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The circular economy potential of reversible bonding in smartphones

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ABSTRACT

The increased use of adhesive bonding in manufacturing is an important barrier to implement circular economy strategies, including repair, refurbishment, and high-quality recycling. The circular economy potential of reversible adhesives that are debondable on demand, however, remains largely unexplored. In this paper we apply an integrated technology-agnostic framework to smartphones to identify and quantify the circular economy potential of reversible bonding. In this framework we combine insights from Life Cycle Assessment, Life Cycle Costing, and Statistical Entropy Analysis. We find that reversible bonding of smartphones can be an enabler for circular strategies and have a considerable positive impact on preserving higher functionality on a product, component, and material level. The major added value of reversible bonding is its potential to replace and update parts, retaining the main environmental hotspot of a smartphone. Firms, however, will not likely switch to this technology, even though bonding and debonding make up only a small fraction of total lifecycle costs. Therefore, policy recommendations include mandatory policies on repairability and public procurement favouring the use of reversible bonding techniques. This would alter incentives in contexts where consumer preferences for lease markets cannot be taken for granted. The evaluation of different debonding scenarios from three distinct perspectives provides a comprehensive, more reliable, and robust understanding of the trade-offs related to debonding and its potential contribution to the circular economy.

1. Introduction

In light of the climate crisis, the need to change the way we use resources, produce, and consume is becoming increasingly urgent. With the European Green Deal (COM, 2019) and accompanying policies (COM, 2020a,b, 2021), one solution is seen in the transition to a Circular Economy (CE), where value of products, materials, and resources is preserved for as long as possible, and the generation of waste, emissions, and the amount of materials extracted is minimized (Eurostat, 2022). However, despite the wide range of CE strategies, recycling represents the most dominant CE strategy (e.g., Potting et al., 2017), in many cases leading to the loss of the original technical properties and specific functionalities (Helbig et al., 2022; Tonini et al., 2022).

One aspect that severely influences the potential to retain value and functionality of products, components, and materials is the degree to which the product can be disaggregated to its components and materials. Design for disassembly (DfD) (e.g., Talens Peiró et al., 2017) as well as design for recycling (DfR) (e.g., Norgren et al., 2020), are only two sets of guiding principles to improve a system's overall circularity potential. However, the use of non-reversible adhesives can act as a strong barrier that not only impedes disassembly, but also reduces material liberation in the recycling process, leading to a lower recovery rate and a reduced quality of the recycled materials (Norgren et al., 2020). With the projected growth of the adhesives and sealant market that is expected to be on average around 3.6 % per year (FEICA, 2023), the overall circularity could be further reduced in the future.

However, there are many good reasons for the use of adhesives. With the overall trend of products becoming more complex with regard to their material combinations as well as the diversity of components (Talens Peiró et al., 2017), adhesives provide the advantage of being able to join dissimilar materials (Mulcahy et al., 2022). Other benefits are related to weight savings, reduced corrosion, a more uniform distribution of stress, high impact resistance, as well as the ability to bond thin films, sheets and more delicate components (Lu et al., 2014). The non-applicability of other joining techniques such as welding or soldering, or limitations regarding space or aesthetics e.g., when using screws, are other reasons for the use of adhesives.

The Ecodesign for Sustainable Products Regulation which follows the

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Ecodesign Directive (COM, 2009), will introduce additional requirements for material efficiency, durability, reparability, upgradability, and recycling that apply beyond energy consuming products (COM, 2022). However, in some product categories the trend is more in the opposite direction. One example is fixing Li-ion batteries with adhesives into phones, thereby reducing repairability and recyclability of the phone as well as of the integrated battery (IIEE and EEB, 2021). Even though regulatory adjustments in this regard may improve the situation, the increased application of adhesive bonding can also be observed for other product categories, such as vehicles (Lu et al., 2014), electric vehicle batteries (Thompson et al., 2020), or photovoltaic panels (Radavičius et al., 2021). For most of these products exponential growth in the production can be expected during the next decades (Gregoir and van Acker, 2022; IEA, 2021). In this context, reversible adhesives could play an important role to increase the potential for higher circularity, while providing the benefits related to the use of adhesives.

Therefore, this paper aims to provide insights into the role that adhesive debonding could play in the context of the CE, with a focus on comparing different CE strategies from a systemic perspective. As debonding affects the functionality of components and materials, including their circularity potential, as well as the economic and environmental performance of the whole system, these three complementary evaluation perspectives are combined in an integrated evaluation framework. The combination of these evaluation perspectives not only provides a more comprehensive view on debonding as a potential enabler for a more circular system, which remains largely unexplored. It also allows to assess trade-offs that are important to discuss when making ex ante and ex post evaluations of the circular potential of technological and related system innovations. By combining the different evaluation perspectives, this paper answers following research questions:

- RQ1: What is the economic, environmental and functionality potential of reversible bonding and its contribution when applied to a smartphone, and what are the trade-offs considering the three evaluation perspectives?
- RQ2: What system designs (e.g., business models) and CE strategies show the best performance, in relation to the three evaluated perspectives in combination with the application with reversible bonding?
- RQ3: How can the introduced analytical framework contribute to assess the CE potential of reversible bonding?

To the best of our knowledge, this is the first paper that evaluates the potential of reversible bonding in the context of its potential contribution to the CE. In this context, a comprehensive assessment of different system scenarios is provided, including functionality, environmental, and business model perspectives. Each of these perspectives captures different aspects, all of which are important in a CE context. The functionality perspective is close to the core of the CE, as it captures the material-related transformations and compositional changes on the product, component, and material level that are important to understand for establishing a system with a higher circularity performance. The environmental perspective captures the changes regarding the environmental impacts related to debonding scenarios and provides insights regarding the environmental hotspots and the contribution of debonding to reducing the impacts. Finally, the economic perspective provides insights on how to operationalize and implement the debonding scenarios and what business-models and regulatory frameworks, could enable the implementation of debonding techniques. By quantifying and assessing the existing trade-offs between all three perspectives, the paper identifies some key conditions for reversible bonding techniques to support the transition to a more circular system.

The rest of the paper is structured as follows. In Section 2 we provide a brief overview of relevant literature on reversible bonding and the challenges of using adhesives in smartphones. In Section 3 we explain the materials and methods used, while in Section 4 we present results of our analytical framework, applied to a smartphone. In Section 5 we present an integrated view of our results to discuss trade-offs, broader implications, and limitations of this research. In Section 6 we conclude with recommendations and the identification of novel research gaps.

2. Literature

2.1. Reversible bonding techniques

Historically, adhesives have been developed to be long-lasting, enabling longer product lifetimes but meanwhile challenge the disassembly and recycling of the product. In most cases, structural adhesive joints cannot be disassembled without destroying the substrates (Banea et al., 2013). As the use of adhesives increases in the manufacturing of products with high value components and materials, interest in adhesive debonding on command technologies increased throughout the last decade. This interest is driven by environmental and economic concerns, to increase repair, reuse, remanufacture, and recycling opportunities. Examples of literature include Russell et al. (2022) on system requirements for repair, Schumacher and Green (2022) on circularity in a high-tech world, and Svensson-Hoglund et al. (2021) on the policy landscape for repair of consumer electronics in Europe and the US. Reversible bonding techniques can also be applied to optimize production processes using temporary adhesives (Bandl et al., 2020), in medical applications (Chen et al., 2022), or in-space assembly (Meyer et al., 2021).

The ability to separate the joint between two materials or components on demand, triggered by an external stimulus (Banea, 2019), can be achieved through a variety of approaches. Thermal treatment is considered to be the most widely studied mechanism for debondable adhesion. Examples include studies on the footwear industry (Arán-Ais et al., 2021) and the automotive industry (Banea et al., 2015). While this procedure may be rather straightforward for hot-melt adhesives, many strong structural adhesives decompose at high temperatures before melting. The use of high temperatures also poses problems for products with temperature sensitive components (Anduix-Canto et al., 2022). A promising evolution is the incorporation of thermally expandable particles (TEPs) in adhesives (von Freeden et al., 2022), that can be triggered by e.g. microwaves or induction heating, leading to their expansion and cracks in the adhesive, which makes the two previously bonded substrates easily debondable..

With photo-debondable adhesives, on-demand debonding can be triggered by using a specific spectrum of electromagnetic radiation, e.g., ultraviolet (UV) light. Light in a specifically defined range of wavelengths is considered to be an attractive stimulus as it allows for an efficient, contactless, remote stimulation that can be temporarily and spatially controlled (Hohl and Weder, 2019). This technique, however, requires the use of transparent substrates and a product design that foresees little or no exposure to the debonding wavelength during product lifetime (Telitel et al., 2017).

The design of new electrically debondable adhesives receives particular interest for the recycling, repair, and reuse of electrical components as it circumvents most difficulties of the formerly discussed debonding techniques (Anduix-Canto et al., 2022). Here, bonding of the adhesive to a metal, or connecting substrates via laminated aluminium sheets, is a prerequisite (Mulcahy et al., 2022). Applications include electronics, medical surgery, dentistry, construction, and general manufacturing (Jeong, 2018). Other debonding techniques include the use of magnetic, ultrasonic, or chemical stimuli (Lu et al., 2014; Ren et al., 2022). Many traditional adhesives, for example, have high water solubility allowing easy debonding (e.g. removing labels from glass bottles, removing wallpaper, etc.) (Mulcahy et al., 2022).

With research and considerable improvements being demonstrated (Elmahdy, 2021), the optimal choice of reversible bonding principle for a specific debonding application could change over time. However, the choice of the most suitable reversible bonding and debonding technique will depend on several key factors. These include the type of adhesive, the type of the materials bonded, the size of the area that needs to be bonded/debonded, environmental conditions during the operation and related mechanical requirements, as well as the sensitivity of other components close to the bonded area (Banea, 2019).

2.2. *Adhesive bonding in smartphones*

Smartphones represent a high-value and high-tech device that a large and increasing portion of the global population uses every day. In many societies, they represent a central element of daily life, providing functions that go beyond remote communication, finding and sharing of information. Smartphones also play an important enabling role for the provision of additional services such as mobility, education, entertainment, and many others. However, subject to rapid technological progress, replacement cycles of smartphones are short and, in most cases, shorter than their technical lifetime. Due to technical aspects, such as low battery capacity, decrease in relative data storage capacity and camera quality, but also due to non-technical aspects such as perceived 'newness' and the duration of service contracts (Proske and Jaeger-Erben, 2019), a replacement of a new phone is set to 2 years, which reflects the overall trend in some major markets (Statista, 2023). Repair, refurbishment and renewal of some components represents one approach to increase the service lifetime and establish more circular practices that can reduce environmental impacts and save valuable resources.

Note that refurbishing in this context means that discarded smartphones go through a process of refinishing, while remanufacturing refers to the reuse of valuable electronic components in new smartphones. The latter, however, is considered as a rarely applied practice given the fast innovation cycles in semiconductor technology (Pamminger et al., 2021). Other authors take a product perspective and consider upgrading smartphone hardware as remanufacturing (Mugge et al., 2017).

Nevertheless, because of new designs and an increasing number of materials in a smartphone, batteries and other components are increasingly glued. This practice deters any exchange or upgrade, while also reducing the potential to recycle valuable materials after the phone reaches its end-of-life (EoL) (Barros and Dimla, 2021; Schumacher and Green, 2022). Also for repair purposes, challenges in overcoming the use of adhesives in smartphones can lead to permanent damage to other parts (Barros and Dimla, 2023). Moreover, the use of adhesives in smartphone battery packs themselves render them difficult to open, making it hard to access battery cells for repair, repurposing, and recycling (IIEE and EEB, 2021).

As smartphones represent an ever-increasing waste and resource stream (Kastanaki and Giannis, 2022), we consider the use of reversible bonding in smartphones a valid demonstration to quantify the potential of reversible bonding from an environmental, economic and functionality perspective. Moreover, for some system elements, the results are likely to be transferrable to other product systems, such as other electronic equipment or electronics in products such as cars.

3. Material and methods

In this section, materials and scenarios for the smartphone application are discussed, as well as the main assumptions and general approach for the functionality, environmental, and economic assessment of reversible bonding when applied to a smartphone. This approach is summarized in Fig. 1.

As discussed in the introduction, the use of a new technology, such as debonding, affects both the functionality of components and materials, as well as the economic and environmental performance of the whole system. Therefore, in this paper these three complementary evaluation perspectives are combined in order to generate a comprehensive view on debonding as a potential enabler for circularity. It also allows to assess trade-offs and key conditions to support a circular transition, which is reported in the Discussion section.

3.1. *Materials and scenarios for the smartphone application*

The material composition of key components of smartphones is based on Roithner et al. (2022) and Proske et al. (2020). The composition of an exemplary smartphone has a mass of 197.5 g, and consists of a display, a printed-circuit-board (PCB), speakers, housing, cameras, vibration motor, back cover, screws, and a battery with a mass of 56 g. This composition is represented in relative terms in Fig. 2.

The recycling system scenario is modelled via two recycling processes. One recycling process represents the pyrometallurgical copper smelting route, using the final recycling efficiencies that are reported by Chancerel and Marwede (2016). This is the default recycling route that is used for the phones and the batteries if the batteries cannot be debonded from the smartphone. An alternative recycling path is employed for the debonded Li-ion battery, representing a more dedicated Lithium-ion battery recycling route, that is based on the recycling efficiencies reported for the Belgian company Umicore (Miao et al., 2022; Velázquez-Martínez, Porvali et al., 2019). Note that the recycling process does not represent detailed process simulations, as this is not the focus of the paper, but only the final output efficiencies of the process are used, employing transfer-coefficients that are considered for each process.

In order to evaluate the potential of reversible bonding in the context of the circular economy, four system scenarios are described, and for each of them the respective material flows are shown in Fig. 3a to d. All system scenarios represent material flows that are needed for the specific scenario over a time frame of 4 years. For example, as the baseline

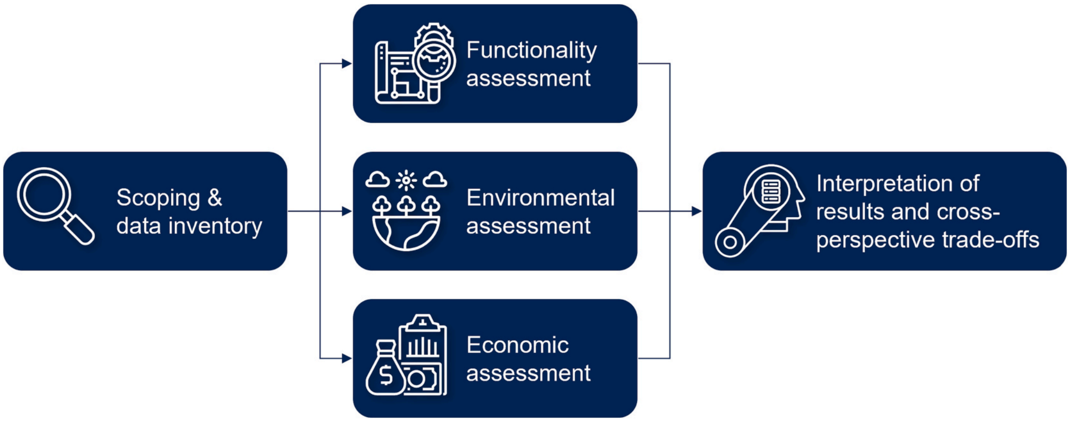


Fig. 1. General overview of the research process.

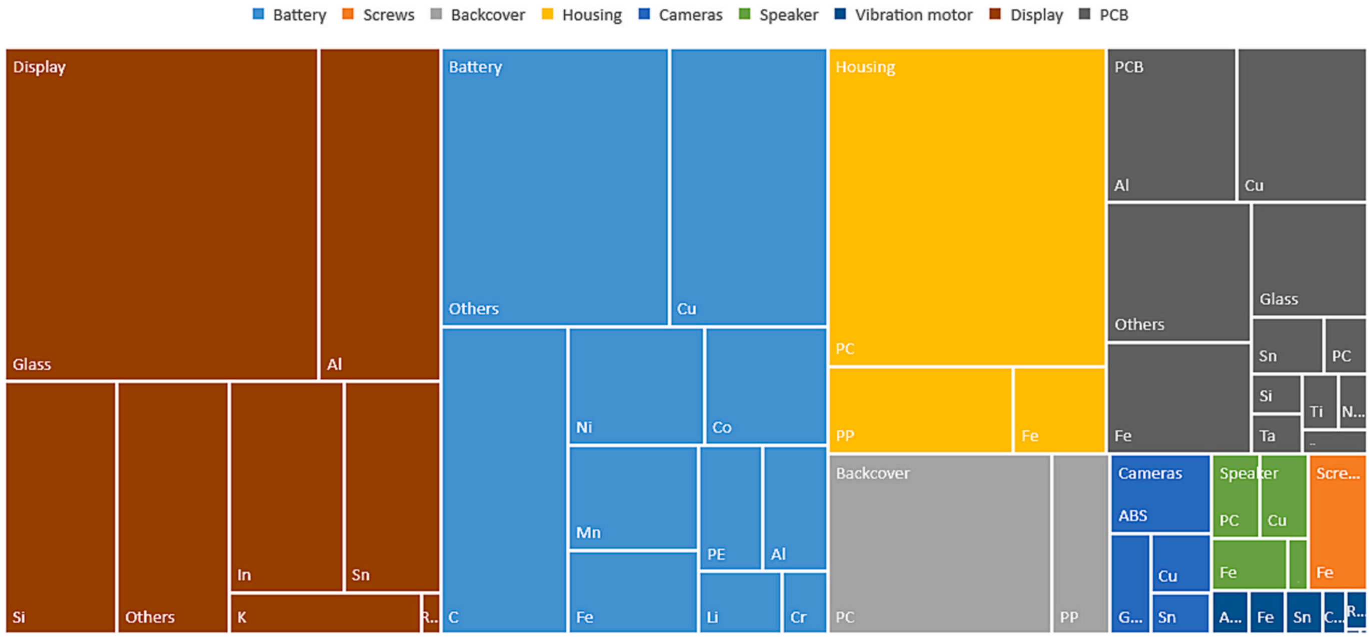


Fig. 2. Treemap of the relative contribution and composition of the components and their key materials, together resulting in an overall smartphone mass of 197.54 g.
Note: For a more detailed representation in a table format see Supplementary information SI_A.

system requires two phones that each serve two years, the overall material throughput is larger than in cases where a component or a phone performs a longer service life.

a. Baseline (Fig. 3a): In this system scenario the smartphone is used for 2 years and is then recycled via the copper-smelting route without prior debonding. After the first lifetime, an additional new smartphone is bought, and again discarded and recycled after 2 years via the same route.
b. Debonding & separate battery recycling (Fig. 3b): In this system scenario, the smartphone is used for 2 years. Debonding allows for separate recycling of the battery and the rest of the phone. An additional new smartphone is bought and discarded and recycled after 2 years, with debonding and dedicated battery recycling for the second phone as well.
c. Debonding & exchange of battery (Fig. 3c): In this system scenario, the smartphone is used for 2 years. After 2 years the battery is replaced and the same smartphone, with a new battery, is used for another 2 years. Both batteries are debonded and recycled in a dedicated battery recycling process.
d. Debonding & maintenance (Fig. 3d): In this system scenario, the smartphone is used for 4 years which is enabled by maintenance by debonding, followed by debonding of the battery at its EoL and separated recycling for battery and phone. To safeguard readability, this scenario is referred to as ‘maintenance’ in the following. This scenario also reflects the situation of prolonging product lifetimes by changing buyer behaviour, careful use, or an improved design for longevity, as long as this requires no material replacements.

Comparing the four system scenarios, some key differences can be observed regarding the number of processes, most specifically the processes of battery recycling, debonding, and phone reuse. The smelting process leads to the first loss of materials such as polymers (e.g. PP, PE, PC, ABS), carbon and others, through oxidation, resulting in emissions that leave the process. The remaining fraction enters the recycling process. For a better comparison of the scenarios, Table 1 provides an overview of the sequence of processes for each of them.

3.2. *Assessment of functionality preservation*

Describing and quantifying the functionality of products, components, or materials is not a trivial task. Relevant characteristics and evaluation perspectives can change with the application, context, and hierarchical levels (e.g., product-, component-, material-level functionality), and the intended use (Iacovidou et al., 2019). Instead of trying to capture the many possible conditions that would limit a component to be remanufactured (Goodall et al., 2014), or a product to be reused (Whalen et al., 2018), the preservation of functionality is captured on all levels by employing a system perspective.

The basis for the evaluation is the mapping of all product-, component- and material flows, that is shown in the respective material flow systems (as depicted in Fig. 3a to d). The presumption is that preservation of functionality avoids any compositional changes in the product-, component- and material flows, including the generation waste and emissions that are measured through the level of mixing and dilution. Any of these changes at any point in the system are captured and assessed by the method of multilevel Statistical Entropy Analysis (SEA), thereby capturing the ability of a system to preserve functionality on the product-, component- or material level (Parchomenko et al., 2020, 2021).

The method has been originally developed to evaluate the results of a material flow analysis. Quantifying changes in the distribution pattern of a substance within a system allows to evaluate the potential of a process and the entire system to concentrate or dilute a substance (Rechberger, 1999; Rechberger and Brunner, 2002). Based on that principle and further extensions of SEA, the applications include very diverse systems such as the European and Chinese copper cycles (Rechberger and Graedel, 2002; Yue et al., 2009), phosphorus use in Austria (Laner et al., 2017), and lead smelting processes (Bai et al., 2015). Other examples include waste water treatment plants (Sobańtka and Rechberger, 2013), recycling of batteries (Velázquez-Martinez et al., 2020), and recyclability assessment of e-waste (Zeng and Li, 2016).

Extended to the component and product level (Parchomenko et al., 2020), multilevel SEA has been applied to CE strategies that go beyond recycling, and include reuse, lifetime extension, including sufficiency strategies that impact the size of the product stocks. The methodology

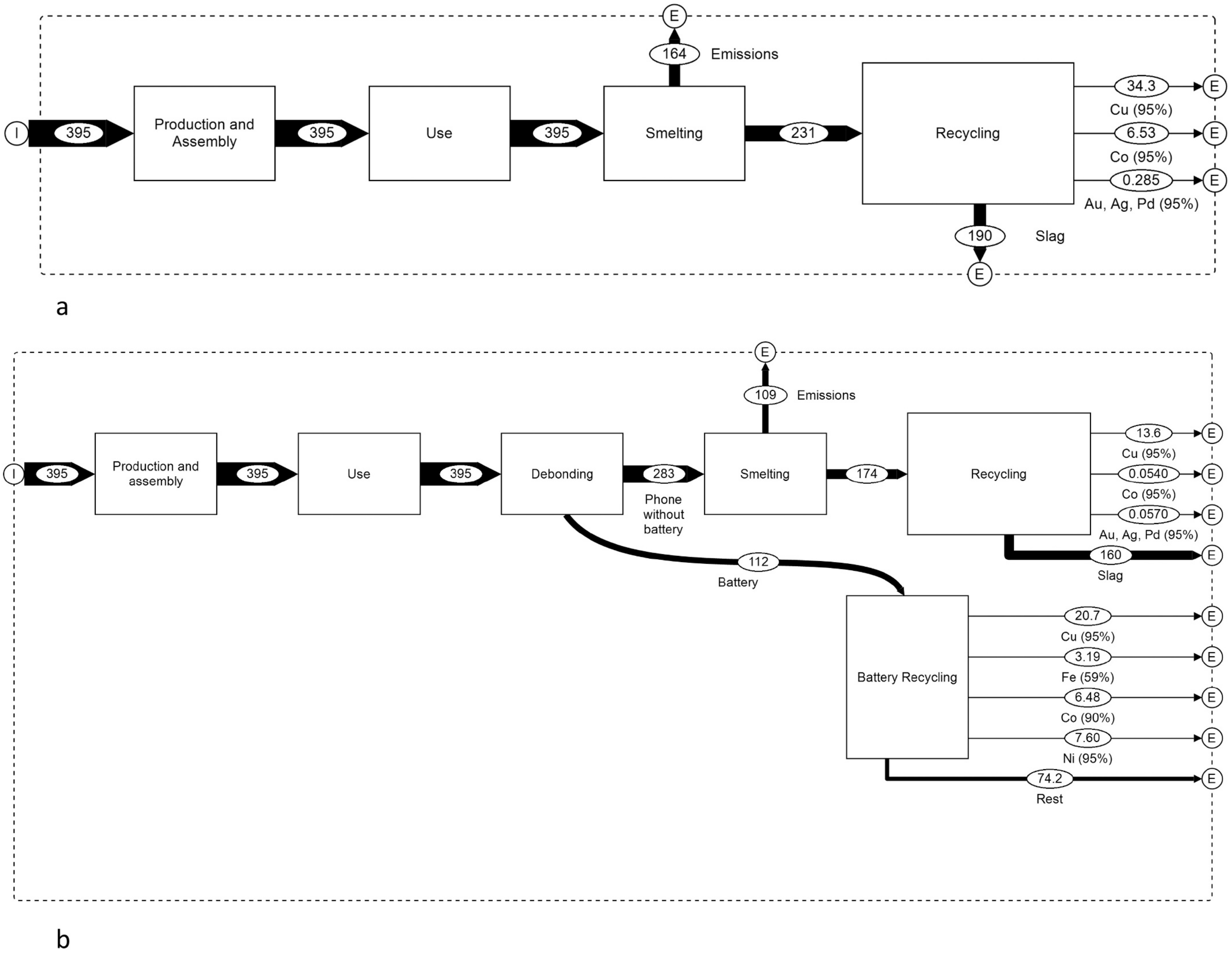


Fig. 3. a: Baseline system scenario, with the use of two smartphones over the period of 4 years.
b: System scenario with debonding & separate battery recycling.
c: System scenario with debonding & exchange of battery, with the remaining smartphone being reused.
d: System scenario with debonding & maintenance (with no material replacements being required).

has been used to assess the separation complexity of plastic waste, extending the assessment by an energy dimension (Nimmegeers and Billen, 2021), or used to assess the recyclability of a material (Nimmegeers et al., 2021) or a product (Roithner et al., 2022).

In this paper multilevel SEA is applied, modelling different scenarios of debonding, including CE strategies such as recycling, repair, reuse, and lifetime extension of components and products. The main principles for interpreting the results are that dilution and mixing increase SEA values, while separation and recycling reduce them. Once the functional product state is reached, the preservation of the product functionality is indicated by the absence of any changes in the statistical entropy values. The values are typically expressed in terms of Relative Statistical Entropy (RSE), which are normalised values calculated in relation to the highest possible state of dilution within the assessed set of systems being evaluated. Changes in RSE are therefore expressed as delta RSE (ΔRSE). A more detailed introduction is provided in Supplementary material B, as well as in Parchomenko et al. (2020).

3.3. *Environmental assessment*

A Life Cycle Assessment (LCA) study was used to identify the hotspots of the described smartphone, over its entire lifecycle and to compare total impact of the smartphone's lifetime when different CE strategies are applied. The functional unit is 'the production, use and disposal of (a) smartphone(s) to have a functional smartphone for four years'. All stages of the life cycle, starting at the extraction of raw materials, transport, production, use, and ending with the final waste disposal and recycling, are considered in this LCA.

Environmental impacts are calculated and assessed using the Product Environmental Footprint (PEF) method, EF 3.0 v1.03 (Fazio et al., 2018), proposed by the European Commission. The characterised results were normalised and weighted, using the normalisation following United Nations (2011) and weighting factors provided by Sala et al. (2018), described by EF 3.0. Next, the weighted EF results were summed across all impact categories to obtain one single environmental score (mPt).

To model the production of the smartphone 'Consumer electronics, mobile device, smartphone {GLO}|market for consumer electronics, mobile device, smartphone|Cut-off, U' from Ecoinvent (v3.8) is used as a basis, while adjusting the weight of components (see Table 2) in alignment with the masses described in the functionality assessment (Fig. 2). For the use phase, only the electricity consumption during charging is

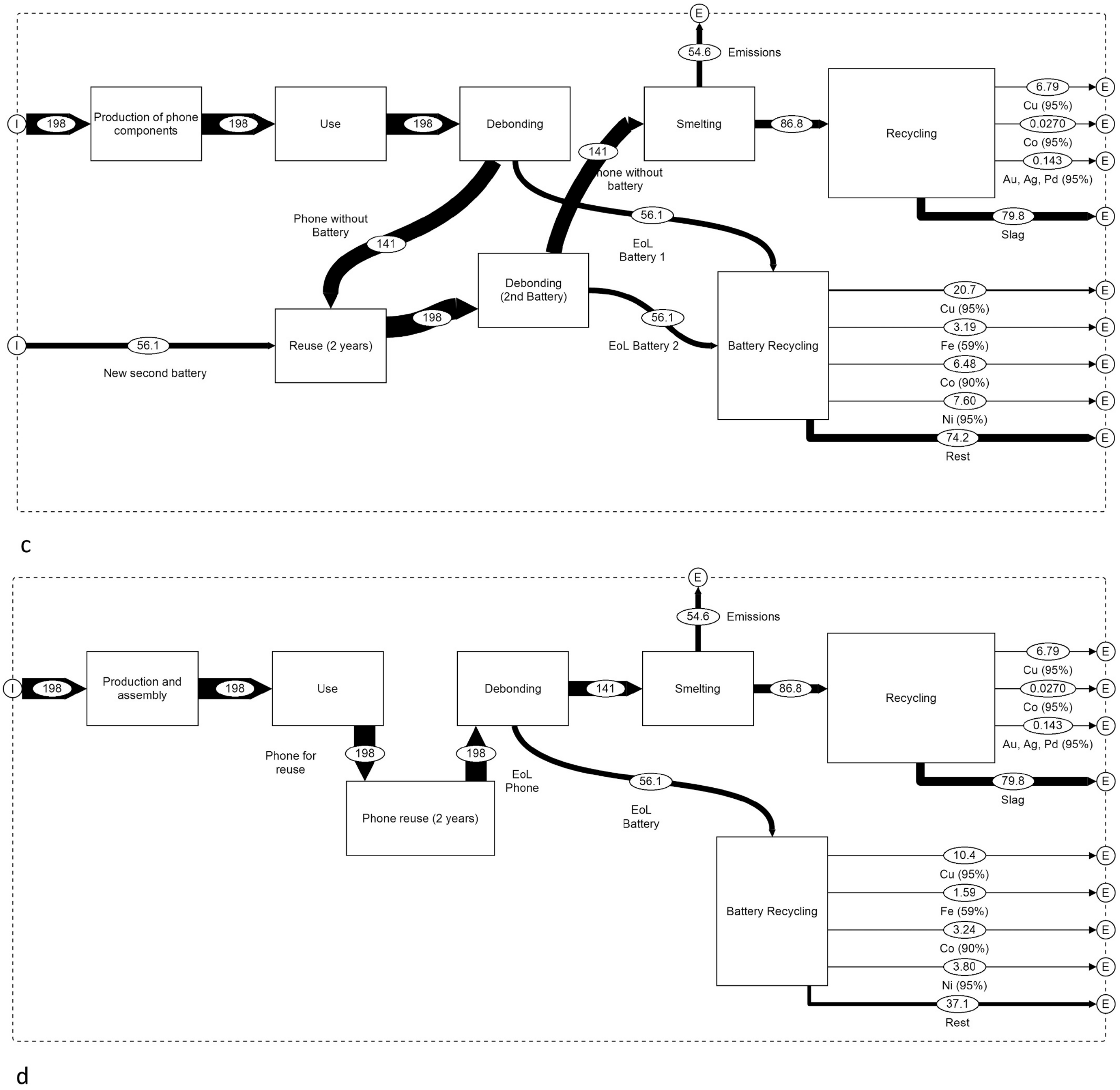


Fig. 3. (*continued*).

considered, for which 7.01 kWh per year is assumed (Proske et al., 2020). The Belgian electricity grid mix, 'Electricity, low voltage {BE}| market for|Cut-off, U', is used as an example in this life cycle. At end of life, the smartphone and battery are recycled, together or separately depending on the scenario. The smartphone is recycled by pyrometallurgical copper-smelting, in which 95 % of Cu, Co, Au, Ag and Pd are recovered (Chancerel and Marwede, 2016). When the battery is debonded, it will be recycled in a dedicated Lithium-ion battery recycling process, where 95 % Cu, Ni, 90 % of Co and 59 % of Fe are functionally recovered (Miao et al., 2022; Velázquez-Martínez, Valio et al., 2019).

For the metals that are recovered at recycling, the PEF methodology provides clear guidelines on how to divide the benefits and burdens of the generation and use of recycled materials between subsequent product cycles. The guidelines come in the form of a formula, known as the Circular Footprint Formula or CFF (paragraph 4.4.8.1 of (European Commission, 2022b)). The A factor in the formula allocates burdens and credits between supplier and user of recycled materials. For Cu, the factor of A = 0.2 as proposed in part C of Annex II (European Commission, 2022a) was used, for all other metals A = 0.5 was assumed, since no specific data was available. However, since the A factor for these recovered metals will most likely be 0.2 as well, a sensitivity assessment was performed with both A factors. R_1 is set at 0, since only virgin materials were assumed to be used during the production. The recovery rates, as described above, were used for recycling at end of life (R_2).

3.4. Economic assessment

The economic assessment in this framework is based on a conven-

Table 1
Process sequence that shows the key similarities and differences between the system scenarios employed.

Baseline a	System scenario b	System scenario c	System scenario d
Materials	Materials	Materials	Materials
Production	Production	Production	Production
Use	Use	Use	Use
•	Debonding	Debonding	•
Smelting	Smelting	Recycling (battery)	•
Recycling	Recycling	•	•
Materials	Materials	•	•
Production	Production	•	•
Use	Use	Reuse (phone)	Use
•	Debonding	Debonding	Debonding
Smelting	Smelting	Smelting	Smelting
Recycling	Recycling	Recycling	Recycling

Source: based on Chancerel and Marwede (2016).

Table 2
Adjusted material composition of smartphone modelling record.

Component	Amount	Ecoinvent record
Screws	2 g	Pig iron {RER}|market for pig iron|Cut-off, U[a]
Backcover	12.6 g	Injection moulding {GLO}|market for|Cut-off, U
	10 g	Polycarbonate {GLO}|market for|Cut-off, U
	2.6 g	Polypropylene, granulate {GLO}|market for|Cut-off, U
Housing	22 g	Polycarbonate {GLO}|market for|Cut-off, U
	2 g	Pig iron {RER}|market for pig iron|Cut-off, U[a]
	4 g	Polypropylene, granulate {GLO}|market for|Cut-off, U
Cameras	4.52 g	Electronic component, passive, unspecified {GLO}|market for|Cut-off, U[a]
Speaker	3.26 g	Electronic component, passive, mobile, earpiece and speaker {GLO}|market for electronic component, passive, mobile, earpiece and speaker|Cut-off, U[a]
Vibration motor	1.68 g	Electronic component, passive, unspecified {GLO}|market for|Cut-off, U[a]
Display	63.2 g	Liquid crystal display, unmounted, mobile device {GLO}|market for liquid crystal display, unmounted, mobile device|Cut-off, U
PCB	6.35 g	Copper, cathode {GLO}|market for|Cut-off, U[a]
	2.89 g	Electric connector, peripheral type buss {GLO}|market for|Cut-off, U[a]
	1.18 g	Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}|market for|Cut-off, U
	0.09 g	Inductor, miniature radio frequency chip {GLO}|market for|Cut-off, U[a]
	6.35 g	Metal working, average for copper product manufacturing {GLO}|market for|Cut-off, U
	0.083 p	Plug, inlet and outlet, for computer cable {GLO}|market for|Cut-off, U[a]
	0.0045 m^2	Printed wiring board, mounted mainboard, mobile device, double-sided, Pb free {GLO}|printed wiring board production, mounted mainboard, mobile device, double-sided, Pb free|Cut-off, U[a]

[a] All inputs of the recovered metals were adjusted, using the principles of the Circular Footprint Formula (European Commission, 2022b).

tional Life Cycle Costing (LCC) approach, as described by the SETAC working group (Gluch and Baumann, 2004; Klöpffer et al., 2014). The Life Cycle Costing (LCC) analysis follows the functional unit and system boundaries as described by the SEA and LCA analyses. All costs and revenues associated to the functional unit are identified and calculated as net annual cash flows. These net annual cash flows are subsequently used to determine overall profitability over the lifetime by calculating the Net Present Value (NPV) (European Commission, 2015). The latter takes into account the time value of money and therefore provides insights into the discounted size of cashflows throughout the full lifecycle.

$$NPV = \frac{CF_1}{(1+i)^1} + \frac{CF_2}{(1+i)^2} + \ldots + \frac{CF_n}{(1+i)^n}$$

where NPV is the Net Present Value, CF_n is the net cashflow in year n and i is the discount rate.

The discount rate is set at 0 %, in line with a common research practice, pointing out the need to move to zero or close to zero discount rates for climate policy related cost-benefit analyses (Arrow et al., 2013; Weitzman, 2013; Worldbank, 2022). For all four scenarios mentioned above, the NPV is calculated for a linear system and for a circular system. To focus in our analysis on circularity aspects, the price of leasing over a two-year period is assumed to be equivalent to that of a one-time sale.

Table 3 provides an overview of the most important assumptions in the LCC analysis. Table 4 contains cost data behind each debonding technology.

4. Results

This section contains the main results of the functionality, environmental, and economic assessment of the reversible bonding scenarios as depicted in Section 3.1.

4.1. Functionality assessment

The results of the functionality assessment for all four scenarios, are shown in terms of the changes in Relative Statistical Entropy (ΔRSE) that are presented in water fall charts (Fig. 4). The results are normalised in reference to the scenario in which the largest possible dilution and functionality loss. In this case, it is the scenario where all materials are maximally diluted, both by mixing of the smartphone materials and by the dilution of some material types to other compartments. An example of the latter are plastics that are burned in the gasification stage of the pyrometallurgical process.

Table 3
Summary of LCC parameters (in EUR).

	Regular bonding	Debonding	Source
Cost			
Smartphone production	369.91	369.91–370.63	Own calculation based on average smartphone retail prices and profit margins (Do, 2023) (see detailed bonding calculations in Table 4)
Battery replacement cost	N/A[a]	20	Cost of replacing a battery (Cordella et al., 2021)
Battery debonding cost	N/A[a]	0.09–5.54	Based on own calculations (see Table 4)
Revenues			
Smartphone sales price	1000		Based on average smartphone market price
Smartphone annual lease price	500		Lease price chosen to equal total smartphone price over the smartphone lifetime (2 year)
Margin on battery replacement	N/A[a]	39	Difference between price paid to professional repairer and cost of replacing a battery (Cordella et al., 2021)
Margin on recycling of smartphone	0.55	0.72	Margin of smartphone recycling in base scenario based on (Geyer and Doctori Blass, 2010). Additional margin in case of smartphone debonding calculated based on difference in efficiencies

[a] N/A stands for Not Applicable, as in the regular application without debonding the battery is not replaced.

Table 4

Bonding and debonding costs for the 'no debonding' scenario and different reversible bonding technologies.

	Adhesives	No debonding	Convection	Induction	TEP	Electric	UV	Microwave
CAPEX bonding	Speed mixer cost				9500.00 €			
	Depreciation period (years)				10			
	Yearly capacity (#smartphone)				10,000			
	Total CAPEX cost (€/smartphone)				0.10 €			
CAPEX debonding	Debonding technology cost		27,469.50 €	26,600.50 €	27,469.50 €	450.00 €	4000.00 €	6050.00 €
	Depreciation period (years)		10	10	10	10	10	10
	Yearly capacity (#smartphone)		10,000	10,000	10,000	10,000	10,000	10,000
	Total CAPEX cost (€/smartphone)		0.27 €	0.27 €	0.27 €	0.00 €	0.04 €	0.06 €
OPEX bonding	Adhesive cost (€/g)	0.72 €	0.72 €	0.72 €	0.72 €	1.44 €	1.44 €	0.72 €
	Additives (€/g adhesive)	- €	- €	- €	0.02 €	- €	- €	- €
	Total adhesive cost (€/g)	0.72 €	0.72 €	0.72 €	0.74 €	1.44 €	1.44 €	0.72 €
	Power mixer (kW)				0.49			
	Time mixing (h)				0.03 €			
	Power usage (kWh)				0.02			
	Cost of power usage (€)				0.00 €			
	Labour cost for mixing (€)				0.97 €			
	Mixer capacity (g)				100			
	Mixing cost (€/g)				0.01 €			
	Total adhesive cost incl. mixing (€/g)	0.72 €	0.72 €	0.72 €	0.75 €	1.44 €	1.44 €	0.72 €
	Adhesive use per smartphone (g/smartphone)	1	1	1	1	1	1	1
	Adhesive cost per smartphone (€/smartphone)	0.72 €	0.72 €	0.72 €	0.75 €	1.44 €	1.44 €	0.72 €
OPEX debonding	Power (kW)		7.55	11.88	7.55	0.11	14.00	1.20
	Time/debonding cycle (h)		0.83	0.17	0.83	0.00	0.02	0.06
	Power usage (kWh)		6.29	2.03	6.29	0.00	0.23	0.07
	Cost of power usage (€)		0.94 €	0.30 €	0.94 €	0.00 €	0.04 €	0.01 €
	Labour cost per cycle (€)		24.25 €	4.97 €	24.25 €	0.08 €	0.49 €	1.70 €
	Capacity for debonding (#smartphones/cycle)		10	1	10	1	1	10
	Debonding cost (€/smartphone)		2.52 €	5.28 €	2.52 €	0.08 €	0.52 €	0.17 €

Source: project data from the Circular Bonding project (www.circularbonding.be).

Each scenario starts with the RSE value of zero, as at this stage the inputs to the system are modelled as pure materials that are imported to be used in the production and assembly process. In the production process, the materials are combined in a very specific way to form the components and the product, resulting in the first dilution of materials. As the product is identical in all scenarios, the RSE increases are the same (+0.130 RSE). At this point the RSE value indicates the value for the state of the functional phone. Therefore, from this point on, ideally, the system state should be preserved over time, which would be reflected in the absence of any RSE changes (ΔRSE), indicating the preservation of functionality. In contrast, further increases of RSE values would indicate a loss of functionality either on the component level, e.g., through the need to replace components, or through the destruction of the entire product. The latter would be reflected in even higher increases of RSE values. For this reason, an ideal circular and functionality-preserving system, maintains RSE values as close to the value of the functional product, for as long as possible.

In the first baseline system, there is no debonding and the phone enters the smelting process after the use phase of 2 years. The smelting process leads to the destruction of the phone and a first loss of material functionality. The 77 % increase in RSE (+0.217) is related to the combustion of volatiles, plastics, and other non-metals, which means that these materials are lost for further potential applications. The remaining 23 % of the RSE increase at the smelting stage are related to the dilution and mixing of metals that enter a subsequent recovery process. In the recycling process, Cu, Co, Au, Ag and Pd are recovered, with the rest being lost to the slag fraction, that could potentially be used for further refining. However, further refining is considered as being not employed within the system, leading to further functionality losses on the material level. With a lifetime of 2 years, the full period of 4 years requires two full product lifecycles that over the entire period result in an output of recycled metals of 34.3 g Cu, 6.53 g Co, 0.019 g Au, 0.029 g Ag, 0.095 g Pd, with Au, Ag, Pd adding up to 0.285 g as it is also shown in Fig. 3. The total difference from the initial functional product state (RSE = 0.130) is shown in terms of ΔRSE, indicating to which degree the final system state deviated from the ideal system, where functionality is maximally preserved over time.

Scenario b is similar to the scenario a, except that the battery is debonded from the phone and enters a dedicated Li-ion recycling process, while the rest of the phone follows the same Cu-smelter recycling pathway. The difference between the Cu-smelter route and the battery recycling process is that besides Cu (95 %) and Co (95 %), and instead of Au, Ag, and Pd, the process recovers Ni (95 %) and Fe (59 %). However, the important aspect is that the effect of reversible bonding can be already observed prior to recycling. This is because, debonding of the battery initially leads to lower dilution and functionality losses at the smelting stage, resulting in a lower ΔRSE of +0.165, compared to +0.217 in scenario a. In addition to that, the battery recycling process leads to a larger restoration of material functionality leading to −0.031 ΔRSE, as compared to −0.023 ΔRSE in the initial scenario. Even though scenario b employs debonding, it also requires two full product lifecycles of 2 years each but is able to restore higher functionality on the material level that is shown in the total ΔRSE to the initial product state of −0.40 compared to −0.52 in scenario a. This effect can be largely attributed to debonding, which has 6.5 times greater effect than improved recycling, calculated from the differences between scenario a and b at each stage (difference at recycling: 0.008 ΔRSE, difference at smelting: 0.052 ΔRSE).

Compared to the previous two scenarios, scenario c is more complex in terms of system structure, component and materials flows as well as interlinkages between the processes (see Fig. 3). Despite the same starting conditions, the key difference is that debonding of the battery enables the reuse of the phone for another lifecycle with a newly produced battery. The RSE increase (+0.047) results from the additional production and input of a second battery to the system, that is accounted for at the 'Debonding + Bat.' stage (in Fig. 3). The following recycling stage only concerns the discarded battery. Next, a new lifecycle of an additional phone use of 2 years starts with minimal changes in terms of ΔRSE, indicating the large preservation of functionality. However, after the second lifecycle, the phone and battery are entering their respective recycling processes after debonding of the battery, as it has been described previously. The treatment of the phone and the debonded

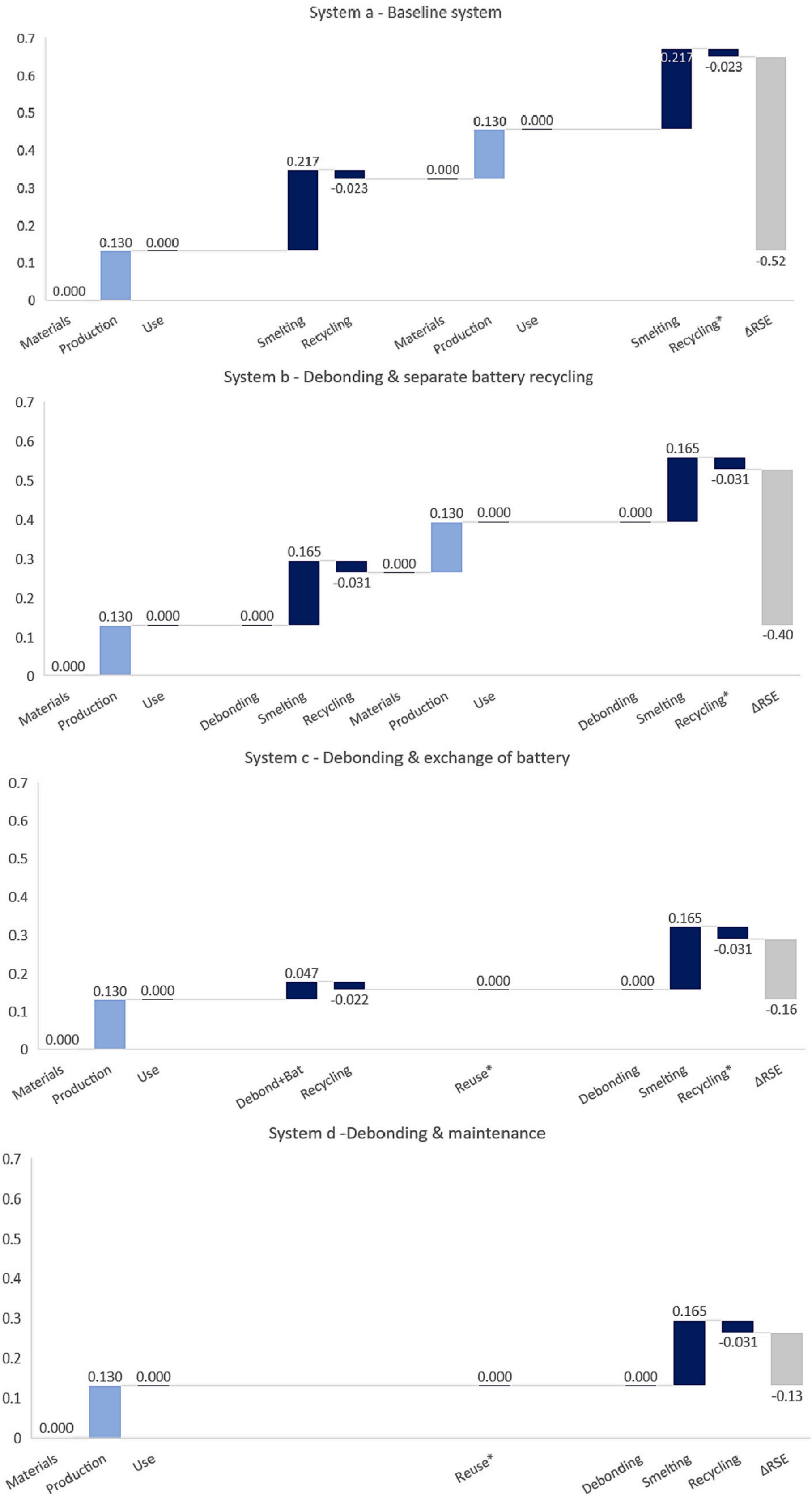


Fig. 4. Results of Relative Statistical Entropy (RSE) changes for the four system scenarios: a) Baseline system, b) Debonding & separate battery recycling, c) Debonding & exchange of battery, d) Debonding & maintenance.

battery after the second lifecycle therefore produce identical changes of +0.165 ΔRSE at smelting stage and −0.031 ΔRSE at the recycling stage. Scenario c, shows that the debonding and the reuse of the phone, combined with an exchange of components results in a more than three times lower overall ΔRSE of −0.16, compared to scenario a. This demonstrates the effectiveness of debonding, combined with a reuse strategy that requires a more complex system structure, but achieves a higher functionality preservation.

Finally, scenario d represents a phone that is maintained without the exchange of components, does not create waste, resource, and functionality losses, which translates to lowest ΔRSE of all scenarios. Here, only after the lifetime of 4 years, the battery is debonded and the phone and battery enter separate recycling processes that are identical to the previous two scenarios (scenario b & c). Overall, the system-wide ΔRSE value is −0.13, which is the lowest value of all scenarios.

However, when comparing system performance in terms of recycling rates (RR), functionality loss (ΔRSE), the mass of recycled materials and the overall system performance across all stages, there is a large difference (see Fig. 5). One observation is that identical recycling rates can lead to different levels of functionality preservation. This situation can be observed when comparing scenarios b and d in Fig. 5, where the overall recycling rate is in both cases 13.1 %, but the loss of functionality is significantly lower in scenario d.

Considering that from a policy perspective, the recycling rate represent one of the key indicator to measure CE performance, it is important to note that the recycling rate alone can lead to a "mismeasuring" of the system performance, especially in system transitions that lead to higher functionality preservation on the product and component levels. As it is shown here, recycling rates could lead to the conclusion that performance is reduced, even though overall functionality (and value) preservation is increased (see comparison of scenario b and c, Fig. 5). Here, an important aspect is also the system size (in terms of material throughput), as it can lead to situations where higher recycling rates can lead to lower overall recycled material mass (see comparison scenario b and c, Fig. 5). Therefore, this exemplary demonstration of the three different perspectives shows that attention should be paid when using RR, or mass-based targets without any system context or complimentary indicators to evaluate system circularity performance.

From the comparison of four different scenarios, it can be concluded that reversible bonding can be viewed as an enabling technique that has the potential to improve system-wide functionality preservation. First, reversible bonding enables reuse, avoiding destruction of functional components, and thus functionality loss. Second, reversible bonding enables more dedicated recycling processes, improving restoration of functionality and increasing system performance. The latter is not only due to higher recycling efficiencies, but especially through an initial reduction of statistical entropy of the input flow entering the process and the related quality gains.

4.2. Environmental assessment

The environmental impact was calculated for the production of one smartphone that serves as a baseline, with a use phase of 2 years and recycling by pyrometallurgical copper-smelting at end of life (EoL). The environmental profile in Fig. 6 shows the relative contribution of different life cycle stages to all impact categories calculated by the EF method, including the total single score (mPt). The production of the PCB (including its EEE components), is the main contributor to all impact categories, except for non-cancer human toxicity and acidification. Here, the recycling process, especially copper smelting, is the most important contributor. The use phase has a relevant influence on ionising radiation, since part of the Belgian electricity mix is produced by nuclear power plants. The avoided impact by recovering certain metals at EoL are shown as negative values on the graph, with a relevant influence on resource use minerals and metals.

Since the production of the PCB is an environmental hotspot, prolonging its lifetime will have most impact on environmental performance. Fig. 7 shows the total single scores of four different scenarios, expressed relatively to the scenario with the highest impact, namely scenario a (baseline). Since the PCB and battery are of special interest in this comparison, these components are shown separately. All other

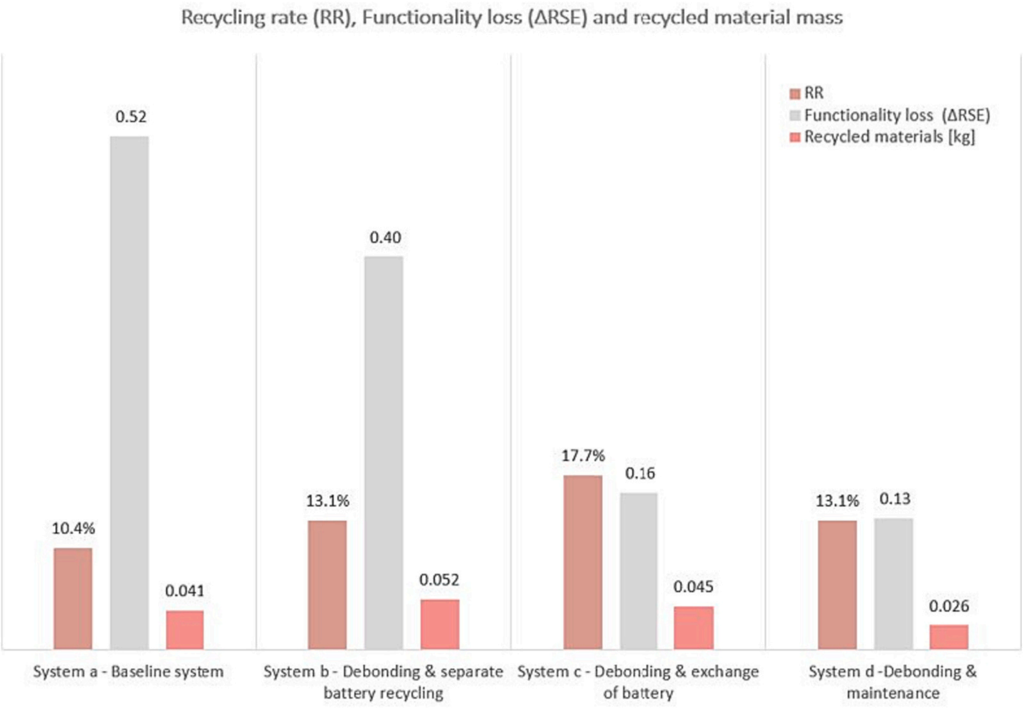


Fig. 5. Recycling rates (RR), recycled material mass and functionality loss for the four assessed scenarios: a) Baseline system, b) Debonding & separate battery recycling, c) Debonding & exchange of battery, d) Debonding & maintenance.

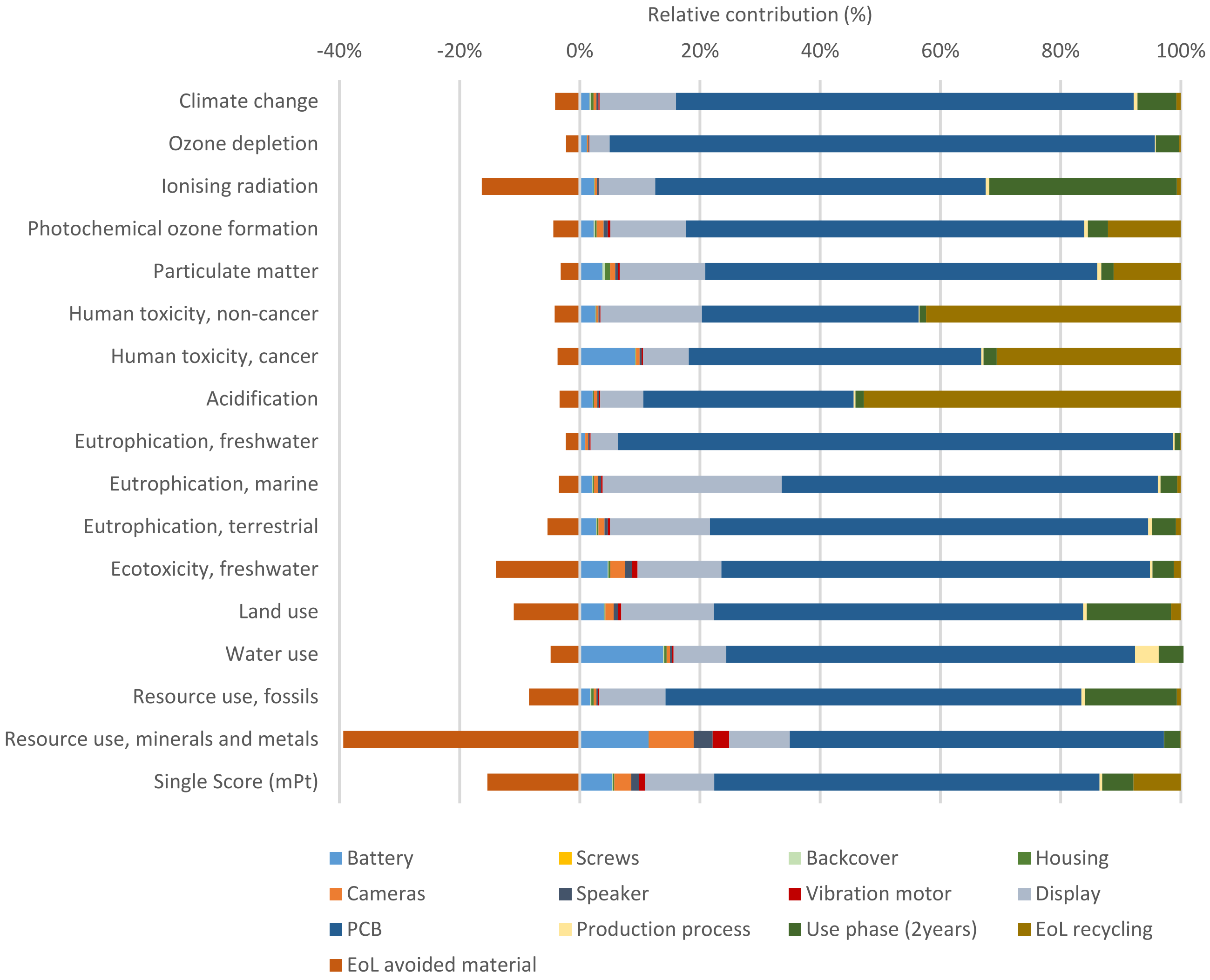
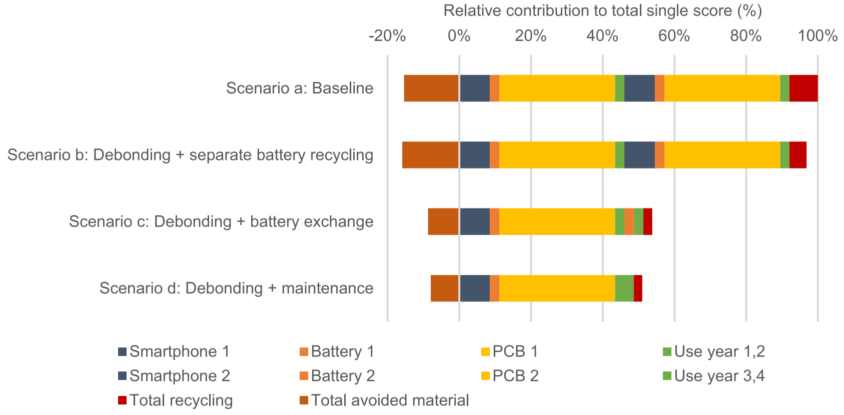


Fig. 6. Environmental profile of one smartphone with a lifespan of 2 years (from scenario a).



Smartphone 1	Battery 1	PCB 1	Use year 1,2	Smartphone 2	Battery 2	PCB 2	Use year 3,4	Total recycling	Total avoided material
9%	3%	32%	3%	9%	3%	32%	3%	8%	-15%
9%	3%	32%	3%	9%	3%	32%	3%	5%	-16%
9%	3%	32%	3%	0%	3%	0%	3%	2%	-9%
9%	3%	32%	3%	0%	0%	0%	3%	2%	-8%

Fig. 7. Comparative profile of the total single score of the different lifecycle scenarios, relative to the highest contribution (Scenario a).

components and the production process of the smartphone are grouped in ‘Smartphone 1/2’. The recycling processes and subsequent avoided material are grouped for all materials over the 4-year span. The A factors (of the CFF formula) used are 0.2 for Cu and 0.5 for all other recovered metals. Scenario a shows the same results as in Fig. 6, but now for 2 phones.

In scenario b, debonding is applied at EoL, thereby allowing the batteries of smartphone 1 and 2 to be recycled by the lithium-ion battery recycling process. This results in a slightly lower impact of the recycling processes (5 %) as compared to scenario a (8 %). In scenario c and d there is no need to produce a second smartphone, thereby avoiding 9 % and 32 % contribution of smartphone 2 and PCB 2. Since less material is produced, less is recycled and recovered. The total impact in scenario d is only slightly reduced in comparison to scenario c, since the impact of the avoided second battery is only 3 %. In conclusion, the environmental impact is most reduced in scenarios c and d, since only one smartphone (including its PCB hotspot) is produced.

When A = 0.2 is used for all recovered metals (in the CFF formula), the relative contribution of the recycling process and avoided material is increased, as compared to the results from Fig. 7. For the recycling process, this increase is not visible on this scale, as shown in Table 5.

4.3. Economic assessment

In our economic assessment, we evaluate each scenario in a sale and a lease business model. Both business models are, by assumption, financially equivalent in the baseline scenario. However, as depicted in Table 6, financial results of sale and leasing models start to differ along different reversible bonding strategies.

Note that bonding and debonding make up only a minor fraction of the total smartphone life cycle costs. Not all debonding methods require the use of specialized adhesives (Banea, 2019). Consequently, in the bonding phase the additional cost of working with 'debondable adhesives' is between €0 and €0.72 per smartphone (see Table 3). On a total smartphone production cost of €370 this is negligible. Secondly, the debonding technologies investigated can be considered as established technologies (e.g., oven, microwave, power supply…) and do not require significant investments. As a result, debonding costs for one smartphone range between €0.09 and €5.54 depending on the technology (see Table 4), again, making up less than 2 % of total production cost.

An important observation is that reversible bonding scenarios render leasing models more profitable, while having a negative financial impact on traditional sales models. If only the sales scenarios are considered the baseline scenario shows the highest total cashflow, while the higher circular strategies (scenarios c & d) generate only about half of that. Replacing the battery generates some revenues as of year 2 but that does not weigh up against the margin that comes from selling a new smartphone. Scenario d, where the lifetime of the phone is extended, results in the highest decrease in NPV. This demonstrates that in a one-off sale scenario, smartphone manufacturers are not incentivised to design a smartphone that is made to last and/or build to repair. However, if one decides to shift to a product-service system and lease the smartphone against a monthly or annual fee, ownership is retained by the producer and consequently there is an incentive to make that smartphone last. Indeed, in the lease scenarios, the lifetime extension scenarios (scenario c & d) show an increase in total cashflow of almost one third compared to the baseline scenario.

Finally, it is clear that debonding for recycling requires external incentives. The cost of debonding, albeit relatively small, outweighs the benefit of separate battery recycling. The increase in recycling efficiency is not sufficient to make the business case for scenario b positive. Consequently, external incentives (such as government subsidies or mandatory regulatory frameworks) are required to engage smartphone supply chain players to apply debonding for a recycling strategy. The higher circular strategies, however, do not require external incentives if combined with a retained ownership by the producer company (i.e., the leasing business model).

Table 5
Effect of the A factor on relative contribution of recycling and avoided material.

Recovered metals (Cu is always A = 0.2)	A = 0.2		A = 0.5 (same result Fig. 7)	
	Total recycling	Total avoided material	Total recycling	Total avoided material
Scenario a: Baseline	8 %	−21 %	8 %	−15 %
Scenario b: Debonding + separate battery recycling	5 %	−21 %	5 %	−16 %
Scenario c: Debonding + battery exchange	2 %	−12 %	2 %	−9 %
Scenario d: Debonding + maintenance	2 %	−11 %	2 %	−8 %

Table 6
Key LCC results: cashflows (CF) per year (in EUR).

CF per year	1	2	3	4	NPV Δ	NPV Δ %
Scenario a1: Baseline (sales)	630.09	0.55	630.09	0.55	0.00	0 %
Scenario a2: Baseline (lease)	130.09	500.55	130.09	500.55	0.00	0 %
Scenario b1: Debonding + separate battery recycling (sales)	629.67	−1.48	629.67	−1.48	−4.91	0 %
Scenario b2: Debonding + separate battery recycling (lease)	129.67	498.52	129.67	498.52	−4.91	0 %
Scenario c1: Debonding + exchange of battery (sales)	629.67	36.98	0.00	−1.48	−596.11	−47 %
Scenario c2: Debonding + exchange of battery (lease)	129.67	477.98	500.00	498.52	344.89	27 %
Scenario d1: Debonding + maintenance (sales)	629.67	0.00	0.00	−1.48	−633.09	−50 %
Scenario d2: Debonding + maintenance (lease)	129.67	500.00	500.00	498.52	366.91	29 %

5. Discussion

In this section trade-offs between the three assessment perspectives are discussed. Next, implications are discussed in relationship to existing literature, and limitations and subsequent pathways for further research are identified.

5.1. Trade-offs

Decision-making by entrepreneurs and policymakers is often governed by multiple criteria. Therefore, we take an integrated approach and analyse trade-offs between the outcomes of several reversible bonding scenarios following the key assessment perspectives outlined in this paper. This allows us to assess the systems scenarios holistically and identify interrelationships between the different dimensions. Fig. 8 shows the performance changes for the four key scenarios, including the sales and lease configurations as separate lines. All system scenarios are set in relation to the baseline scenario, expressed in relative terms (in %), which allows to consider all three assessment perspectives (economic impact, environmental impact, functionality impact) in the same chart.

Starting from the baseline scenario, the largest benefits from debonding and separate battery recycling (scenario b), can be observed for the preserved functionality (23.1 %) and followed by the environmental performance (4.3 %). The economic impact of debonding and separate battery recycling is slightly negative (−0.4 %). Due to the low cost of debonding, the negative economic impact is negligible.

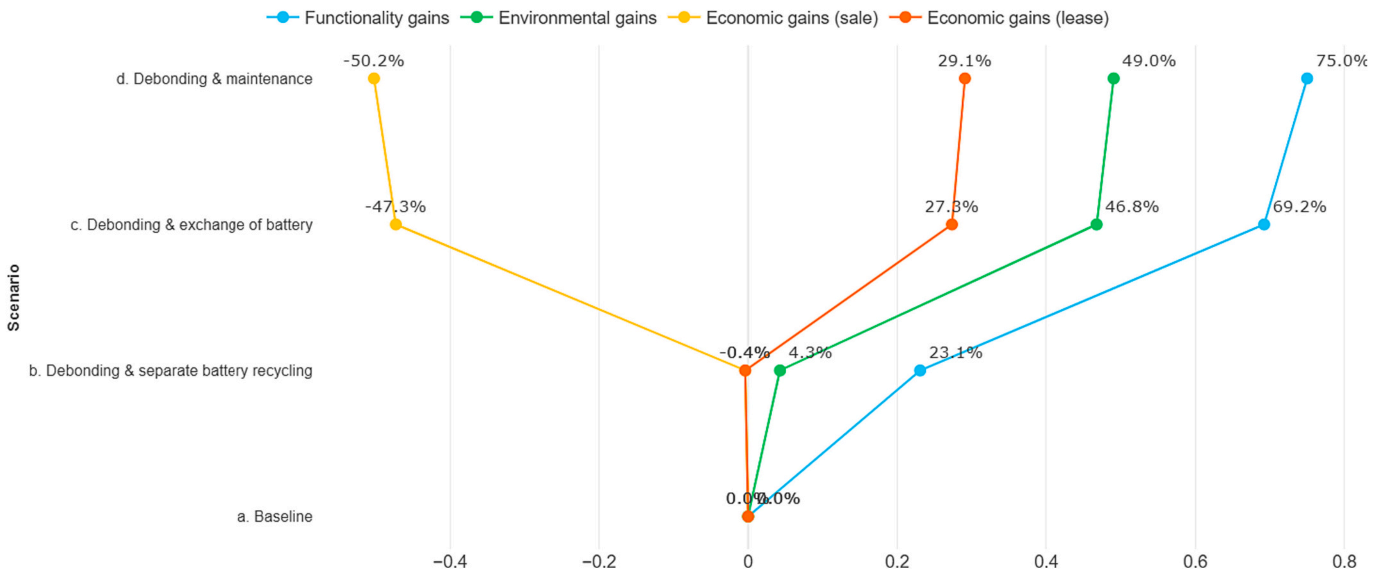


Fig. 8. Trade-offs between economic, environmental, and functionality impacts as relative changes to the baseline scenario, expressed in relative terms.

Debonding of the battery enables the separate battery recycling process that translates to a better environmental performance and a considerably more positive functionality result. The relative environmental gains are smaller compared to the functionality gains, as the battery is only responsible for a small fraction of the phone's environmental impact. The debonding of the battery and its separate processing, avoids higher dilution in the smelting phase, while additionally improving recycling of the battery through a dedicated process, leading to larger benefits for the overall system performance.

The scenario with debonding of the battery allows to replace the battery and to reuse the phone for an additional lifetime of two years (scenario c). This scenario shows considerable benefits from the environmental and functionality perspective. In fact, the environmental and functionality gains have the same magnitude. The main benefits result from avoiding the loss of functionality of the phone and from avoiding the production of a new one. Regarding the economic performance, the reduction of the cash-flows from the foregone additional sales of a second phone are large, resulting in a −47.3 % worse performance compared to the baseline scenario. Nonetheless, these losses can be translated to gains by changing the business model to a lease model. In the leasing case, a longer lasting phone with a new battery could result in an improved economic performance compared to the base case.

The scenario showcasing a longer lasting phone and battery (scenario d), has small additional environmental gains (+2.3 %) and functionality gains (+5.8 %) increase compared to scenario c. In this constellation, the use of a sales model leads to the largest economic losses (−50.2 %) compared to the base case. In contrast, a transition to a leasing model adds +29.1 % to the economic performance compared to the base case scenario.

5.2. *Implications*

There is a clear trade-off between environmental and functionality gains that are attributed to a transition to a more circular economy, and the economic losses that would directly affect the existing sales-based business models. This trade-off only holds for traditional sales business models and is reversed when a lease model is applied. An important implication is that companies are not incentivised to apply reversible bonding techniques, since their business-as-usual provides a superior financial outcome in the short term. This invites us to consider alternatives that may alter incentives and align trade-offs to enable the use of reversible bonding as a sustainable and circularity-enhancing technology.

One option is to apply policy measures that alter costs, benefits, and competitive dynamics for companies that apply a traditional sales model, affecting the financial payoff in the considered scenarios. Mandatory policies (such as mandatory regulations on repairability or the use of reversible bonding) may align the current sales model with more circular outcomes. Especially in global competitive markets, levelling the playing field among competitors using mandatory policies is challenging (Manshoven and Van Opstal, 2022). Nevertheless, mandatory regulations in strong internal markets, such as the European Union, followed by circular public procurement practices may generate a market pull that triggers dynamic economies of scales (learning curves) and enables the development of markets for reversible adhesives and debonding technologies (Ghisetti, 2017; Kirchherr et al., 2018). Mandatory regulations may likewise resolve split incentive problems between players along the value chain, enabling the redistribution of costs and benefits following the implementation of a sustainability-enhancing innovation (Van Opstal et al., 2023).

Another option, which can be implemented independently from the former one, is to stimulate the uptake of leasing models or other product-service systems. Leasing models and other product service systems can increasingly be found in capital goods and durables, such as cars (Tukker, 2015), e-bikes (Ma et al., 2020), or even services that replace physical goods, such as Netflix and Spotify (Kühl et al., 2022). However, as indicated in a recent study on smartphone leasing among millennials in Flanders, support from consumers for leasing smartphones cannot be taken for granted (Rousseau, 2020). The main barriers appear to be contractual uncertainty, financial considerations, and identity-related aspects such as privacy concerns and a strong preference for ownership. Similar considerations can be found in other studies that investigate value propositions of leasing models in markets that are traditionally dominated by sales models, such as car seats for children (Catulli, 2012), fashion products (Lang et al., 2019), and solar PV panels (Van Opstal and Smeets, 2023). The most important drivers for individual consumers to engage in leasing models for smartphones turn out to be the perception of a positive environmental impact, flexibility, and variety (Rousseau, 2020). A more promising pathway, however, is to stimulate the uptake of leasing models in business-to-business and business-to-government markets, as they tend to be frontrunner markets for circular business models (as demonstrated in Notebaert and Delagrange (2019) and Van Opstal and Borms (2023)).

Managerial implications of implementing reversible bonding technologies may include switch costs, short-term capacity constraints, and a misalignment of incentives between organizational divisions of smartphone manufacturers (Van Opstal et al., 2023). It also requires collaboration and partnerships along the value chain, with partners such as waste management companies, repair service providers, and adhesive manufacturers. While the creation of joint ventures or even vertical integration could enable this circular value chain, such a transition may require significant transaction costs (Nygaard, 2022). The transition from sales models to leasing requires a different type of customer relationships (and subsequent customer relationship management processes) (Hofmann and Jaeger-Erben, 2020). It also leads to higher financial insecurity, as for instance maintenance and repair costs are highly dependent on how the product is used and cared for by the lessee (Oghazi and Mostaghel, 2018). Moreover, adopting circular business models may lead to internal resistance, as they require significant changes in processes, operations, and organizational cultures (Rizos et al., 2016).

The integrated framework, shown in Fig. 8, is technology-agnostic and application-independent. Therefore, it is applicable to evaluate the circular economy impact of a technological innovation on other product systems. Nevertheless, product-specific challenges and market-specific characteristics, including regulatory boundaries, must be considered. Therefore, we must be cautious to transfer the implications from this smartphone example to other applications without any further investigation.

5.3. *Limitations and further research*

While we present an integrated approach to evaluate the circular economy potential of reversible bonding, on the application of a smartphone, several limitations apply. First, we applied a technology-agnostic approach, assuming low costs for implementing reversible adhesives and debonding. This assumption only holds in a context of mature technologies, fully developed markets, and sufficient economies of scale. Therefore, further research should focus on the development of business cases for different technologies, paying attention to transition pathways that consider scale conditions and dynamic market effects. An inspirational framework for this pathway may be (Guzzo et al., 2022) who developed a system dynamics based framework for examining CE transitions to support decision-making at the micro-, meso-, and macro-levels.

A second limitation comes from the fact that we apply a market-agnostic approach, assuming access to markets and technologies, and competitive prices. However, to enable the implementation of reversible bonding, future research should identify barriers and enablers along the value chain and within companies. This entails considering the effect of market power, lock-in effects, and switch costs to alter production processes and create circular supply chains. Inspirational references are (González-Sánchez et al., 2020) on the main dimensions of building circular supply chains, and the literature review of (Farooque et al., 2019) on circular supply chain management. Likewise, the role of intellectual property rights, warranties, and product responsibilities has to be taken into account, as manufactures sometimes deliberately do not want their products to be opened because of these considerations (IIEE and EEB, 2021).

Further, the employed system scenarios are simplified to the degree that the diversity of phone models, level of process and composition detail, losses of phones at several stages of the system (potentially as hibernating stock in households, collection losses, etc.), are not considered and might not only decrease the economic benefits but also decrease the environmental gains, as well as the functionality performance of the systems that employ reversible bonding technology. These considerations and their impact on the beneficial role of reversible bonding, if employed with a suitable CE business model as shown above need to be further refined in the future. Likewise, as suggested by an anonymous reviewer, it would be worthwhile to explore remanufacturing scenarios as well.

Finally, an important limitation of this research is that it evaluates the circular potential from a societal perspective, largely neglecting the value proposition of reversible bonding for companies along the value chain and not the least, end-consumers. Further research should therefore investigate the willingness to pay a circular premium for products with an increased repairability, a higher reuse value, or an improved recyclability due to reversible bonding. Inspiring examples of such research can be found on green purchase intensions for smartphones (Bigliardi et al., 2022), and antecedents of the consumption of remanufactured smartphones (De Guimarães et al., 2023). Future research should also incorporate other aspects of consumer behaviour that affect the circular economy potential of reversible bonding. This includes potential rebound effects following from improved reuse and refurbishment possibilities (Makov and Font Vivanco, 2018), the willingness to engage in repair activities (Schischke et al., 2016), the proclivity of households to return end-of-life smartphones for recycling (Poppelaars et al., 2020), and the design of disposal destinations (Sonego et al., 2023).

6. Conclusions

In this paper we assessed the circular economy potential of reversible bonding using the application of a smartphone. We identified and calculated the impacts of four different scenarios, including enhanced recycling, reuse, and longer product lifetimes. From a functionality perspective, reversible bonding can be considered as an enabling technique that has the potential to improve system-wide functionality preservation. Reversible bonding may avoid initial functionality losses through reuse and destruction of functional components, and material functionality losses, while enabling improved restoration of functionality through dedicated recycling processes. It has been also shown that a focus on recycling rates can be misleading in some situations, where functionality is preserved on higher levels, such as on the level of the product or the component. Moreover, higher preservation of functionality can lead to reduced recycling rates and recycled materials mass, which should be taken account when setting new or higher recycling rates that typically do not reflect the quality dimension.

From an environmental perspective, the major value-added through reversible bonding is its potential to replace and update degraded parts to prolong the lifetime of the main environmental hotspot (in the case of a smartphone its PCB). From an economic perspective, the profitability of reversible bonding scenarios appeared to be strongly dependent on the underlying business model.

An important finding of our integrated analysis is that companies are not incentivised to apply reversible bonding techniques if it turns out that their business-as-usual scenario provides a superior financial outcome in the shorter term. Therefore, we recommend policymakers to formulate regulations that adapt cost structures and competitive dynamics in order to alter incentives for manufacturers to adopt reversible bonding. Examples of relevant policy options are mandatory regulations on repairability and public procurement guidelines favouring the use of reversible bonding applications. Such policies would stimulate market and technology development of reversible bonding techniques. Moreover, these policies could support manufactures in contexts where consumer preferences for lease markets cannot be taken for granted.

As this is, to our knowledge, the first paper that identifies and calculates the circular economy potential of reversible bonding, we invite scholars to address some important research gaps. First, as the costs and benefits of implementing reversible bonding may be distributed unequally along value chains, it is important to grasp implicit knowledge along value chain actors. Second, since the conclusions from this smartphone example can only be transferred to other products with caution, we invite other researchers to study the circular economy potential of reversible bonding in some promising fields, such as automotive, electrical and electronic equipment (EEE), construction, and textiles. Finally, as the introduction of reversible bonding potentially involves many actors along the value chain, we suggest investigating the strategic interaction involved using game theoretical frameworks to evaluate circularity enhancing policy options.

CRediT authorship contribution statement

Alexej Parchomenko: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, writing – review and editing.

Stefanie De Smet: methodology, validation, formal analysis, resources, data curation, writing – original draft preparation.

Emma Pals: methodology, validation, formal analysis, data curation, writing – original draft preparation.

Ive Vanderreydt: methodology, investigation, resources, writing – review and editing.

Wim Van Opstal: conceptualization, methodology, validation, investigation, writing – original draft preparation, writing – review and editing.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

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Supplementary data

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