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Towards a Digital Knowledge Base of Circular Design Examples through Product Teardowns

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Abstract

Design of more circular products is key to achieving Sustainable Development Goal 12, Responsible Consumption and Production. However, many designers lack the knowledge and confidence to bring aspects of circular design into their design practices. One problem is the lack of examples on how circular design is implemented in different types of products and their components. In this work, we present a framework to generate a digital knowledge base of circular design examples from product teardowns (product dissections). Leveraging teardowns, a commonly practiced activity among product designers, can allow the knowledge base to include rich and up-to-date design examples and help inspire future design. The knowledge base covers three categories of circular design aspects: reliability, RRU (repair, reuse, upgrade), and recycling. Under each aspect, we generate a comprehensive list of prompts to guide designers to analyze the product and collect circular design examples. A subset of prompts is showcased in a study of a newly released laptop. We also gathered feedback and suggestions for future developments from experienced design practitioners.

Keywords: Circular Design Thinking; Environmental Impacts; Product Design; Product Teardowns; Responsible Consumption and Production; Knowledge Base

1. Introduction

The design of more circular products is key to achieving Sustainable Development Goal 12, Responsible Consumption and Production. This is particularly the case for electronic devices, which are made of a heterogeneous mix of materials, including chemicals and precious/critical minerals. Furthermore, electronic waste, or e-waste, grew more than 38% between 2010-2019 and less than 20% of the electronic devices are properly recycled at the end of life [1].

To reduce the amount of waste that is being created from the disposal of products, principles from the circular economy, such as increasing the reliability or repairability of a product, can be leveraged at the design stage [2]. In fact, the environmental impacts of a product's materials, production, use, and end-of-life are to a large extent dictated by decisions made in the early stage of product research, conceptualization, and design.

However, enacting sustainable and circular design practices at the early design stage is a fundamental challenge for designers. We use designers generally to refer people who participate in the activity of product design and development; they can include industrial designers, mechanical and electrical engineers, and product managers. In practice, there are complex and often conflicting interdependencies between circular design decisions and user experience, costs, manufacturing constraints, as well as product performance and sustainability. Additionally, the interdependencies are often dictated by the type of product being designed and the product's use case, making the one-to-one transfer of strategies from one product type to another difficult. These complexities can contribute to a lack of awareness of circular design strategies among designers, hindering the momentum for circularity in product development to be a standard practice.

Designers can learn how to navigate these complexities by studying tangible examples of previous products as a method to extract design strategies from successful designs. They often

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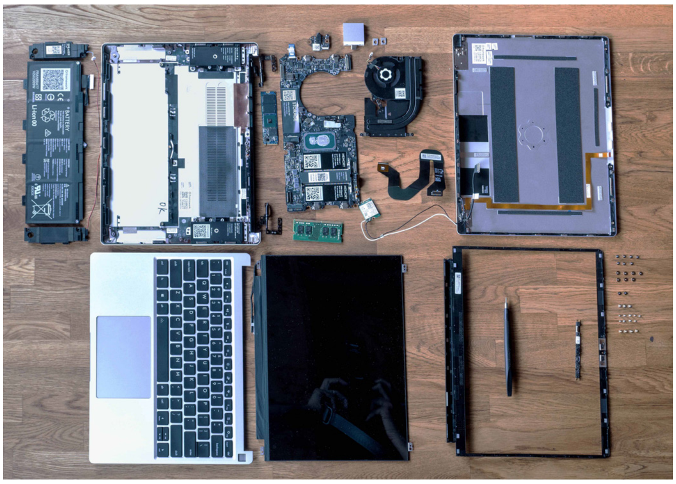

Fig. 1. Product teardown of the Framework Laptop.

rely on teardowns (Figure 1), the analysis of an existing system to assess its content, and establish a baseline to facilitate the projection of technology trends, developments, and capabilities [3]. A typical teardown involves designers ”reversely engineering” a product by disassembling the product down to its base components. During this process, the designer can consider how certain features within the product create tradeoffs with other priorities the product is balancing, such as cost or manufacturing ability, and hypothesize opportunities for improvement. This documentation is then typically shared with other design team members, though the information is not usually stored as a knowledge base.

There are eco-design frameworks and tools [4] that can help designers evaluate circularity and sustainability aspects in an early design phase. In particular, they can offer the possibility of analysing circular design strategies integrated in the product, and quantify the environmental impact of the product or services along their life cycle phases through the ISO standards of 14040 and 14044 and tools such as life-cycle assessment (LCA) [4, 5, 6]. However, the early design phase faces with considerable uncertainty factors (e.g., about shape and component interactions), and requires extensive data to provide high fidelity results [7, 8]. When decisions need to be made rapidly and detailed information is scarce, the effective usage of LCA remains challenging [9, 10]. In addition, scaling up design knowledge is usually not in the consideration of these tools.

In the presented context, this paper describes a framework that can guide designers during product teardowns to collect and share design examples and conduct qualitative and quantitative analyses for circular design. This paper does not aim to provide a review on previous eco-design tools, instead, we focus on demonstrating how and why building a collective knowledge base of circular design examples can promote circular design practices. We do this by leveraging a commonly practiced knowledge transfer activity, product teardown, and propose a framework that allow designers to collectively build up a circular design knowledge base to easily search for examples of circular design strategies in existing products, and correlate those examples to their own design challenges.

2. Circular Design Knowledge Base through Product Teardowns

In a product teardown, designers follow these three steps to collect design examples and perform qualitative and quantitative analyses for the creation of a knowledge base:

1. Analyze the product and choose one or more *circular design prompts* in six circularity aspects (Section 2.1). Commence the teardown process.
2. Conduct *qualitative and quantitative analyses* on the product, or its components if specified in the prompt (Section 2.2) .
3. Evaluate how the design of the product and its components perform against the prompt and digitally record *design examples* on the design of the product and its components (Section 2.3). For each insight, designers can tag the associated components and list design tradeoffs (see Figure 2).

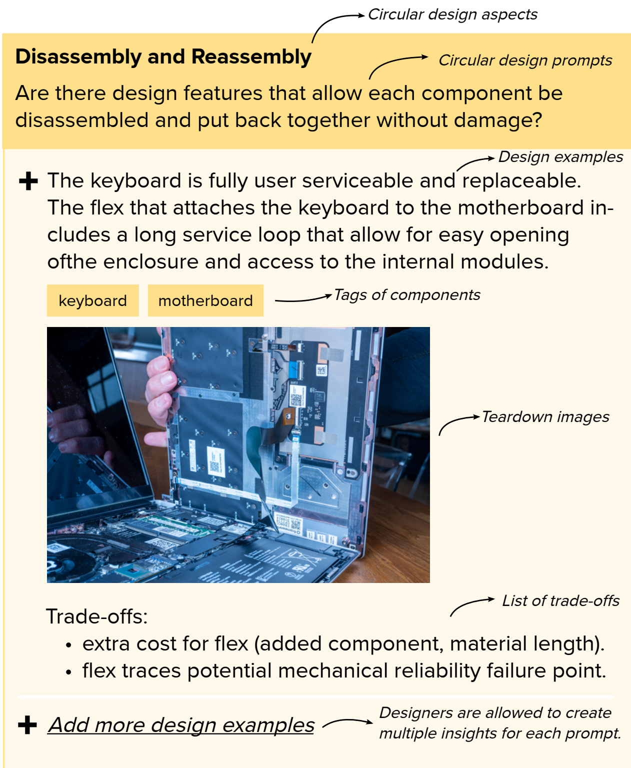

Fig. 2. Illustration of the prompt and data in the knowledge base.

There are two main principles we used to develop the knowledge base. First, the knowledge base is built to inspire designers to incorporate circular design thinking in their future design practice. The knowledge base focuses on collecting real design practice examples. When designers search for inspirations for a design, they can query the knowledge base to find relative examples to gain more confidence. To make the query results more relevant, it is important capturing the design context, such as design tradeoffs and key components, during data collection.

Secondly, data collection for the knowledge base can be distributed among different designers and at different time. To lower the barrier for entry, the knowledge base allows designers to pick and choose prompts to contribute. Designers can also focus on different activities, e.g. some generate design examples, while others analyze the tradeoffs and tag components. Distributing data collection helps engage more designers and build up a richer knowledge base based on different design experiences.

2.1. Step 1: Choose circular design prompts

Inspired by previous work [11, 12, 13], we choose the following aspects to present the prompts for designers.

- *Reliability*, reducing the likelihood of failures to extend product lifetime [14].
- *Repair, Reuse, Upgrade* [15], including: *disassemblability and reassemblability*, designing products and their parts to be easily separated and reassembled [11, 16]; *repairability*, facilitating the restoring of a functional state in case of failure [14, 17], *upgradability*, enhancing the functionality of a product, independently of failure [17] and *reusability*, facilitating the reuse of a product after its lifetime [12].
- *Recycling*, facilitating the recovery of materials (e.g. use of recycled materials and recyclability of the product) [18].

The integration of such aspects in the design of products can lead to environmental benefits [19]. However, it must be noted that each design aspect is not independent from the others, requiring designers to actively analyze design tradeoffs. For example, optimize for reliability of a smartphone, may result in design decisions that use stronger adhesives and make the phone less easy to repair [14]. Hence, guiding designers to analyze all these aspects on real design examples during teardowns can trigger them to actively consider design tradeoffs, and come up with balanced solutions in specific design contexts.

For each aspect, we develop prompts as inquiries to guide designers' analysis. These prompts are based on previous work as listed above, and we will introduce them in Section 3.

2.2. Step 2: Conduct quantitative analysis

Some prompts ask designers to provide quantitative analysis. For example, to evaluate how easy a component can be disassembled and reassembled, one prompt asks designers to record the number of steps for taking a component apart. The collected data can be used to create quantitative benchmarks. For example, instead of asking designers in prompts to qualitatively judge whether the product is *quick* to disassemble, we ask designers to record the number steps they take to disassemble key components from the product. Once we collect the disassembling steps for many similar products and from different designers, *quickness* can be referred to an absolute number, e.g., the average steps needed to disassemble similar products. Conducting quantitative analysis can reduce subjectivity, and allow updating benchmarks over time.

2.3. Step 3: Collect design examples and their associated components and tradeoffs

Prompts aim to stimulate circular design thinking. For each prompt, designers record their examples on the design of the product or its components as notes and images. Examples can include direct observations (e.g. "QR codes are attached to individual component for identification." and an image of a component), speculated design considerations (e.g. "The enclosure uses minimal recycled materials likely for structural requirements."), as well as suggestions for improvement (e.g. "Keyboard design on this product can be more dust resistant."). See more examples in Section 4. After designers record their design examples, we encourage them to tag the related component and link to other examples.

Design examples can be related to multiple components. For example, a designer analysing a laptop observes a good practice adopted for battery, memory and mass storage and creates an insight, "QR codes are attached to individual key component for identification.". The practice, attaching QR codes, cannot be applied on all components, for example those extremely small or non-flat. With component tagging, other designers who want to search good practices for component identification can get relevant results for their design cases.

Relationships between examples are another important information to capture. Relationships can include design tradeoffs (e.g. tradeoffs between "Using strong adhesives make the smartphone more resistant." and "Using strong adhesives make replacing battery very difficult for regular users.") and dependencies (e.g. "Good availability of options for ports on the company's website for upgrading purposes." depends on "Implementation of a detachable IO system that allows users to customize the ports on the machine"). Design consists of intertwined decisions. Capturing the relationships between examples allows designers to get a fuller picture when adopting a new circular design practice, and hence, gain more knowledge and confidence.

3. Circular Design Prompt Demonstration

As discussed in Section 2.1, we generated a comprehensive list of prompts adjusted to consumer electronics. For different products, designers can exclude prompts that do not apply, and introduce new ones as appropriate. Each of the following subsections corresponds to a circular design aspect to analyze when tearing down consumer electronics, a priority sector for the circular economy because of the rapidly evolving technology and the environmental concerns associated with their production, use and disposal. Every prompt asks designers to provide qualitative design examples (Section 2.3), and some prompts also guides designers to provide quantitative analysis (Section 2.2). Each quantitative analysis is presented as *(Q)* with steps and units specified. As designers go through the list, they can make new suggestions for prompts.

3.1. Reliability

REL_1 What design features can help protect the product against common mechanical stresses (e.g. accidental drops and scratch)?

REL_2 What design features can help protect the product from common environmental factors (e.g. water and dust)?

REL_3 Are there other common failure modes, and how does the design of the product help mitigate these risks?

REL_4 Are users instructions and information on correct use and maintenance of the product publicly available?

REL_5 *(Q)* If there is a battery, how many number of cycles can the battery function properly? You can perform test or read the data sheets of the battery.

REL_6 If there is a battery, is there battery management software installed for smart charging and provision of state of health data?

REL_7 Is an extended guarantee offered for the product or some key components by manufacturer and/or retailer? *(Q)* Report the number of years of guarantee.

3.2. Repair, Reuse, Upgrade

3.2.1. Disassembly and Reassembly

$D\&R_1$ What design features allow quick identification for key components? *(Q)* Report how the identification is designed. For example, identification can be engraved, marked, or labeled.

$D\&R_2$ What design features can allow key components being disassembled and put back together without damage? *(Q)* Report the steps to disassemble and put back key components.

$D\&R_3$ Can components be disassembled and put back together with common tools [15]? *(Q)* Report the tools used to disassemble and put back different components.

$D\&R_4$ Are non-removable and non-reusable fasteners (e.g. adhesives) avoided for the assembling of components?

3.2.2. Repairability

REP_1 Are diagnosis support and interfaces available to aid the identification of failure modes?

REP_2 Are users instructions and information on repair of the product publicly available?

REP_3 Are official or compatible spare parts and information on spare parts available? *(Q)* Report the number of years spare parts are available for, their cost compared to the product, and the waiting time for their delivery.

REP_4 What design features allow no or minimal loss of quality and aesthetics after repairing the product?

3.2.3. Reusability

REU_1 What functionalities are installed that facilitate the reuse of the product and its components? For example, secure data deletion in storage components, password reset and restoration of factory settings.

REU_2 What design features can allow components to be reused? For example, standardized components and interfaces.

3.2.4. Upgradability

UPG_1 Is software upgrade or update supported?

UPG_2 Is hardware upgrade or update supported for components?

UPG_3 Is software and hardware upgrade reversible?

3.3. Recycling

REC_1 *(Q)* How much recycled materials are used? For example, recycled plastic, aluminium, copper, tin and tungsten.

REC_2 What design features can facilitate the recovery of components and materials? For example, components and materials are easily identifiable and separable.

REC_3 Is an extended producer responsibility or taking-back strategy in place?

4. Design Examples

To illustrate the methodology in action, a set of design examples have been generated from a teardown of the Framework Laptop (see Figure 1). The laptop, released in mid-2021, is described by the manufacturer as “a high-performance, thin and light notebook designed to last.” This product was chosen as an example because it contains many instances of circular design best practices that could be valuable to elevate in awareness among the design community.

While conducting the teardown, each category of circular design aspects and their associated prompts were used to guide the inspection and capture examples. Design examples were documented in this way (see Figure 2 for an illustration), with a partial sample of examples showed as an illustration in the following sections .

In accordance with the framework, associated tradeoffs were also noted alongside each design example to capture design considerations related to the practical implementation of circular design aspects. Section 4.5 shows a set of tradeoffs as an example.

4.1. *D&R$_1$ What design features allow quick identification for key components?*

(1) Inside the device is a high-level explanation of the use of QR code as pointers to repair guides, new replacement parts, and a marketplace for second-hand parts. The QR codes can be easily scanned by a smartphone while doing repairs to provide instructions and support (Figure 3 (a)).

(2) The battery is easily removable and is clearly marked with a QR code to help with disassembly instructions, ordering replacement parts, and battery recycling / disposal options (Figure 3 (b)). [battery]

Fig. 3. (a) QR codes for repair guides. (b) Battery repair instructions.

4.2. *D&R$_2$ What design features can allow key components being disassembled and put back together without damage?*

(1) The keyboard is fully user serviceable and replaceable. The flex that attaches the keyboard to the motherboard includes a long service loop that allow for easy opening of the enclosure and access to the internal modules (Figure 4 (a)) [keyboard, motherboard]

(2) The bezel around the display is held into place by magnets and is easily removable by hand to facilitate replacing the LCD screen itself or the user-facing camera plus microphone module (Figure 4 (b)). [screen, camera, microphone]

(3) The user-facing camera is integrated into a removable module containing related subsystems (camera sensor and lens itself, microphone, ambient light sensor) with a ZIF (zero insertion force) connector as the interconnect. It is mounted with standard size screws to the top chassis and can by easily replaced. [camera, microphone]

Fig. 4. (a) User-replaceable keyboard; (b) Magnetic removable bezel.

4.3. *REP$_2$ Are users instructions and information on repair of the product publicly available?*

(1) The online repair guides provide information on the level of difficulty, the steps involved, typical time required, tools and parts required, and detailed step-by-step directions with in-process photographs. The guides also allow for inline commenting for questions and support dialog between users and the Framework team.

4.4. *UPG$_2$ Is hardware upgrade or update supported for components?*

(1) There's a modular IO system that allows users to customize the ports on the machine (like SD card, USB-C, and HDMI) as well as supporting third party developers of additional modules (Figure 5 (a)). [IO, SD card, USB-C, HDMI]

(2) The system has two slots for DDR4 memory modules that can be individually swapped out by hand without replacing the entire motherboard. No de/resoldering required. QR codes are used for instructions and to link to a store for upgrade parts (Figure 5 (b)). [memory]

(3) The hard drive is an SSD and can be easily upgraded by hand. No de/resoldering required. QR codes are used for instructions and to link to a store for upgrade parts [mass storage]

Fig. 5. (a) IO system that allows users to customize the ports on the machine; (b) Memory modules slots.

4.5. *Tradeoffs for modular IO system design (UPG$_2$)*

(1) Reliability: The additional connectors and locking mechanism are potential reliability failure points for mechanical stress, moisture intrusion points, and electrostatic discharge.

(2) Cost: Extra cost is added to the overall solution for the additional connectors, PCB, and enclosure parts of the modules themselves as well as system-side requirements to support third-party modules (power, reverse/over voltage protection, etc).

(3) Design: The module design impacts the overall form factor of the device to accommodate the additional volume required as well the industrial design impact of additional part breaks and gaps.

(4) Material: More material is used in the overall solution for the additional enclose wall thickness and extra connectors.

5. User Feedback and Future Work

Through this framework, we have provided a method to gather rich insights from designers on designing for circularity. Its format supports future development of searches of circular design examples of products. It also aims to be agnostic to specific product types or use cases. With our circularity-focused prompts, designers have an opportunity to share their knowledge on circular strategies and learn how others have implemented these strategies within the context of design tradeoffs.

Preliminary feedback received from experienced design practitioners supports the usefulness of the framework to raise awareness of circular design practices and help knowledge transfer. It is considered that main users might be product designers, since they already do teardowns in their work. Designers who work for larger companies might not want to share all teardown notes, since some of them can be a competitive advantage for an organization. In addition to designers, technical support, repairers and consumers can also be potential users for consuming the presented knowledge base. In this sense, a smart search interface is necessary to help filter out or curate the content on top of the knowledge base. However, to enhance the collected knowledge, writing down thorough notes during teardown is difficult, especially if one person does it alone. An auto audio transcription system could be of help, as well as including videos to capture the behavior of components such as how hinges move. Practitioners also showed interests in connecting the circular example with LCA to gain more in-depth understanding of the trade-offs. One practitioner suggested regularly curating circular design practice examples from the knowledge base can help guide designers during design even more.

Although distributed teardowns can be a effective method to gather hard to capture insights about a product, we recognize that not all the information about a product can be captured in this format. For example, detailed material information about recycling is many times not publicly available for teardown analysis. Furthermore, prompts to enhance remanufacturing were not explicitly included due to the need for more information from producers. In addition, the analysis of circular design strategies and associated tradeoffs would benefit from the integration of LCA and life-cycle inventory data in teardown analyses to further assess environmental impacts associated with different design options.

Further developments of this work will seek to handle such limitations and run a series of teardown studies to test the ease of use of the framework, and organize the design examples that have been gathered. The qualitative data we collect gives opportunities to leverage natural language processing to analyze the content, and store all collected data as a retrievable dataset. Such information can be then utilized to support prototyping a knowledge-search software tool allowing for a user-friendly way to search through the relationships between product's structure, circularity strategies associated to that structure, and related tradeoffs and impacts.

These future investigations support our goal to both gather and organize, and synthesize circularity data for designers, and through the use of software automation, make that data widely accessible. By supporting designers with tools with which to easily find the most relevant design examples of the circularity strategies for their design problems, we can help solidify sound circular design practice as the standard design practice.

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