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How to balance Repair and Recycling

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Designing Electronics for a Circular Economy: How to balance Repair and Recycling

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Introduction

The short lifespans and rapid innovation cycles of electronic products result in the loss of valuable and critical resources (Bakker, Wang, Huisman, & den Hollander, 2014; Baldé et al., 2024). Strategies aimed at extending product lifetimes, such as design for repair, focus on improving the ease of manual disassembly (De Fazio, Bakker, Flipsen, & Balkenende, 2021). However, connections optimized for repairability can hinder the mechanical separation of materials during recycling. This highlights a critical trade-off: improving repairability can often conflict with recyclability, emphasizing the need for balanced design approaches that address both recovery goals.

Navigating these trade-offs requires a deeper understanding of how materials and connection types in electronics affect circular strategies. This research aims to investigate tensions between repairability and recyclability by analyzing a diverse set of electronic products and relating the findings to their design architecture. This study seeks to inform design strategies that optimize for both repairability and recyclability, thus prolonging product lifetime while minimizing resource losses at end-of-life.

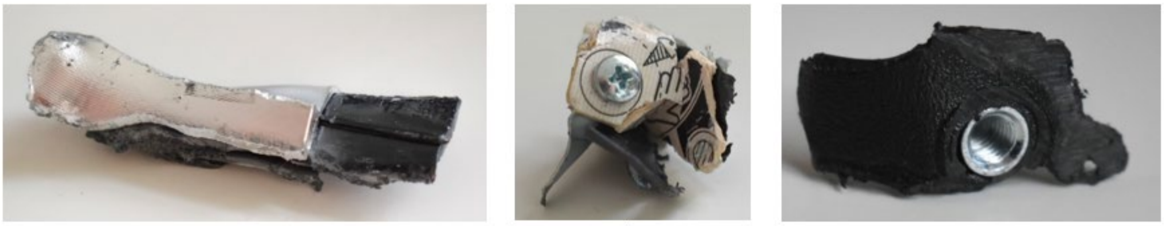
Method

While repairability assessment has become mature over the past years and the effect of various connection types is well established (Flipsen, Depypere, Huisken, & Opsomer, 2019; Vanegas et al., 2018), the field of design for recycling remains less developed. To address this gap, our experimental setup prioritized recycling-focused investigations to evaluate how design choices influence material recovery outcomes.

The design architecture of electronic products varies significantly, which affects their end-of-life outcomes. To investigate the impact of design choices on recyclability, we analysed a selection of products – four smart TV models, a streetlamp and an office luminaire – chosen for their diverse design architecture and material compositions.

Our method combined manual disassembly analysis and destructive mechanical shredding tests to evaluate recyclability. Each product was disassembled to component level, with all parts documented in a Bill of Materials (BoM) that recorded their mass and material composition. All disassembly actions were noted, including tool type, applied force, fastener type, and fastener and component visibility. A disassembly map was created for each product following the procedure outlined in (De Fazio et al., 2021), providing insights on the products' architecture.

We assessed material liberation using a 4-shaft e-waste shredder, with experiments conducted at an E-waste recycling plant to ensure alignment with industry practices. The resulting fragments were hand-sorted to trace material flows and assess the separation of different connection types. Homogeneous fragments – composed of a single material – were sorted by material type, while heterogeneous fragments – containing multiple materials – were classified based on likely recycling stream destinations, informed by expert consultations. Further analysis quantified unbroken connections in heterogeneous fragments. This allowed us to identify the effect of product architecture features on recyclability and find tensions between design for repair and design for recycling.



a b c

Figure 1. Heterogeneous fragments from a shredded smart TV.
a: A piece of aluminum is still attached to part of the plastic housing because of an adhesive (material closure) used in the design.
b: A piece of plastic, steel and PCB are still connected because of an unliberated screw (force closure).
c: The metal insert (force closure) is still attached to the plastic housing.

Connections — Suitable for...

Class	Connection type	Manual dis- and reassembly (for repair)	Mechanical disintegration (for recycling)
Form closure	Friction fit	Compatible	Compatible
	Hook	Compatible	Compatible
	Turn lock	Compatible	Compatible
	Click connection	Compatible	Compatible
Form & force closure	Fold lock	Compatible	Design dependent
	Side lock	Compatible	Design dependent
	Top lock	Compatible	Design dependent
Force closure	Snap fit	Compatible	Compatible
	Magnetic connection	Compatible	Compatible [a]
	Screw	Compatible	Design dependent
	Nut and bolt	Compatible	Design dependent
	Rivet	Not compatible	Design dependent
	Folding	Not compatible	Design dependent
	Crimping	Not compatible	Design dependent
	Clinching	Not compatible	Design dependent
	Heat staking	Not compatible	Design dependent
Material closure	Pressure sensitive adhesives	Compatible	Design dependent
	Hot-melt adhesives	Design dependent	Design dependent
	Irreversible glue	Not compatible	Design dependent
	Soldering	Design dependent	Not compatible
	Welding	Not compatible	Not compatible
	2K molding	Not compatible	Not compatible
	Coatings	Not compatible	Not compatible

[a] Even though magnetic connections often break in a shredder, permanent magnets pose problems in the recycling process because they stick to ferrous fragments and to machines in the recycling line.

Compatible
Design dependent
Not compatible

Table 1. Evaluation of connection types regarding their suitability for manual dis- and reassembly and mechanical shredding, based on disassembly and shredding experiments. The table highlights the tensions between design choices for repairability and recyclability, providing insights into how different connection types perform in each recovery pathway.

Results and discussion

Disassembly revealed that the products contained non-recyclable materials such as coatings, plastics and rubbers, which reduced their theoretical recyclability to 70-95%. In addition, non-recyclable materials complicate material streams.

Repairability was visualised through disassembly maps, showing the ease of removing priority parts (i.e. those parts that are critical to the product's function and are known to be vulnerable) (De Fazio et al., 2021). Favorable connections for ease of disassembly are 'form closures', 'force closures' and reversible 'form and force' closures that can be easily accessed, as shown in table 1 (based on (Peeters et al., 2018; Vanegas et al., 2018)).

Shredding experiments provided valuable insights into the impact of different connections on material liberation. It revealed that some components, such as supportive steel structures in the back of some TV's, were so rigid that they could strain or even block the shredder, demonstrating a clear obstacle to effective recycling. In general, 'form closure' connections like friction fits and turn locks easily break down during shredding, while 'material closure' like glues, soldering and coatings remain connected (figure 1). For 'form and force' closures like fold locks, and 'force closures' like screws, rivets and crimping (figures 2 and 3), connection behaviour was less predictable. For example, screws separated cleanly in some products but remained embedded in others, likely due to variations in tolerances and material properties. Table 1 provides an overview of the likelihood of connection break-down during shredding.

While designing for disassembly often improves repairability, large-scale recycling mostly relies on shredding rather than manual disassembly. As a result, repair-friendly connections do not necessarily translate into better recyclability. At the same time, waste processing technologies continue to evolve, but instead of only expecting recycling to adapt to new designs, this study highlights the importance of designing with existing recycling infrastructure in mind. If a designer should prioritize repairability or recyclability depends on the product's End-of-Life scenario, requiring careful consideration of environmental impacts using Life Cycle Assessment and other decision-making tools.

Our findings identified tensions between repair and recycling, as many connections that facilitate repair might hamper recycling (Table 1). This shows the need for design approaches that consider both recyclability and repairability. Our results form the basis for a design guide to help designers addressing conflicts between recovery strategies and to improve simultaneously on repair and recyclability.

Acknowledgments

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