GUIDELINE DEVELOPMENT TO DESIGN MODULAR PRODUCTS THAT MEET THE NEEDS OF CIRCULAR ECONOMY

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The intended paper presents the development of a guideline on how to design a modular product concept for smart mobile devices to meet the needs of Circular Economy.

First the D4R-Modularity was defined. Usually, smart mobile devices get obsolete caused by a failure or damage of only one single part, although all other parts are still working. These parts could serve more than one product lifetime. To continue the reuse of those parts, mixing different end-of-life strategies in one product is needed.
The resulting design process shown in the guideline is divided into five tasks: The definition of an adequate main CE-strategy of the product, the development of an appropriate business model, the definition of CE-strategies of subassemlies, parts the definition and the actual design of modules. For these steps useful tools and methods are given to support the development of a product concept.

The case study in this paper is a “Phillips Digital Voice Recorder”. The modular product concept of the digital voice recorder, together with a circular business model, aims at extending the lifetime of the whole product, the lifetime of different modules and supports efficient material recycling. The case study indicates that economic advantages as well as reduced environmental impacts can be achieved with applying the proposed guideline for modular products.

1. INRODUCTION

Smart mobile devices contain valuable materials like gold, silver and rare earth metals. In 2012 there were about 160 million obsolete and uncollected devices in Europe, representing a material loss of 427 million € annually [1]. According to the Global E-waste Monitor, worldwide about 435 kt of mobile phone waste accumulated in 2017 representing a value of about 9.4 billion € [2]. Most users change their smartphone frequently not because it is broken, but because of status symbol and to keep up with the technology changes [2]. As a result, wasted mobile phones are products which are actually not defective but working smartphones.

In 2012 the Ellen McArthur Foundation published that mobile phone design became increasingly integrated with no possibility for component reuse or remanufacturing [1]. Today, this situation seems even more hopeless, the potential for reuse or remanufacturing of modern smartphones has been further reduced by the increased performance and packaging density, or the use of adhesives.

A promising approach to overcome this wastage and its environmental burdens is the realisation of Circular Economy. Circular Economy is a concept where the value of products, materials and resources is maintained in the economy for as long as possible and the generation of waste is minimised through establishing circles. The Circular Economy System Diagram [3], published by the Ellen MacArthur Foundation, illustrates the different CE-strategies in circles. A simplified version with suitable end-of-life strategies for modular smart mobile devices is shown below in Figure 1. While repairing a defective phone preserve the highest value (inner circle), recycling only prolongs the use of materials and the value generated during manufacturing is lost (outer circle).

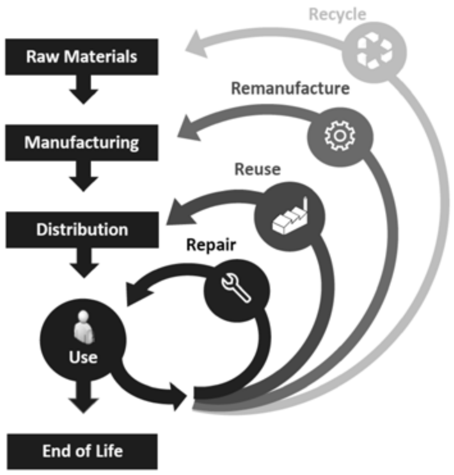

Figure 1: Different End-of-Life Strategies depict in a simplified Circular Economy System Diagram [4]

Currently the bottle neck is the failed implementation of Circular Economy, caused by product design that impedes proper product reuse and remanufacturing [5]. One way to facilitate reuse and remanufacturing from products perspective is a modular product design. Having structured the product in modules eases also the reparability and exchange of (broken or outdated) modules and components.

This paper focuses on the application of modularity on smart mobile devices, like tablets, mobile phones, digital voice recorders, etc. and the aim to improve the environmental performance by realising Circular Economy principles.

2. DEFINITIONS

2.1 General Definitions of Modularity

In modular products, parts and components are separated and grouped to modules. These modules are independent elements or subassemblies, usually connected via interfaces. These interfaces enables the main interactions and flows between them [5] [6] [7] [8] [9]. The field of modular product designs covers a wide range of different design approaches, with different aims and applications.

Over the last years, modularity in products was in general used for easier product design, manufacturing and assembly.

A basic concept of modular product design is the so called platform modularity, used in products that can be configured for a range of individual specifications [7]. The idea behind this modularity concept was to save development and manufacturing costs while bringing flexibility to the product design [6]. Without these modularisation, customized products could be only produced with huge effort in construction and production [8].

Another goal of modularity is splitting of work in complex products like cars, airplanes etc. Problems can be solved easier by breaking it into a set of smaller problems that are easily to handle, so the engineer team can research solutions for each small piece [10].

Recently, with the arising idea of Circular Economy, people started to think about the importance and the opportunities modularity can also create in this field. Fraunhofer IZM [7] published five modularity types that can be found in various tablets or smartphones in 5 modularity levels, shown in Figure 2. These are sorted by their environmental importance and represent 5 different life cycle profiles of smart mobile devices. This means, the classification is based on the environmental impact during all life cycle phases (material extraction, manufacturing, distribution, use, and end-of-life). Mix & match modularity has the highest environmental improvement, in contrast Add-on modularity cause even a higher environmental impact.

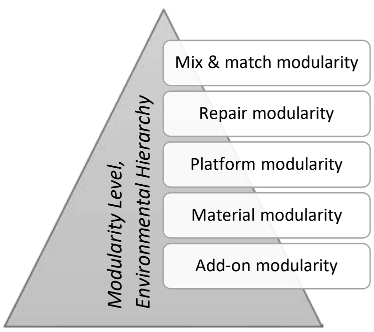

Figure 2: Definition of Modularity Levels by Fraunhofer IZM

- An example for the Add-on modularity is the Moto Z phone family and the belonging modification modules from Motorola.
- A product representing Material modularity is optimised for recycling, meaning for example its materials can be easily separated.
- An example for the Platform modularity is the RePhone, a modular, open source smartphone platform, where the product can be configured and adopted for different needs.
- Already established in the market is the mobile phone Fairphone 2 with a design based on Repair modularity. Broken Modules can be easily replaced by customers themselves.
- The most challenging modularity type, Mix and match modularity, has not yet reached the marketability. The idea is to create modules that can be mixed and matched even cross-over different products and brands. A well-known representative, the Google ARA mobile phone has been revised recently.

2.2 Definition of D4R-Modularity

Modularity within the meaning of Circular Economy, shall be understood as a potential contributor to resource efficiency [7]. But a modular product design needs in the most cases a higher material consumption and production effort, due to additional sub-housings or interfaces [7]. This can be clearly seen with the non-modular Fairphone 1, whose environmental impact is lower than the one from the modular Fairphone 2 [11]. This additional effort has to pay off through a longer use of the phone or the individual modules. In the case of the mobile phone Fairphone 2, for replacing the various modules a different need regarding time to exchange exists. During a 5 year life time, the battery (two pieces), or the display (0,6x) fail quiet often, in contrast to the rest of the modules (0,1x and 0,2x) [11]. Within the Fairphone 2 example, the potential of modules with a low need for replacement won't be fully used.

As mentioned, smart mobile devices which will be no longer used, are in the most cases not defective. And if a smart mobile devices get defective, the failure is mostly caused by a damage (broken display), wear (battery with limited charging cycles), tear (scratched housing), or as a result of a technology leap, whereby the old technology is no longer satisfying for the customer (camera solution, memory capacity).

To continue the reuse of some components, while others cannot be reused and have to be recycled for example, different end-of-life strategies gets necessary for these parts, in this example simply "reuse" and "recycling". The four possible strategies are the ones shown in Figure 1: repair, reuse, remanufacturing and recycling. Mixing all these strategies in one product, will increase the complexity. These complexity can be solved by applying modular product architecture, as proposed with the "D4R Modularity".

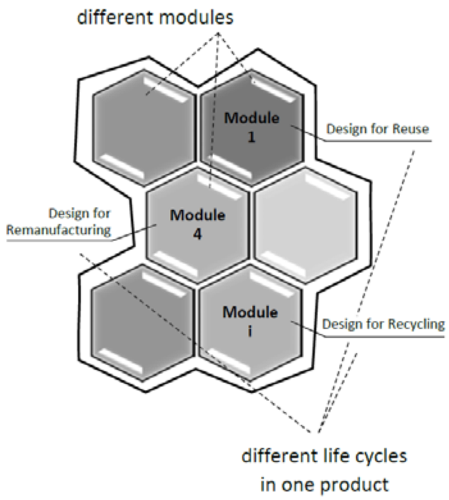

Figure 3: D4R Modularity

With a conventional modularisation method the parts and components are clustered regarding their technical properties (function, suitability or interaction). Within the D4R-Modularity the parts and components are clustered into modules also with regard to the same end of life strategy. To enable the CE-potential of these modules, they should be designed for easy dismantling from the product or other modules and be optimised for their relevant end-of-life strategy.

The related product designs to the different end-of-life strategies are "Design for Repair / Reuse / Remanufacture / Recycling", thereafter abbreviated in this paper as D4R.

Looking at the whole product structure, different levels of end-of-life strategies exists, which have to be considered separately. On the top there is the main product strategy. In the Fairphone 2 example, this strategy would be Design for Repair. Below this level, there is the module's strategy. Replacing a defective module, and keeping the working ones, requires the strategy Design for Reuse. Sometimes more than one strategy is reasonable and can be realised. Especially when thinking at the actual end of lifetime, every module, component or part should have the possibility for proper recycling.

Compared to the definition of modularity levels by Fraunhofer (Figure 2), which classifies product groups regarding different over all life cycle profiles, the developed D4R-Modularity is on the component level of one single product.

3. METHOD

3.1 Developing the Design Guideline

To develop a guideline which helps designing modular products, that meets the needs of Circular Economy, the most important "perspectives" on smart mobile devices were defined. This way questions which have to be considered within the design guideline were established.

When designing a modular product with regards to CE, not only the physical product design, but also its environment has to be taken into account: the business model whereby the product is marketed, new service providers like collectors, repair centres or remanufacturing firms, country specific laws (considering electronic waste or data security etc.) and of course the user and his usage behaviour.

Taking a look at the life cycle assessment studies of a smartphone and a digital voice recorder. Most of the contribution to the impact are resulted from the materials in the product and the production [11] [12].

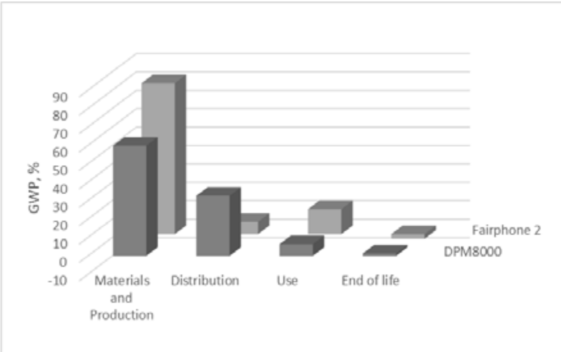

Figure 4: GW Potential per Life Cycle Stage, %

The materials and the effort in production is accumulated in the assembled product (and also in its components and parts). These potential could be saved if those components or parts will get reused because there lifetime will be extended. If the product is a use-intensive one, other eco-design measures (for instance increasing the energy efficiency by using other technical principles etc.) will guarantee better environmental improvements. Also the distribution phase needs to be considered. Getting the used product back, will cause a logistic effort, which can be even higher than the original distribution. The take back's impact will hinder the efficiency of the desired circularity. In summary, the product needs to be investigated from an *Environmental Perspective*, meaning the relevance of the different life cycle phases needs to be determined. This task must be covered by the guideline.

Circular Economy requires circular business models. When selling a modular smart mobile device with the existing linear business model, no environmental savings can be achieved. Changing an existing, linear business model to a circular business model effects all fields and even requires new key elements like take back schemes, additional services that might be needed, extended product responsibility, etc. At a first glance, it seems that these additional efforts decrease the profit of the circular business model. But according to Gama et al. [13] the economic impact of going circular is positive. This can be a potential for additional value creation. As a result, the *Economic Perspective* is important. The business model cannot be neglected when designing a modular product serving CE.

A previously mentioned key element of a circular business model is the take back scheme. Without a chance to establish take back possibilities, circularity do not really work. Logistic issues are: incentives for the user to return their products, reverse logistics processes, for example that are hindered by geographical distribution, or difficulties in generating a stable flow of returned products, and also regulatory complexity [14]. For the development of the guideline, taking a detailed look at the *Logistic Perspective* is essential.

The new, circular business model must be accepted by the customers. A fundamental issue is that the customers will buy or rent in the most cases products with repaired, used or remanufactured parts, components, or modules in contrast to buying brand new products. Therefore, user perception is one of the main topics when taking a look at circular smart mobile devices from a *Sociotechnical Perspective*. In the electronics sector there are multiple factors deterring users to use used or refurbished devices [14]. According to the Ellen McArthur Foundation burdens are: Financial risk in case of a failure. Considering only new devices as one wants to stay up-to-date with continual technological change. Used products are associated with being “left behind”. Or data safety concerns. [14] Another *Sociotechnical Perspective* covers the argument life-time vs. use-time. To get working components and parts from an obsolete product, it is obvious the life-time of those must be longer than the use-time of the product. Such robust and longevity components and parts are first targets when thinking of reuse and remanufacturing.

The physical product design (how the product is built up, types and use of materials and joining techniques, electrical circuits, connectors, etc.) is covered by the *Technical Perspective*. This perspective focusses also on appropriate design strategies. Beside the already mentioned D4R strategies, “Design for Repair, Reuse, Remanufacturing and Recycling”, other design strategies are important too like “Design for Manufacturing, Assembly and Disassembly”, “Design for Logistic”, “Design for Durability” etc.

Another characteristic of the physical product design is the granularity of modules, meaning the right level of modularisation. Knodel et al. [15] pointed out that it requires always the right level of modularisation, keeping balance between cost for creation and maintenance and the savings generated by modularity. Achieving full modularity is not sufficient and by the way impossible [15]. Although this content is related to software engineering, it might be valid in product development too. Within the change to a modular product that meets the needs of Circular Economy, together with a circular business model, concerns from a legal point of view can occur. Barneveld et al. [16] identified regulatory barriers that make electronics less suitable for reuse or recycling. One of the main barrier is that reuse organisations are restricted from accessing collection points [16]. Getting one's own old, discarded products back, might be also facing similar difficulties. This obstacle could be avoided by establishing rental or service models instead of selling products.

Another issue to consider is data storage and data security. For example smart mobile devices are often used in sensitive areas of application like in public agencies, hospitals or by lawyers. A possibility for data erasure must be arranged within the new circular business model. To conclude, the *Legislative Perspective* needs to be considered.
For developing the guideline the product design process is divided into five tasks. These structure was also taken for the guideline itself. These five tasks were worked out with focus on the 6 perspectives defined:

〉 Environmental Perspective
〉 Economic Perspective
〉 Logistic Perspective
〉 Sociotechnical Perspective
〉 Technical Perspective
〉 Legislative Perspective

In the last years environmental awareness and Circular Economy got more in the focus of product development. As a result, in the meanwhile different tools exists which helps for example doing a screening life cycle assessment, or analysing and developing a circular business model.

During a research phase relevant tools and methods were listed and allocated to the different tasks. Most of them are free available and assist during the modularisation process, and are chosen in regard to easy and simple usage. More details about the tools can be found at the references. The intended guideline is developed for product designers and gives a possible way towards a modular product concept with a focus on Circular Economy.

4. DESIGN GUIDELINE FOR MODULAR PRODUCTS

The design guideline shows how to design a modular product concept for smart mobile devices to meet the needs of Circular Economy.

It is divided into five tasks as shown in the Figure 5, including a range of questions from the environmental, economic, sociotechnical, logistic, technical and legislative perspective as defined in Chapter 3. From the definition of an adequate main CE-strategy of the product, the development of an appropriate business model, up to the physical design of modules themselves.

This guideline is particular desired for electronic products especially smart mobile devices. But it can also serve as food for thought for the development of products from other fields.

The guideline can be applied on a reference product, a previous model, a rough product sketch, or just an idea of a new product concept.

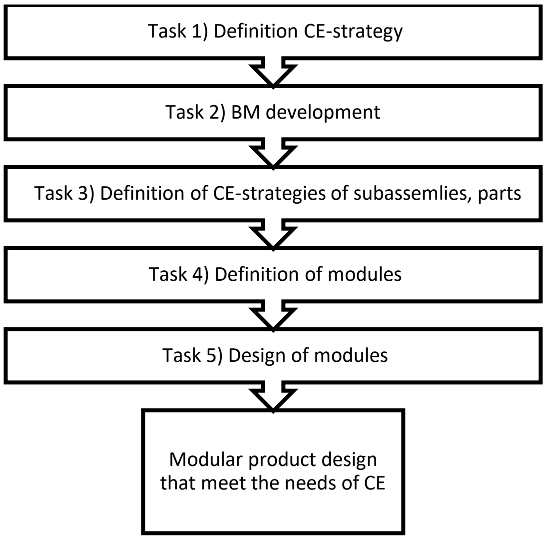

Figure 5: Way to achieve a Modular Product Design that meet the Needs of Circular Economy

4.1 Task 1 - Definition of the product's CE-strategy

The first task is to find an adequate main-CE-strategy. There are four end-of-life strategies (Repair, Reuse, Remanufacturing and Recycling) to close the circle. The choice depends on different aspects like how does the current business model look like, where gets the value lost, or product life-time vs. product use-time.

One should consider, that as shown in the Circular Economy System Diagram (Chapter 1), the inner circles are preferable, because more value can be preserved in the system. Repair should be favoured instead of reuse, reuse instead of remanufacturing, and remanufacturing instead of recycling. Recycling should be the last option to choose. This principle is called the Hierarchy of CE-Cycles [3], and should be considered also at all further decisions.

To support the alignment of the suitable product's CE-strategy, the following questions from the environmental perspectives should be answered.

〉 Is the material and/or the production phase relevant? *(Env.Pers.)*
〉 Do my product contain valuable parts from an environmental perspective? *(Env.Pers.)*
〉 Is the distribution phase relevant? *(Env.Pers.)*
〉 What is the best matching main CE-strategy for my product? *(Env.Pers.)*

To find the right strategy, studying the current situation with the following tools will help. For example, the Circular Economy Toolkit gives matching CE-strategies for a given product.

- ResCoM Circular Pathfinder [17]
- Circular Economy Toolkit [18]
- Ecodesign online Pilot - Assistant [19]
- ECODESIGN+ [20]
- LCA to go / electronics [21]

4.2 Task 2 - Business Model development

A circular product design can only realise its full potential with an appropriate business model. A linear business model, which might represent the status quo, needs to be adopted to fulfil supplementary needs: reverse logistic, additional products like spare parts, new services, new activities, etc.

Achterberg et al. [22] mentioned that business models are generally sales oriented and revenues come from selling products, which forces to design products with a short lifespan to maximise selling new ones. They also identified three main challenges for the transformation to a circular business model: The need to keep control over the resources, to preserve the value added as well as optimize the residual value of the product after use.

Within these step the following questions need to be answered in order to define the Business Model.

- What are the customer's needs? *(Econ. Pers.)*
- Can I retain ownership and product maintenance? *(Econ. Pers.)*
- Can the business model be adapted to help capture additional value? *(Econ. Pers.)*
- How can the residual value of my product be fitted to the need of a (new) user? Cascade use? Application for components or parts for a future life? *(Econ. Pers.)*
- Are my customers willing to accept products with used or refurbished parts? *(Socio. Pers.)*
- How do I get the used products back? *(Log. Pers.)*
- Are incentives necessary and how could they look like? *(Log. Pers.)*
- Do I have already the infrastructure for reverse logistic, or can a new one be realised? *(Log. Pers.)*
- Can I sell my product as new, if it contains used parts? *(Legis. Pers.)*
- Are there concerns from a legal point of view, regarding (transnational) take back actions, or regarding data security? *(Legis. Pers.)*

The following tools will support the development of circular Business Models:

- Value Proposition Canvas [23]
- Business Modell Canvas [23]
- Value Hill Business Model Tool [22]

4.3 Task 3 - Definition of CE-Strategies of subassemblies and parts

In the third task, the product is investigated at component level. Depending on attributes like environmental impact, value, function, size or lifetime, the main components and parts can be identified.

For each of the main components or parts, an end-of-life strategy has to be defined, similar as with the main end-of life-strategy of the product (Task 1), but with the additional requirement, that those sub-strategies have to serve of course the product's main-strategy.

Influencing factors for selecting the right strategy are the life time & wear, again the environmental impact, the value, and are also caused by the previous defined, circular business model. As with the product's main end-of-life strategy, the Hierarchy of CE-Cycles should receive attention.

Questions to be answered in this step are listed below.

- What are the relevant parts of my product from an environmental perspective? *(Env. Pers.)*
- What are the relevant parts of my product from an economic perspective? *(Econ. Pers.)*
- What are the main components and parts of my product? *(Tec. Pers.)*
- How long is the average use time of my product? *(Socio. Pers.)*
- How long is the average life time of my product, components and parts, especially the environmental or economic worthy one's? *(Socio. Pers.)*
- What are the best matching end-of-life strategies of the main components or parts? *(Env. Pers.)*

Methods and tools that help choosing the right end-of-life strategy of subassemblies and parts:

- LCA Software to achieve a more detailed result on a component level
- Value Hill Business Model Tool [22]

4.4 Task 4 - Definition of Modules

This task represents the original idea of modularisation. Components, parts, and subassemblies have to be clustered to modules with similar properties, end-of-life strategies, technical possibilities (interfaces…), requirements derived by the products use or the business model. A reasonable granularity should be achieved without a to detailed modularity, since a to detailed modularity will cause negative effects regarding product design, environmental impact, assembly, all sort of costs and failure susceptibility.

Questions to be answered in this step are the following:

〉 What additional requirements, derived by the business model, are important for the definition of modules? *(Econ. Pers.)*
〉 Can parts and components with the same intended end of life strategy and/or second life purpose be reasonable clustered? *(Tec. Pers.)*
〉 Are there inseparable interactions between the parts and components, which can hinder a successful seperation? *(Tec. Pers.)*
〉 Especially between the (main) parts and components with different end-of-life strategies? *(Tec. Pers.)*
〉 Or are there components or parts with the same end-of-life strategy that should not be bundled together in a single module? *(Tec. Pers.)*
〉 How do the modular structure of my product look like? *(Tec. Pers.)*
〉 How do a reasonable module-granularity of my product look like? *(Econ. Pers.)*

Usually, defining the modules at this point won't be that difficult and complex, when considering the aspects mentioned above. If the design is too fuzzy, common modularisation methods found in literature could help e.g. [6], [24].

〉 Heuristic Function Structure Method
〉 Design Structure Matrix

4.5 Task 5 - Design of Modules

The last task includes creating the module's technical structure. Questions which arises at this stage are for example how are the modules connected to each other, or how do the electronical interfaces look like?

〉 Are there interfaces within my product design, able to be standardised, which facilitate the modularisation? *(Tec. Pers.)*
〉 Can an easy and non-destructive separation of modules, which are meant for reuse or remanufacturing be realised? *(Tec. Pers.)*

Focus on design rules like "Design for Manufacturing" and "Design for Assembly" helps achieving an appropriate design. Relevant hints related to such rules can be found in literature, e.g. [8], [19]. Also automated disassembly will reduce costs with the right quantities. Include possibilities for failure detection to ensure that modules which will be reused work properly. So they can be taken again for a second life without any concerns, a convenient quality can be achieved. For a non-destructive disassembly, easy separation of modules for reuse or remanufacturing is important. In contrast, modules "designed for recycling", could be possibly removed destructive (for example milling the housing or drilling clips or screws). When designing modules for recycling, select proper material combinations which ease the recycling process, or enable a good separability, guidelines for design for recycling, e.g. [25] can be taken into account. Below a list with different design strategies is given.

〉 D4R Methodology [26]
〉 Design for Manufacturing
〉 Design for Assembly (and Disassembly)
〉 Design for Maintenance, Serviceability
〉 Design for Logistic
〉 Design for Recycling
〉 Design for Ergonomics and Aesthetics

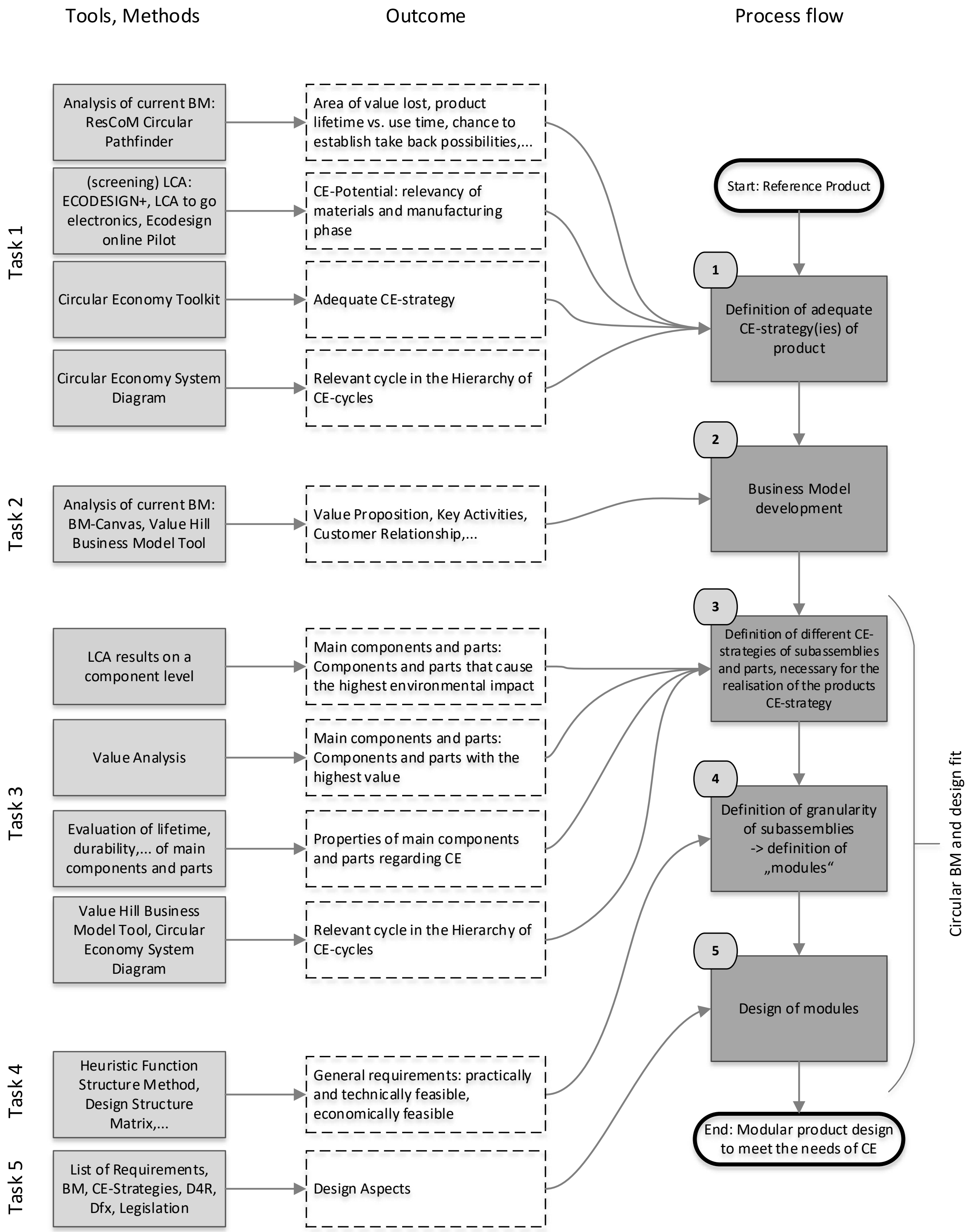

Figure 6: Design Guideline – Process Flow

Figure 6 shows the design guideline. The tools and methods listed on the left side will support the answers of the questions. The results and influencing factors are shown in the middle section. On the right side the process flow is pictured.

5. CASE STUDY DIGITAL VOICE RECORDER

Based on the proposed guideline a new modular product concept for a digital voice recorder developed by the ECODESIGN research team from the Vienna University of Technology within the sustainablySMART[1] project, together with the project partner Speech Processing Solution. All guidelines and tasks are applied to a digital voice recorder.

5.1 Reference Product

The digital voice recorder Philips Digital Pocket Memo 8000 (DPM) was chosen as a reference product. It is intended for frequent, professional users in the hospital sector, by lawyers or notaries.

Product	Philips DPM 8000
Function	Voice recording
	4000 hours
Use time	4 years in average
Life time	>4 years
	(except battery)

Table 1: Reference Product

5.2 Application of the Guideline

Task 1 - Definition of adequate CE-Strategy of Product

Taking a look at the DPM from the environmental perspective indicates that 56% of the GWP is due to the raw materials and the production phase, compared the use phase with just 6% (tool applied: ECODESIGN+). This means that there is a high impact coming from materials and production which should be kept as long as possible on a high value. Especially electronics (printed circuit board has 40% of the GWP, materials and production) are valuable and should be circulated. A share of this potential (56%) could be saved if components or parts with a high impact will get reused.

Based on this high reuse potential, the long lifetime of the parts and the slow innovation cycle of digital voice recorders, the whole product as well as its valuable parts would be suitable for reuse. But for the customers it is important, that the outer housing should always appear like new. So the best matching strategy is “Design for Remanufacturing”. Also the Circular Economy Toolkit [18] was used to confirm the selected strategy.

Task 2 - Business Model Development

Low investment costs and having reliable devices are important, for example in the hospital sector. Employees are used to work with shared devices. Therefore, user perception for used devices is given. Based on the idea of “refurbished devices” a suitable business model was looked for. A rental model with the option to replace old products with refurbished ones, update or just repair them, have been developed [27] using the value proposition canvas and the business model canvas method [23]. Often take back is a challenging issue. But in this case, as most sales are B2B, this effort seems to be manageable, as bigger chunks of used products can be taken back at once. However reverse logistic must be developed, due to current indirect sale via vendors. But all in all, a transition to a rental models seems possible.

Task 3 - Definition of CE-Strategies of Subassemblies and Parts

In average the life time of the product is longer than the average use time. From the sociotechnical perspective, nearly all main components could be reused or remanufactured (except battery, or parts with high wear like housing parts or buttons).

The main components are: rear and front housing, display glass, PCB-parts (biggest environmental impact), memory card, battery, speaker, microphone, display and frame.

The three different end-of-life strategies for the components were defined:

〉 Components that can be used only once for various reasons: “Design for Recycling”. For example the battery or all the parts of the housing and the buttons.
〉 Components that can be used only in the same type of product and even in the updated product: “Design for Reuse”. For example electronic parts like the display, loudspeaker or the microphone.
〉 Valuable components that needs to be changed for a reuse in the updated product: “Design for Remanufacturing”. Here especially the PCB is notable.

These three categories represent only the main end-of-life strategy of each component.

[1] ‘sustainablySMART’ is a project driven with 17 partners from 9 different countries under European Union’s Horizon 2020 research and innovation programme under grant agreement No 680604.

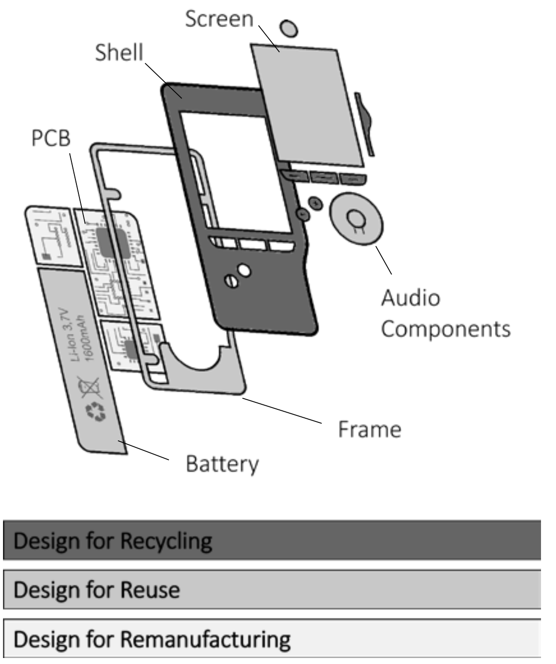

Figure 7: Modules with the belonging end-of-life Strategies

Task 4 - Definition of Modules

Based on the following attributes the modules were grouped:

- must: same end-of-life strategy
- should: similarly expected life time
- simplification for the remanufacturing process
- simplification of the structure
- the need to replace critical (parts that become easily defective) parts

Figure 7 shows the 6 modules with the end-of-life strategies assigned in the previous task "*Definition of CE-Strategies of subassemblies and parts*".

For example, the "shell"-module consist of all outer parts, which can get worn or tattered by time and use, housing parts, display glass, all sort of control buttons etc. These parts can only bear one use phase, afterwards they must be replaced ⇨ "Design for Recycling" is the appropriate strategy.

The "audio"-module contain the microphone and the loudspeaker, both parts are mainly independent from the electric design of the voice recorder and can be reused ⇨ "Design for Reuse" even in an updated product.

Task 5 - Design of Modules

The product requirements of the DPM are allocated to the single modules, and additional requirements are defined which result from the modularisation. Based on these requirements and the D4R-Methodology [26], specific design measures for the realisation of these modules were derived.

Due to ergonomic reasons a minimum size and thickness of the voice recorder is required. So, sufficient design space for additional interfaces and detachable joints and connectors exists, which are necessary because of the modular design.

Figure 8 shows the concept of the Frame for an example. It fulfils all the mounting and positioning functions to holds all other modules.

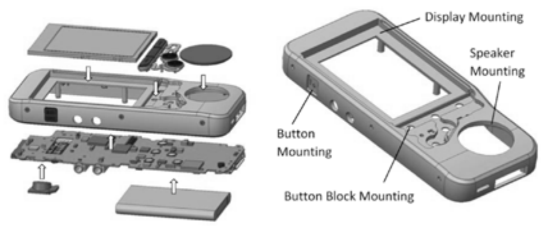

Figure 8: Functionality and Realisation of the Frame

5.3 Case Study Results - Modular Product Concept "Digital Pocket Memo D4R"

The different end-of-life strategies in one product improves the possibility to reuse or remanufacture the devices modules and enables product updates. This CE-optimised product concept results in a lifetime extention and should also result in environmental savings. Beside the modular product design, various other improvments resulted.

Other improvements at a glance:

- The new design with an improved material mix improves the material separability and the recyclability of the device.
- Together with a business model focusing on circularity of products a better environmental performance over a longer product lifetime can be achieved. Comparing the reference product DPM8000 and the new product concept DPM D4R in a scenario with a linear life cycle with no real circular approach, the impact of the DPM D4R is 12% higher. Mainly caused by the new PCB design, which enables the PCB remanufacturing. If the DPM D4R is just reused once, meaning 2 life cycles, the GWP can be reduced by 21% in comparison to the reference product, if 3 life cycles can be realised, the GWP is reduced by 35% CO_2 eq. per product cycle [28].

- Beside the environmental advantages, innovations for the customer are realised in the product concept. OLED display with less power consumption leads to a longer operating time, a durable housing fully made out of stainless steel results in a high quality appearance.
- Detachable electrical connections via cable and plug, spring fingers etc., together with self-locating features for components enables easy dis- and reassembly.
- A scenario analysis was carried out to address the economic situation. After six years, the result of the "circular scenario" (based assumptions, no growth rate above the average) of the rental model is more than 50% higher than the "linear scenario" (status quo sales figures, no growth rate above the average) of standard sale [27].

By the use of the guideline, the D4R Modularity was applied to the DPM 8000. Together with a circular business model such a modular design should results in environmental savings. As shown, this savings could be achieved with the "Digital Pocket Memo D4R".

6. INTERPRETATION AND DISCUSSION

With this design guideline and its suggested tools and methods a modular product design for smart mobile devices to meet the needs of Circular Economy can be realised.

In literature different methods exists already to design a modular product architecture. But applying these methods results in a product design with no special aspect to Circular Economy, because there is simply no attention on this field. Current research in modular design mainly focuses on function and production issues. Li et al. [5] published already a paper with an approach to form a modula product considering different end-of-life strategies. Li et al. suggested to model products by a connected fuzzy graph, and express the connectedness between the single components with a calculated relationship value. The values represents the degree if two components should be connected or not. The values are calculated by four design objectives: Disassembly, Recycling/reuse/disposal, Material selection and Serviceability [5]. Calculating the single values, e.g. for disassembly time or energy consumption for disassembly, is complex and inaccurate, especially if the product is just in the design phase. In this paper a more heuristic and tool-based approach is pursued, which is more common to product developers and therefore more likely usable than a strict forward abstract mathematical method.

A difficulty when designing the guideline was the implementation of the task on developing the circular business model. At a first glance, this task seems is not needed to achieve a modular product structure. But to meet the needs of Circular Economy, the application of the guideline only have an impact regarding Circular Economy if the D4R designed product is accompanied by a circular business models, as this will finally secure that e.g. products are taken back and can reused. In general many steps and considerations During the implementing of the D4R-Modularity are dependent on the business model, and vice versa. Accordingly, the business model should be simultaneous developed to the tasks which focus on the modular product structure.

The targeted audience of this guideline are product developers, but with the focus on business models also divisions like the business development, marketing, logistic or the management needs to be involved in order to achieve a feasible result.

The proposed guideline in this paper represents a first draft version. The guideline and its D4R-Modularity was only applied to the digital voice recorder, as shown in the case study chapter. Using the guideline on different products would demonstrate its strengths and weaknesses leading to an improved methodology.

Further Circular Economy has become recently an area of active research, where continuously new papers or online tools regarding CE are published. The guideline should be updated with Regent methodology and tool developments.

Currently tools and methods which assist during the development process are only listed to the belonging tasks of the guideline. Explicit interfaces from these tools to the guideline are in most cases missing and need to be defined in detail, in order o have a clear work flow in the guideline.

However, we think tat this guideline represents a useful tool to target smart mobile devices which helps realising circular economy principles.

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