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Circularity of consumer electronics within Life Cycle Gap Analysis

Michael Dieterle[1*], *Corinna* Lätsch[1], *Peter* Brantsch[1] and *Ana Claudia* Nioac de Salles[1]

[1]Fraunhofer Institute for Chemical Technology ICT, Joseph-von-Fraunhofer-Straße 7, 76327 Pfinztal, Germany.

Abstract. Life Cycle Gap Analysis (LCGA) interprets the LCA results of a product from a different perspective, focusing on circular economy thinking in order to identify potential for further improvement of the product life cycle's environmental impacts. This study analyses and compares the LCA results of a smartphone and a notebook as two representative products for consumer electronics. Based on identified life cycle gaps of higher than 80 %, the study highlights the need to focus not only on the potential for improvement in manufacturing and use of consumer electronics, but also to shed light on end-of-life management and the effective closure of consumer electronics' material and energy flows to foster circular economy and sustainability.

1 Introduction

The main goal of the Circular Economy (CE) - with the support of the Life Cycle Assessment (LCA) tool - is to reduce environmental impacts by closing loops and to support sustainable development [1]. From this point of view,

- CE is understood as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops" [2].
- LCA is understood as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [3].

However, apart from these parallels and synergies, different mindsets and perspectives - such as thinking in circles vs. thinking in (linear) life cycles, also cause potential areas of challenges. This is illustrated in this study by focussing on two different electronic products.

On the one hand, from an LCA perspective, highlighting and communicating the increased use of recycled materials (e.g. use of 100 % recycled plastics or rare earth elements) in new electronic products is one of these challenges. Depending on the way such results are communicated, they may not answer the question, whether the increased recycled content really leads to a reduction in the overall (life cycle) environmental impacts of an electronic product.

On the other hand, from a CE perspective, the interpretation of LCA results in common bar charts is also challenging. Especially in regard to the circulation of products and materials

* Corresponding author: michael.dieterle@ict.fraunhofer.de

as one of CE's three principles [4]. Here, the end-of-life phase is often indicated only as a limited (positive) effect on the total balance and is, therefore, treated rather vaguely in comparison to the other life cycle stages.

In a review of various LCA studies for smartphones and tablet computers, Clement et al. [5] for example conclude that "*production and use phases are undoubtedly the life cycle phases contributing most strongly*". Other LCA studies for smartphones, tablet computers and notebooks underline these findings in many cases [6-9]. Such conclusion within the LCA interpretation of consumer electronics raises the question as to whether there is relevant potential for further improvement that can support the promotion of a CE, and if yes, how to identify them within (conventional) LCA communication?

In order to meet these challenges, a Life Cycle Gap Analysis (LCGA) [10] was developed as a systematic option by following six pre-defined steps on how to address a CE mindset within LCA interpretation. In the core of the methodology, a product's life cycle gap (LCG) is identified, which results from the difference between the environmental impacts of the product's initial manufacturing and its environmental credits after recycling.

This study illustrates the additional value of the LCGA method for consumer electronics using two comprehensive LCA studies for a smartphone and a notebook [6; 7]. This case study suggests how LCA results of consumer electronics can be communicated and interpreted in order to identify potential for further improvement from a CE perspective within LCA interpretation.

2 Methodology

The most common method to quantify potential environmental impacts of products and services throughout their value chain is LCA, which is standardized by the ISO 14040 series. [3; 11] This study is prepared corresponding to the ISO standards and focuses on two publicly available LCA studies for consumer electronics. Both comprehensive and detailed studies have the same goal: identify hotspots and main drivers of consumer electronics' (smartphone [6] and notebook [7]) life cycle, which cause environmental impacts. To fulfil this goal, the system boundaries of the two studies include the entire product life cycle from raw material extraction, manufacturing, transport, assembly, use to end of life. The functional unit for the smartphone is defined as "*intensive smartphone use over three years*" as baseline scenario, considering "*as delivered to the customer including sales packaging, manual, screwdriver and protection bumper, but without charger*" [6]. Within the study they also focus on different scenarios by taking into account the use phase and different repair or replacement options that affect the extension of the lifetime and hence the functional unit definition (three years of lifetime; vs. five years; vs. seven years) [6]. For the notebook, the functional unit is set as "*1 piece of laptop and its provision of portable computing functionalities for five years*" [7]. The data used for the life cycle inventory of the smartphone and notebook are delivered by collection of primary data from component manufacturers and secondary data from LCA databases as referred in the corresponding studies [6; 7]. The environmental impact assessment of the two studies is predominantly based on the CML impact assessment methodology framework [12] and covers the environmental effects on global warming potential. In addition, within the smartphone LCA study, the impacts on abiotic resource depletion, human toxicity and ecotoxicity are assessed; and for the notebook LCA study, the impacts on non-renewable primary energy demand, eutrophication, acidification, photochemical ozone creation potentials and ozone depletion potential are analysed [6; 7].

In order to identify hotspots and main drivers during the LCA interpretation, the final results for the smartphone and notebook are summarized using bar chart diagrams. These overall results serve as the starting point for the application of the LCGA, as illustrated in chapter 3.

3 Identifying life cycle gaps

The interpretation of consumer electronics' LCA results focuses on climate change - Global Warming Potential 100 years (GWP) in kilograms of carbon dioxide equivalents (kg CO_2-eq.), as GWP is considered in both LCA studies the most robust and widely used impact category. *Table 1* summarizes the overall LCA results of the two comprehensive studies [6, see p. 35; 7, see p. 35] according to the *first step* of the LCGA methodology.

Table 1. Climate change - GWP results of a smartphone and a notebook

Life cycle phase	Smartphone [6, see p. 35]		Notebook [7, see p. 35]	
	absolute (kg CO_2 -eq.)	relative (%)	absolute (kg CO_2-eq.)	relative (%)
Manufacturing	32.2	81.5	109.9	74.9
Transportation	0.6	1.5	13.6	9.3
Use	8.4	21.3	35.0	23.8
Recycling	0.1	0.3	1.0	0.7
Credits	-1.8	-4.6	-12.6	-8.6
TOTAL	*39.5*	*100*	*146.8*	*100*

The results underline that the manufacturing phase, including raw material acquisition as well as production, is the main driver within the total balance of the two products. Both have a share of more than 74 % of the total emissions, 74.9 % for the notebook and 81.5 % for the smartphone. On the other hand, the results from End-of-Life (EoL), indicate a limited (positive) effect on the total balance of the smartphone and the notebook (see also *figure 1*). The results from EoL are calculated as follows: EoL impacts for recycling minus credits for recovery of energy and materials.

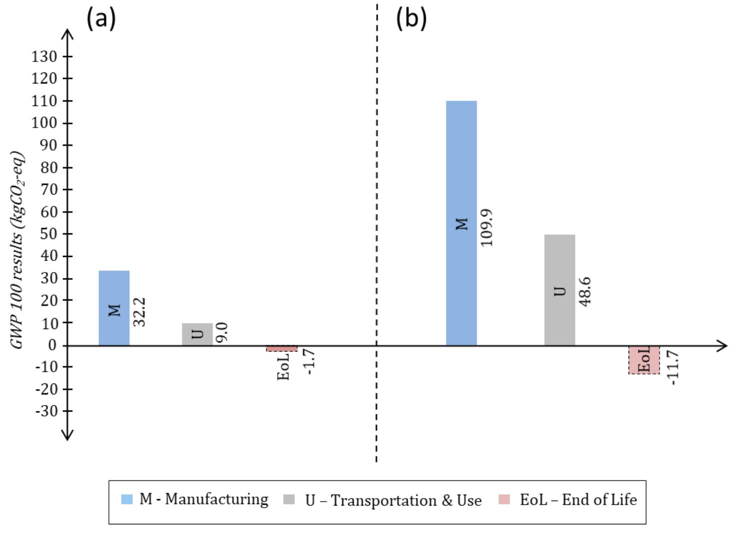

Fig. 1. LCA results of a smartphone (a) and a notebook (b) (visualization according to [6; 7]).

In a *second step*, the life cycle gap of the smartphone (1) and the notebook (2) is assessed, which results from the difference between the environmental impacts for manufacturing and the environmental credits after recycling.

$$LCG_{0;\,phone} = 32.2\ kgCO_2eq - 1.8\ kgCO_2eq = 30.4\ kgCO_2eq \quad (1)$$
$$LCG_{0;\,notebook} = 109.9\ kgCO_2eq - 12.6\ kgCO_2eq = 97.3\ kgCO_2eq \quad (2)$$

Figure 2 illustrates the LCA results from a life cycle gap perspective. In comparison to common assessment and disclose of the LCA results (see *figure 1*), the environmental credits in the EoL phase of the smartphone (see *figure 2 (a)*) and the notebook (see *figure 2 (b)*) are uncoupled from the environmental impacts for recycling and shifted to the initial impacts of the manufacturing phase. In this way, the LCA results are interpreted with different perception and CE thinking reveals its own stage within LCA interpretation, as illustrated by the magnifier.

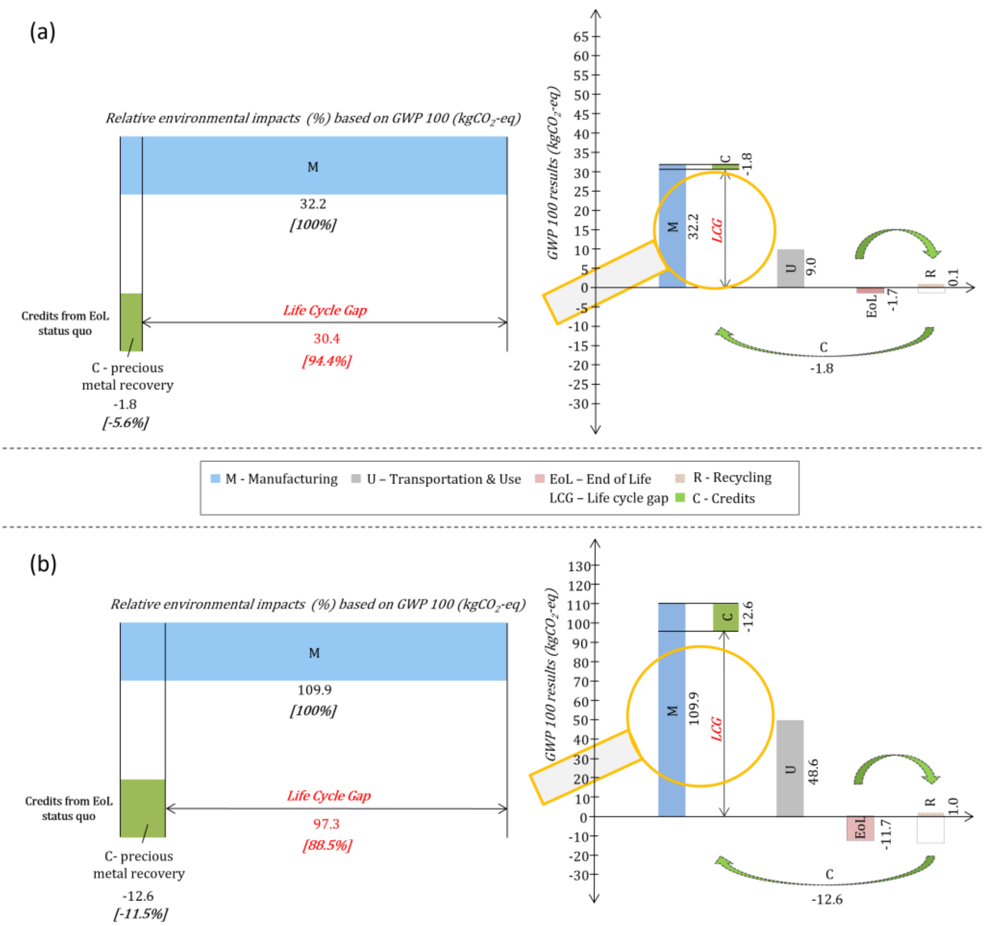

Fig. 2. LCA results of a smartphone (a) and a notebook (b) from a life cycle gap perspective.

The results indicate that there is a significant potential for further improvement from a CE perspective, as the identified life cycle gap of the smartphone is about > 94 % (30.4 kg CO_2-eq.) and of the notebook about > 88 % (97.3 kg CO_2-eq.).

According to steps 3 and 4 of the LCGA methodology [10] there needs to be the identification of new solutions and developments towards a reduction in life cycle gaps for consumer electronics. This requires also to take into account the whole life cycle impacts of the new product systems ($total_{new;\ phone} \leq 39.5$ kg CO_2-eq.; $total_{new;\ notebook} \leq 146.8$ kg CO_2-eq.), before their implementation according to step 5 and step 6 of the LCGA methodology [10].

Repair and maintenance of single subcomponents can have a significant contribution on the total GWP of consumer electronics. There is a potential for reduction in emissions up to 40 %, as shown in [6, see p. 35] for the lifetime extension of a smartphone from three years up to seven years. This is also affecting the functional unit defined in the LCA study. Nevertheless, even after seven years, the smartphone with all its components is recycled. This still ends up in open loops and hence relevant life cycle gaps which can be expected as higher than 80 %. Attention should be also paid to these gaps and minimized as far as possible.

4 Conclusion

This paper conducted a detailed comparison of the LCA results of two consumer electronic products, focusing on their EoL circularity in terms of life cycle gaps. Significant potential for further improvement was identified, as life cycle gaps of higher than 88 % (97.3 kg CO_2-eq.) for the notebook and higher than 94 % (30.4 kg CO_2-eq.) for the smartphone were highlighted.

A key finding for LCA studies of consumer electronics is that EoL phase can have a relevant contribution on the total life cycle balances. It is now up to companies, engineers & researchers to find solutions to reduce such existing gaps for consumer electronics. This can be realised for example by considering the three principles for Circular Economy propagated by the Ellen MacArthur Foundation [4]:

(i) Eliminate waste and pollution, e.g. by harnessing new materials and technology;
(ii) Circulate products and materials, to keep them in circulation;
(iii) Regenerate nature, by enhance natural resources.

Even after lifetime extension through strategy and innovation such as reuse, repair & maintenance, which can have a significant (positive) contribution on the total environmental impact of consumer electronics, the products (including its components) will reach their end-of-life. In that way and especially from a CE perspective, it will be also decisive to guarantee that the materials after use are kept in circulation within the entire system.

The identification of new solutions and developments towards a reduction in life cycle gaps for consumer electronics requires also to take into account the whole life cycle impacts of the new product systems ($total_{new;\ phone} \leq 39.5$ kg CO_2-eq.; $total_{new;\ notebook} \leq 146.8$ kg CO_2-eq.), before their implementation. Such cross-check contributes and ensures the avoidance of negative trade-offs to foster circular economy and sustainability.

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