Achieving 'Sustainable Smart Mobile Devices Lifecycles Through Advanced Re-design, Reliability, and Re-use and Remanufacturing Technology'

Max REGENFELDER [1], Karsten SCHISCHKE [2], Stefan EBELT [1], André P. SLOWAK [3]

[1] ReUse e.V. (gemeinnützig), Am Forstacker 7a, 13587 Berlin, Germany, email of corresponding author: max.regenfelder@reuse-verein.org.
[2] Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration IZM, Gustav-Meyer-Allee 25, 13355 Berlin, Germany.
[3] Royal Docks School of Business and Law, University of East London.

Abstract

The EU-funded Horizon2020 project sustainablySMART will change the lifecycle of mobile ICT (information and communication technology) devices by developing new product design approaches. This includes enhanced end-of-life performance, re-use and remanufacturing aspects implemented on the product and printed circuit board level, as well as new re-/de-manufacturing processes with improved resource efficiency. The project will create economic advantage compared to the current end-of-life practices (e.g. shredding), including development of underlying product design, production, testing and remanufacturing technologies. Practical implementation of novel business models is demonstrated via nine in-depth case studies. This paper provides an outline on the project and its goals.

Keywords: Re-use, recycling; remanufacturing; mobile electr(on)ic appliances; sustainablySMART.

1. INTRODUCTION: MOBILE DEVICES' ENVIRONMENTAL IMPACT, THE CIRCULAR ECONOMY APPROACH AND BUSINESS MODELS FOR SUSTAINABILITY

Mobile information and communication products, such as smartphones and tablets, feature an enormous environmental footprint whilst having short product life. For instance take the case of Apple's current devices: The iPhone 6S smartphone generates 80 kg CO_2e over its product life, the iPad Pro (12.9-inch) 270 kg CO_2e. These figures equal 559.44 kg CO_2e respectively 373.44 kg CO_2e per kg/device and thus constitutes dense and high environmental impact [1, 2]. Moreover, electronic devices incorporate a number of scarce and valuable natural resources, in terms of their electr(on)ic components or battery unit. Out of those scarce resources, several cannot be recovered on sufficient process or economic efficiency level. Thus, there is only a small credit regarding the environmental impact through material recycling [3]. Despite, some raw materials such as rare earth elements are labelled as strategic or scarce regarding supply and economy relevance [4,5]. The environmental challenge becomes even more intense, if seeing the short use phase of most contemporary smartphones. Consequently, only keeping those products or components 'alive' allows continuous efficient use of the once invested natural resources and emitted greenhouse gases.

The terminus 'circular economy' or 'closed-loop economy' subsumes approaches for keeping natural resources, materials, components and products in the industrial cycle beyond a first use phase. Loop-closing assumes materials recycling, reparability, refurbishment re-use and remanufacturing [6,7,8,9,10]. Figure 1 gives an overview of the circular economy approaches. Those relevant for technical materials are all addressed by the project sustainablySMART.

Likewise, circular economy's implementation into corporate practice is discussed as 'business models for sustainability'. A business model describes how a company and its partners create value for the customer and how the company can capture the value. In the case of sustainability, the value created is more than economic one. It covers environmental value created (environmental impact; raw materials savings from recycling) and beneficial aspects for society. Amongst others, closed-loop, cradle-to-cradle and recycling-re-use-remanufacturing business models are discussed in this regard, scoping beyond efficiency strategies. [11,12,13]

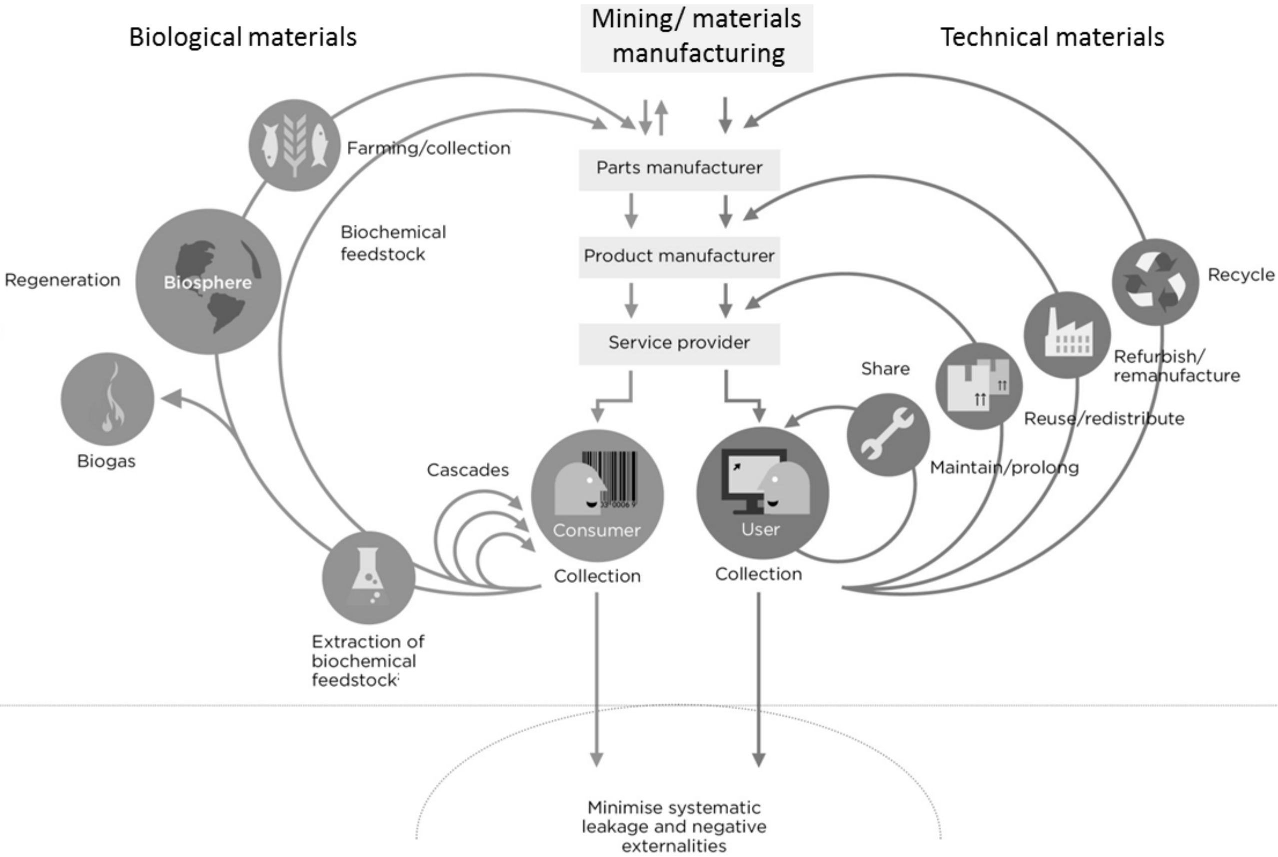

Figure 1 - Circular economy approaches [14]

A business model also determines how developed new technologies can be best marketed and diffused. The choice of an appropriate business model becomes a significant success factor for technology breakthrough [15]. Also the configuration of firm internal resources, networks and strategy alignment is part of a business model [16]. Concerning the depicted circular economy approaches, the business model is not only scoping on technology implementation but also on organizing take-back infrastructure for assuring the materials, components or products circular flow. This includes identification of new relevant actors and changes respectively prolongation of the companies' value chains [17].

2. THE SUSTAINABLYSMART PROJECT

2.1. Goals and Rationale

The sustainablySMART project begun in September 2015, running thereafter over a period of 50 months. Partners are manufacturing companies, research institutions and universities.

An effective circular economy approach for smart mobile devices prioritises lifetime extension of products and components. It is a challenge of these times to tap into the wave of end-of-life mobile ICT devices: Smartphones where introduced to the market at large only in 2009, tablets slightly later. We expect in the near-term future high return rates of these devices, which is confirmed by recycling companies, getting back increasing, but still low amounts of smartphones and tablets. The market perspective indicates that we only see the beginning of a larger wave of discarded units. This is a perfect timing to invest in research to reuse and refurbish these products with sophisticated technologies. Apart, we consider technological evolution toward the Internet of Things, which may provide a wide field for cascade re-use of single components. For example, take the idea of developing smartphones which consist of modularized components. This calls for standardized interfaces, easily to disassemble, to upgrade and to repair – even by the customer herself. Whereas, in the past, used electronics components were solely re-used in low-cost products, growing digitalisation of our daily lives comes with numerous new product concepts. The latter could make perfect use of parts and components harvested from used smartphones and used tablets.

The project sustainablySMART aims at keeping products and electr(on)ic components in the use cycle. It especially focusses on inquiring the modularization, longevity and reparability of products and disassembly of modules as well as components. Advanced disassembly and advanced component remanufacturing technology can keep electronics in the market sphere (extending lifetime); and can provide numerous other product markets almost environmentally "for free" in terms of the otherwise enormous environmental footprint. The yet mostly missing link between first life of products and second life cascades' reuse occurs to be a market and/or public policy failure. European industry may close the gap with advanced technologies and with novel business models. Figure 2 depicts project activities in correlation with the product life cycle.

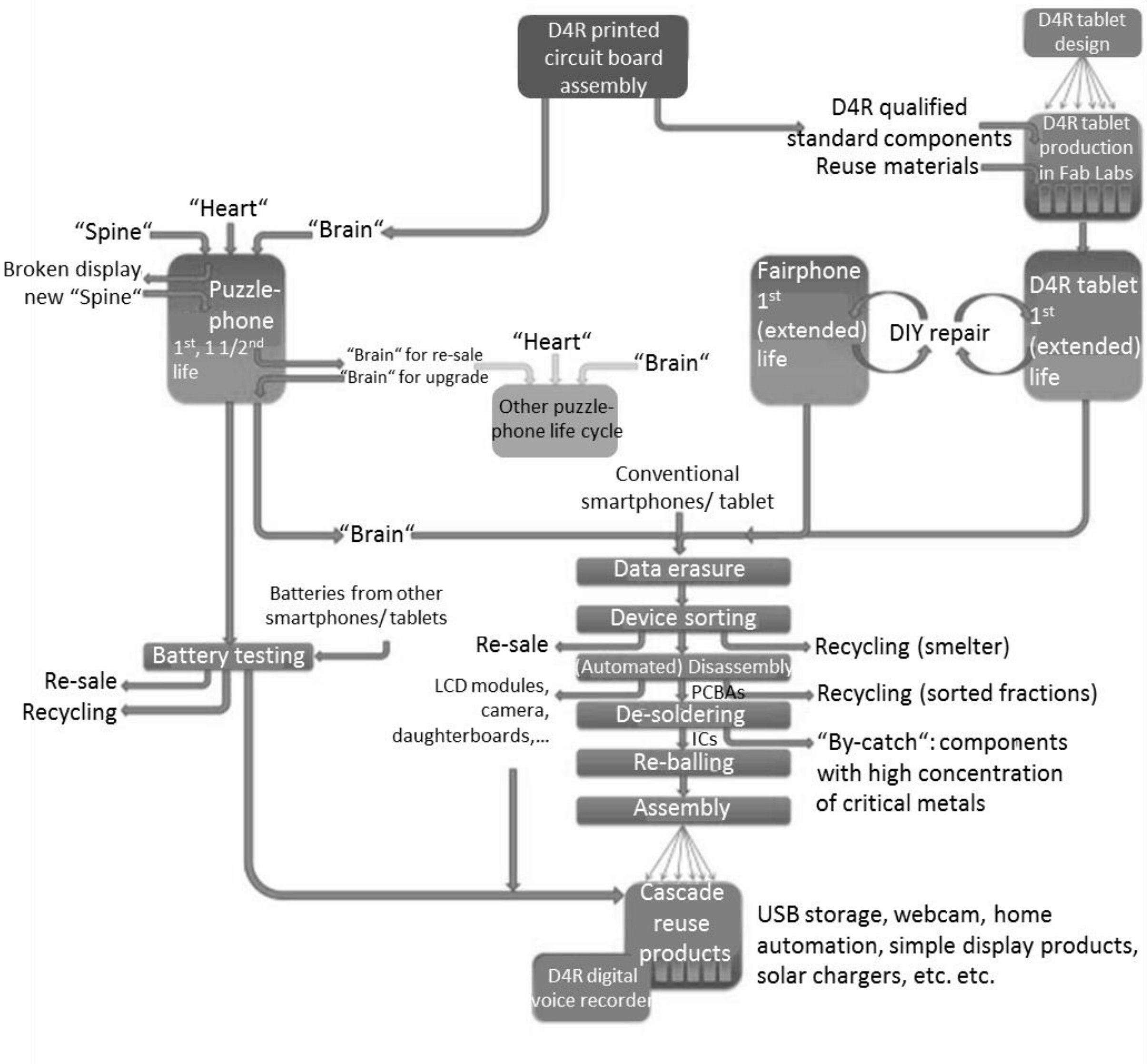

Figure 2 - Systemic product lifecycle approach of sustainablySMART

The project's main goals are as follows:

- Demonstrate the feasibility of a modular product approach for smartphones: The concept of a modular smartphone (Puzzlephone) shall be shown in an industrial environment.
- Demonstrate the feasibility of a 'design for circular economy' approach for more conventional mobile IT designs: On the example of the design of smartphones and tablets the implementation of environmental design criteria, i.e. long lifetime (reliability of target parts and components for second

life / cascade reuse), reparability, design for manual and automated disassembly, implementation of verified data erasure compatibility will be demonstrated.

- For the first time in this industry's context, a printed circuit board assembly will consider explicit design targets for the 'Circular Economy'.
- Automated high-speed sorting and disassembly of end-of-life devices, enabled through a combination of advanced optical recognition; handling technology; tooling and robotics: The project implements a disassembly speed, which makes processing competitive with given high-volume destructive shredding processes, and with recycling the devices as a whole in a copper or precious metal smelter. The latter conventional processes mean that some key elements are recovered but many others lost inevitably: such as, aluminium, steel, magnesium, indium, rare earth elements, gallium, silicon and tantalum.
- Implement 'smartness' for a state-of-health monitoring in batteries: Health monitoring is essential for a quality tested battery reuse because it provides an alternative to lengthy full-cycle testing that is a major current barrier for battery re-use. Through monitoring algorithms embedded in the Smart Battery Specification data becomes extractable and in so doing, is made accessible at the point of potential battery re-use.
- Sound data erasure is a major barrier for product and memory re-use. The topology of solid state memory hinders straightforward erasure routines. Erasure processes shall thus be verified for solid state memory devices.
- High-quality desoldering and remanufacturing of semiconductor components for re-use: The project develops a desoldering process, a process in compliance with the initial component specification regarding i.e. thermal stress as well as remanufacturing of semiconductor components.
- Cascade re-use of selected components: Numerous potentially harvested components and subassemblies from smartphones and tablets meet the technical specification of a broad range of other products. They can be a sound source and substitute elsewise new components.
- Develop a scientifically validated reparability score system, to allow for ranking products. Environmental product policies are meant to make use of our results; they can make various stakeholders reflect such new kinds of environmental ranking.
- Re-use and remanufacturing requires new business models, acknowledging value generation happens among new actors in reverse supply chains. The new kinds of business models are already implemented for some low-cost products but not any close in sophisticated applications having higher reliability and quality requirements.

The project sutainablySMART thereby addresses product and process-oriented technological approaches and runs well-aligned business model case studies.

2.2 Structure of the Project

The project is structured into nine work packages (WPs; WP 9 for project coordination). They are designed to cover the most relevant steps in a sustainable product life cycle of mobile IT devices. That is, from product design to recycling, and to re-use and remanufacturing. Some work packages explicitly cover sustainable product design dimensions (WP 1, WP 2), and (first) production as well as recycling remanufacturing process technology (WP 3, WP 4, WP 5). The latter three work packages look at optimization of reverse logistics. They analyse such opportunities in a way asking how to secure the supply of products, components and sub-assemblies. This supply of products, components and sub-assemblies is not abundant available at the moment and thus the project may unlock new markets for re-used components and products. Innovation activities are linked and complemented by the WPs dedicated to developing appropriate business cases, assuring economic and ecological efficiency, and providing policy implications (WP 6, WP 7, WP 8). Altogether these WPs are designed to address all the direct and indirect aspects of a 'recycling, re-use and remanufacturing factory of the future' including then proper business models.

'WP 1: Eco-Innovative approaches for product design of small mobile information technology products' addresses product design issue for smartphones, tablets and digital voice recorders. Approaches with in the product development are modularization, longevity for lifetime extensions and other D4R approaches.

Aspects on a more specific technical level regarding system integration technologies are addressed in **'WP 2: Eco-innovative approaches for advanced printed circuit boards'**. Printed circuit boards are part of all target products. The options after a first product life for re-usability or disassembly depend crucially on circuits design, e.g., interconnections, modularity and embeddedness.

'WP 3: New technologies and automation solutions for the effective disassembly/ separation and recovery of advanced materials' develops advanced sorting, separation and disassembly technology to provide the capability to sort, disassemble and recycle end-of-life products or their materials in an unmixed way. This facilitates remarketing of value-added from end-of-life materials. Likewise, it improves the ecological aspects of recycling loop closing.

Advanced recovery and refurbishment of components and sub-assemblies is addressed in **'WP 4: New Manufacturing and equipment concepts for re-use and remanufacturing'**. This includes desoldering of components, their rework and their re-use in new devices.

'WP 5: New testing, processing and equipment concepts for verifying the condition of re-use parts: Data erasure and battery testing' targets the quality assurance of re-used and remanufactured devices. More specifically, the state of the battery is essential for mobile technology. And concerns of data security may impede consumers and firms from giving away their devices to collection schemes [18,19].

The business potential of the technology developments will be analyzed in '**WP 6: Generation and validation of new business models'**, which has also the function of providing guidance for the technology tasks: how the research and innovation strategy should be adapted so that large scale market uptake is encouraged and becomes likely. In a sense, WP 6 includes a market screening taking into account latest product and technology trends. Business plans for all technologies will be developed and refined under this work package.

The project contributes to eco-innovation, toward integrated assessment of achieved productivity gains and toward required more environmental performance of newly developed technologies. Related tasks are pooled in **'WP 7: Support for design and technology developments'**. It includes the evaluation of available technologies; of efficiency gains; and environmental assessments. Other work packages likewise receive generic guidelines for disassembly and the development of a reparability score for products from the support activities in the project consortium.

Accounting that the implementation of radically new reuse and refurbishment concepts will require a sound public and policy environment, we installed a dedicated work page: **'WP 8: Dissemination and policy impact'**. It will roll-out a comprehensive dissemination and communication plan, which is targeting at end users (social media and conventional media); at potential industry partners throughout the product lifecycle of mobile IT products; policy makers, and the research community. The role of the wider community may be about getting our research findings validated.

For an overview of WPs and the project's structure see Figure 3

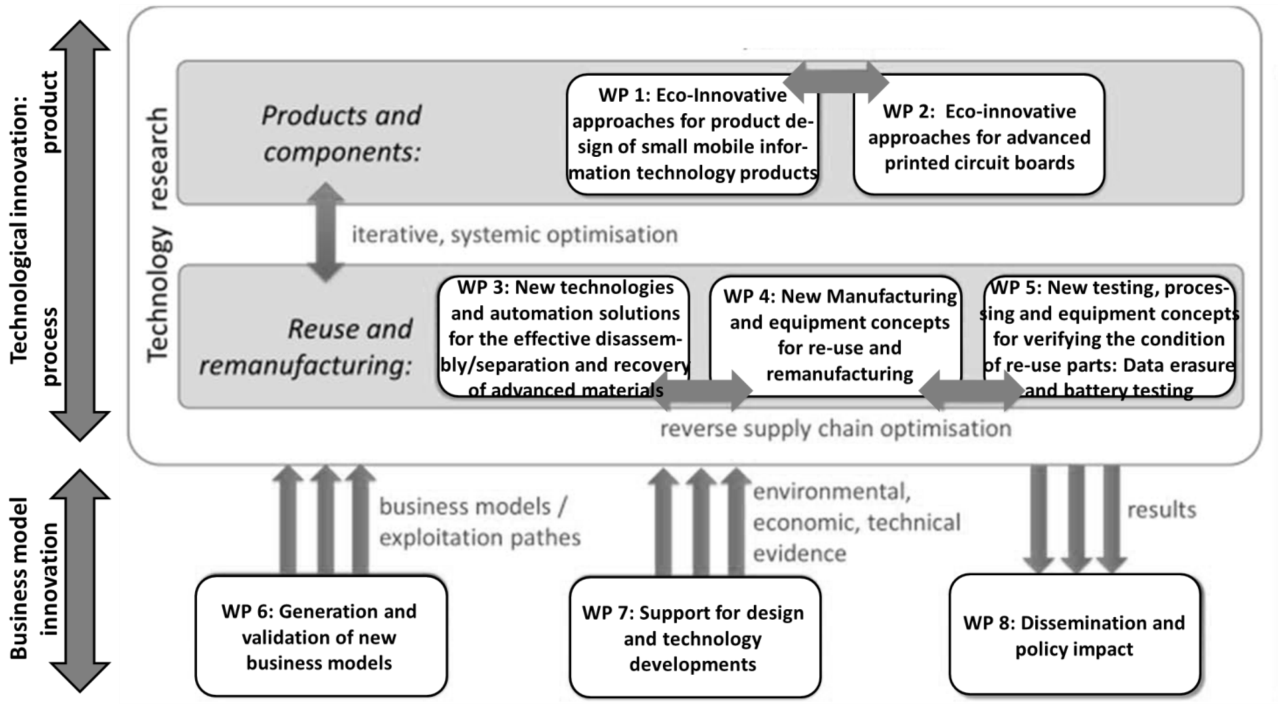

Figure 3 - Structure of the project sustainablySMART

2.3. Integrated Approach: Product and Process Technology Blended with Business Models

Besides the integrated technological product and process developments, the sustainablySMART project has one work package that is dedicated to closed-loop and circular economy business models. Within nine case studies, the practical implementation is supported and proven.

A business model describes how a company creates value for the customer, how the company can appropriate revenues, and which other actors are relevant (that is, within the company's business networks or regarding the business model environment). A business model is closely linked to configuration of the value chain and value constellation of the company (external perspective: What does define value from the customer's or other stakeholders' point of view?). It is also closely linked to the configuration of firm internal resources, capabilities and their alignment with corporate strategy and with business processes (internal perspective: How can the company create the value?) [16, 20]. In addition, business models are seen as critical success factor for the commercialization of technological inventions [15]. Underlying technology has to provide fit with the business model, and vice versa, if successfully operating in the market. In this respect, business model innovation does not first focus on product and service offerings to the customer; it is much more about changing the way one does business, the way of rather radical innovation than incremental [21]. A business model perspective shifts the focus away from developing individual technologies and turns our eyes toward creating new systems. Particularly, from firm-internal value chains to value networks [22].

This applies especially for circular economy business models: First, the prolongation of use phases of products and components implies competition with future products which raises complexity e.g. in technology forecasting and time lags. Second, circular economy business models prolong the traditional value chain respectively, they reconfigure the value system. Even if maintaining a linear pattern of an original value chain and in a value system, there needs to be then an extension for collection and remanufacturing, refurbishing and for recycling steps. In other cases, after a first use phase, the product is transferred to a different value chain (that is, of another product or industry). Finally, the value chain may be destructed or redefined; value creation takes place in parallel and multi-directional value constellation [16, 17]. This especially applies where the consumer of a product (first lifecycle) serves as input source for another, second product lifecycle. Figure 4 illustrates the argument.

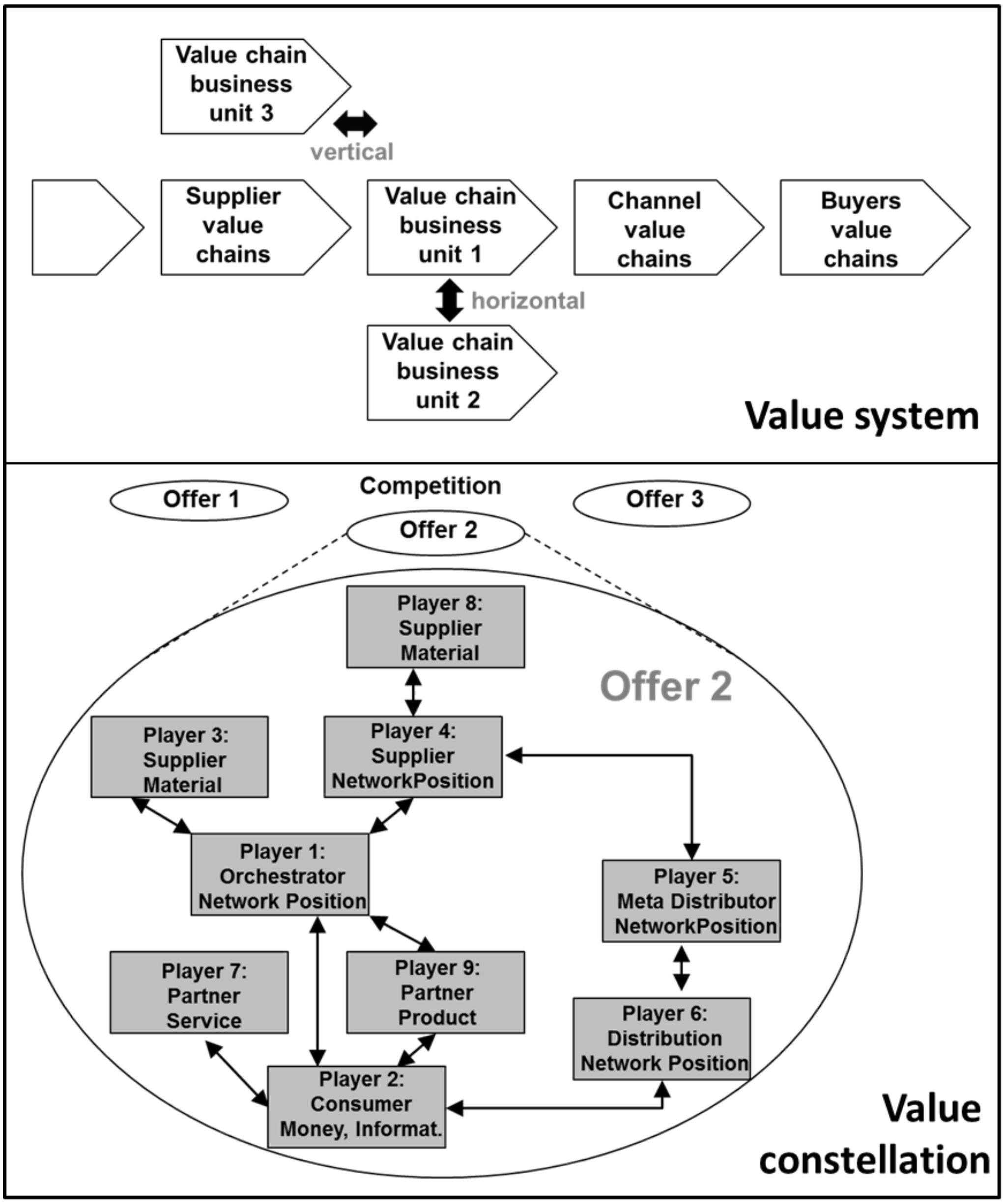

Figure 4 - Value system and value constellation [16, 17]

However, business models consist out of three main pillars [20]:

- Value proposition: How is value defined by the customer?
- Value creation: Which key activities create this value? Which resources or capabilities are needed as input? Which actors and partners are involved?
- Value capture: How does the company generate revenues from the business model's value proposition, or its positioning within an open business model? Which complementary assets or protection rights are available?

The business model WP follows above approach. First, it shall be explored which value propositions are deemed possible from the customers' perspectives. We incorporate value propositions enabled by innovative technologies developed in WPs 1-5. Vice versa, appropriate business models for developed technology are explored. Somewhat, technology and business models have an ambiguous role: Technology shapes the business models whilst business model choice biases subsequent or future technology adoption. Beginning from the value proposition, key activities are determined for creating this value; firm internal resources are configured and relevant actors of the business model ecosystem identified. Finally, we assess how the project sustainablySMART's partners may best capture value created from generating business models and within those. Can we identify complementary assets, specific threats and opportunities? The purpose is to provide detailed value systems reviews and blueprinting value constellations in the nine in-depth case studies. Thereby, the structure of circular value creation shall become clear in both the conceptual and the practice angle. Figure 5 illustrates the holistic approach.

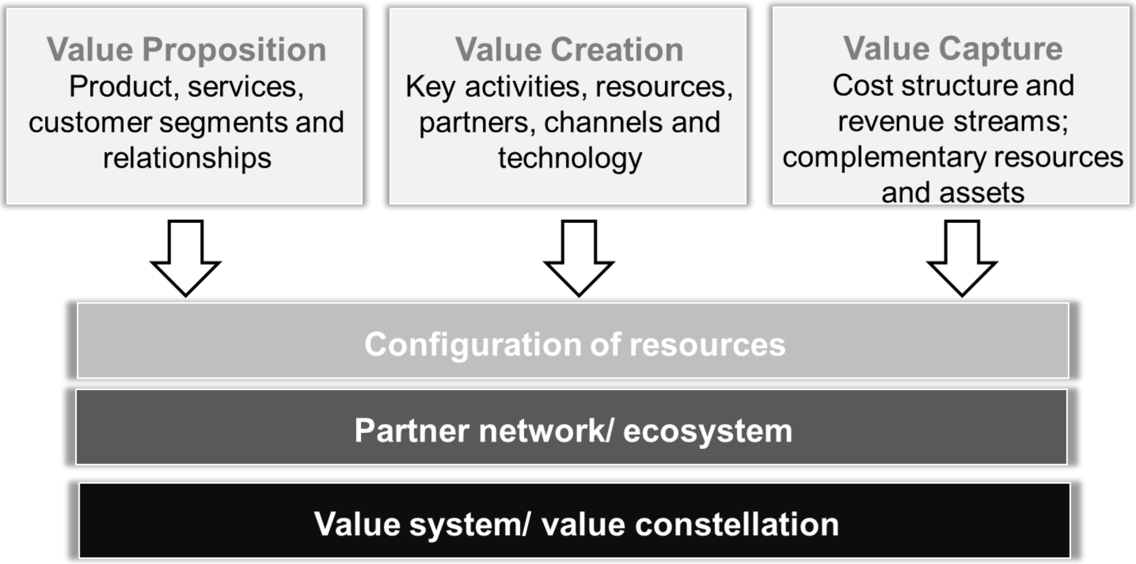

Figure 5 - Approach for business model generation in sustainablySMART

The business model approach of this project goes beyond usual approaches in similar projects where business plans are developed commercializing (technological) projects' results. sustainablySMART assesses and creates circular business models from scratch, and for a wider analytic purpose. Business models themselves become innovation beyond product provision. As such, they complement technological innovation. Simultaneously, technological and organisational innovation are combined to ecosystems of business models.

3. DISCUSSION AND CONCLUSIONS

The paper outlined the environmental impact of mobile information and communication devices. Compared to their product weight, smartphones and tablets represent quite high impact. Environmental impact can be mitigated best if keeping products or components in use, enabling further lifecycles. This idea corresponds with approaches of the circular economy and recycling, re-use and remanufacturing in particular. The project sustainablySMART targets above device classes on the product and component level and in the context of technology as well as business model innovation and policy implications. The aims and structure of the project have been described. Also, the new approach for generating circular business models was introduced: Beginning from value propositions, over firm-internal resources reconfiguration, to creating novel value systems and value constellations. This shall, in the course of the project, lead to an iterative process refining and evolving cutting edge business models and facilitating a better assessment of developing opportunities, the threats and circular economy success factors, all aligned business model evaluation and generation.

4. ACKNOWLEDGEMENTS

For more information on the sustainablySMART project, its partners and publications please refer to http://www.effra.eu/roadmap/application.project.view.php?id=1544.
The project sustainablySMART has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 680640.

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