The "Environmental Activation Energy" of Modularity and Conditions for an Environmental Payback

Karsten Schischke, Marina Proske, Rainer Pamminger, Sebastian Glaser, Nils F. Nissen, and Martin Schneider-Ramelow

Abstract Similar to the meaning of "activation energy" in physics and chemistry, there is a certain environmental investment needed for some circular design approaches: On the example of modular mobile devices, the additional environmental impact of implementing "modularity" is explained. This additional impact can be overcompensated through lifetime extension effects, if the design and related business models trigger the intended circularity effect. The paper systematically categorizes the different variants of modularity, explained on the example of smartphones. Each modularity approach features specific circularity aspects, including repair, upgrade, customization as a means to not over-spec a product, reuse and repurposing of modules. These life cycle management aspects are discussed on the example of various smart mobile products.

1 Introduction

Activation energy is the energy which must be provided to trigger a chemical reaction. Similarly, to foster a better environmental life cycle performance of a product in most cases, an additional initial manufacturing effort is needed in support of a circular design: Increased reliability might require high-quality materials, better

K. Schischke (✉) · N. F. Nissen
Fraunhofer Institute for Reliability and Microintegration (IZM), Berlin, Germany
e-mail: karsten.schischke@izm.fraunhofer.de

M. Proske · M. Schneider-Ramelow
Fraunhofer Institute for Reliability and Microintegration (IZM), Berlin, Germany

Technische Universität Berlin, Research Center Microperipheric Technologies, Berlin, Germany

R. Pamminger · S. Glaser
Technische Universität Wien, Vienna, Austria

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robustness can be achieved with higher material intensity, and reparability requires a modular instead of a monolithic design. Also design for recycling might require initially design changes, which do not reduce manufacturing impacts – but are supposed to reduce impacts at end-of-life significantly. Only the use of recycled materials, as a circular design approach, tends to reduce environmental impacts right in the production phase. Figure 1 shows the comparison of an iPad with a mobile computer, which was designed with several circular design strategies in mind, such as:

- Better compatibility with accessories (see the nine-pin serial port and the RJ45 Ethernet connector, which are not found in conventional tablet computers).
- Exchangeable connector blends to allow for a shell reuse in case of changing internal electronics.
- Wood as sustainable material, which does not allow similarly small form factors as metals.
- Reparability and replaceable battery, etc.

For a more comprehensive overview of design features of this mobile computer, see Ospina et al. [1]. What is evident is the significantly larger form factor, more total material use of the circular design approach.

With this in mind, our research suggests the term "environmental activation energy" to illustrate the fact that circular design requires additional efforts – and bears the risk that these additional efforts might not pay off as expected in later product life cycle phases. Our research focusses on several examples of modular

Fig. 1 Mobile computer designed by an SME following circular design principles compared to an iPad (fifth generation)

design, as one prominent circular design approach in support of better reparability, reusability, upgradeability and recyclability.

2 Life Cycle Assessment of Modularity

With a range of examples from latest design research, the environmental impacts of circular design strategies and modularity in particular are explained to road-test our thesis that modular design comes at the cost of an "environmental activation energy".

2.1 Smartphone Modularity

The Fairphone is the most prominent example of a modular smartphone designed for do-it-yourself repairs. The Fairphone 2 launched in 2015 featured larger internal modules, mainly connected with spring-loaded connector arrays. These are robust connectors which can also withstand a rude handling by the user. These gold-coated connectors, additional printed circuit board area for contacts and module housing all resulted in a significantly higher environmental impact than a comparable conventional design [2–4].

Depending on the impact category, the impact share of modularity components is between 2.2% and 12.9% (Table 1). System boundaries are cradle to readily manufactured phone.

These additional impacts need to be compensated by the effect of a longer product lifetime due to enhanced reparability. Proske et al. [4] calculated a significantly improved environmental footprint in case this measure increases the product lifetime from in average 3 years to 5 years. This takes into account also repairs and battery replacements.

The next generation of the Fairphone launched in 2019 [5] addressed this aspect of a modularity overhead by changing the connector concept towards mezzanine strip connectors, which require only a small additional PCB footprint and feature a smaller contact area, thus less gold-coated surface finishes (Fig. 2). Some connections from the core module now had to be made with flex PCBs to bridge distances.

Table 1 LCA results: Fairphone 2 modularity (cradle to gate)

	Fairphone 2	Modularity components
Global warming (kg CO_2e)	35.16	0.77 (2.2%)
Resource depletion (abiotic, g Sb-e)	0.788	0.102 (12.9%)
Resource depletion (fossil, MJ)	139.51	8.05 (5.7%)
Human toxicity (g DCB-e)	8.290	280 (3.4%)
Ecotoxicity (g DCB-e)	110	5.79 (5.3%)

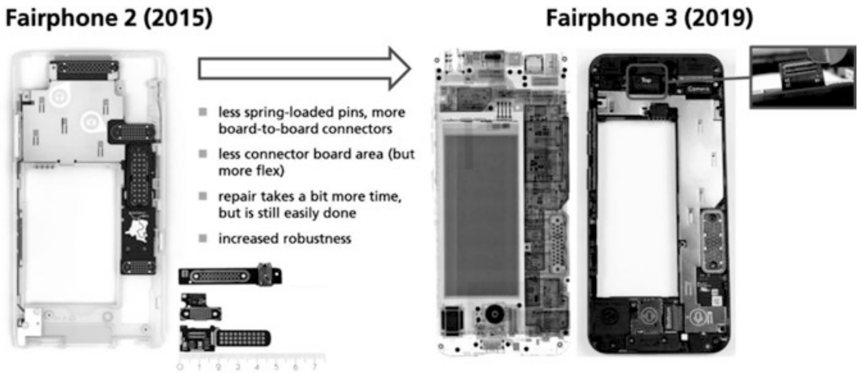

Fig. 2 Evolution from modular fairphone 2 to modular Fairphone 3 and major design changes

This might affect the manufacturing impact adversely. It remains to be seen, by how much these design changes reduce the modularity-related environmental impacts and thus the "environmental activation energy", but the tendency definitely is positive.

A life cycle assessment study for the Fairphone 3 is currently work in progress. Results are expected mid-2020.

2.2 Digital Voice Recorder Concept DPM D4R

Professional digital voice recorders cover a wide range of functions. Not only the basic function "voice recording", but much more subsequent processing of the recorded files like voice recognition, creating and editing documents, adding and managing additional information and supporting the workflow via cloud solutions are in the focus. Such devices are designed for professional use in the hospital sector, by lawyers or notaries. Enabling those functions, digital voice recorders have a design similar to that of today's average smart mobile product.

A modular concept of a Digital Pocket Memo (DPM) has been designed together with a new B2B rental service [6]. This intended business model opens the possibility to replace old products with refurbished ones, update or just repair them. This leads to a lifetime extension of the whole product or single modules, and the overall life cycle impact decreases.

With this product concept, a D4R modularity approach (D4R means *design for repair*, *reuse*, *remanufacturing* and *recycling*) was applied. The product's modules are defined by components with similar end-of-life strategies (Fig. 3).

This circular design approach leads to the following six modules: The shell (mainly made out of recyclable stainless steel) consists of all parts, which are in direct contact to the user. To assure a visually nice product, these parts can only be used once, and the main end-of-life strategy is *design for recycling*. The battery is

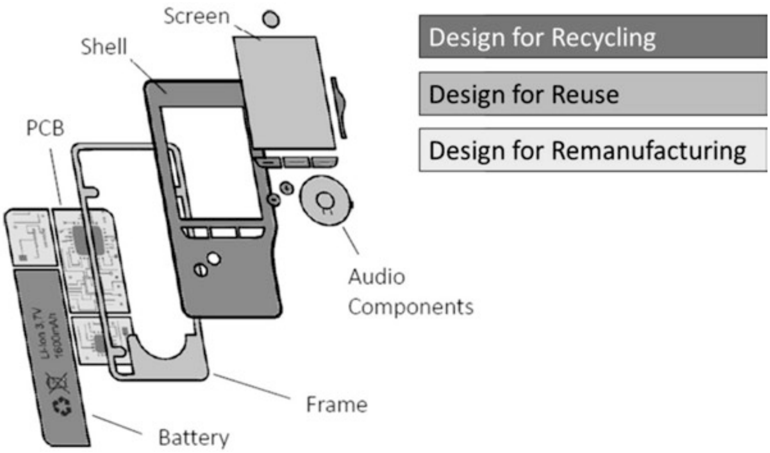

Fig. 3 Design strategies implemented with the digital voice recorder redesign

designed for recycling as the lifetime is relatively short and a certain performance is expected by a new customer. The frame (made out of recycled plastic) is the supporting structure for the PCB modules, the screen and the audio components. The frame is hidden inside (no aesthetic requirements) and meets future requirements of product updates and therefore has to be *designed for reuse*. Also, the audio module and the screen (using detachable connectors) are long lasting and are *designed for reuse*. As the environmental impact of the PCB assembly is very relevant, it should be reused. But due to short innovation cycles, the whole PCB assembly cannot be reused. Instead, the PCB itself is split into functionally grouped modules with the advantage of enabling exchange of single modules during product updates, and the PCB is *designed for remanufacturing*.

Comparing a reference product like the Philips DPM8000 and the 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. This “environmental activation energy” is caused by additional manufacturing efforts, mainly the new, modular PCB design, which enables the PCB remanufacturing. If the use time is doubled (by a second user), meaning two life cycles are taken into account (including exchange of shell module and battery, assumptions for repair of broken parts and product update, including transport, etc.), the GWP can be reduced by 21% in comparison to the reference product. If three life cycles can be realised, the GWP is reduced by 35% CO_2 eq. per product cycle [6].

Figure 4 depicts clearly the “environmental activation energy”: Impacts go up with the implementation of circular design strategies and go back down only with extended lifetimes. Then, however, the positive effect can be very significant. The crucial question again is if this extended lifetime is realistic or if other limiting factors, such as component obsolescence, software obsolescence and incompatibility, might limit the possibilities for further use at the end of the first product life.

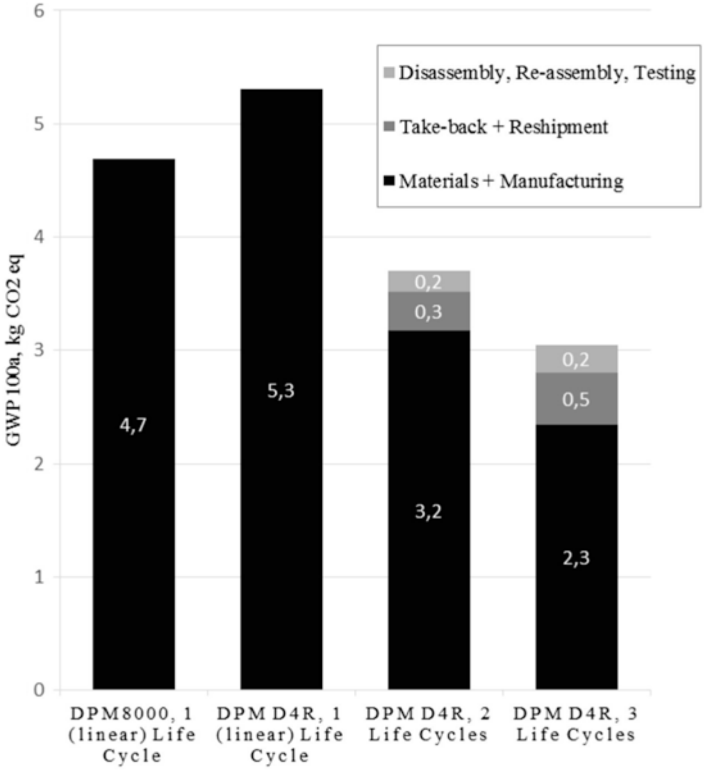

Fig. 4 Life cycle assessment results (GWP) for DVR design variants and lifetime scenarios

2.3 Embedding of Components for a Modular Printed Circuit Board Assembly

The idea of circular design has been advanced even a step further on the example of the digital voice recorder: Embedding is an advanced integration technology, where electronics components are not only placed on the surface of the PCB but are also buried in the PCB substrate. This reduces the needed area footprint for electronics modules. The PCB of the digital voice recorder is split into four distinct modules, the digital signal processor part, the internal power management, the USB connectivity and a backbone board similar to a PC mainboard [7]. The first three modules feature embedded components, and the power and USB module are assembled with non-permanent interconnection technology (screws, spring connectors, ZIF connector). This allows for a repair and refurbishment as indicated in the DVR concept outlined in the chapter before, but now with a miniaturized overall design (Fig. 5).

The image below clearly shows how complexity has been “outsourced” to the modules, featuring embedding. These modules now can be easily exchanged, easing the reuse of either modules or the backbone PCB.

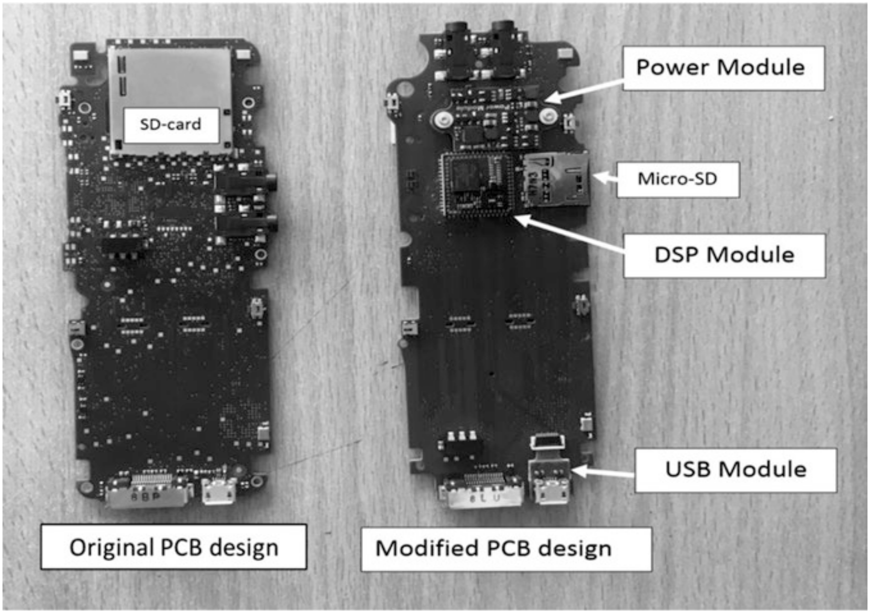

Fig. 5 Printed circuit board design changes towards modularity with embedded components

Table 2 LCA results: Digital voice recorder PCB assembly variants (cradle to gate, components excluded)

	Carbon footprint (kg CO_2 eq.)		
	Standard design	Six-layer backbone with three modules	Four-layer backbone with three modules
PCB/ backbone	1.01	1.01	0.90
USB module	–	0.17	0.17
Power module	–	0.32	0.32
DSP module	–	0.16	0.16
Connectors	–	0.007	0.007
Totals	1.01	1.67	1.57

Although Kupka et al. [8] identified a positive environmental effect of embedding as such, this does not materialize in the given design study [9]: The environmental impact is driven by the additional surface area of backbone and modules, which are – except for the DSP module – electroless-nickel/gold finishes with a high contribution to overall impacts (Table 2). Although not implemented, it seems feasible to reduce the layer count for the backbone from six to four layers. As the backbone board was not miniaturized, but defined by the existing physical dimensions of the handset, the potential of embedding is not fully exploited in this case.

As with the other examples, modularity comes at an initial environmental investment, which is likely to pay off only through lifetime extension of the device as a whole or at least high-impact key components. In mobile electronics, these high impacts in most cases are related to processors and memory (RAM or flash).

3 Design Rules for Modularity

The findings from the modularity assessments indicate how important it is to implement a circular design in a thought-through way and that modularity serves a well-defined (circularity) purpose.

Usually, smart mobile devices get defective 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 product's modules are defined by its components with similar end-of-life strategies.

The following design guideline (as proposed in detail by Pamminger et al. [6] and depicted in Fig. 6) shows roughly how to design a modular product that meets the needs of circular economy using the D4R modularity approach.

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 and what are the customer's needs and does my product contain valuable parts

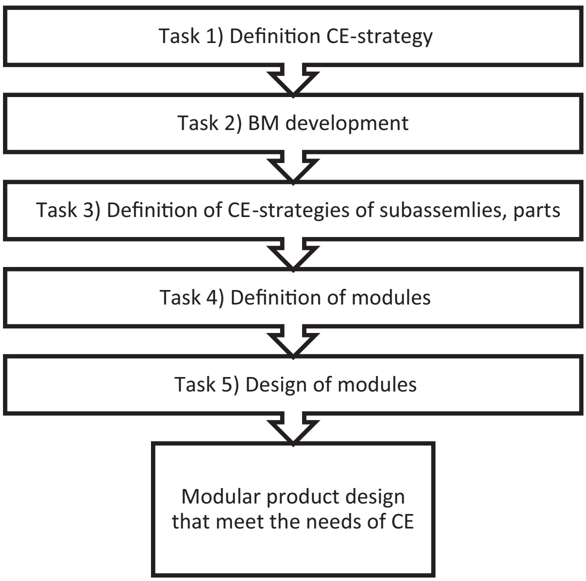

Fig. 6 Stepwise design approach for modular product designs

from an environmental perspective or product lifetime vs. product use-time considerations. By defining the main CE-strategy, a general direction is set for the second task, the business model development.

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.

Tools like the CE Strategist [10] offer great help in developing circular business models.

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

In the third task, the product is investigated at the 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 lifetime and wear, the environmental impact and the value. They are also caused by the previously defined circular business model. As with the product’s main end-of-life strategy, the hierarchy of CE-cycles should receive attention.

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, etc.) and requirements derived by the products use or the business model. A reasonable granularity should be achieved without a too detailed modularity, since a too detailed modularity will cause negative effects regarding product design, environmental impact, assembly, all sort of costs and failure susceptibility.

Task 5 – Design of Modules

The last task includes creating the module’s technical structure. Questions which arise at this stage are, for example, how are the modules connected to each other, or how do the electronic interfaces look like? Can an easy and non-destructive separation of modules, which are meant for reuse or remanufacturing, be realised? Focus on design rules like “Design for Manufacturing” and “Design for Assembly” helps achieving an appropriate design. 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 in a destructive way (e.g. 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.

4 Conclusions

The comparison of modularity approaches shows the broad variety circular design strategies can have even for a rather narrow product segment: smart mobile devices.

The "environmental activation energy" is higher for those products which are built for end-user interaction, such as the DIY repair approach of the Fairphone 2 or a mix-and-match approach of functional modularity, than for those which follow, e.g. the serviceability approach only [2], where connectors do not need to withstand laymen's interaction. The potential environmental payback however is the highest, where the product remains in the hands of the end-user for a repair or even upgrade. However, also business models, which are built on modularity in a business-to-business market, can yield significant environmental savings over the lifetime. Some modularity concepts are at risk not to contribute to circularity at all, but have an adverse environmental impact over the full product life cycle: Where modularity is likely to trigger major rebound effects, the overall life cycle impact is likely to increase on top of the "environmental activation energy" of modularity. It is therefore of high importance to get clarity on the circular economy strategy and to implement appropriate design strategies stepwise, as outlined in this research.

This discussion on modularity and related environmental life cycle impacts is meant to contribute to a better understanding of the right drivers for more sustainable product concepts and factors fostering those developments.

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