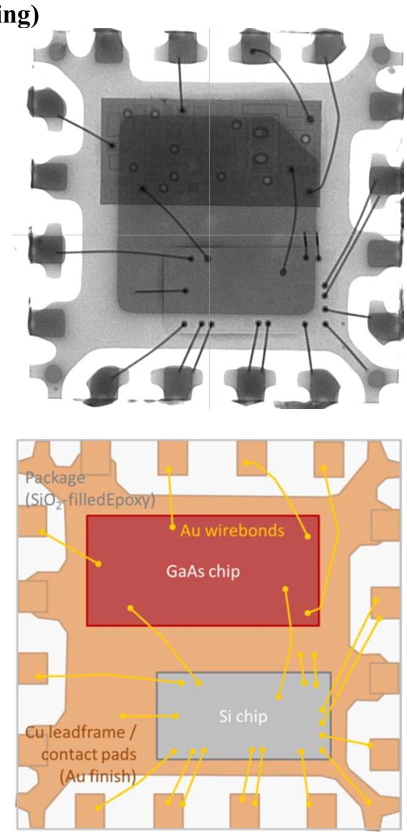
A recycling rate of 10-25% for tungsten refers basically to the recycling of massive tungsten alloy parts (hard metal) with high tungsten content and limited impurities.

Tantalum and tungsten are also among the regulated conflict minerals, thus a recovery of the metal might be a viable source to avoid sourcing from conflict regions and for better control of the material supply as such.

4.1. Gallium

Gallium is among the critical raw materials. However, only the semiconductor grade gallium is really of high economic interest. The recyclability potential becomes clear when analyzing how gallium is embedded in smartphones (Figure 4): Combined with arsene as III-V semiconductor, in a package combined with silicon chips, connected with gold wire bonds and encapsulated in an epoxy matrix on a copper leadframe. For such a material mix, where gallium is only a small share of the total weight and where other well recyclable materials are contained (gold, copper) no viable recycling process is in place.

Figure 4: WLAN module with GaAs and Silicon chips in one package (Quad Flat No-Lead package: X-ray, and schematic drawing)

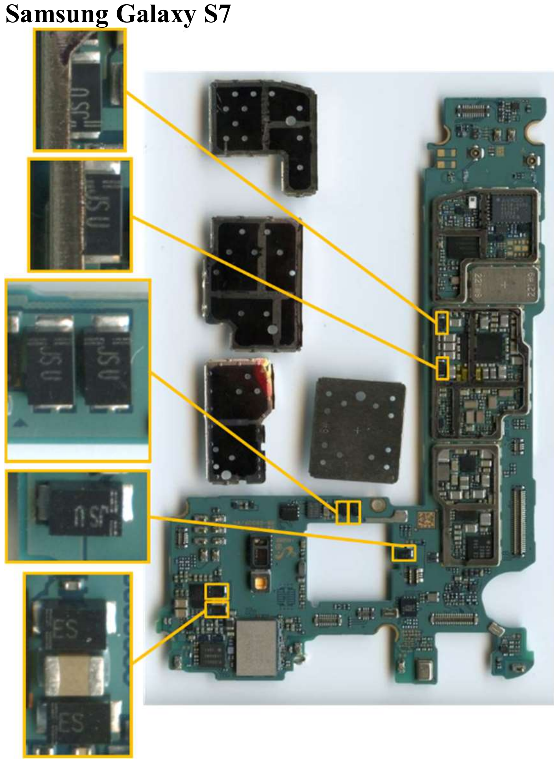


Another application of gallium in smartphones are LEDs. Besides the flash-light and indicator lights LEDs are particularly used as background lighting of the LCD display. The amount of gallium in these components is much lower than in the radio-frequency chips. Material composition of these LEDs is even more complex and potential target materials might be rather the rare earth elements used in LEDs and rather not the gallium.

4.2. Tantalum

The use of tantalum capacitors in smartphones did not change much in recent years. Most smartphone models contained 2 – 4 tantalum capacitors. The logic board of the Samsung Galaxy S7, featuring 7 tantalum capacitors (Figure 5), is a rather extreme case. In this design all tantalum capacitors are placed on the same side of the logic board, which is good for an efficient desoldering process, but some of the semiconductor components qualifying for a reuse are placed on the opposite side of the board. Desoldering reusable BGAs and tantalum capacitors for material recycling therefore is not straight forward.

Figure 5: Use of Tantalum Capacitors in the Samsung Galaxy S7



There are several recycling processes for tantalum capacitors in place, recovering also silver, which is contained in the capacitors. These recycling processes are usually operated for rejects from production. The logistical challenge for recycling from disassembled smartphones is the required amount to be pooled before a significant mass flow for recycling can be established.

4.3. Tungsten

Tungsten has three primary uses in electronic products:

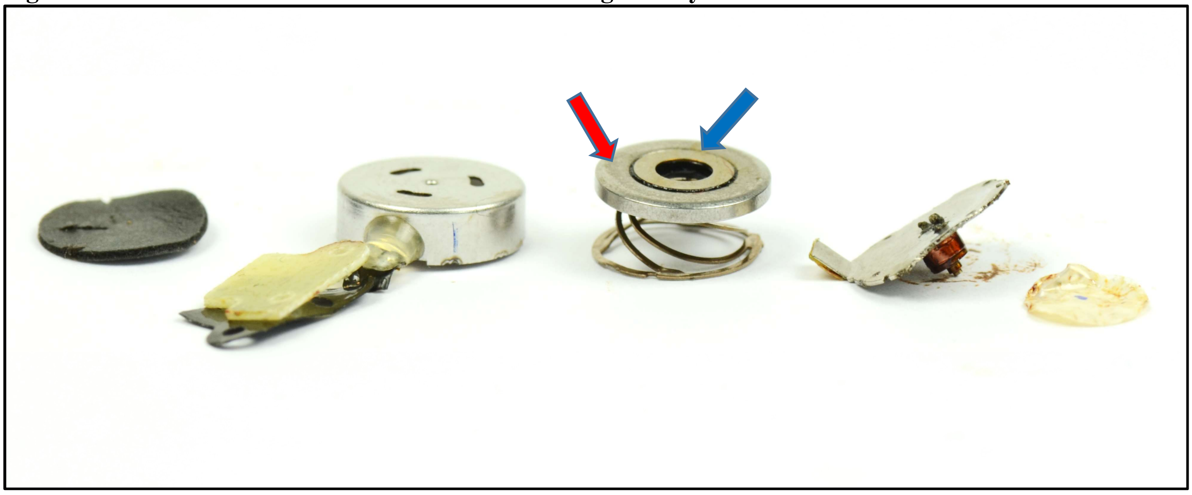
- vibration motors,
- integrated circuits
- and liquid crystal displays (LCD).

Only the material content of tungsten in a typical smartphone vibration motor in the range of 400 – 500 mg (cylindrical vibration motor) is potentially of interest for recycling. In integrated circuits and LCDs the amount is negligible.

Tungsten is used as a weight in vibration motors of smartphones. There are different designs of vibration motors, coin-shape types being the most popular ones. Coin-shape motors increasingly replace linear motors with an exposed tungsten counterweight as used in the Fairphone 2. As these coin-shape motors are usually lightly fixed with an adhesive in a cavity of the midframe, a disassembly robot could easily pick out the motor component as such, although with an extra process step. The separated vibration alarm however is still a complex electro-mechanical assembly (Figure 6). The share of tungsten in this motor assembly is in the range of 50%, thus representing a significant share. In case a small PCB is contained with related contacts, gold might play a role and loosing precious metals in the disassembly and recycling processes should be strictly avoided.

Recycling of tungsten as a hard metal from e.g. used tools is an established process. A vibration motor needs further disassembly and separation of the tungsten weight before a metal recycler can process the tungsten. This gap in the process chain is currently not closed, furthermore the potential amount of tungsten coming from smartphone disassembly is not comparable to recoverable tungsten from other sources, thus not of major interest for recyclers.

Figure 6: Dismantled Vibration Motor from Samsung Galaxy S3 LTE



The red arrow indicates the outer tungsten ring and the blue arrow presents another inner magnetic ring which has to be removed for the following recycling

4.4. Summary Material Recycling Potential

The main technical aspects of separating components with target metals in the process of harvesting reusable components is summarized in the table below. The material value of tantalum and gallium in smartphones is in the sub-cent range, for tungsten below 2 Euro-Cents. Compared to this, it should be kept in mind, that the recycling material value of smartphones is roughly in the range of 1 Euro. Actually, the extraction of individual components is apparently not economically feasible, except for tungsten, if a viable process to pre-treat the vibration motor further is developed (mechanical separation of counterweight and motor parts). For tantalum recycling might be advisable, as it is one of the potential conflict minerals and recycling is considered a conflict-free source (but does not help to strengthen fair mining operations close to conflict areas). For tantalum it is a logistical task to channel separated capacitors into existing recycling processes – technologically this is doable.

Table 1: Disassembly strategy and technology concept for recovery of tantalum, gallium, tungsten

	Ta	Ga	W
Potential target component	Tantalum capacitors	GaAs semiconductor modules	Vibration motors
Existing recycling process for post-consumer scrap	yes	no	no
Recycling of post-consumer scrap potentially feasible	yes, large scale processes for post-industrial scrap of same composition in place	no (Ga content too low)	requires pre-processing of vibration motors to separate the heavy metal from motor parts (requires R&D)
Recovery of contained precious metals feasible	yes (Ag)	no	not clear yet
Material value per smartphone	< 0,2 Euro-Cents	< 0,03 Euro-Cents	max. 1,8 Euro-Cents
Economically viable	no	no	to be assessed in conjunction with overall disassembly process
Recovery advisable due to high environmental impact of primary material	no	no	no
Recovery advisable due to conflict minerals issues	yes	no	yes
Automated separation process (sustainablySMART target products)	Desoldering (jointly with reusable semiconductors)	Not advisable	Mechanical separation after removal of LCD magnesium frame

5. CONCLUSIONS

Smart mobile devices provide numerous opportunities for implementing principles of a Circular Economy. The example of the project sustainablySMART illustrates the multitude of strategies to address product design and lifetime, innovative business models for a more efficient use of information technology, repair and reuse, including repurposing of components. The last resort is an improved recycling of waste devices although under current raw materials prices there is limited potential for better material recovery. Even more important is the focus on the inner circles of the Circular Economy, as shown also by Life Cycle Assessment evidence.

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