PAGE BY PAGE

A REPAIRABLE HEADPHONE, RETHOUGHT THROUGH ITS USER GUIDE

TU Delft Iza Bosch | Integrated Product Design | MSc. Graduation Thesis SONY

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MSc. Graduation Thesis
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Abstract

This graduation project, conducted in collaboration with Sony Corporation, explores how over-ear wireless headphones can be redesigned to better align with the principles of the circular economy. The current design of consumer electronics, including headphones, largely follows a linear model. This results in short product lifespans, limited repair options and significant challenges for recycling. This project takes a different approach, fundamentally rethinking how users interact with and care for their products.

While most consumer electronics are designed as closed systems, this project investigates how design can shift the perception of headphones from being a 'black box' to an understandable and approachable object.

The analysis of five existing headphone models identified key barriers to circular user behaviour, including complex design, inaccessible critical components, difficult disassembly processes due to interdependencies, the extensive use of adhesives, lack of intuitiveness and the product being perceived as a 'black box'.

In response, a new concept was developed that centres on re-teaching the practice of product care through clarity. Central to the design is an illustrated book featuring transparent elements that serves as a walk-through of the headphones. This allows users to familiarise themselves with the headphones' internal architecture, functions and maintenance possibilities without risking damage.

According to the principles of this book, the Sony WH-1000XM5 has been redesigned to follow the same modular, layered structure. Transparent structural parts and colour coding by function reinforce the visual connection between the two. The book and the headphones work together as a single system, with each one strengthening the other.

The final concept demonstrates how design can encourage users to take care of their products by teaching them how to maintain, repair and handle them responsibly throughout their lifecycle.

This project introduces a new approach to circular design and product design in general, placing the supply of information at the centre and adapting and optimising the design of the product to support it.

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1. Introduction

1.1 Problem statement

We are consuming resources at a rate that exceeds the earth's capacity to regenerate them. As a result, sustainability and circularity are becoming increasingly important topic. This is especially true for consumer electronics, which often contain valuable and critical materials, such as rare-earth metals and precious minerals, with only a small percentage being properly recycled. The lifecycle of these products is predominantly linear: they are typically bought new and rarely repaired before being thrown away. In Europe, e-waste amounts to 17.6 kg per capita, with the majority coming from small electronics (Baldé et al., 2024). Adopting circular models in consumer electronics can reduce their environmental impact by retaining as much value as possible and extending product lifecycles.

Headphones are a clear example of this issue. While they were once seen primarily as functional tools, they are increasingly treated as lifestyle or fashion items, with trends influencing their aesthetics and perceived relevance. Many people own multiple pairs of headphones, of which one or more are often no longer in use due to breakage or perceived obsolescence. Despite containing high-value components, headphones are rarely repaired, and design decisions frequently prioritise performance and appearance over disassembly or recyclability.

At the same time, circularity is becoming more important within companies like Sony, driven by (impending) legislation and growing consumer awareness. Circular business models present new opportunities, such as offering spare parts to ensure long-term customer relationships. Additionally, more circular products can benefit consumers by lasting longer and offering greater modularity and customisability. However, to ensure customers actually choose more circular products, it is crucial that the experience, ease of use, and quality are not affected.

While the current Sony WH-1000XM5 model excels in functionality and user experience, it also presents challenges from a circularity perspective, such as the complex disassembly and the limited availability of spare parts. By identifying opportunities and translating them into a new design vision, this project investigates how headphones can be designed to support repair, reuse, and longevity, not just in theory, but also in actual user behaviour.

1.2 Scope

This graduation project focuses on the design of wireless over-ear headphones, also known as circumaural headphones, where the earpads fit around the ear. The aim is to develop a headphone concept that fits within the circular economy, with an emphasis on long-term use, repairability, and clear communication to the user. This involves assessing the current level of circularity of this type of headphone and identifying design decisions that support or hinder their potential for more circular use

The main focus is on the physical product itself: its design, architecture, assembly, and disassembly. In addition, the project explores how product design can be supported by information design, for example through manuals or packaging, to help users better understand, care for, and interact with the product throughout its lifecycle.

While the design must remain feasible and realistic, it is not limited by Sony's current product portfolio or logistics system. Broader systems such as business models or product flow fall outside the scope of this project.

1.3 Research questions

RQ1 How does the product architecture of over-ear wireless headphones affect the product's circularity?

→ *Answered in Chapter 2: Context.*

RQ1.1 What components do wireless headphones consist of, and how do variations in these components influence the product architecture?

RQ1.2 What developments are there for headphones, and how do these affect the product architecture?

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→ *Answered in Chapter 3: Circular design.*

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→ *Answered in Chapter 5: Key findings.*

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→ *Answered in Chapter 6: Vision and Chapter 7: Final design.*

RQ5.1 How can supporting materials simulate product interaction and build user confidence?

RQ6 How does the new circular headphone concept improve upon the current Sony WH-1000XM5?

→ *Answered in Chapter 9: Concept validation.*

RQ6.1 What are the potential pain points of the concept?

RQ6.2 What is the ease of disassembly of the concept?

1.4 Approach

The approach for this graduation project follows a structured design process grounded in research, analysis, and iterative development. The project started with an in-depth analysis of the current state of wireless over-ear headphones, including disassembly studies and a review of relevant circular design strategies. This analysis was used to identify key barriers to circularity, as well as opportunities for improvement.

Based on these insights, a set of key findings was created, which formed the foundation for three different visions. Each vision outlined a different approach to enabling more circular use of headphones, considering aspects such as user behaviour, product architecture, and long-term use.

These three visions were explored and evaluated through sketching and prototyping in individual Design in a Day sessions. From this vision development process, a final vision was selected that best aligned with the key findings and created an opportunity-rich design space. This vision was then used as the basis for generating three design directions, each embodying the vision in a different way.

After comparing and evaluating these directions, one was chosen and further developed into a detailed final concept. This concept was refined through multiple iterations of prototyping and testing.

The result is a design proposal that aims to make circular use of headphones more achievable and intuitive by addressing both the physical product and its supporting information.

Analysis

2. Context

This chapter outlines the context of the project. It discusses the product architecture, and recent and future technological developments and how these affect the product architecture, with the aim of creating a base understanding of what an over-ear headphone is and what aspects could play a role in circularity.

2.1 Headphone architecture

This chapter addresses *RQ1.1 What components do wireless headphones consist of, and how do variations in these components influence the product architecture?* To properly assess the circularity of a product, identify causes and limitations, and eventually design a headphone with circularity in mind, it is necessary to have a clear understanding of its components and product architecture. To answer this, I analysed existing headphone models and looked into the effect of variations in key components on product architecture.

The exact product architecture of headphones varies by model, but they generally consist of the same key components, of which the specific types can vary. These variations can influence other aspects of the product architecture. The parts can be divided into structural components and electronics. Figure 1 and Figure 2 show overviews of the product architecture, with Figure 1 focusing on structural components and Figure 2 on the electronics.

As there is a range of functionalities between headphones, especially the exact configuration of electronics can differ.

- **Controls** can take the form of physical buttons, switches, or touch sensors or a combination of these. Especially touch sensors can have a big impact on the product architecture, as they need a large free surface on the inside of the earcup housing.
- The **battery** is most often a single soft pack lithium-ion battery, although some companies use multiple battery packs.
- **Speaker drivers** work by converting electrical signals into mechanical movement of a thin membrane, the diaphragm, which creates vibrations (Panasonic, n.d.). There are different types of drivers, but dynamic drivers are most common. These drivers consist of a magnet, an electromagnetic coil, and a diaphragm.
- The number of **microphones** depend on whether the headphones have Active Noise Cancellation (ANC) or not. Headphones that have ANC have at least one additional microphone per ear for this function. These extra microphones take up space inside the earcup and create additional holes where moisture or dust could enter the headphones.
- Nowadays, all **charging ports** for new products sold in the EU have to be USB-C (Directive 2022/2380).
- Headphones contain multiple **PCBs**. Some models have one PCB per earcup, but most have multiple. Having only one PCB has the advantage that no additional wiring is necessary to connect the different PCBs, but the footprint of the PCB does have to be bigger in that case.

Product architecture analysed headphones

In Chapter 4, five different headphones are analysed. These are the Sony WH-1000XM5, Bose QuietComfort Ultra, Fairphone Fairbuds XL, Repeat Prince, and AIAIAI TMA-2 Move Wireless. Three of these, the models from Fairphone, Repeat, and AIAIAI, are marketed as more circular options. Table 1 compares the product architecture of these five headphones.

The product architecture of the five headphones is largely similar, especially when it comes to the battery and drivers. However, the circular headphones generally have fewer additional functions that would introduce more complexity. Because of this, they contain fewer electronic components than the more conventional models from Sony and Bose, as they do not require proximity sensor or touch sensors or complex PCBs.

Key takeaways:

- Differences in components and product architecture between headphones are largely due to varying levels of additional functionality.

Figure 1. Headphone architecture: structural components (Sony Group, n.d.-d).

Figure 2. Headphone architecture: electronics.

Table 1. Product architecture of the headphones analysed in Chapter 4 (AIAIAI, n.d.-c; Bose, n.d-a.; Fairphone, n.d.-a; Repeat, n.d.-b; Sony Group, n.d.-c).

	Controls	Battery	Speaker driver	Microphones	PCBs	Additional functions
Sony WH-1000XM5	Touch sensor for playback controls, 2 buttons for noise-cancelling modes and for power and Bluetooth	Single soft pack lithium-ion battery	30mm dynamic drivers	9. of which 2 internal (5 left and 4 right)	7, of which 3 flexible PCBs (3 left and 4 right)	ANC with adaptive modes; Head detection; Spatial audio
Bose QuietComfort Ultra	Touch sensor for playback controls, 2 buttons for noise-cancelling modes and for power and Bluetooth	Single soft pack lithium-ion battery	35mm dynamic drivers	10, of which 2 internal (5 left and 5 right)	9, of which 7 flexible PCBs (5 left and 4 right)	ANC with adaptive modes; Head detection; Spatial audio
Fairphone Fairbuds XL	Joystick for power and playback controls,, and a button for Bluetooth and noise-cancelling modes	Single soft pack lithium-ion battery in a hard case	40mm dynamic drivers	5, of which 2 internal (2 left and 3 right)	6 PCBs (2 left and 5 right)	ANC
Repeat Prince	4 buttons, one for power, Bluetooth, and play/pause; one for noise-cancelling modes, and two for volume and playback controls	Single soft pack lithium-ion battery	40mm dynamic drivers	5, of which 2 internal (3 left and 2 right)	2 (1 left and 1 right)	ANC
AIAIAI TMA-2 Move Wireless	Joystick for power, Bluetooth, and playback controls	Single soft pack lithium-ion battery	40 mm dynamic drivers	2 (2 left and 0 right)	3 PCBs (1 left and 2 right)	-

2.2 Headphone development

Building on the product architecture outlined in the previous chapter, this chapter addresses *RQ1.2 What developments are there for headphones, and how do these affect the product architecture?* Like other small electronics, headphones are continuously evolving as new technologies emerge. To understand the effect of these developments on circularity, it is important to know how these trends shape the design, functionality, and product architecture of headphones. This chapter explores recent developments and their influence on the product architecture.

Developments in headphones mainly focusses on enhancing the listening experience through better sound quality and additional features. This is reflected in the recent trend towards more luxurious headphones, where companies use the additional functionalities to set themselves apart. Recent developments include:

- Improved Active Noise-Cancellation: next to more advanced ANC and transparency modes, which allow external sound to pass through, headphones now often include adaptive ANC that adjusts to the environment.
- Improved wireless technology and connectivity: advancements such as Bluetooth 5.0 have increased connection stability, range, and energy efficiency.
- Spatial audio with dynamic head tracking: also known as 360 or immersive audio, spatial audio creates a 3D sound environment where audio appears to come from all around you rather than the fixed point of your speakers.
- Improved speaker drivers and materials: innovations in driver technology, such as the use of new materials, can enhance sound quality while making the driver thinner and stronger.
- Lossless audio support: lossless audio formats offer higher fidelity sound.

A lot of these advancements make the product more complex, affecting the product architecture. Some features require additional components, such as microphones for ANC, and accelerometers for spatial audio. They can also require more advanced PCBs. Additionally, these added functionalities often drain more battery, which can lead to larger battery packs. These additional, advanced electronics and larger battery packs add weight and impact the internal layout and overall product design.

Key takeaways:

- Technological advancements introduce additional and complex electronic components, leading to a more complex product architecture. → *Key Finding 1*
- Rapid technological advancements bring the risk of headphones becoming 'outdated' before the end of their designed lifetime.

2.3 Conclusion

This section brings together the findings from Chapter 2 to answer *RQ1 How does the product architecture of over-ear wireless headphones affect the product's circularity?*

Headphones typically consist of the same key components, but the exact configuration of these components individually and the product architecture as a whole varies significantly, especially as functionalities increase.

Additionally, headphones are not a static product category. Like other small electronics, they continuously evolve, incorporating new features that enhance the user experience. These developments often involve hardware changes, such as additional components and more advanced PCBs, increasing the complexity of the product. However, these rapid advancements also mean that headphone models are at risk of becoming outdated after just a few years, as new technologies and features emerge.

These increasingly complex products also impact end-of-life recovery. The additional and complex electronics are valuable and contain critical materials, increasing the importance of effective end-of-life recovery of these parts for reuse and recycling.

Key takeaways from this chapter were translated into early idea sketches exploring options such as defined levels of access to internal components and recognising product functions, see Figure 3.

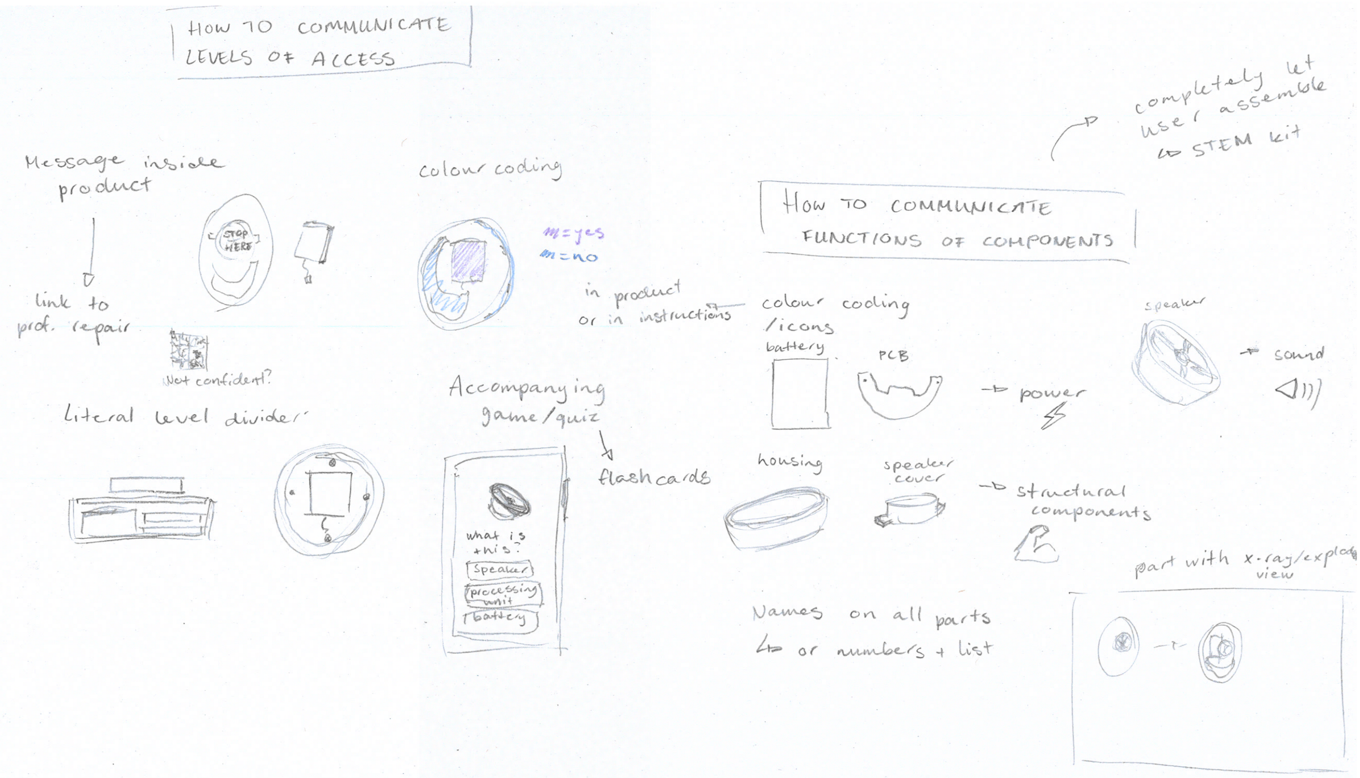


Figure 3. Sketches from early stage idea generation.

3. Circular design

To design a circular product, it is essential to understand the broader system it will operate in. This chapter explores the principles of the circular economy, relevant legislation that could influence future headphone design, and barriers users experience for circular product use.

3.1 Circular economy

This chapter addresses *RQ2.1 What are the key principles of the circular economy, and how do they apply to headphones?* To design a headphone that fits into the circular economy, it is important to understand what the circular economy is and how it differs from the current linear model. This chapter introduces its core principles and visual frameworks.

Our current economy is largely based on a linear system: we extract materials, turn them into products, and eventually discard them. The Ellen MacArthur Foundation (n.d.) calls this the 'take-make-waste system'. In contrast, the circular economy aims to eliminate waste by keeping products and materials in circulation (Ellen MacArthur Foundation, n.d.).

The butterfly diagram, see Figure 4, visualises this continuous flow of resources. Instead of a straight line, it introduces loops that keep resources within the system (Ellen MacArthur Foundation, 2021). It differentiates between two cycles: a biological cycle for biodegradable materials and a technical cycle for products and materials. The technical cycle includes processes such as maintenance, reuse, refurbishment/remanufacturing and recycling to keep products and materials in circulation.

By producing and selling products, we add value to the original resources. However, as soon as the customer uses a product, this value starts decreasing. In a circular economy, the goal is to retain as much of this value for as long as possible (Achterberg et al., 2016). The Value Hill, see Figure 5, shows the same processes as the butterfly model, but adds a clear hierarchy based on their effectiveness in retaining or recapturing value. To keep a product at its highest value and enable 'optimal use', maintenance and repair are the preferred first steps, while recycling is a last resort.

Key takeaways

- To fit in the circular economy, the headphone should be suitable for maintenance, reuse, refurbishment, remanufacturing, or recycling. → *Key Finding 8*
- The product should be able to maintain its highest value for as long as possible, and thus be suitable for maintenance and repair. → *Key Finding 8*

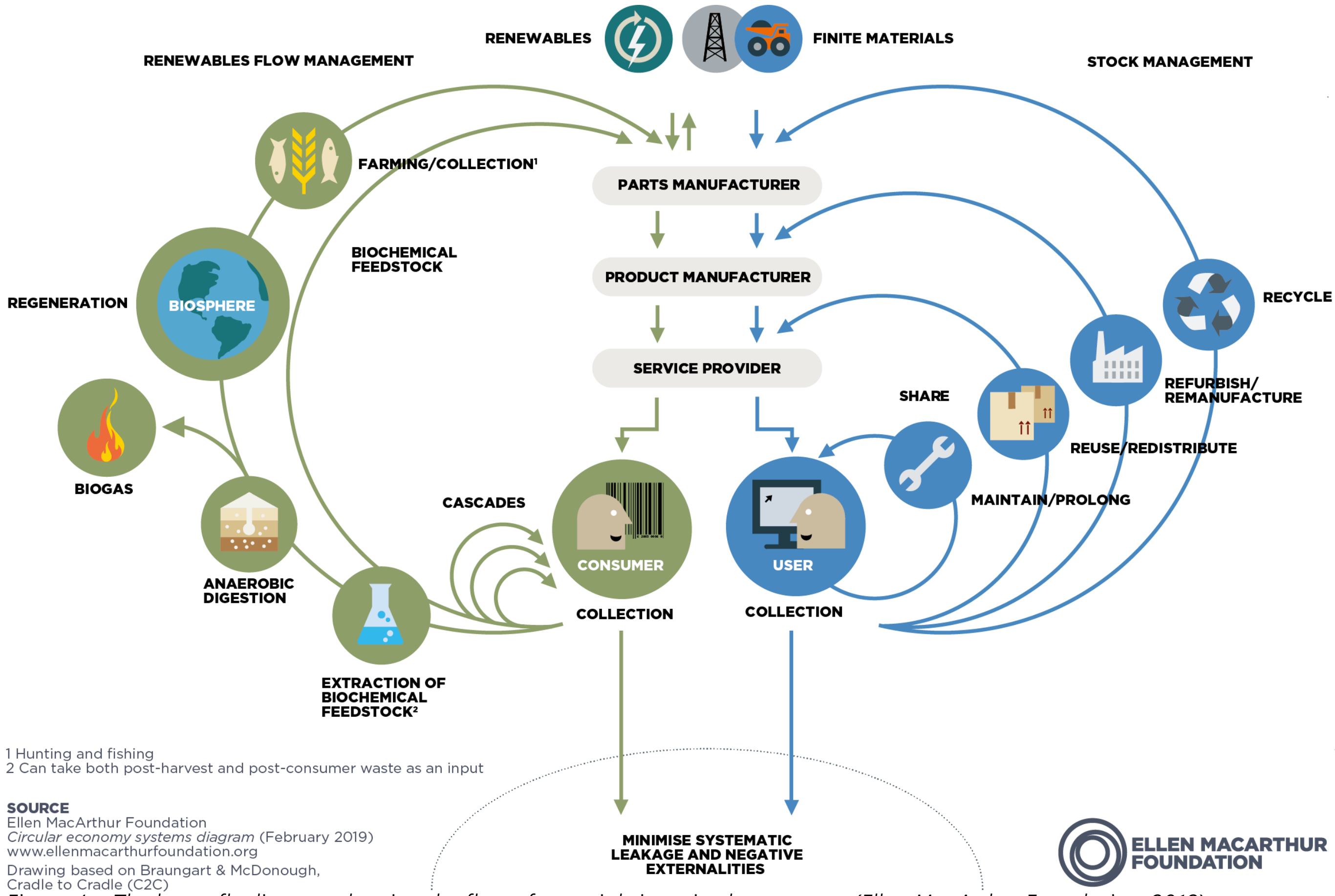


Figure 4. The butterfly diagram showing the flow of materials in a circular economy (Ellen MacArthur Foundation, 2019).

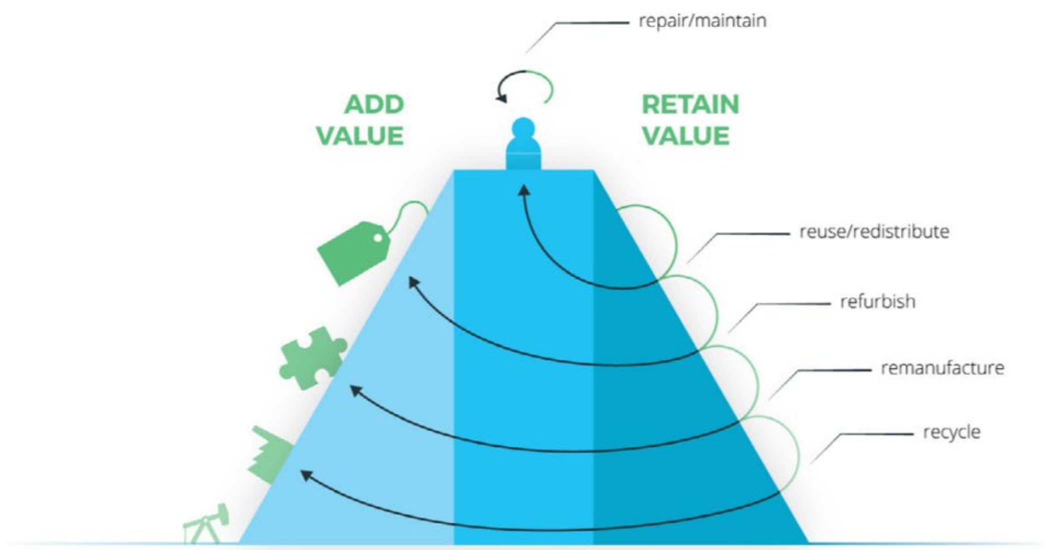


Figure 5. The process of retaining value, as visualised in the Value Hill (Achterberg et al., 2016).

3.2 Legislation

This chapter addresses *RQ2.3 How could existing and upcoming legislations regarding sustainability and circularity affect the design of headphones?* As policy makers and governing bodies introduce new policies to reduce environmental impact, product design is increasingly shaped by legal requirements. An overview of some key EU directives and regulations can be found in Appendix B. This chapter discusses how these key EU directives and regulations could influence the design of over-ear headphones.

One of the most prominent developments in the European Union when it comes to circularity is the Ecodesign for Sustainable Products Regulation (ESPR). The ESPR is part of the European Green Deal and pushes for more circular product design (Regulation 2024/1781). Like many of the other EU directives, the ESPR currently only applies to specific product categories. Headphones are not yet included, and there is no set timeline for when they will be.

However, the regulations and directives emphasise the growing importance of sustainability, including durability, repairability, and recyclability.

For example, Regulation (EU) 2023/1670 on ecodesign requirements for phones and tables includes a requirement — stated in Annex II, point 1.4 of sections A, B, C, and D — that manufacturers must make disassembling information publicly available for the components listed in Annex VII, point 1, of the WEEE Directive (Directive 2012/19/EU). These include batteries and PCBs larger than 10 cm^2, which must be removed from all disposed electronic devices before recycling.

Similar requirements can be found in the regulations for other product groups, and it is likely that they will be applied to other electronic products in the future, including headphones.

Following Regulation (EU) 2023/1670, this could mean the following for the design of headphones:

- Batteries and PCBs larger than 10 cm^2 should be removable for recycling and disassembling information should be publically available
- Fasteners should be removable, replaceable, or reusable
- Battery replacement should be able to be done by a non-expert in a use-environment, with no tools, supplied tools, or basic tools

Key takeaways:

- Recent and upcoming EU regulations and directives emphasise the importance of designing products for durability, repairability, and recyclability.
- Sony could benefit from playing into future regulations by:
  - Providing easily accessible repair information.
  - Improving the availability and accessibility of spare parts.
  - Giving consumers the ability to repair key components or have them repaired.
  - Avoiding hardware techniques that could hinder the repair or recycling of the headphones.

3.3 User barriers

This chapter addresses *RQ2.4 What are the barriers users face regarding circular use of their products?* While product design and legislation play an important role in promoting circularity, it is ultimately users who determine whether a product stays in use and retains its value. They are responsible for care, maintenance, repair, and proper end-of-life steps. To design a headphone that truly supports circular behaviour, it is important to understand why users do or do not engage in this behaviour. This chapter explores the user perspective on circularity through existing literature, identifying the main barriers to circular behaviour.

One of the most widely recognised barriers is a lack of information. Users are often unaware of how products work, what components they consist of, and repair possibilities (Sonego et al., 2022). The absence of repair manuals or guidance contributes to this, leaving users unsure about how to diagnose errors, perform a repair themselves, where to find a repair service, or even leaving them to believe a product is irreparable.

> *"As the consumers are "in the dark" considering the product architecture, they could fail to make simple and quick repairs due to the lack of information"*
> (Sonego et al., 2022, p.560)

Roskladka et al. (2023) found that this lack of clarity about how repair works is a key barrier to not only the technical possibility of repair, but also users' willingness to repair. However, according to their research, the most important barrier related to users' willingness to repair is that many users simply lack repair habits or awareness of its impact. Without this awareness, users are less motivated to act, even when repair is technically possible. Sonego et al. (2022) note that many electronic products are stored away while they are still functional, indicating a deeper behavioural issue rather than absolute technical obsolescence.

Arcos et al. (2021) emphasise that a product's design should enable the user to understand its' condition, construction, and function, i.e. to 'read' the product. One of the proposed design guidelines is to "facilitate navigating through the product's construction. For instance by arranging components at the same disassembly level and making their relationship visible." (Arcos et al., 2021, p. 13). Many of the design features they identify as either facilitating or hampering the diagnosis process are related to this type of product clarity: helping users understand their product's construction, identify components, and understand their function and the working mechanism of the products as a whole.

Without these types of guiding features, users are left with guesswork and frustration. Arcos et al. (2021) found that the most common source of frustration was the difficulty of disassembly, especially opening up the product's housing, which often led to participants giving up on fault diagnosis and repair. While clear information and guidance are ideal, the study showed that, in their absence, visibility and accessibility of internal components can still make diagnosis achievable. Participants relied on being able to visually trace component relationships to understand how the product worked. This once again highlights how important it is for users to understand their products. Not just to use them, but to care for them, diagnose them, and repair them.

Key takeaways

- Many users simply do not consider repair as a possibility because they lack the habit of repairing things or are unaware of its impact. So it's not just about technical feasibility, but also about informing and motivating users.
- Products are often perceived as a 'black box': users do not know how they work, what components are inside, or whether they are even repairable. This uncertainty creates a psychological barrier that discourages users from attempting repairs. → *Key Finding 7*
- A lack of accessible information, such as repair manuals or clear guidance, prevents users from diagnosing faults and performing simple repairs or finding repair services. It can even make them believe a product is irreparable.
- Design can play a role in removing these barriers. Features that guide users through their product can turn a confusing and overwhelming product into an understandable one. Examples include visible relationships between components, visible seams and fasteners, and visually distinct components. → *Key Finding 7*

3.4 Conclusion

This section bring together the findings from Chapter 3 to answer *RQ2 How can over-ear wireless headphones be designed for the circular economy?*

Circular economy frameworks stress that the most value is retained when products are kept in use for as long as possible. Legislation increasingly pushes manufacturers to support these longer lifespans and enable better repairability and responsible end-of-life handling. However, it is the behaviour or users that ultimately determines whether this circular potential is realised. A product might be suitable for the circular economy in theory, but if users don't know how to engage with it, or don't feel motivated to, it's unlikely to stay in use.

Together, these findings indicate that designing for the circular economy requires a multifaceted approach that prioritises clarity, accessibility, and long-term usability. For users, this means a product should be understandable, navigable and approachable: they should be able to identify components, understand how they work together, and feel confident maintaining or repairing their product when needed.

Key takeaways from this chapter were translated into early idea sketches exploring options such as encouraging maintenance and care, and personalisation, see Figure 6.

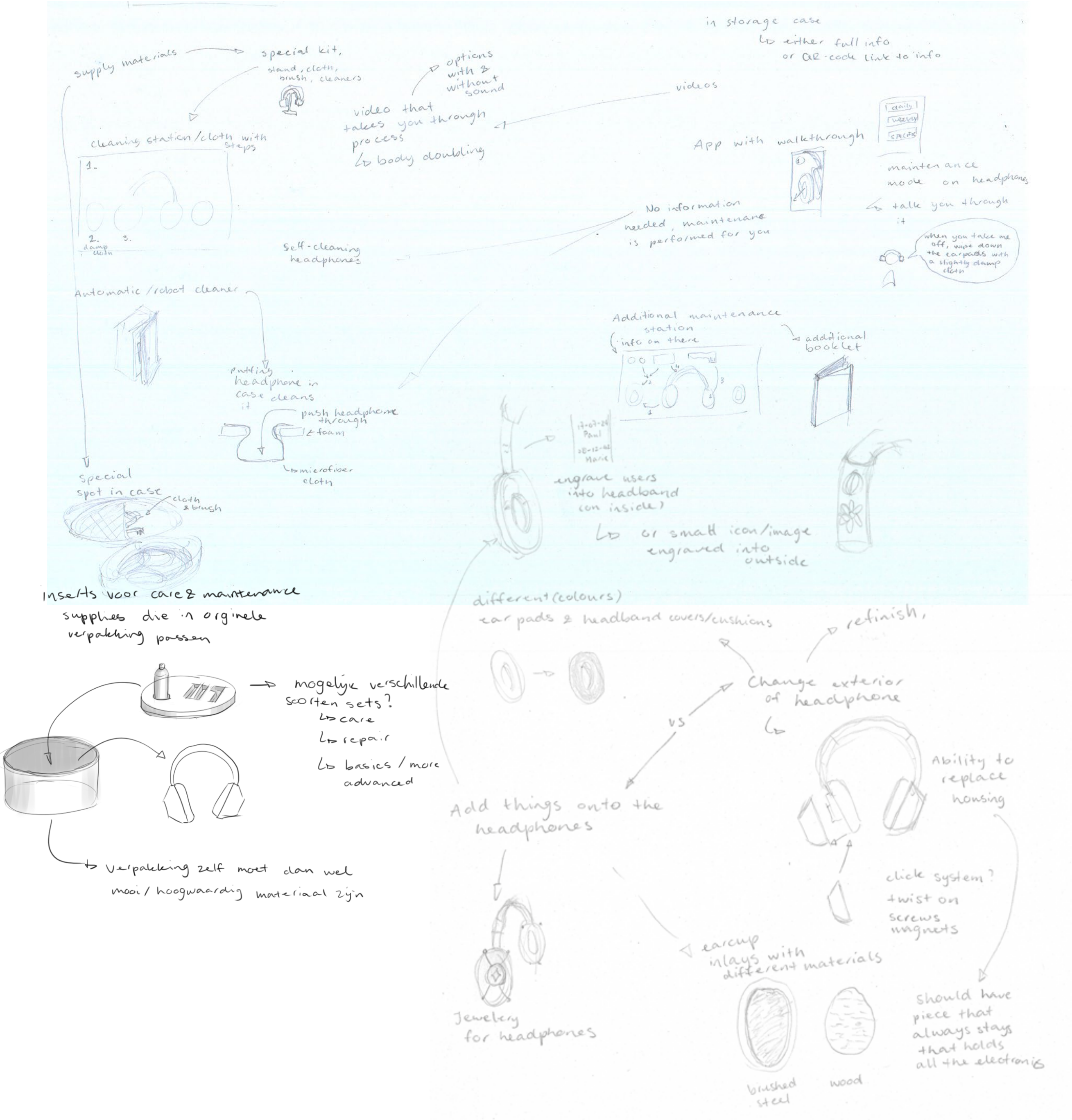


Figure 6. Sketches from early stage idea generation related to the key takeaways of Chapter 3.

4. Assessment of current headphones

To define what a more circular headphone could look like, it is important to understand how current headphones perform. This chapter analyses five existing headphones, three marketed as sustainable and two conventional. The goal is to identify the design decisions that either support or hinder circularity.

4.1 Ease of disassembly

This chapter addresses *RQ3.1 What are the critical components that should be easily accessible for repair and reuse or recycling?* and *RQ3.2 How easily can current headphones be disassembled, and what features influence this?* To support repair, reuse, and recycling, it is important to identify the most critical components and determine how easily they can be reached.

Five different headphone models were disassembled and analysed to assess the ease of disassembly and the features that affect it, three of which are specifically marketed as sustainable. Each headphone was dismantled into its individual components as far as possible, even if this meant undoing irreversible connections or taking destructive steps. The disassembly process was recorded from above using a DSLR camera mounted on a tripod with a visible stopwatch to track the disassembly time. These videos were used as a reference for further analysis.

Hotspot Mapping was used to identify the critical parts and activities in the Sony WH-1000XM5, following the method described by Flipsen et al. (2020). Disassembly Maps were then used to visualise the disassembly process and the path to the critical parts for each model (De Fazio et al., 2021). These maps form the basis for analysing disassembly depth and penalties. Disassembly time and specific features impacting the ease of disassembly were assessed based on the disassembly process itself and video recordings.

4.1.1 Hotspot analysis

Hotspot Mapping identifies the parts in your product that are most valuable or important to reach, and how difficult it is to reach them. This doesn't just include priority parts, but also valuable parts that have a high economic or environmental value. The excel-based hotspot mapping tool flags the activities or parts that need attention. These hotspots are divided into five hotspot indicators. Three critical part indicators, priority part, environmental, and economic and two critical activities indicators, time and activity. These critical activities should be optimised, and critical parts should be easy to reach.

Hotspot Mapping has only been done for the Sony WH-1000XM5 headphones. The full Hotspot Map can be found in Appendix B. Additional information about the overall results and the critical activities can be found in Appendix D.

Table 2. Sony WH-1000XM5 parts flagged with a yellow or red critical part indicator in the Hotspot Map.

Part name	*Priority Part Hotspot*	*Environmental Hotspot*	*Economic Hotspot*
Ear pads		X	X
Ear cup shells		X	X
Battery	X	X	X
Power PCB		X	X
Right NC microphone PCB		X	X
USB-C PCB	X	X	X
Speaker drivers	X	X	X
Earcup base		X	X
Main PCB		X	X
AUX PCB	X	X	X
Left NC microphone PCB		X	X
Earcup arms (hinges)	X	X	X
Headband cable	X	X	X

Critical parts

There are several parts with all three critical part indicators. These parts have a high maintenance or failure rate and/or a high functional relevancy (Priority Part Hotspot), are made from materials with a high environmental burden (Environmental Hotspot), and with a high economic value (Economic Hotspot).

Repair data on 446 (attempted) headphone repairs from 2017 to Q1 of 2024 from Repair Cafes worldwide was used to determine the level of maintenance of parts (RepairMonitor, 2024). The analysed data is shown in Appendix E.

Table 2 gives an overview of all Sony WH-1000XM5 parts with multiple hotspot indicators.

Critical activities

Several steps have with both critical activity indicators, meaning they take a long time (Time Hotspot) and require a non-standard tool, a lot of force and/or precision, and/or the part is hard to access (Activity Hotspot). Table 3 lists these critical activities and the attributes that contribute to their difficulty. For steps involving earcup components, the task frequency and time reflect the total for both the left and right earcup. If the force, accessibility, or positioning differed between left and right, the table includes the higher value.

This overview highlights that de-soldering, de-glueing, and hidden snap fits or other concealed connectors strongly affect the ease of disassembly. So does the need for precise positioning.

Key takeaways

- Several components score high on all three critical part indicators, including the battery, speaker drivers, PCBs (especially those with charging ports), hinge components, and the headband cable. These parts should be made easily accessible to extend the life of the headphones and increase the chance of valuable end-of-life recovery. → *Key Finding 3*
- Critical activities for the Sony WH-1000XM5 often involve de-soldering, de-glueing, high precision due to limited space, or hidden connectors. → *Key Finding 5 & Key Finding 6*

Table 3. Critical activities of the Sony WH-1000XM5 headphones.

Step	*Time Hotspot*	*Activity Hotspot*	*Task frequency*	*Time*	*Force*	*Visibility*	*Positioning*
De-glueing NC microphones	X	X	7	228	High	Clear	High
De-glueing NC microphone housing	X	X	7	266	Moderate	Clear	High
De-glueing the speaker covers	X	X	2	107	High	Recessed	High
Removing the power button	X	X	1	24	Light	Clear	High
Disconnecting the snap fits of the headband cover clamps	X	X	8	26	Moderate	Obstructed	High
De-glueing the headband cover	X	X	4	119	Moderate	Obstructed	Moderate
Removing/peeling off the headband cover	X	X	1	107	High	Clear	Moderate
Unscrewing the headband slider covers	X	X	4	26	Light	Obstructed	Moderate
Disconnecting the snap fits of the headband slider covers	X	X	6	24	Moderate	Obstructed	Moderate

4.1.2 Disassembly Map

A Disassembly Map can be seen as a visual representation of the Hotspot Map. It visualises where critical parts are situated in the product architecture, and how many steps are needed to reach them. Disassembly Maps can help determine what parts and activities harm the recovery of critical parts (De Fazio et al., 2021). The critical parts can be recognised by the target indicator icons, while critical activities are highlighted by penalty icons , see Figure 7 and Figure 8, or the colour of the step indicating a high force. Additionally, a Disassembly Map helps determine the disassembly depth of components. In this case, the disassembly depth increases by one whenever a part is removed or a tool is changed.

Figure 11 on the next page shows the disassembly map of the Sony WH-1000XM5 headphones. The disassembly maps of the analysed competitor headphones can be found in Appendix F.

Disassembly depth

The Sony WH-1000XM5 required the most steps for disassembly, with only Bose requiring a similar number of steps, see Figure 9. Its maximum disassembly depth was more than double that of other headphones, performing particularly poorly on headband components such as the hinges and cable compared to the competitors, see Figure 10.

This high disassembly depth isn't just caused by Sony containing 1.5 times as many parts, it is also because of the headphones' sequential and interdependent vertical disassembly structure. As illustrated in the disassembly map in Figure 11, many tasks must be performed in a specific sequence to access parts. While some steps are possible in parallel, the disassembly map reveals multiple points where parts are dependent on the removal of earlier ones, indicated by the "&" symbols.

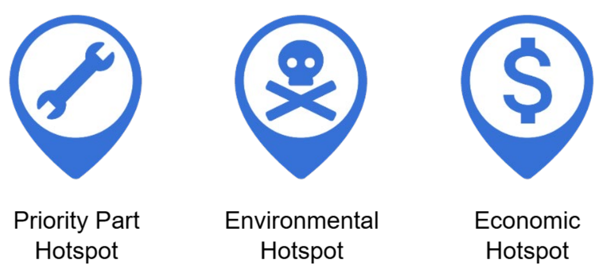


Figure 7. Target parts for recognising critical parts in the Disassembly Map.

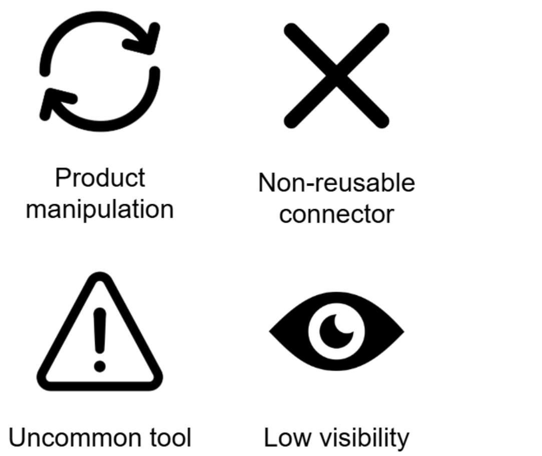


Figure 8. Penalty indicators for recognising critical activities in the Disassembly Map.

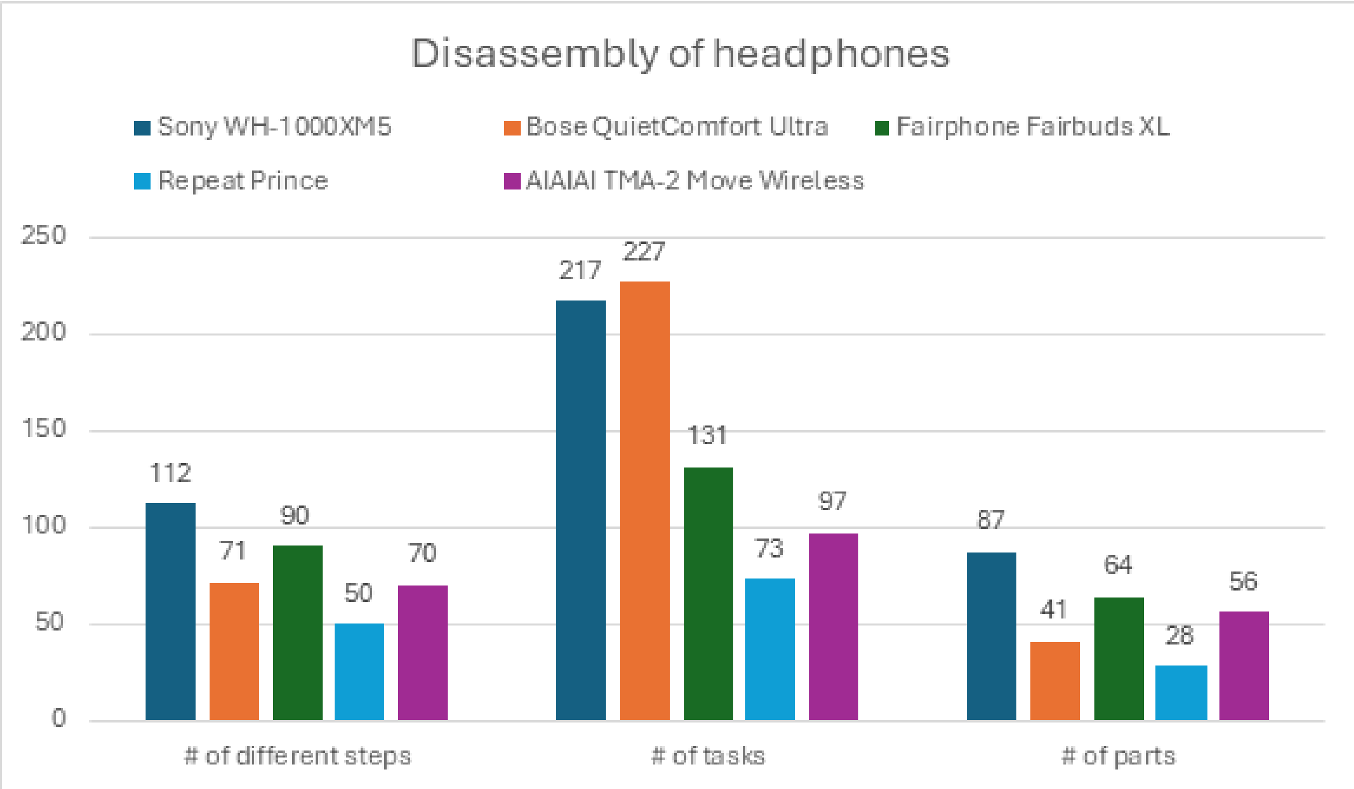


Figure 9. Number of steps, tasks, parts, and maximum disassembly depth.

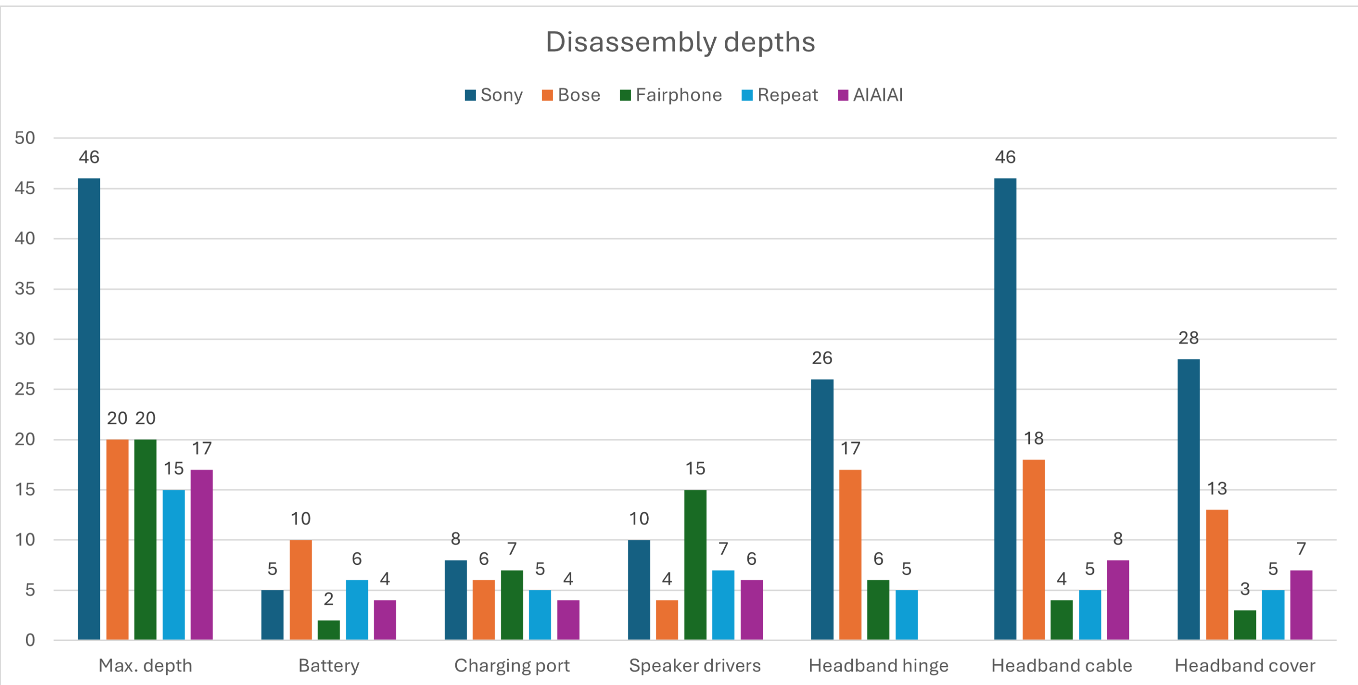


Figure 10. Overview of the disassembly depth of critical parts.

1. Left ear cushion
2. Right ear cushion
3. Left foam insert
4. Right foam insert
5. Left earcup shell
6. Microphone cover
7. Silicone cable plug
8. Left speaker microphone
9. Proximity sensor
10. Main PCB
11. Left housing shield seal
12. Cable gasket (grey)
13. Left housing shield
14. AUX PCB
15. Left LED diffuser
16. Button padding
17. Power button
18. NC button
19. Left speaker cover
20. Left speaker driver
21. Left speaker seal
22. Left speaker shell
23. Silicone NC PCB stopper
24. Felt NC PCB cover
25. NC microphone housing
26. Left NC microphone PCB
27. Right earcup shell
28. Touch sensor
29. Right speaker microphone
30. Fabric battery tape
31. Battery
32. Power PCB
33. Thermal padding
34. Right housing shield seal
35. Cable gasket (blue)
36. Right housing shield
37. USB-C PCB
38. Right LED diffuser
39. Right speaker cover
40. Right speaker driver
41. Right speaker seal
42. Right speaker shell
43. Right NC microphone PCB
44. Headband arm clip
45. Headband cable cover
46. Left headband cover clamp
47. Right headband cover clamp
48. Headband cover
49. Headband slider outside cover
50. Headband slider inside cover
51. Left earcup arm
52. Right earcup arm
53. Headband cable clamp
54. Headband slider sticker
55. Headband cable
56. Headband cushion
57. Headband cable guide
58. Headband metal wire
59. Earcup arm O-ring
60. Foam headband topper

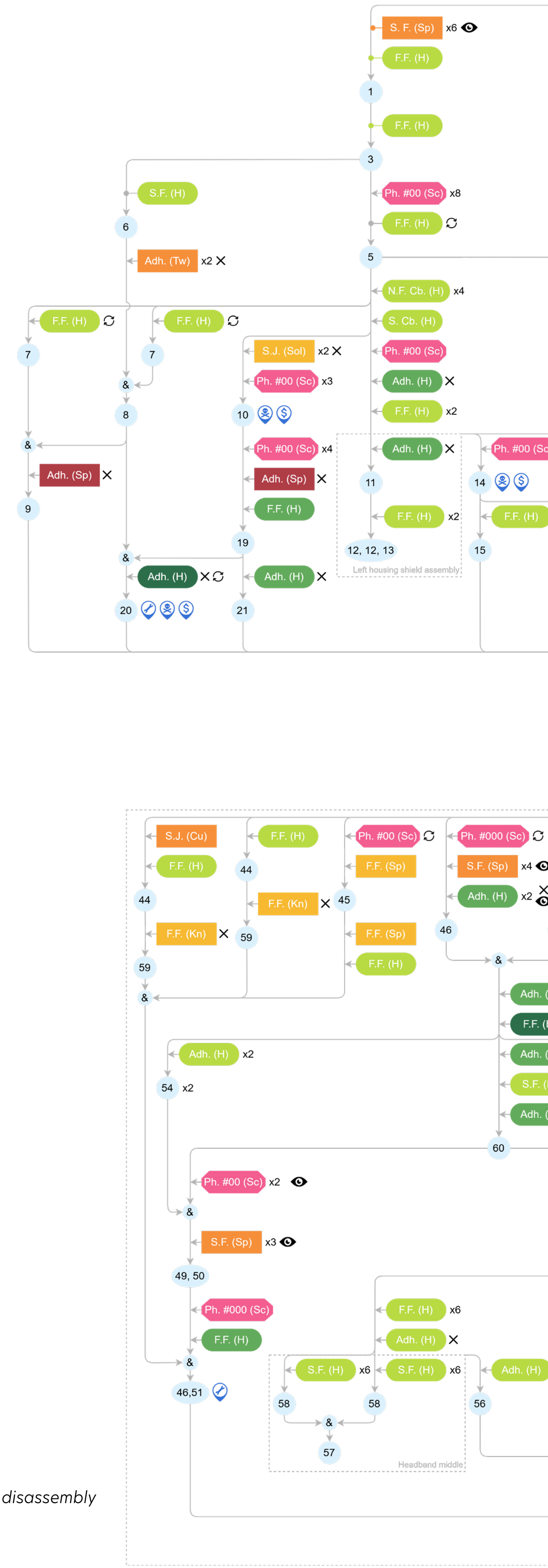
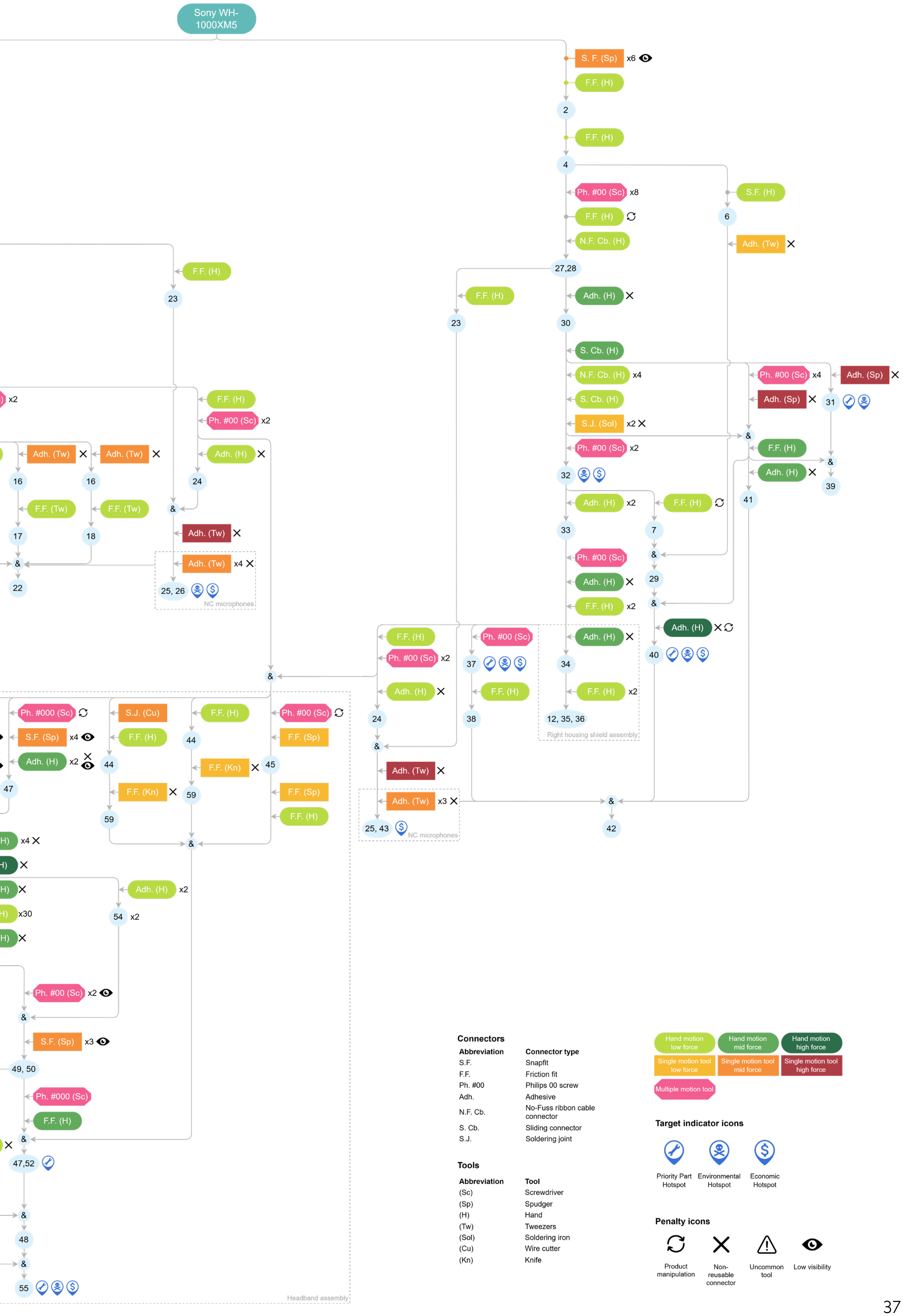


Figure 11. Disassembly map of the Sony WH-1000XM5 headphones. The disassembly maps of the competitors can be found in Appendix F


Sony WH-1000XM5
NC microphones
Right housing shield assembly
Headband assembly
Connectors
Abbreviation
Connector type
S.F.
Snapfit
F.F.
Friction fit
Ph. #00
Philips 00 screw
Adh.
Adhesive
N.F. Cb.
No-Fuss ribbon cable connector
S. Cb.
Sliding connector
S.J.
Soldering joint
Tools
Abbreviation
Tool
(Sc)
Screwdriver
(Sp)
Spudger
(H)
Hand
(Tw)
Tweezers
(Sol)
Soldering iron
(Cu)
Wire cutter
(Kn)
Knife
Hand motion low force
Hand motion mid force
Hand motion high force
Single motion tool low force
Single motion tool mid force
Single motion tool high force
Multiple motion tool
Target indicator icons
Priority Part Hotspot
Environmental Hotspot
Economic Hotspot
Penalty icons
Product manipulation
Non-reusable connector
Uncommon tool
Low visibility

To highlight the impact of Sony's sequential and interdependent disassembly structure, Table 4 compares the disassembly depth of critical parts and the number of steps needed to reach them between Sony and Fairphone, which has a more horizontal and sequence-independent disassembly structure. The percentage of total steps needed to reach a part is included to provide a better comparison of accessibility.

To reach the deepest part of the Sony headphones (the headband cable), 66% of all disassembly steps must be performed. In comparison, reaching the deepest component in the Fairphone headphones (the left speaker driver) only requires 22% of the total steps.

Figure 12 shows the path to the deepest critical component for both headphones. The path through Fairphone's disassembly map is fairly straightforward, while the path through Sony's disassembly map involves a lot of loops and dependencies, making disassembly more complex and time-consuming. These significant difference highlights the impact of the disassembly structure and product build-up on the ease of disassembly.

Table 4. Comparison between Sony and Fairphone

Part	Depth		# of steps		% of total steps	
	Sony	Fairphone	Sony	Fairphone	Sony	Fairphone
Battery	5	2	9	2	8.0	2.2
Charging port	8	7	17	12	15.2	13.3
Speaker driver	10	15	19	20	17.0	22.2
Headband hinge	26	6	56	10	50	11.1
Headband cable	46	4	74	6	66.1	6.7
Headband cover	28	3	59	5	52.7	5.6

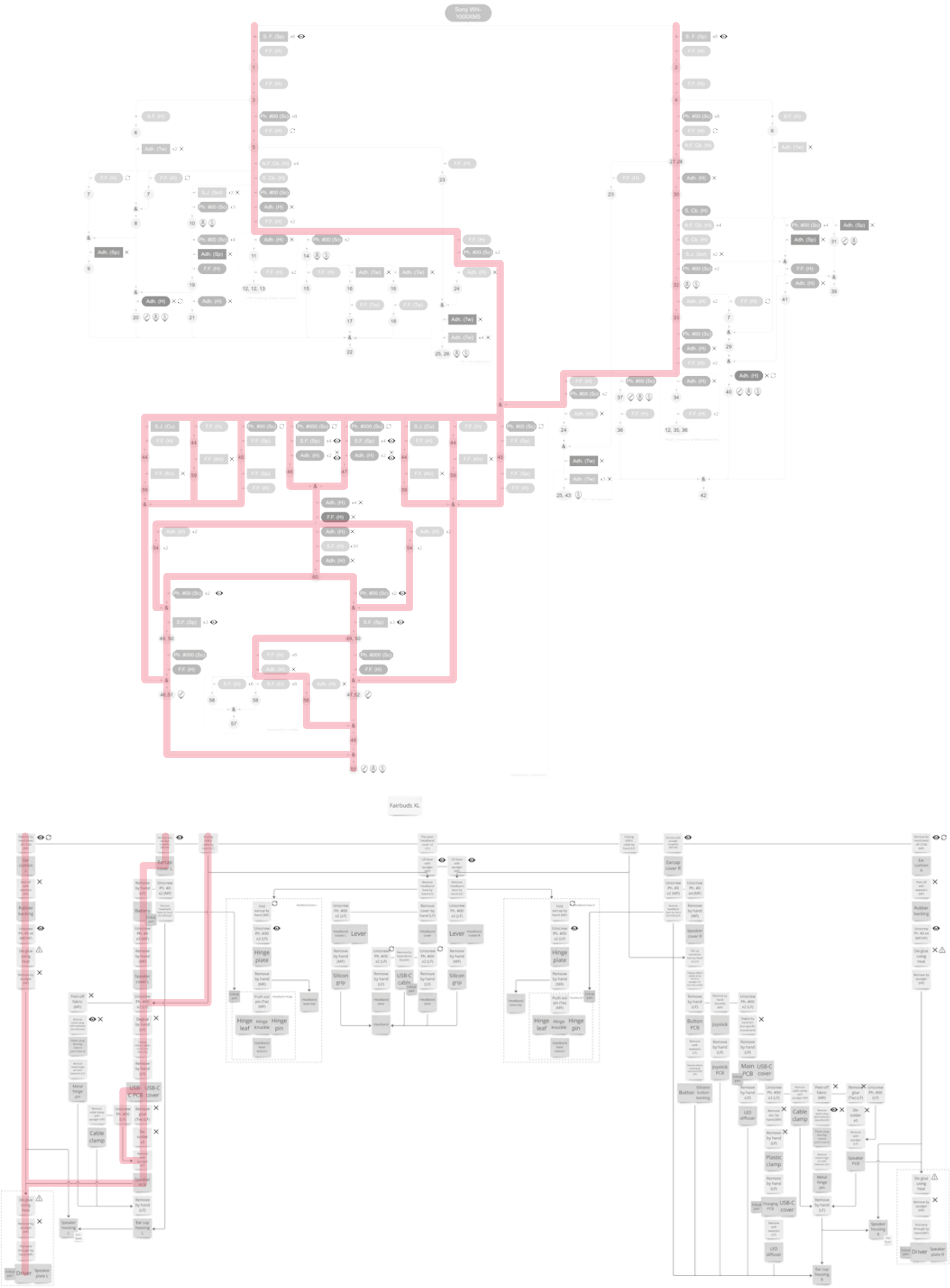


Figure 12. Paths to the deepest parts in the disassembly maps of Sony WH-1000XM5 (above) and Fairphone Fairbuds XL (below).

Penalties

The penalties in the Disassembly Map highlight critical activities that negatively affect the ease of disassembly (De Fazio et al., 2021). These includes product manipulation, such as flipping the product, low visibility or identifiability of fasteners, the use of uncommon tools, defined as any tool not listed in the standard NEN-EN 45554:2020 (2020), non-reusable connectors, and the need for a high amount of force. Figure 13 shows the penalties for all five headphones.

Sony received significantly more penalties than the others, 67 total, with the majority being from non-reusable connectors. This is mainly due to the high amount of glue and adhesive used throughout the headphones, as discussed in Section 4.1.1 on Hotspot analysis.

Sony is the only pair of headphones that does not require uncommon tools for the disassembly. This is because all other headphones required the use of a heat gun or other heated tool to soften strong adhesives used for the driver.

Key takeaways

- Critical parts are often hard to reach. For Sony, only the earpads and battery can be reached in ≤ 5 disassembly steps. The hinge, headband cable, and headband cover/padding require more than 10 steps to reach. While the three sustainable brands perform better, half of their critical parts are not accessible within 5 steps. → *Key Finding 3*
- The ease of disassembly is heavily influenced by a sequential disassembly structure and multiple dependencies in the disassembly process. A sequence independent disassembly structure, on the other hand, reduces the maximum disassembly depth and improves access to critical components. → *Key Finding 4*
- The maximum disassembly depth of the Sony WH-1000XM5 headphones is very high at 46. To align with competitor headphones, the maximum disassembly depth should be 20 or lower. → *Key Finding 4*
- Almost half of the penalties in the disassembly maps (112 out of 234) were for the use of non-reusable connectors. A large amount of this were adhesives. → *Key Finding 5*
- The only uncommon tools used were circlip pliers (once) and a heated tool (twelve times). The heated tool was used to soften strong adhesives used for the driver housing, driver, and/or battery. → *Key Finding 5*

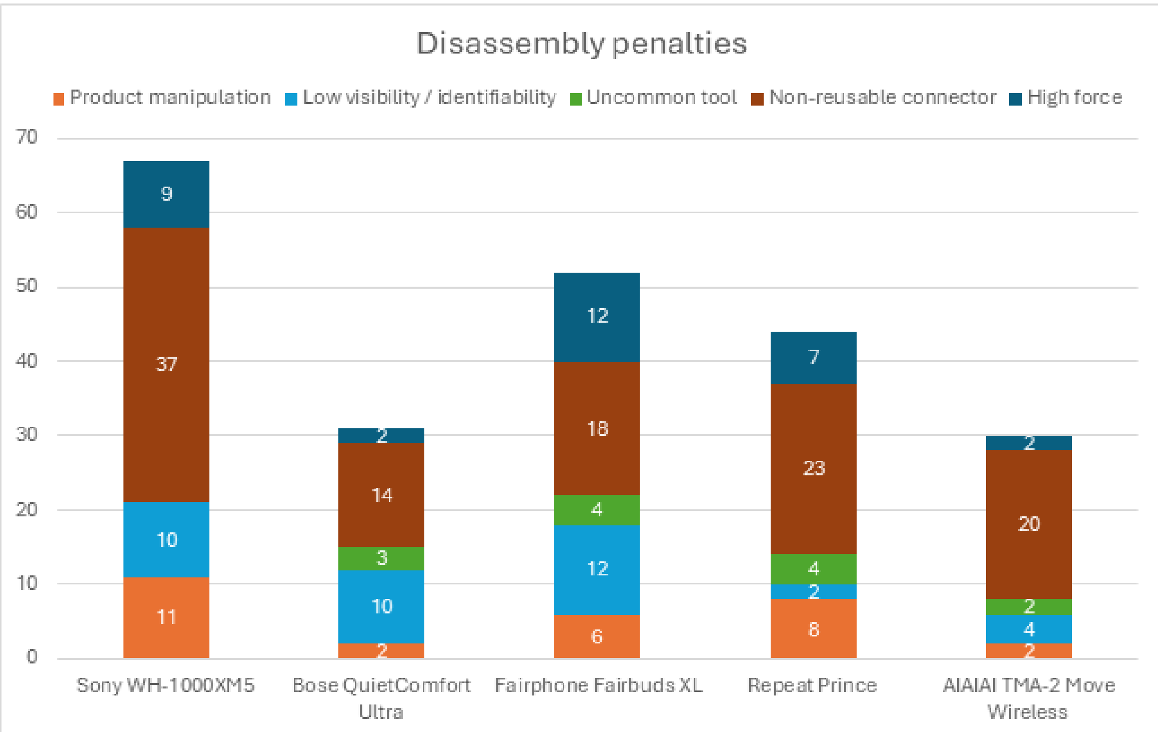


Figure 13. Penalties of the five analysed headphones.

4.1.3 Disassembly time

The disassembly times are based on the recordings of the gentle dismantles of the five headphones and later supplemented by steps that required desoldering, the use of heat to soften glue, or other destructive steps. Figure 14 shows the disassembly times, with AIAIAI being the fastest at 40 minutes and Bose and Fairphone taking the longest at approximately 75 minutes.

Bose's high disassembly time is largely due to the high number of solder joints (43 in total) and the strong adhesive used for the battery, and the drivers and their housing, as these require tools that need to heat up before you're able to use them.

Fairphone's long disassembly time is mainly due to the difficulty of disassembling the hinge in the earcups and getting to and de-glueing the drivers.

Sony falls in the middle with a disassembly time of 58.5 minutes. However, it's important to note that due to the sequential and interdependent nature of Sony's Disassembly Map, nearly the full disassembly time is required to reach the deepest component, the headband cable, meaning that even simple repairs may take a long time.

In contrast, the other headphones have a more sequence-independent and horizontal Disassembly Map structure, with a maximum disassembly depth half that of Sony. This means that in real life scenarios the actual disassembly time for Bose, Fairphone, Repeat, and AIAIAI will often be significantly shorter than the total times shown in Figure 14, as most repairs typically involve replacing only one or a few components rather than fully disassembling the headphones.

Key takeaways

- The longest disassembly times, from Bose and Sony, are a result of the use of strong adhesives and many soldering joints, as these require heated tools. → *Key Finding 5*
- A long total disassembly time does not necessarily mean individual repairs will take long. However, in products with many sequential dependencies, a large portion of the full disassembly must be performed even for minor repairs, significantly increasing repair time. → *Key Finding 4*

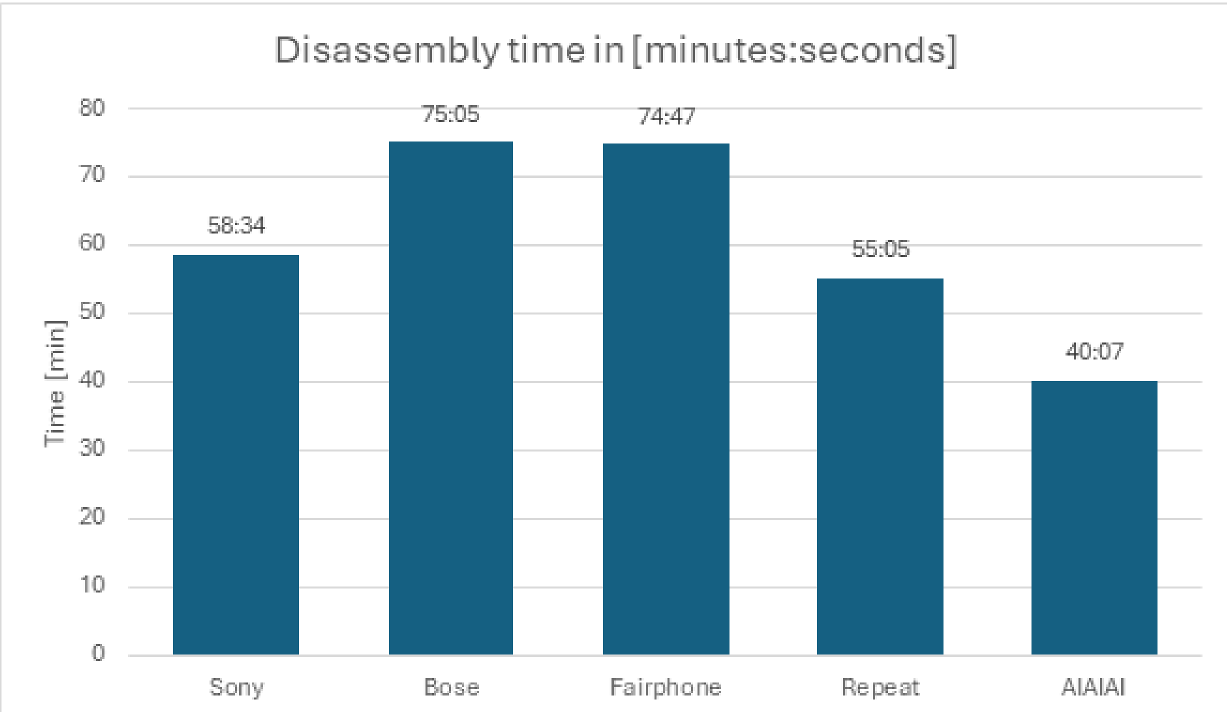


Figure 14. Disassembly times of the analysed headphones in [minutes:seconds].

4.1.4 Features affecting ease of disassembly

By now, it is clear that various design choices, such as the use of adhesives, fastener types, and internal layout, directly influence the ease of disassembly. To optimise a design for disassembly, it is important to pinpoint the specific features that either hinder or facilitate the process.

Table 5 provides an overview of the key features that influence the ease disassembly, focussing on those with significant differences between the analysed headphones, and highlights the specific design choices in each headphone model that impact this either positively or negatively.

Key takeaways

- Every single headphone contained multiple features that negatively affect the ease of disassembly. → *Key Finding 6*
- The internal layout of a headphone has a strong effect on how easily critical parts can be reached. Stacked components make disassembly more difficult, especially if the critical parts are located at the bottom of the stack. → *Key Finding 4*
- The use of adhesives was widespread across many models, often requiring heat or force for removal. Headphones that used reversible alternatives like snap fits or friction fits were noticeably easier to disassemble and reassemble. → *Key Finding 5*
- Using the same screws to fasten multiple components helps reduce unnecessary steps and makes disassembly easier. → *Key Finding 6*
- The way earpads are attached matters: friction-fit mechanisms enable easy removal without damaging components, unlike snap fits that can break. → *Key Finding 6*
- Hidden connectors, when unlabelled or not visually indicated, make disassembly more confusing and prone to error. → *Key Finding 6*
- Soldered cables complicate disassembly and reassembly. Using connectors instead enables quicker, tool-free replacements.

4.1.5 Conclusion

This section answers *RQ3.1 What are the critical components that should be easily accessible for repair and reuse or recycling?* and *RQ3.2 How easily can current headphones be disassembled, and what features influence this?*

The hotspot analysis revealed that the battery, speaker drivers, PCBs, specifically those with the charging port, the headband hinges, and the headband cable are especially important to make accessible. These parts are prone to failure or essential to the functioning of the product, and have a high environmental and economic value. However, across all models, many of these components are difficult to reach.

In addition to the accessibility of critical components, the overall disassembly structure strongly influences the ease of disassembly. Headphones with a sequential and interdependent disassembly structure require more steps to reach critical components. In contrast, more horizontal and sequence independent structures make targeted disassembly easier and faster.

Across the models, common barriers include adhesives, soldered connections, hidden or obstructed fasteners, and complex internal layouts. These make disassembly more complicated and time-consuming, and can discourage users from even attempting disassembly. Even in headphones marketed as sustainable, such features limited deeper repair or recovery of internal components. This can be explained by the fact that they follow a modular design approach, where individual modules can be replaced easily, but the modules themselves are not intended to be disassembled by users.

The Sony WH-1000XM5 consistently performed poorly compared to the other analysed models. It has the highest disassembly depth, the most disassembly penalties, specifically non-reusable connectors, and the most features that negatively impact the ease of disassembly.

Table 5. Features affecting the ease of disassembly.

	Sony	*Bose*	*Fairphone*	*Repeat*	*AIAIAI*
Stacking of components	✗ All components inside the earcup are layered on top of each other, with the driver at the bottom ✗ Additional structural components to support the stacked layout	✓ Spacious layout, utilises walls of the earcup ✓ All components except battery reachable when opening the earcup	✗ Modular layout requires additional housing → more stacking ✗ Components inside earcups are all stacked on top of each other ✓ Modules themselves are quick & easy to access		✗ Earcups involve a lot of stacking ✓ All electronics are at the top. Components placed at the bottom are not likely to need repairs
Use of glue	✗ Glue used throughout the entire headphone	✓ No glue in the headband, instead mainly uses snap fits ✗ Strong adhesive for the battery & drivers required an uncommon tool	✗ Largest amount of glue, driver housing completely glued shut ✗ Glue on most PCBs. ✗ Strong adhesive for the speaker housing & drivers required an uncommon tool ✓ Battery clicks into place instead of being glued ✓ No glue in the headband	✗ Strong adhesive for the battery & drivers required an uncommon tool	✓ No glue used for microphone attachment, instead uses silicon sleeves to keep them in place. ✗ Strong adhesive for the drivers required an uncommon tool
Number and type of fasteners	✗ High number of screws, 48 in total ✗ 8 screws used to attach the earcup housing	✓ Big PCBs kept in place by one or two screws and one screw used for the housing. ✗ High number of screws, 38 total ✗ Uses two retaining rings, which require a specialised tool to remove	✗ High number of screws, 39 total ✓ Smaller PCBs slot into place without any fasteners	✓ Least amount of screws, only 12 ✓ Only 4 bolts & nuts used to attach the earcup shell to the base, which also keep the PCB in place	✓ Uses very few fasteners, instead uses a lot of friction & form fits. (Only 22 screws) ✓ Smaller PCBs slot into place without any fasteners
Hidden fasteners	✗ Hidden snap fits in earpads and headband, which are easy to break off due to incorrect handling or excessive force	✗ Hidden snap fits in earpads and headband	✗ Hidden screws concealed by foam sticker to reach driver	✓ Only hidden connector is the twist mechanism of the ear pads	
Cable connecting the earcups	✗ Large connectors prevent cable removal without cutting and hinder disassembly of the headband	✓ Easy access to cable, as headband padding uses snap fits. ✗ Uses 20 solder joints on each side to connect cable to PCB	✓ Cable can be unplugged without opening earcups ✓ Cable slots into headband using two silicon stoppers on the cable ✓ Possible to replace just the cable	✗ Cable glued onto headband padding ✓ Cable can be unplugged without opening earcups	✗ Cable glued onto headband padding ✓ Cable can be unplugged without opening earcups
Attachment method for earpads	✗ Hidden snap fits	✗ Hidden snap fits	✓ Twist off mechanism	✓ Twist off mechanism ✗ Unclear which direction to twist ✗ Tight tolerances require high force	✓ Friction fit design, earpads can be pulled off without the need of significant force
Manufacturer support	✗ No disassembly guided	✗ No disassembly guided	+- Guides to disassemble into modules	+- Guides to disassemble into modules	✓ Detailed repair guides beyond basic module separation

4.2 Circular design principles

This chapter addresses RQ3.3 What circular design principles are currently used in headphones? While the previous chapter focused just on ease of disassembly, this chapter explores how other circular design principles are embedded in the design of existing headphones.

To answer this, five headphone models were analysed, three of which - the Fairphone Fairbuds XL, Repeat Prince, and AIAIAI TMA-2 Move Wireless - are marketed as sustainable alternatives. These brands actively incorporate strategies aimed at reducing the environmental impact and extending the lifespan of products.

This chapter evaluates how these five companies apply circular design strategies to prolong the life of their headphones. Additionally, it reflects on circularity in their business practices, such as take-back programs, repair services, and economic models. The analysis focuses not just on identifying circular features, but also on critically assessing the choices each company made and what they left out.

4.2.1 Circular product design strategies

The design strategies used to analyse the headphones are the six circular product design strategies aimed at prolonging the life span of a product outlined in Products that Last by Bakker et al. (2014). An explanation of these strategies can be found in Appendix G.

Design for Attachment and Trust

AIAIAI's fully modular design allows users to customise sound quality, comfort, and functionality, offering a high degree of personalisation. Users can select speaker units, earpads, headbands, cables, and accessories to create a personalised headphone that aligns with their needs, see Figure 15.

Both Repeat and AIAIAI make users assemble the headphones themselves before use. This could lead to the IKEA effect, where people value products more when they've built or assembled them themselves (Norton et al., 2012). The

Table 6. Application of circular strategies in the analysed headphones.

	Attachment and Trust	*Durability*	*Standardisation and Compatibility*	*Ease of Maintenance and Repair*
Sony WH-1000XM5		✔ Protective case with purchase		✘ Service-repair only
Bose QuietComfort Ultra		✔ Protective case with purchase	✘ Custom connectors for internal components	✘ Service repair only
Fairphone Fairbuds XL		✔ IP54 rating ✘ No protective case available	✘ Custom connector for battery	✔ Module based self-repair ✔ Battery available for self-repair
Repeat Prince	✔ Self-assembly			✔ Module based self-repair
AIAIAI TMA-2 Move Wireless	✔ Self-assembly		✔ Intercompatible modules	✔ Online repair guides

assembly process itself is simple and accessible even to users who aren't technically inclined.

Design for Durability

The Fairbuds XL are the only model with an IP rating (IP54), despite water damage being a common risk for headphones. The lack of water resistance in the other four models impairs their durability.

Sony and Bose provide hard-shell carrying cases along with their headphones to encourage customers to protect their headphones when not in use. In contrast, AIAIAI and Repeat sell cases separately, while Fairphone does not even offer a case, only a soft pouch. While this may save materials, it also increases the risk of damage over time, shortening the product's lifespan.

The Sony WH-1000XM5 has received criticism from users for its fragile hinge.

Design for Standardisation and Compatibility

While none of the headphones are compatible with components outside their own ecosystem, AIAIAI stands out or its internal compatibility: all modules within the TMA-2 product line are interchangeable.

The lack of compatibility across brands means that users and repair services rely on spare parts from the brands themselves, limiting the possibilities of repairs.

IEC 61076 is a relevant standard in this context, covering connectors for electronic equipment (International Electrotechnical Commission, 2019).

Two of the analysed headphones include non-standard connectors. Bose uses several push connectors for components such as the speaker drivers and microphones. These connectors appear proprietary. Fairphone uses a custom spring-contact battery connector, which limits compatibility to Fairphone's own batteries only.

The connectors of the other models closely resemble standardised types. However, due to a lack of visible markings or documentation, it is difficult to determine whether these connectors are officially standardised.

Design for Ease of Maintenance and Repair

The headphones all differ in where they fall between fully service-based and self-repair options, see Figure 16.

Sony and Bose fully rely on service-repair: users must contact the company or go to licensed

Adaptability and Upgradability	*Dis- and Reassembly*	*Business strategy*	*End-of-life*
✗ No (future) possibilities for upgrades	✗ Sequential and interdependent disassembly		
✗ No (future) possibilities for upgrades		✗ Only uses virgin materials	
	✓ Disassembly into modules with only a Ph. #00 and a credit card	✓ Uses not only recycled plastic, but also aluminium. ✓ E-waste offset program	✓ Battery clicks in place ✗ Glued PCBs
	✓ Disassembly into modules without tools	✓ Return flow for broken components for reuse/ recycling	✗ Bolts and nuts hinder separation of PCBs, housing, and fasteners
✓ Upgradable electronics	✓ Disassembly into modules without tools	✓ Trade-in program for products and modules ✓ Refurbished products	

repairers for repairs. They only offer the ear pads for self-repair. Bose sells replacement ear pads on its website, while Sony provides information on how to replace them, but does sell the replacement parts directly to customers.

The modular headphones from Fairphone, Repeat, and AIAIAI are all designed for some level of self-repair. All three brands offer spare parts for the modules, which users can replace themselves. Fairphone offers the most modules, 11, and is the only brand that offers the battery as a spare part to customers. However, both Fairphone and Repeat have a clear boundary between self and service repair. While users can repair their headphones by replacing broken modules, they are not encouraged to repair broken modules themselves. AIAIAI does offer this as an option by providing troubleshooting and repair guides on their website, although they don't offer spare parts for individual components.

Repeat streamlines the repair process for users. They offer a repair subscription with unlimited free repairs for €16.99 a year or €99 once. Users receive a return envelope for the broken module along with their spare parts. Repeat then repairs and reuses or recycles the module. This lowers the barrier for repair and encourages users to keep using the same product

Design for Adaptability and Upgradability

AIAIAI's modular system allows users to change or upgrade parts as their needs evolve. For example, users can switch from wired to wireless configurations, or change to a headband with thicker padding for additional comfort. The other four headphones don't allow for hardware upgrades at all, although the modular design of Fairphone and Repeat could make this a possibility in the future.

Design for Dis- and Reassembly

Fairphone, Repeat, and AIAIAI are all designed to be taken apart and put back together. The headphones from Repeat and AIAIAI can be disassembled into modules without the use of tools, and the headphone from Fairphone only requires a Phillips #00 screwdriver and a credit card or spudger. Repeat's speaker housings are fastened with four visible bolts and nuts, making them the only model with visible fasteners.

Sony's WH-1000XM5 is the opposite: their sequential and interdependent disassembly process makes disassembly difficult, and the large amount of non-reusable connectors hinders reassembly.

Key takeaways:

- The three sustainable headphone brands all incorporate modularity to support easier replacement of parts. However, the extent to which this modularity enables broader circular practices such as upgradability, compatibility or product attachment varies between brands. → *Key Finding 8*
- Through their modular approach, Fairphone and Repeat provide a clear boundary between self and service repair, making repair feel more attainable. → *Key Finding 1*
- There is an opportunity for Sony to introduce circular strategies other than durability.

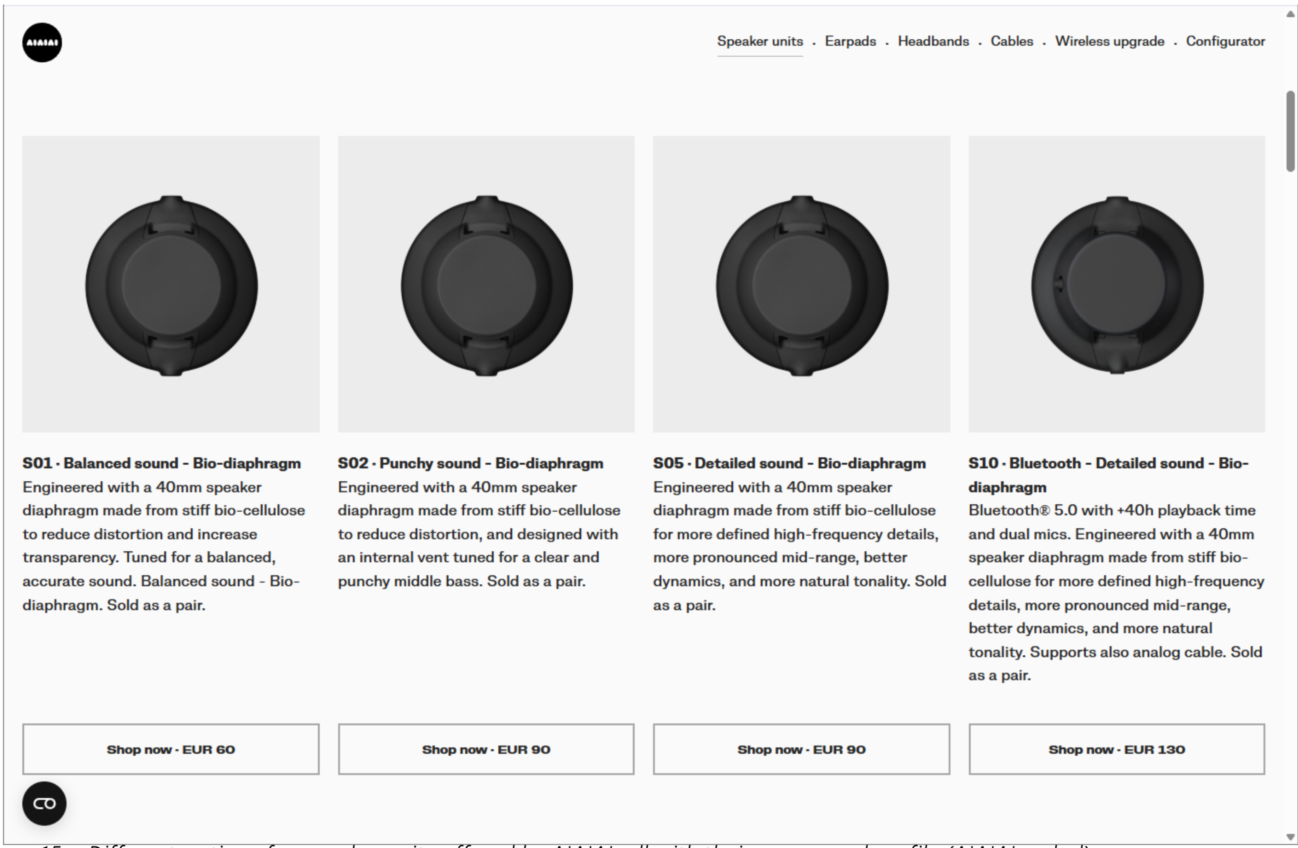


Figure 15. Different options for speaker units offered by AIAIAI, all with their own sound profile (AIAIAI, n.d.-d).

Figure 16. Scale showing where each headphone/brand falls between service vs self-repair.

4.2.2 Circular principles from a business standpoint

In addition to the circular product design strategies, which mainly focus on keeping the product in use, some brands apply circular principles in how they handle returns, repairs, and materials.

Reuse and Refurbishment

AIAIAI has a trade-in program where customers can return headphones or individual modules for store credit (AIAIAI, n.d.-a). These are then refurbished and resold at a lower price. Repeat repairs and reuses returned modules in a similar way, but they do not differentiate between 'new' and 'refurbished' parts on their website.

Sony and Bose also sell refurbished products, but the programs are hard to find on their websites and do not seem to be available in all regions (Bose, n.d.-b; Sony Group, n.d.-a).

Recycling

Fairphone uses 66% recycled materials in the Fairbuds XL, including 95% recycled aluminium, (Fairphone, n.d.-c) and has a program that offsets the weight of each new product by recycling an equal amount of electronic waste, making their products 'electronic waste neutral' (Fairphone, n.d.-d). They also take back used products, but only phones, no headphones or individual modules.

Repeat uses 50% recycled ABS and ensures that returned parts that cannot be repaired are properly recycled (Repeat, n.d.-a). Their repair system doubles as a return flow for recycling, reducing user effort and room for error at the product's end-of-life.

AIAIAI's speaker units are made from 100% recycled plastic (AIAIAI, n.d-b). However, there is limited transparency about the source or about own recycling initiatives.

Sony uses 85-98% recycled plastic in their headphone housing, sourced from the automotive industry (Sony Group, n.d.-b). However, this isn't connected to a broader repair, reuse, or take-back system.

In addition to using recycled materials, recyclability at the product's end-of-life is crucial to avoid loss of valuable and critical raw materials. PolyCE has developed a set of guidelines for designing electronic devices that enable better and easier recycling (Feenstra et al., 2021). The main topics and guidelines relevant for headphones can be found in Appendix H.

The five analysed headphones showed varying levels of attention to these principles.

Fairphone uses a click solution for the battery instead of glue, allowing for easier removal. However, they also use glue on several PCBs, either to keep them in place or for waterproofing, which can hinder recycling.

Repeat's design includes bolts and nuts that hold the two halves of the earcup housing together, but these bolts also go through the PCBs, meaning that the PCBs cannot be separated from the housing and the bolts and nuts when shredded.

Key takeaways:

- While many brands use recycled materials, few integrate this into a broader take-back, refurbishment, or recovery strategy. → *Key Finding 8*
- Only Repeat tries to control the full product flow. This is done by providing return options for broken modules with their spare parts. This enables the recycling and reuse of modules. → *Key Finding 8*

4.2.3 Conclusion

The analysis shows that while circular strategies are present across the five headphone models, their implementation and depth vary widely. Brands like Fairphone, Repeat, and AIAIAI embed circularity into both their product design and business model, especially in areas like self-repair, modularity, and take-back programs. In contrast, Sony and Bose incorporate some circular elements — such as recycled materials and refurbishment programs — but fall short in areas like repairability, upgradability, and user involvement. These differences reflect not just technical design choices but also brand values and priorities.

Key takeaways:

- The biggest difference between the sustainable brands and conventional ones like Sony and Bose is the level of user involvement. Fairphone, Repeat, and AIAIAI actively engage users by delivering the product unassembled, offering product customisation, and offering opportunities for self-repair. → *Key Finding 7*

4.3 Conclusion

This section brings together the findings from Chapter 4to answer *RQ3 What is the current state of over-ear wireless headphones in terms of circularity, and what design decisions support or hinder circularity?*

The analysis shows that while some brands, particularly Fairphone, Repeat, and AIAIAI, have begun integrating circular strategies into both design and business practices, the overall state of circularity in over-ear wireless headphones is still inconsistent and limited.

The most common approach to circularity is modularity with the aim to improve repairability. However, electronics are often grouped into one module, meaning critical components are not always accessible. In addition, only one brand (Repeat) effectively connects circular design to end-of-life strategies through a closed product loop.

Design decisions that significantly hinder circularity include the use of strong adhesives, sequential and interdependent disassembly structures, the need for heated tools, component stacking, hidden connectors, and the lack of information and transparency from the company. These make repairs more difficult, limit recyclability, and increase dependency on manufacturer-led services.

Finally, one of the clearest dividing lines between the sustainable and conventional brands lies in user involvement. Fairphone, Repeat, and AIAIAI encourage users to interact with and care for their product, whereas Sony and Bose present headphones as closed systems with limited repair options.

In short, while circularity is becoming more common in companies' initiatives like material sourcing or refurbishment programs, few headphones fully embrace it in ways that empower users, extend product life, and ensure valuable materials are recovered at end-of-life.

Key takeaways from this chapter were translated into early idea sketches exploring themes such as internal part visibility, quick disassembly, and simplifying the headphone architecture, see Figure 17.

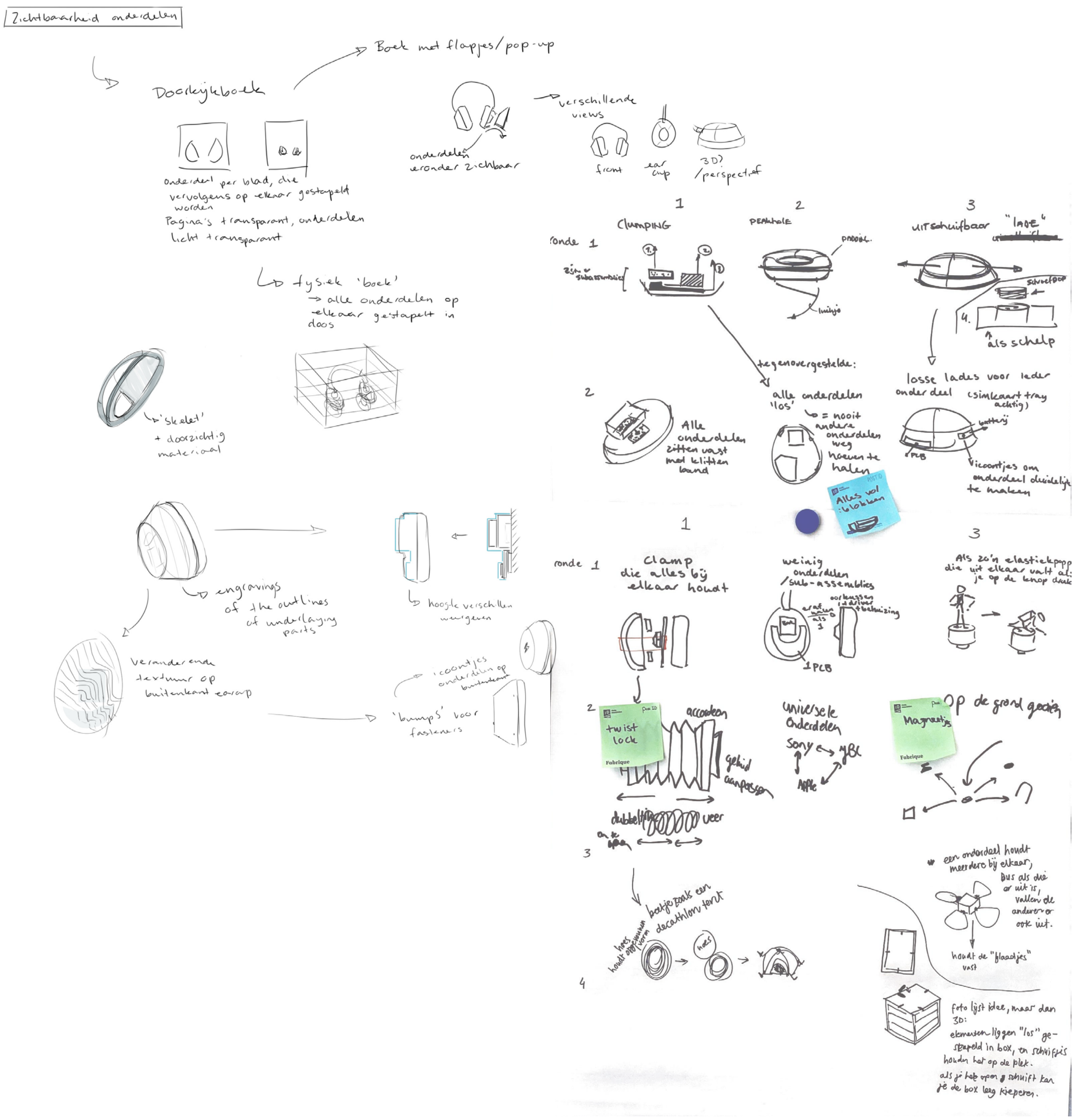


Figure 17. Sketches from early stage idea generation related to key takeaways from Chapter 4.

5. Key findings

This chapter summarises the most important insights gathered throughout the analysis. These findings help identify opportunities for improvement in current headphone design and form the foundation for the vision in Chapter 6.

1.

Headphones are becoming increasingly complex, exposing the need for clear boundaries between self and service-repair.

Headphones are continuously evolving as new technologies emerge, requiring additional (electronic) components, more advanced PCBs, and larger battery packs. These features increase both the complexity of the product architecture and of the workings of the headphone. The more complex these products get, the less you can expect users to be able to repair them themselves. To ensure repairs are feasible and effective, there need to be clear boundaries between self and service repair.

2.

Even in modular designs, critical components are often bundled into a single module, limiting the potential for self-repair at the component level.

Most companies, like Sony and Bose, opt for fully service-based repairs, where self-repair is not facilitated and users must go to licensed repairers.

Fairphone and Repeat choose for a combination of the two. They offer self-repair on a module level: users can replace broken modules themselves, but self-repair within the modules is not facilitated or encouraged, creating a clear boundary. Fairphone also offers a repair service to replace these modules, and Repeat repairs and reuses the broken modules it receives where possible.

AIAIAI also follows a modular approach, similar to Fairphone and Repeat, but provides more possibilities for self-repair at the component level. They actively encourage this by offering troubleshooting and repair guides.

While self-repair on a component level isn't always necessary, as it's often not feasible for most users, it is important to carefully consider how the product is divided into modules. For example, if all critical parts are grouped into a single module, it raises the question of whether modularity actually makes a meaningful contribution to the circularity of the product.

3.

Not all critical components are easily accessible, even ones that will wear down during the life of the headphone.

While ear cushions are replaceable by users themselves, this often is not the case for the headband cushioning or cover, even though these are also usually made of PU leather which has a tendency to start flaking over time. Sometimes the headband cover isn't even separately replaceable and inseparable from the headband itself.

Other critical components are the battery, speaker drivers, PCBs (specifically the PCB including the charging port), headband hinges, and the cable connecting the earcups. Easy access to these part is important to extend the life of the headphones and increase the chance of valuable end-of-life recovery. The battery and large PCBs are often pretty accessible, while drivers and, for the non-sustainable brands, headband hinges and headband cable are a lot harder to reach.

4.

A sequential and interdependent disassembly structure has a major influence on the ease of disassembly.

A disassembly process where components have to be removed one by one and in a specific order increases the amount of steps needed to reach components (disassembly depth), the time needed for disassembly, and the complexity of the disassembly process, making the disassembly process harder and more complex.

Sony performs very badly on this, with a maximum disassembly depth 2 times higher than the other analysed headphones, requiring 46 steps to reach the component deepest in the product architecture. The sheer number of parts play a role in this, but also the stacking of components.

5.

The extensive use of (strong) adhesives has a strong negative effect on both the ease of disassembly and recycling possibilities.

Strong adhesives are used in multiple places throughout all headphones, for speaker drivers, microphones, batteries, housings, PCBs, etc. These are valuable components, that you want to be able to repair/replace or recycle, especially batteries should be easily removable. However, the adhesive makes separating out these valuable materials difficult, if not impossible, when they are shredded for recycling.

These adhesives also have a huge negative impact on the ease of disassembly, as they often need a combination of a heated tool to soften the glue and a lot of force to be removed. Reassembly is also harder for users, as the layer of adhesive gets left behind when you remove the components but is often not sticky enough anymore to ensure a secure connection.

6.

Most headphones do not take the intuitiveness of the disassembly process for users into consideration.

The extensive use of adhesives and other non-reversible connectors, hidden fasteners, stacked (and thus hidden) components, cluttered product architectures, the amount of different parts and fasteners, and need for specific disassembly sequences all point to this. Sony scores the worst on this.

AIAIAI and Repeat score better on this. They don’t use as much adhesive as other headphones, and have a limited amount of parts and additional fasteners such as screws, instead opting for friction and form fits.

A more spacious layout would create a less overwhelming experience for users.

7.

Headphones as a 'black box' is a huge barrier to circular user behaviour.

A lot of user perceive their small electronic products as a 'black box', something that you don't know how it works or what its internals look like. Not only does this lead to fixophobia from the customers side, the reluctance to repair your product, it can also lead to people undermining the value of proper end-of-life steps. This is not a weird phenomenon with the increasing complexity of our products or the way companies play into it with their sleek & seamless designs.

The first barrier is that users do not know how their headphone works and what components it consists of, so they also do not know what the issue is when something does not work or which component could be the cause. The second barrier is that these sleek designs deliberately hides entry points, making disassembly intimidating. You don't want to have to 'explore' your headphone (for the first time) when something is broken. This makes the threshold to try to repair your product too high. If you do open up your headphones, you get to the third barrier: the complex internals of the headphone. The overwhelming product architecture with lots of parts, cables, and fasteners connected to and stacked on top of each other make it unclear where to start a repair. Most companies/suppliers actively enable these barriers by not provide information about the internals of the headphones or guidance for repair or disassembly.

AIAIAI and Repeat eliminate the first barrier by delivering their headphones in the separate modules. Before using it, users first have to assemble their headphones, which helps them learn how the modules are connected and fosters confidence in their own abilities. Clear, easily accessible, instructions on disassembly help with the third barrier.

8.

Current circular design strategies in headphones mainly focus on modularity.

The sustainable headphone models analysed all focussed on modularity and the easy replacement of broken modules. Modules of Fairphone and Repeat can only be replaced with the exact same module, while AIAIAI offers headphones that are fully customisable: users can choose their own speaker unit, headband, earpads, and cable and these can all be upgraded or swapped later on. AIAIAI also focusses on design for disassembly beyond the modules, which is noticeable during the disassembly process.

However, all these headphones have one module which contains the majority of the electronics: the speaker unit/earcup. Fairphone still has the battery separately, but for AIAIAI and Repeat the battery, speaker drivers, charging port, and other PCBs are all in same module.

So while modularity is a partial solution, it misses important aspects regarding repairability and recyclability, especially when the company does not have any specific strategies regarding end-of-life in place.

Design

6. Vision

The previous chapter highlighted key challenges that currently make headphones unsuitable for a circular economy - particularly around disassembly and user engagement. This chapter presents the vision that responds to these challenges. It defines the opportunity space and provides a starting point for designing a pair of headphones that re-teaches product care through clarity and no longer feels like a black box to the user.

6.1 Towards the final vision

Before ending on the final vision that guided the rest of the project, several potential directions were explored. These were captured in three different vision statements and tested through a Design in a Day session for each vision. The goal of these session was to explore the design space and evaluate the relevance, feasibility, and design potential of each direction. Figure 18, Figure 19, and Figure 20 contain the results of the Design in a Day sessions for each vision. A more in depth explanation of the considered visions can be found in Appendix I.

Prioritising care and maintenance

This vision focused on reframing care and maintenance as a positive experience: a relaxing and enjoyable ritual that strengthens the relationship between user and product. The idea was to use the headphones and accompanying products and services to make care and maintenance a natural part of ownership. While this direction had strong potential, especially since this aspect is often overlooked despite having a significant impact on product lifespan, headphones contain very few parts that need regular care. It also lacked a clear connection to the physical design of the headphones itself , which limited its value for this specific project.

Headphones that last a lifetime

This vision was based on the concept that the most sustainable product is the product that lasts the longest. It aimed to maximise durability, modularity, and upgradability. While it aligned strongly with circular principles, the vision felt too broad and was difficult to translate into a tangible design direction.

Clarity

The last vision focused on enabling users to understand their headphones and feel confident in their ability to use, care for and maintain, repair, and eventually responsibly discard their device. It directly addressed frustrations experienced during the disassembly of the analysed headphones, such as unclear component functions or intimidating product architecture. This direction proved to be both rich in design opportunities and well-aligned with the key findings of this project. However, for it to succeed, the vision should go beyond just the headphones itself.

These vision explorations formed the basis for selecting a final direction. The next section introduces and elaborates on the chosen vision of clarity, and how it shaped the rest of the design process.

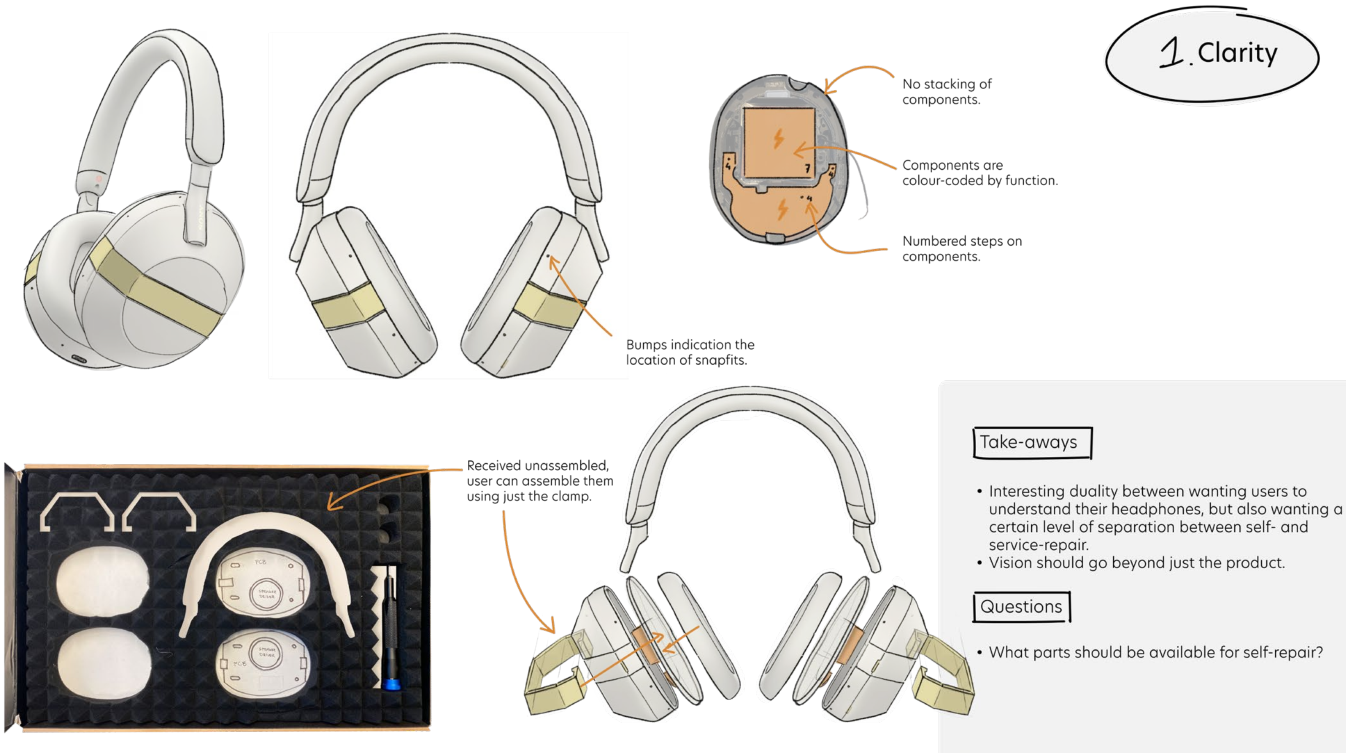


Figure 18. Results Design in a Day for the vision of 'Clarity'.

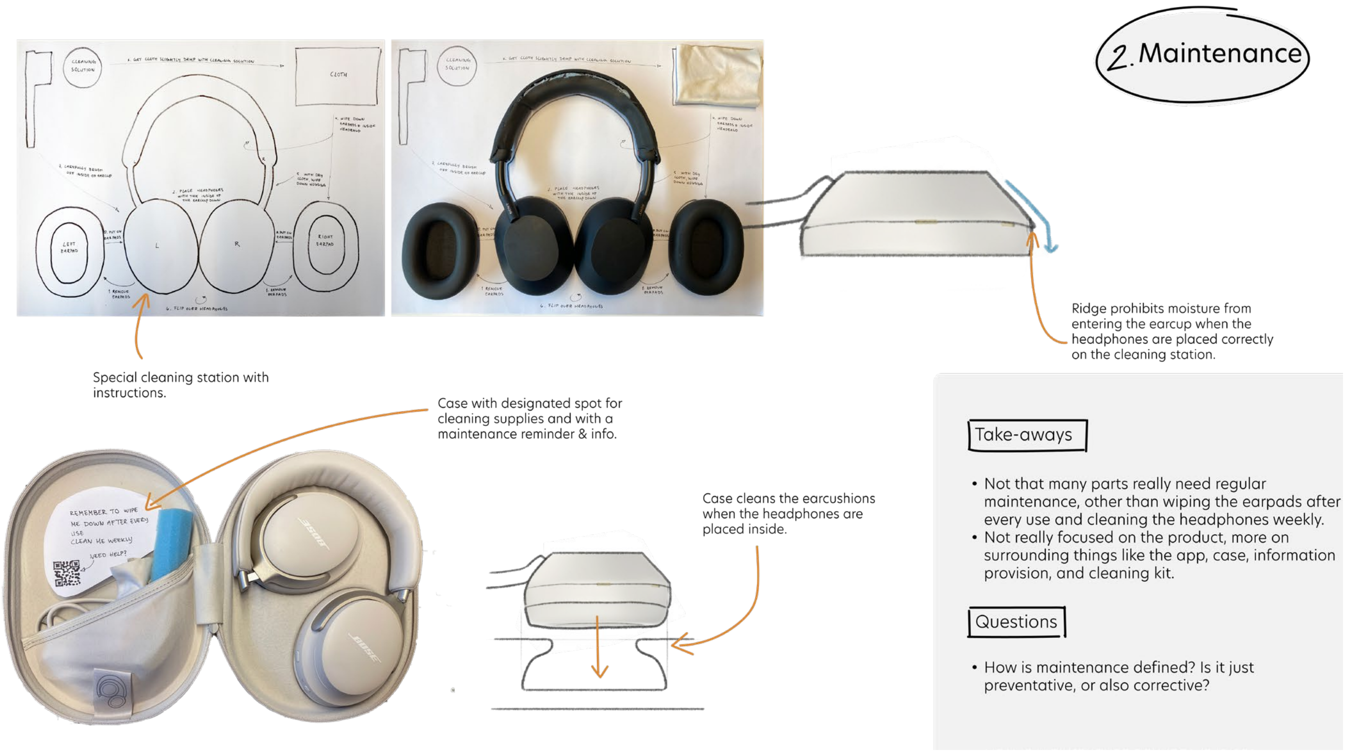


Figure 19. Results Design in a Day for the vision of 'Prioritising care and maintenance'.

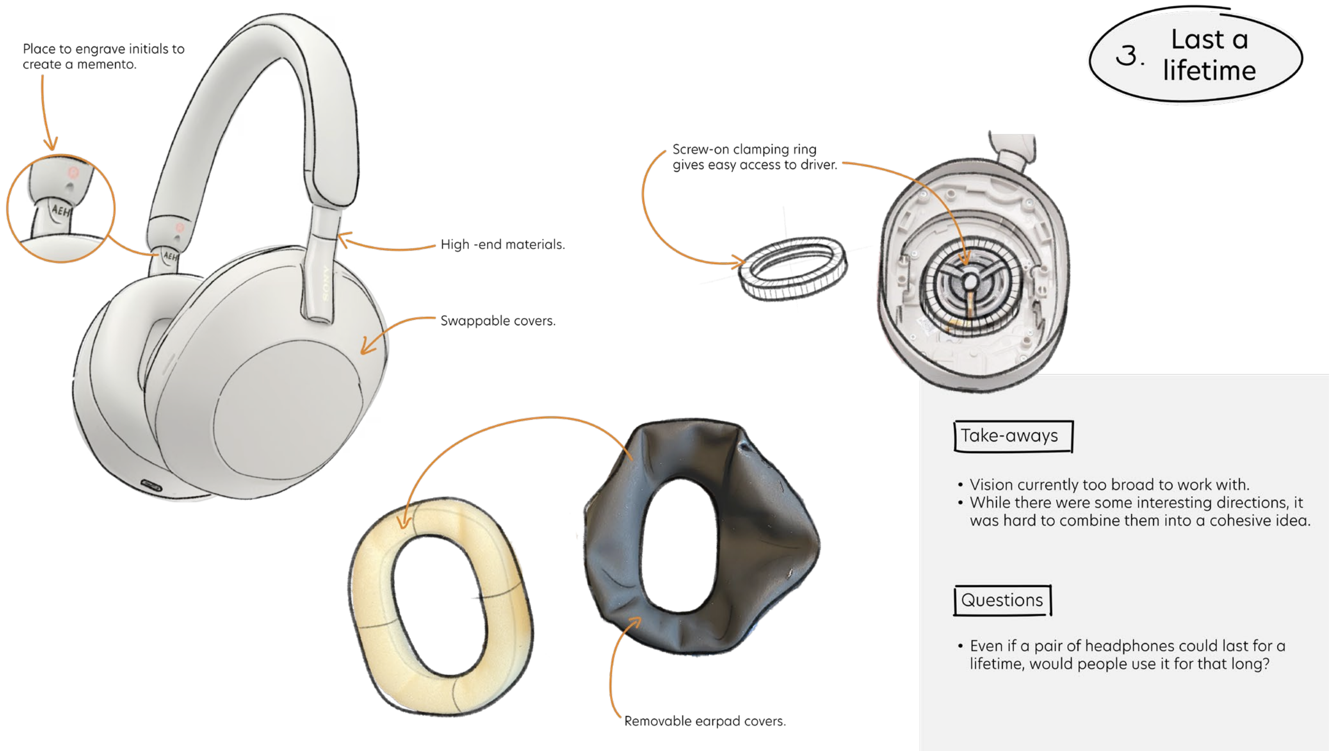


Figure 20. Results Design in a Day for the vision of 'Headphones that last a lifetime'.

Headphones that re-teach the practice of product care through clarity about functions, product architecture, upkeep, and end-of-life, so the product no longer feels like a black box to users.

Vision statement

6.2 Background vision

In today's world, people have become unaccustomed to taking care of their products, and product care has become a lost skill. In a circular economy, however, this kind of user involvement is essential. Users should be retaught how to care for their products and why their care is important. This vision focuses on using **clarity** as a tool to support this shift in the context of headphones. Not just clarity in written instructions, but clarity embedded in the design of the headphones, product architecture, and supporting ecosystem.

The initial design brief for this project focused on designing circular headphones, but change isn't achieved by designing only the product itself, but by opening up the 'black box' that users experience their product to be. Therefore, my starting point should be to create a prybar to open that black box and help users relearn product care, rather than the technical design of a pair of headphones.

This starts with users understanding their headphones, their components, how they work, and the role that they play in the lifecycle of their product. This includes knowing how to care for their headphones and perform basic repairs to extend their life, as well as the proper end-of-life steps. This is particularly important for the critical parts such as the battery, PCBs, speaker drivers, hinges, and headband cable.

The supply of information plays a key role in this, but it must go beyond a support article buried on the company's website. Instead, the information must be embedded in the headphones and accompanying products themselves as well. The product should guide the user.

But it is not just about providing information, it is about breaking down the barriers that make users unsure of their own abilities when it comes to product care. This includes making a clear distinction between what users can do themselves and what should be left to professional repairers, making basic repairs possible without prior experience, and making disassembly feel approachable.

To realise this vision, the design must combine simplicity, ease of disassembly, information supply, and gentle reminders that care is not only possible, it is expected.

6.3 From vision to concept

After defining the vision of re-teaching the practice of product care through clarity, the next step was to explore how this vision could be translated into a concrete design direction. This started with a group brainstorm session followed by individual ideation. Together, these produced a large collection of ideas, which were then clustered into three promising design directions: **visual connections**, **interactive information**, and **bringing the inside outside**.

These three directions were explored further through prototyping. Each direction explored a different way of supporting clarity, but they were all based on making the invisible visible.

Visual connections

This direction focused on making all fasteners and connections between components visible and immediately understandable through form or colour. The goal was to remove doubts and hesitation by making the product's construction self-explanatory.

Bringing the inside outside

This direction aimed to remove the 'black box' feeling entirely by exposing the product's internal structure through transparent materials, colour, or textures, so you can know what is inside of your product without having to open it up.

Interactive information

This direction explored a supporting product that visually guides the user through the internal architecture and functioning of the headphones. It re-imagines the traditionally dry and boring, manual as an explorative and engaging book. By simulating the disassembly process, it allows users to gain confidence before actually opening the product.

This final direction was choses as the basis for the concept. Not only does this direction align the strongest with the idea of opening the 'black box', it also offers the strongest narrative, and creates a unique opportunity to bridge product and information supply. Rather than trying to do everything through the headphones alone, the book allows the product to remain more 'conventional' while still communicating its internals and care and repair instructions in a clear and user-friendly way.

However, an informative book cannot exist without a product to convey information about. And because the layered structure of the book places restrictions on how it can replicate a disassembly process, it also places restrictions on the headphones themselves. The book cannot exist without a headphone that is designed with the book in mind.

Figure 21. Collections of sketches made during the group brainstorm and individual ideation and prototypes of the three design directions.

6.4 Requirements

To ensure the final concept aligns with the vision and supports a more circular user interaction, several design requirements have been defined. These are based on the eight key findings defined in Chapter 5, the vision introduced in Chapter 6.2, and the restrictions introduced by the accompanying book, which forms the basis of the chosen design direction from Chapter 6.3.

Due to the conceptual and speculative nature of this project, most of these requirements do not have hard numbers assigned to them.

6.4.1 Requirements stemming from the Key Findings

KF1 Boundaries between self- and service-repair

KF1.1 The product should clearly communicate which components are meant for self-repair and which require professional repair services.

KF2 Self-repair at a critical component level

KF2.1 Critical components should be individually replaceable. This includes the battery, speaker drivers, PCBs, headband hinges, and the headband cable.

KF3 Accessibility of critical components

KF3.1 Critical components should be accessible within 5 disassembly steps.

KF3.2 The headband padding and earpads should be individually replaceable.

KF3.3 The headband padding and earpads should be accessible within 1 disassembly step.

KF4 Sequence-independent disassembly

KF4.1 The maximum disassembly depth should be ≤ 20.

KF4.2 Once the shell has been removed, components inside the earcups should not be dependent on the removal of more than two other components.

KF5 Limited use of adhesives

KF5.1 Users should be able to disassemble the headphones without the use of heated tools.

KF5.2 Critical components should use reversible and reusable fasteners.

KF5.3 Critical components should be reachable without having to undo non-reusable connectors.

KF6 Intuitive disassembly

KF6.1 Connectors should be visible or clearly indicated.

KF6.2 Components should be visible enough to be identifiable.

KF6.3 The use of cantilever snap fits should be avoided.

KF6.4 The number of total parts should be reduced compared to the Sony WH-1000XM5 headphones.

KF6.5 The number of different tools required for disassembly should be reduced compared to the Sony WH-1000XM5 headphones.

KF6.6 The number of screws should be reduced compared to the Sony WH-1000XM5 headphones.

KF6.7 Users should be guided through the disassembly process.

KF7 Eliminating the 'black box'

KF7.1 Information about the headphones' components, disassembly, and repair should be easily accessible to users.

KF7.2 The product should educate users about its product architecture and how it functions.

KF7.3 The product should encourage user involvement to foster product attachment.

KF7.4 The housing should use visible fasteners.

KF8 More than modularity

KF8.1 Users should be educated on end-of-life steps.

KF8.2 Modules should contain a limited number of components and no more than one critical component.

6.4.2 Requirements stemming from the Vision

V1 The headphones and supporting products should provide information about care, repair, and end-of-life steps.

V2 The headphones and supporting products should make basic repairs feasible for people without repair experience.

V3 The headphones and supporting products must make the product architecture, functioning, and disassembly understandable to non-technical users.

V4 The headphones and supporting products should encourage regular care and maintenance.

6.4.3 Requirements stemming from the Book

B1 The headphones should foster the same feeling of clarity and transparency as the book.

- B1.1 Once the earcup is opened up, parts should never fully hide or obscure other parts.
- B1.2 Fasteners should be visible.

B2 The component order and orientation must match the book's structure.

- B2.1 The headphone should allow parts to be disassembled in the same order as the book.

B3 All parts should be accessible from one side, without product manipulations.

B4 There should be a clear visual distinction between parts. It should be possible to identify the different parts, even for users who aren't technically inclined.

7. Final design

7.1 Page by Page

Page by Page is a redesign of the Sony WH-1000XM5 headphones which takes a new approach to circular product design, pairing the headphones with an educational, interactive book, see Figure 22 and Figure 23. Together, the headphones and book aim to increase clarity, support product care and repairability, and encourage sustainable behaviour throughout the product's lifecycle.

The book provides an in-depth walkthrough of the headphones and its components, helping users to understand how their product works and how to maintain, repair or dispose of it responsibly. This builds user confidence and reduces the threshold for product care and repair.

The design of the headphones is in line with the book: transparent structural parts make internal components visible, and colour coding helps users locate and identify parts with ease. The book and the headphones work together as one system, where each one strengthens the other.

Customers can opt to purchase the book alongside their headphones. This ensures that the book is only provided to those who will actually use it, while those with no interest in it, or who perhaps already have access to a copy, can choose to leave it out.

Figure 22. Render of the Page by Page headphones

Figure 23. The Page by page book.

7.2 The book

Instead of adapting the method of supplying information to the product, this concept takes the opposite approach: the design of the product is adapted to the way information about the product is supplied. The starting point of the concept is the accompanying book, which serves as a walk-through of the headphones, see Figure 24.

Each page in the book has a transparent cut-out with a different component of the headphones, see Figure 25. Layered on top of each other, these transparent sections create an X-ray-like view of the headphones. This allows users to see all internal components of their headphones without opening them up.

The book familiarises users with their headphones by introducing them to the internal components and their place in the product architecture. Users can see how their product is built up without having to open it. The book simulates the disassembly process, providing a safe environment in which users can become accustomed to it without the risk of damaging their product. This builds users' confidence and introduces them to repair and end-of-life processes early on. It can also serve as a memento of the headphones and help to discourage holding onto broken or unused products.

Each page discusses a different (group of) components, taking the user deeper into the architecture of their headphones with eahc page turn. The front of each page contains basic information about the function of the components, while the back provides additional information about attachment, errors, and repair.

In addition to the component-specific information, the book includes general information about spare parts, available repair services, and responsible end-of-life steps.

The book is designed in A4 format. This makes it is large enough to clearly show the components and provide enough detail, while still being compact enough to ship with the headphones. Although it is slightly larger than the current Sony WH-1000XM5 packaging (24 x 21 cm), the difference is acceptable and manageable within existing logistical flows.

To preserve the transparency of the polyester sheets used for the cut-outs, the number stacked on top of each other is limited. For this reason, and to avoid overwhelming users with information, there is no individual page for every single part.

Instead, components are clustered together. The book consists of the following nine component pages, which are all colour-coded by the main function of the components:

- Headband
- Earcup shell
- Main PCB
- Battery
- Power PCBs
- Audio
- User inputs
- Base
- Earpads

Figure 24. The hardcover Sony Page by Page book, which provides users with information about their product and responsible and circular use.

Figure 25. The book's transparent cut-outs allow users to walk through their product component by component.

7.3 The headphones

The design of the headphones reflects the main visual aspects of the book, supporting recognition and reinforcing the connection between product and book.

Like the transparent windows in the book, the headphones have transparent structural components that allow users to see the product's internal elements that are not usually visible, such as the speaker driver. Additionally, the components are colour-coded according to the function-based system used in the book to help users recognise and locate parts.

The headphones are designed with a strong focus on disassembly and repairability. Due to the 2.5D build up introduced by the book, all components are accessible from one side. Additionally, all fasteners and components are visible to support an intuitive and accessible disassembly process. The disassembly itself can be carried out using just a single screwdriver.

However, not all components are intended to be individually repaired or replaced by users. This is due to safety concerns, functional integrity, or the skill required for the disassembly and repair of specific components. Some components, such as the battery or the drivers, use strong adhesives. These adhesives are difficult to remove without specialised tools and force, which poses a risk of damaging the product or injuring the user. They also complicate reassembly, since specialised adhesives are required to ensure structural and functional integrity. For example, improper reassembly may affect acoustic performance.

The components that are not suitable for self-repair are grouped into modules that can be removed and replaced by the user.

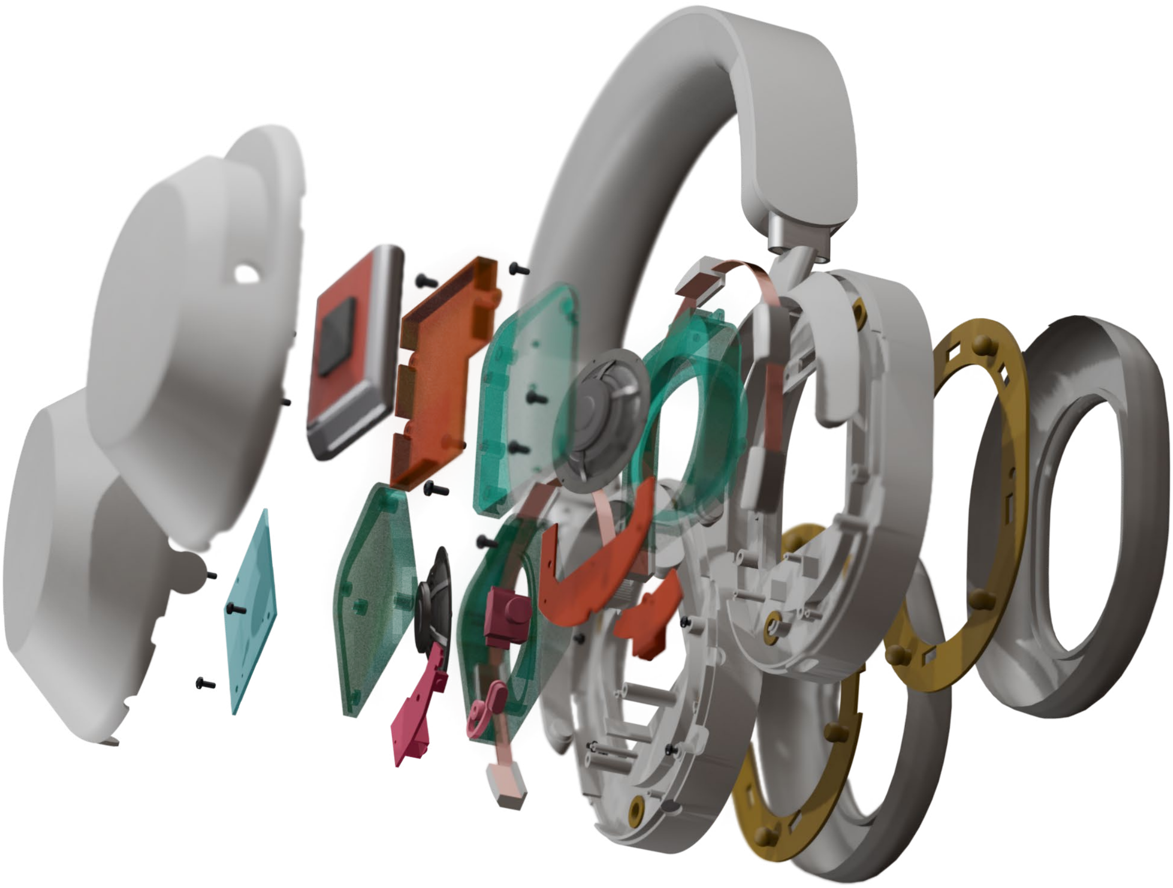


Figure 26. Exploded view of the headphones showing all components.

Figure 27. Prototype of the headphones fully assembled (left), and with the shell removed, showing the components inside the earcup (right).

8. The concept in detail

This chapter dives into how the concept addresses the Key Findings introduced in Chapter 5.

8.1 Boundaries between self- and service-repair

Compared to current headphones, this design offers more opportunities for component-level self-repair. However, that doesn't mean that all individual components are intended to be accessed by users. Instead, the design supports self-repair where feasible, while clearly signalling which repairs are best left to professionals.

Separate part IDs for spare parts

Each page in the book represents a separate component or cluster of components. In cases where a cluster contains several individually replaceable components, such as the input cluster, each part is giving its replacement part ID to the corresponding spare part, see Figure 30, right. If the different components cannot be individually replaced, it is treated as a single unit with just one replacement part ID, see Figure 30, left. This makes it immediately clear what the user can and cannot replace themselves.

Fastener placement to indicate user repair

The headphone reinforces these boundaries. All fasteners users may need to undo are visible and accessible from the top view of the headphones, see Figure 28, whereas fasteners that should only be handled by professionals are 'hidden' and only accessible from the underside, see Figure 29. These visual cues are shaped by the way the book guides users: if the book does not guide the user to open something, then the headphone should also not look like it could or should be opened.

Transparency as a visual cue

The clusters that are treated as a single unit do not require users to directly handle individual components. Instead, users only interact with their structural housing. These structural parts are made from transparent material, making the internal components visible, while also indicating these are not parts users need to separate from the cluster, see Figure 31. In the book, these modules can be recognised both by the same transparent structural parts, and by the clear, bolded statements that the cluster on that page should not be disassembled, see Figure 32.

Additionally, using the same transparent material for both parts of the driver housing creates an almost seamless design. This helps convey the idea that these parts should not be disassembled.

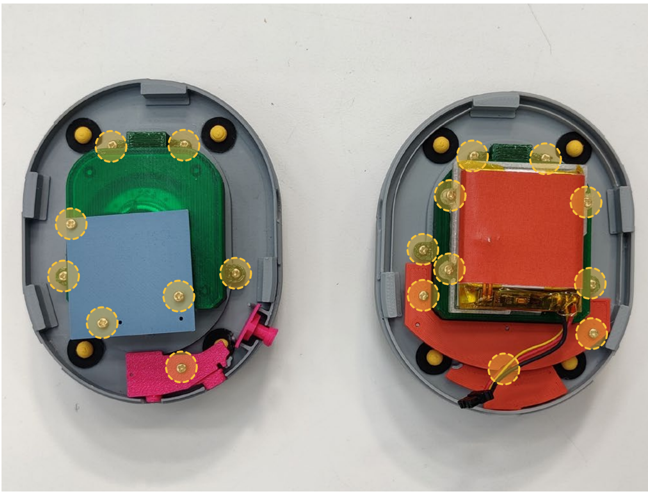


Figure 28. All fasteners in the earcup available from the top.

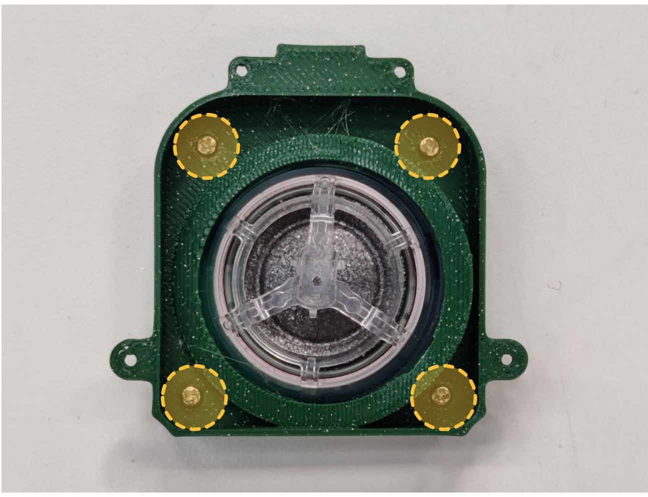
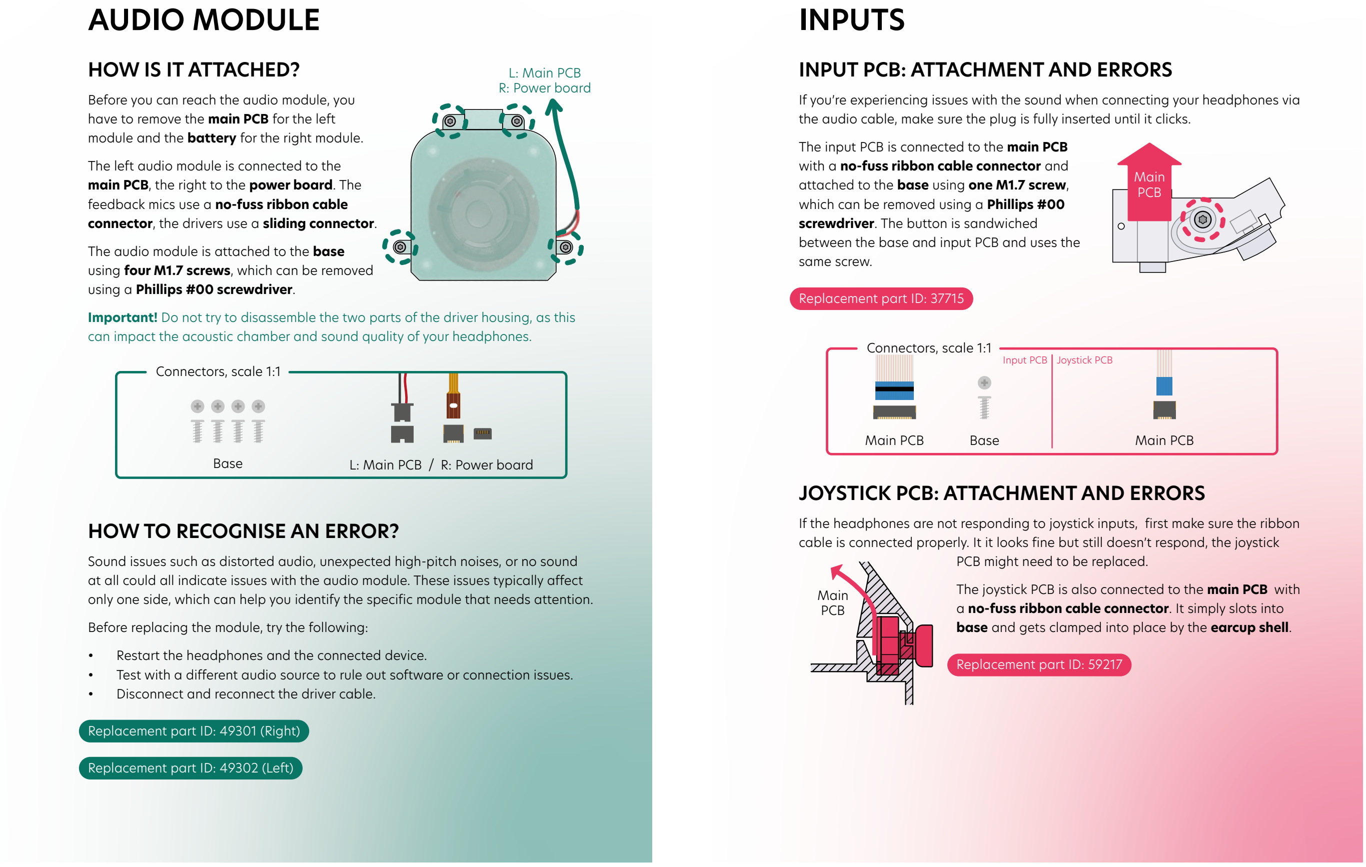


Figure 29. 'Hidden' screws on the underside of the driver housing.



AUDIO MODULE

HOW IS IT ATTACHED?

Before you can reach the audio module, you have to remove the **main PCB** for the left module and the **battery** for the right module.

The left audio module is connected to the **main PCB**, the right to the **power board**. The feedback mics use a **no-fuss ribbon cable connector**, the drivers use a **sliding connector**.

The audio module is attached to the **base** using **four M1.7 screws**, which can be removed using a **Phillips #00 screwdriver**.

Important! Do not try to disassemble the two parts of the driver housing, as this can impact the acoustic chamber and sound quality of your headphones.

HOW TO RECOGNISE AN ERROR?

Sound issues such as distorted audio, unexpected high-pitch noises, or no sound at all could all indicate issues with the audio module. These issues typically affect only one side, which can help you identify the specific module that needs attention.

Before replacing the module, try the following:

- Restart the headphones and the connected device.
- Test with a different audio source to rule out software or connection issues.
- Disconnect and reconnect the driver cable.

Replacement part ID: 49301 (Right)

Replacement part ID: 49302 (Left)

INPUTS

INPUT PCB: ATTACHMENT AND ERRORS

If you're experiencing issues with the sound when connecting your headphones via the audio cable, make sure the plug is fully inserted until it clicks.

The input PCB is connected to the **main PCB** with a **no-fuss ribbon cable connector** and attached to the **base** using **one M1.7 screw**, which can be removed using a **Phillips #00 screwdriver**. The button is sandwiched between the base and input PCB and uses the same screw.

Replacement part ID: 37715

JOYSTICK PCB: ATTACHMENT AND ERRORS

If the headphones are not responding to joystick inputs, first make sure the ribbon cable is connected properly. It it looks fine but still doesn't respond, the joystick PCB might need to be replaced.

The joystick PCB is also connected to the **main PCB** with a **no-fuss ribbon cable connector**. It simply slots into **base** and gets clamped into place by the **earcup shell**.

Replacement part ID: 59217

Figure 30. Replacement part IDs for the Audio module page, where it's replaced as a single part (left), and the replacement part IDs for the User Inputs page, where components can be replaced individually.

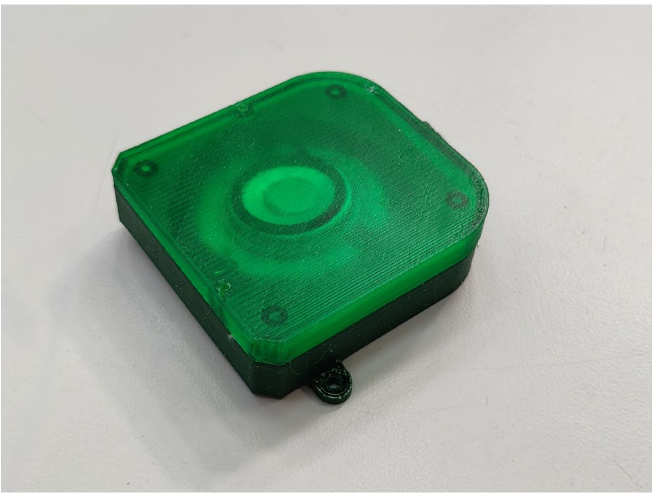
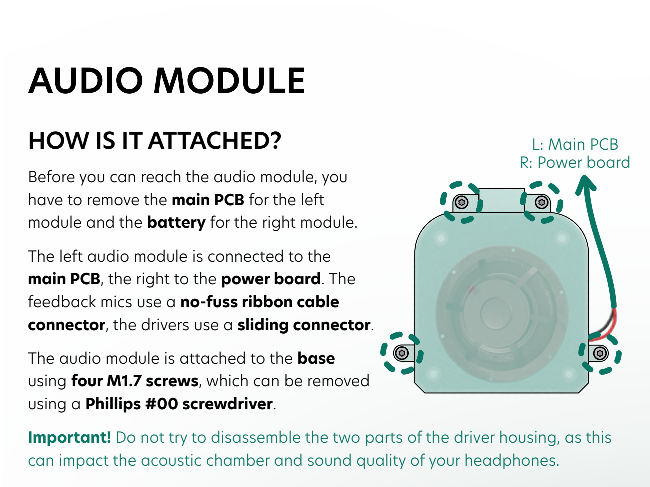


Figure 31. The audio module with its transparent housing.



AUDIO MODULE

HOW IS IT ATTACHED?

Before you can reach the audio module, you have to remove the **main PCB** for the left module and the **battery** for the right module.

The left audio module is connected to the **main PCB**, the right to the **power board**. The feedback mics use a **no-fuss ribbon cable connector**, the drivers use a **sliding connector**.

The audio module is attached to the **base** using **four M1.7 screws**, which can be removed using a **Phillips #00 screwdriver**.

Important! Do not try to disassemble the two parts of the driver housing, as this can impact the acoustic chamber and sound quality of your headphones.

Figure 32. Statement on the audio module page that the housing should not be disassembled.

8.2 Self-repair at a critical component level

To increase the potential for meaningful self-repair, critical components are accessible either as standalone parts or grouped in small, clearly defined clusters, rather than being bundled into a single unit as is often the case in modular headphones.

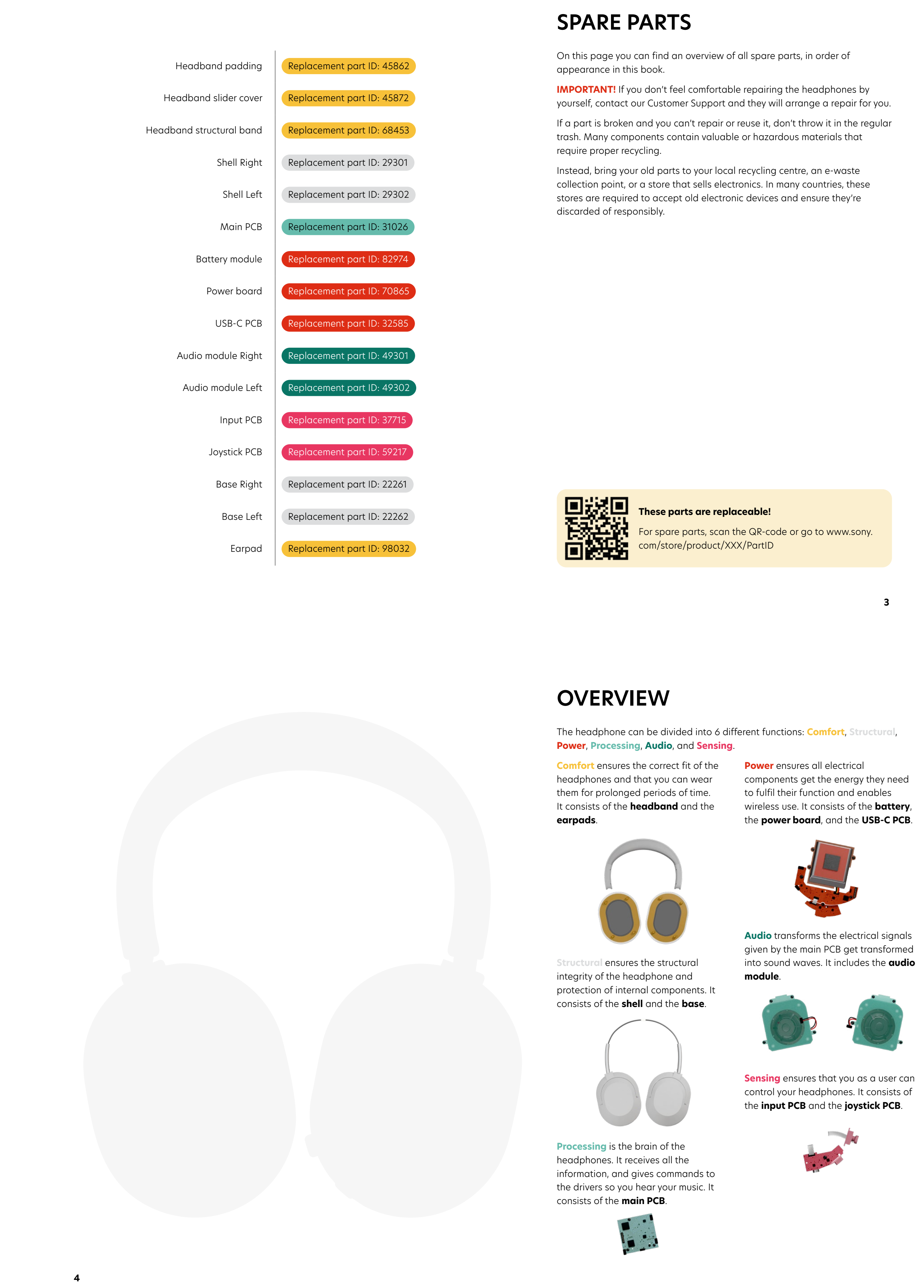
Overview of individual components

To help users understand what can be replaced, the book includes a visual overview of all components, see Figure 33. This is more than just a table of contents: each item in the overview represents a component or cluster that is replaceable. Even when multiple components are discussed on the same page in the book, they are still listed separately if they can be individually replaced.

Division within the earcup

The earcups are not treated as sealed, all-in-one modules in this design. Instead, the electronic components housed in the earcups are each accessible as separate entities. PCBs are accessible individually, while critical components that would require more complex disassembly if they were to be replaced individually, such as the battery and the speaker drivers, are part of slightly larger clusters that eliminate the need for users to perform these disassembly steps.

This approach increases the effectiveness of self-repair while balancing it with what users can reasonably be expected, and trusted, to do themselves. Instead of forcing users to replace large modules when only a single component fails, repairs become more efficient, less wasteful, and more cost-effective. At the same time, components that require professional skills or tools remain grouped in smaller, pre-assembled modules that can be replaced as a whole.



SPARE PARTS

On this page you can find an overview of all spare parts, in order of appearance in this book.

IMPORTANT! If you don't feel comfortable repairing the headphones by yourself, contact our Customer Support and they will arrange a repair for you.

If a part is broken and you can't repair or reuse it, don't throw it in the regular trash. Many components contain valuable or hazardous materials that require proper recycling.

Instead, bring your old parts to your local recycling centre, an e-waste collection point, or a store that sells electronics. In many countries, these stores are required to accept old electronic devices and ensure they're discarded of responsibly.

Headband padding	Replacement part ID: 45862
Headband slider cover	Replacement part ID: 45872
Headband structural band	Replacement part ID: 68453
Shell Right	Replacement part ID: 29301
Shell Left	Replacement part ID: 29302
Main PCB	Replacement part ID: 31026
Battery module	Replacement part ID: 82974
Power board	Replacement part ID: 70865
USB-C PCB	Replacement part ID: 32585
Audio module Right	Replacement part ID: 49301
Audio module Left	Replacement part ID: 49302
Input PCB	Replacement part ID: 37715
Joystick PCB	Replacement part ID: 59217
Base Right	Replacement part ID: 22261
Base Left	Replacement part ID: 22262
Earpad	Replacement part ID: 98032

These parts are replaceable!

For spare parts, scan the QR-code or go to www.sony.com/store/product/XXX/PartID

3

OVERVIEW

The headphone can be divided into 6 different functions: Comfort, Structural, Power, Processing, Audio, and Sensing.

Comfort ensures the correct fit of the headphones and that you can wear them for prolonged periods of time. It consists of the **headband** and the **earpads**.

Structural ensures the structural integrity of the headphone and protection of internal components. It consists of the **shell** and the **base**.

Processing is the brain of the headphones. It receives all the information, and gives commands to the drivers so you hear your music. It consists of the **main PCB**.

Power ensures all electrical components get the energy they need to fulfil their function and enables wireless use. It consists of the **battery**, the **power board**, and the **USB-C PCB**.

Audio transforms the electrical signals given by the main PCB get transformed into sound waves. It includes the **audio module**.

Sensing ensures that you as a user can control your headphones. It consists of the **input PCB** and the **joystick PCB**.

4

Figure 33. Spare Parts and Overview pages in the book displaying all individually replaceable components and modules.

8.3 Accessibility of critical components

Making critical components individually replaceable is only effective if those parts can also be reached with minimal effort. Both the book and the design of the headphones ensure that key components can be accessed in a straightforward way.

Component overview

As mentioned in Chapter 8.1, each page in the book includes the product ID for the corresponding replacement parts, removing any insecurities about what can be replaced and how to get it. Additionally, the tab structure gives an overview of the components and their functions, see Figure 34, allowing users to easily locate critical components, without needing to flip through the entire book.

Physical accessibility in the headphones

The headphones themselves are designed to reflect the same accessibility standards communicated in the book. Critical components can be accessed easily and without the use of heated tools or de-glueing.

- The **earpads** are attached using simple friction pins, allowing users to remove the by hand by just pulling them off, see Figure 35 and Figure 36.
- The top band features a guiding rail that the **headband padding** slides along. Once the ends of the padding are unscrewed, it can simply be slid off, see Figure 37 and Figure 38.
- The **battery** module includes an additional structural component. This plate below the battery ensures that no de-glueing is needed for disassembly, only a screwdriver, see Figure 39. A similar method is used for the **speaker drivers**.

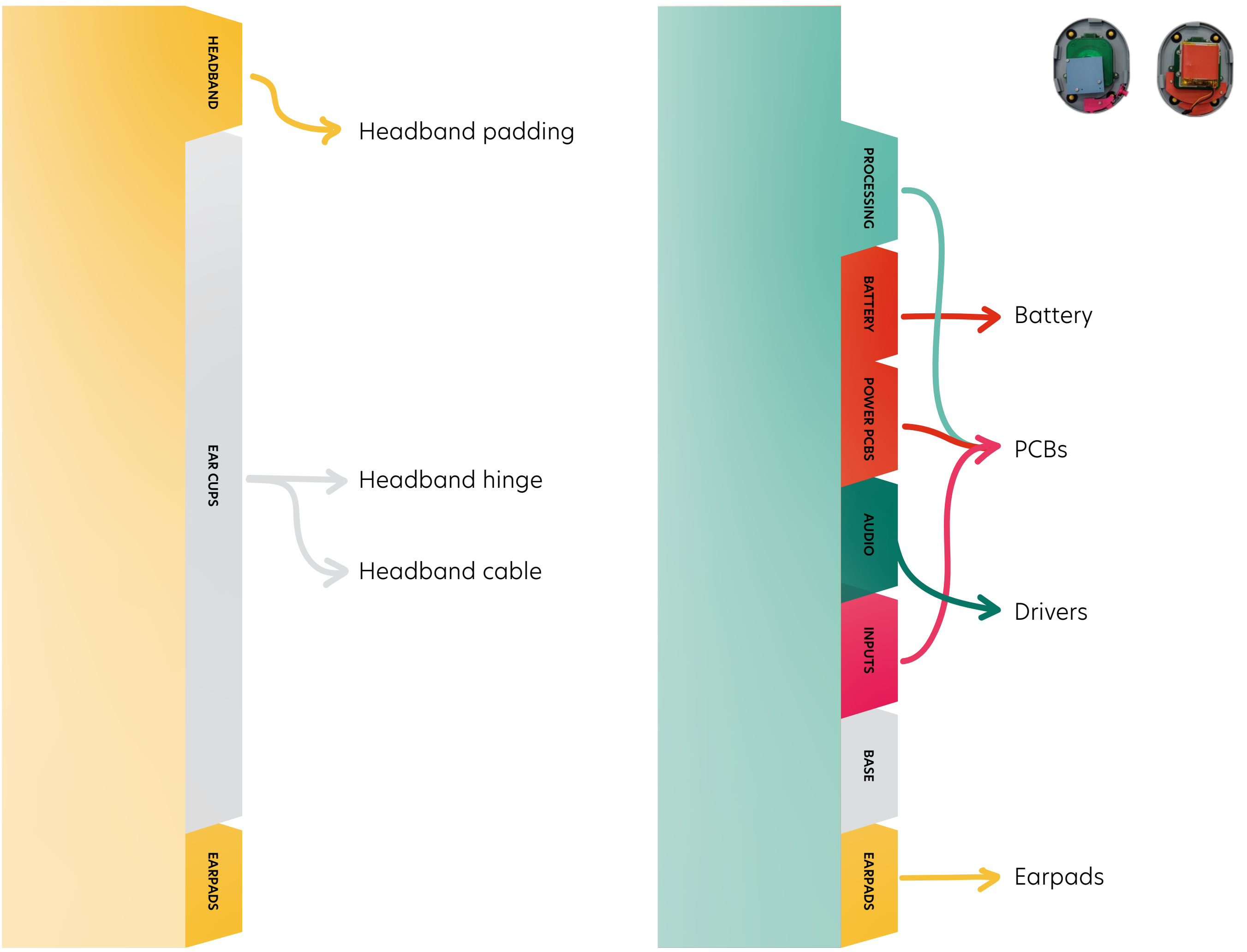


Figure 34. The tabs in the book, and to which critical components they are linked.

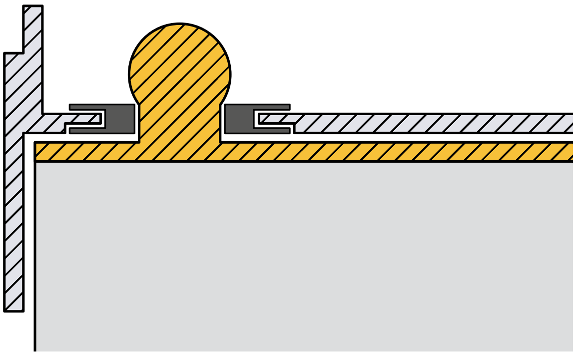


Figure 35. Illustration of the earpad attachment in the book.

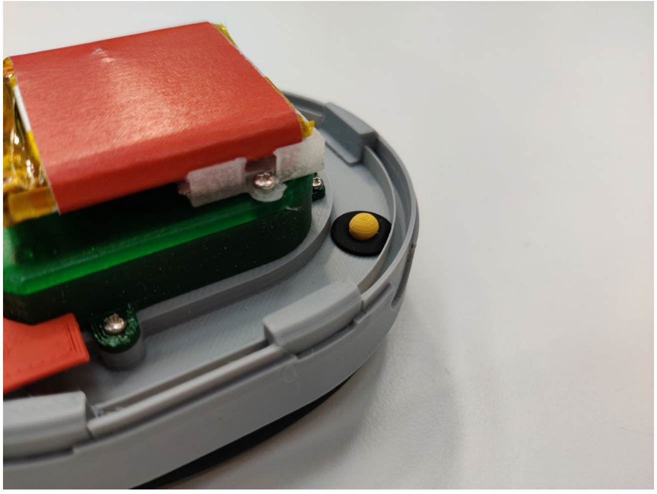


Figure 36. Earpad attachment pin visible through the headphone's earcup base.

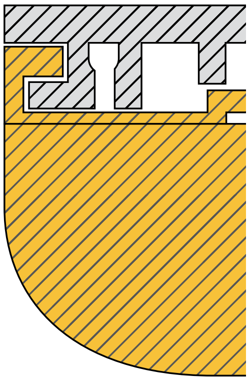


Figure 37. The guiding rails in the headband padding (left), top band (middle), and as shown in an illustration on the headband page in the book (right).

Figure 38. The headband padding can easily be slid on and off.

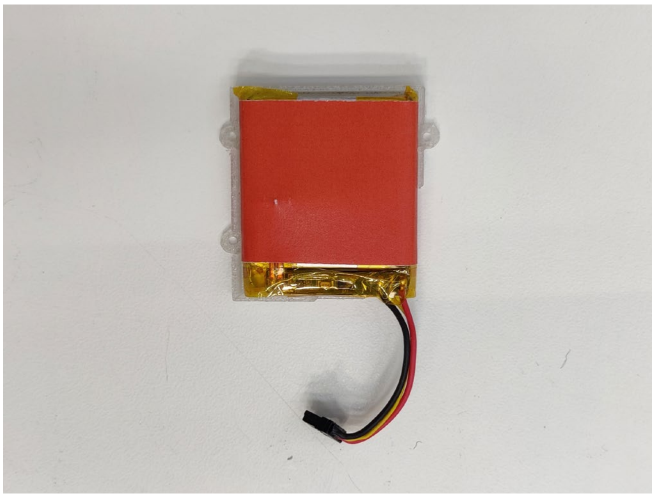


Figure 39. The battery on top of its attachment plate.

8.4 Sequence-independent disassembly

Disassembly becomes unnecessarily time-consuming and complex when parts are stacked in a fixed order. This design avoids that by reducing interdependencies between parts and communicating clearly when a specific sequence of steps is required.

Tabs reflecting the product architecture

The structure of the book directly mirrors the product architecture, and vice versa. However, while the book is built up layer by layer, component by component, this doesn't mean disassembly has to be done in a strict sequence. Instead, the first visible tabs, the headband, earcup, and earpad, represent components that can be reached without opening the earcup. When the user turns the earcup page, mimicking the act of physically opening the earcup, all other tabs for internal components become visible at once. The same thing happens in the headphones: when the user removes the earcup shell, all internal components become visible, just as in the book, see Figure 40.

Independent part accessibility

The product architecture of the headphones are designed to minimise stacking. Once the earcup is opened up, most components can be accessed without having to remove others. For instance, the power board includes a cut-out that allows the USB-C PCB to be reached and unscrewed directly, see Figure 41. This reduces the number of steps and the overall disassembly depth.

Guidance when order does matter

In cases where the order of disassembly is relevant, for example, if a component is blocked by another, the book communicates this explicitly, see Figure 42. This ensures that users are only asked to follow a specific sequence when truly necessary.

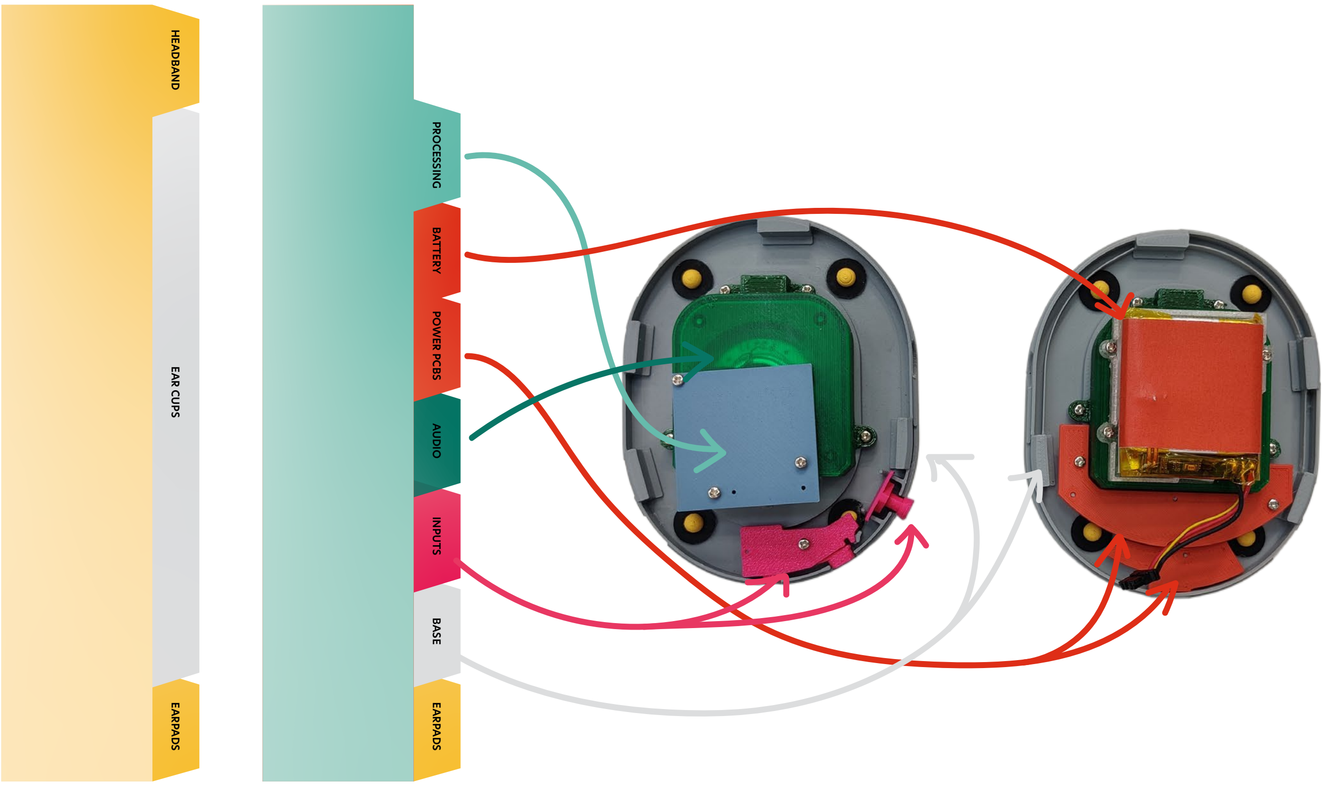


Figure 40. The book's tabs before and after 'opening' the earcup and the corresponding parts in the physical headphones.

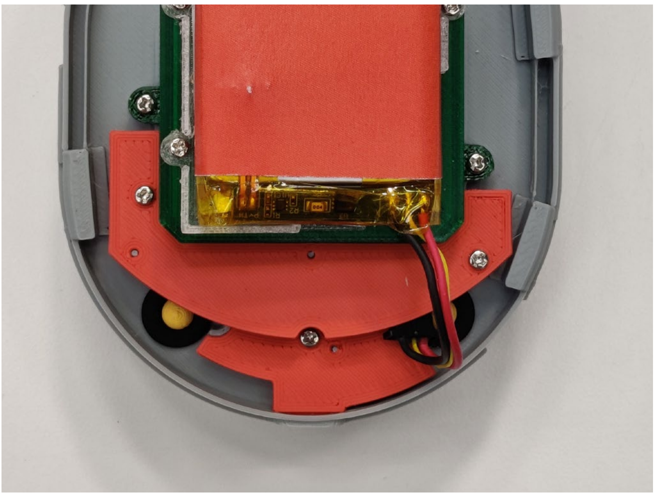


Figure 41. A cut-out in the power board makes the screw of the USB-C PCB accessible for easy removal.

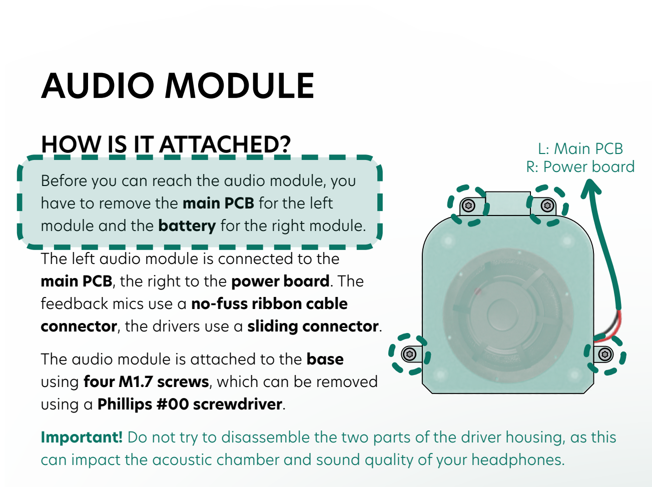


Figure 42. Statement on the audio module page about the disassembly order.

8.5 Limited use of adhesives

Adhesives are avoided wherever possible, specifically for components users are expected to interact with.

Adhesive-free design for self-repair components

Users do not have to interact with glued components during disassemblies and repairs. Instead, all components that users are expected to remove are secured with reversible connections like screws, snap fits, or friction fits.

Instead of a touch sensor for playback control like in the WH-1000XM5, which needs to be glued to the inside of the earcup housing, a joystick input is used. This joystick is mounted on its own PCB, which slots into the base of the earcup and is held in place by the shell, see Figure 43.

Use of adhesives in the modules

When adhesives are used, they are limited to securing components within the modules that users replace as a whole. For example, adhesives are still used to attach the drivers and feedback microphones to their housing, the battery to its plate, and the ANC microphones to the base, see Figure 44.

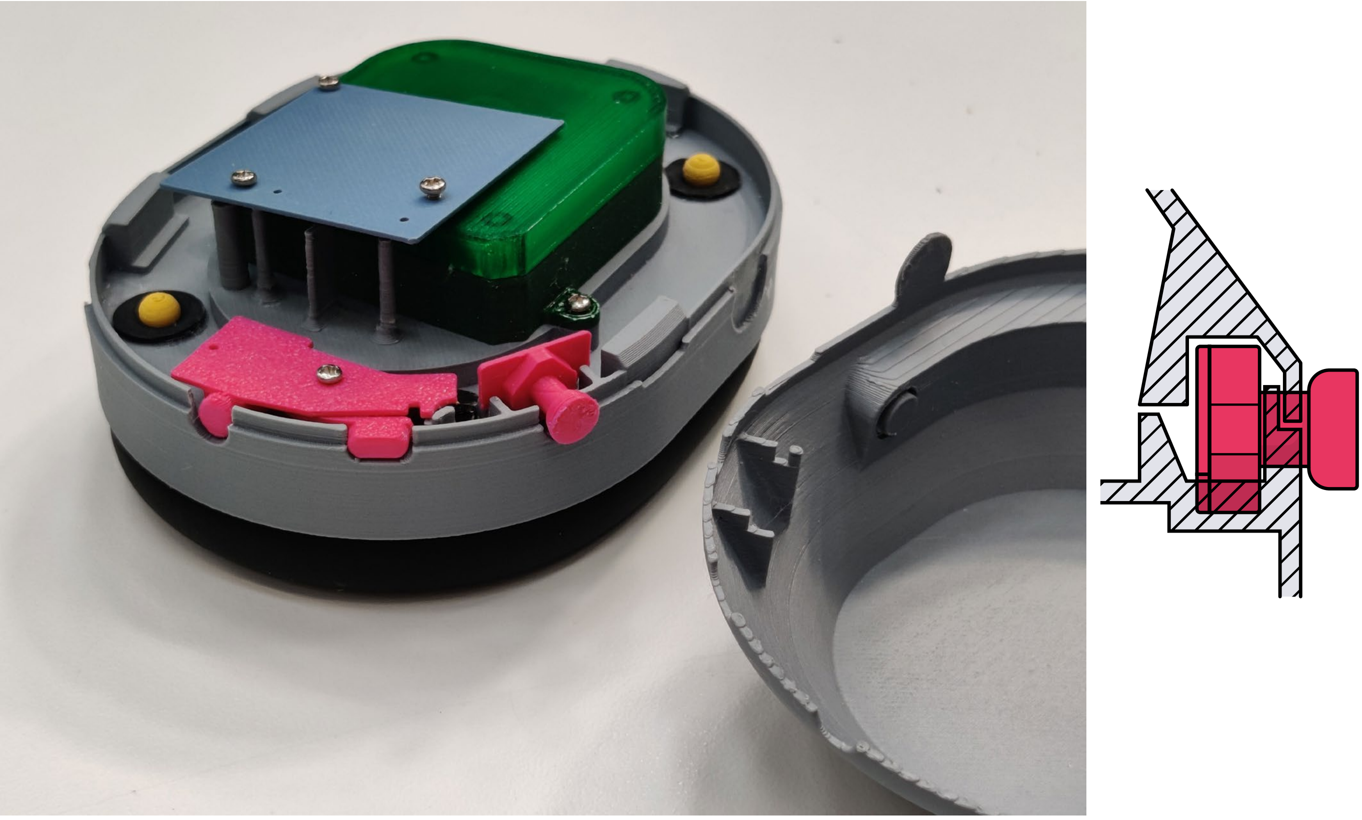


Figure 43. The joystick PCB slots into the earcup base and gets clamped by the earcup shell.

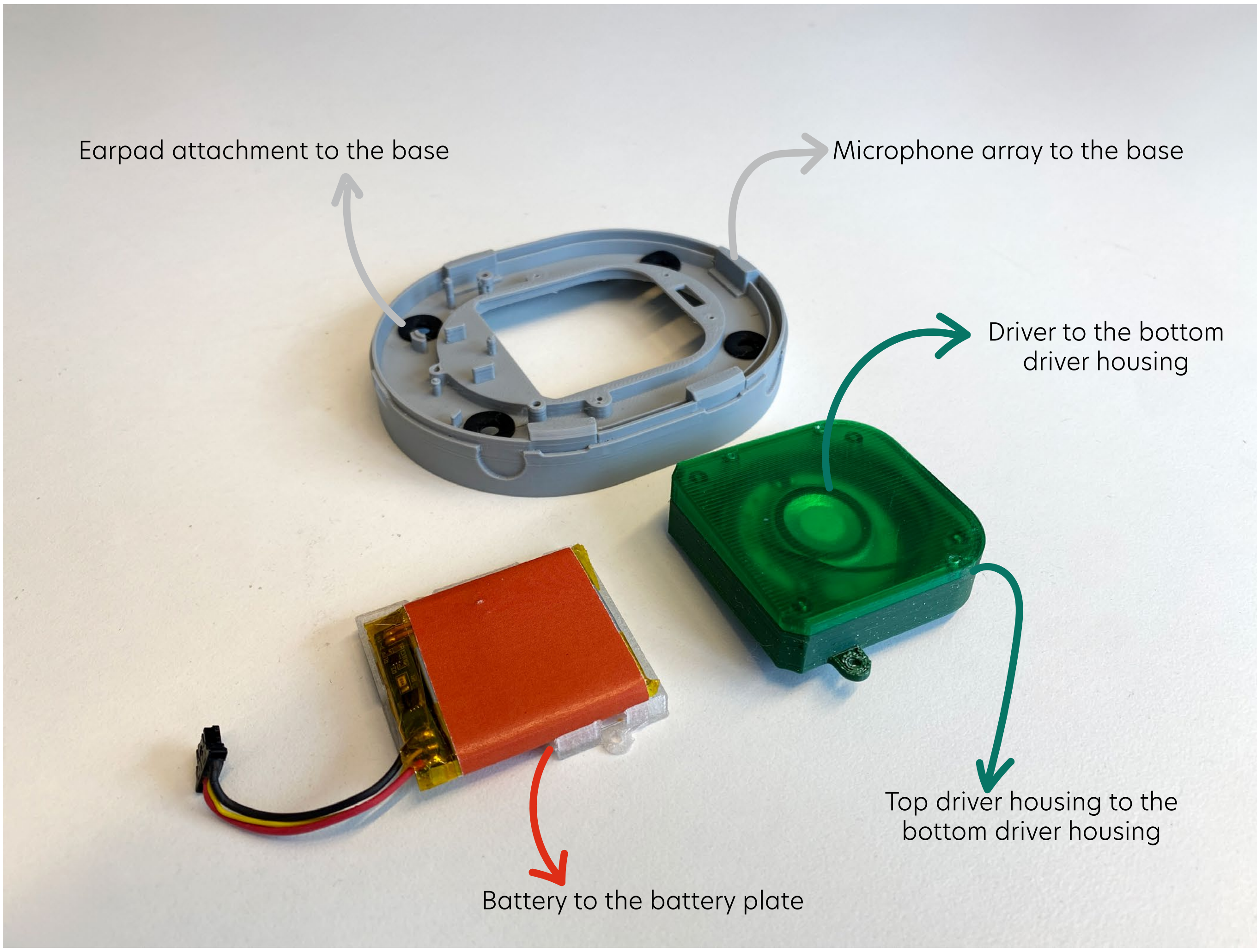


Figure 44. Glue is still used in some modules that are replaced as a whole, such as the battery, earcup base and audio modules.

8.6 Intuitive disassembly

To make disassembly more intuitive, both the book and the headphones are designed to guide the user step by step, both visually and structurally.

The book as the disassembly process

The book is the user's first introduction to the disassembly process and plays a central role in making it intuitive. Its structure mirrors the real-world layering of the headphone: each page represents a different layer, and the tabs guide the user through the headphone one component or cluster of components at a time. The transparent cut-outs in the book also accurately shows how the headphone should be positioned for disassembly, see Figure 46.

This orientation and structure is also reflected in the headphone itself. All components are accessible from one side, just like in the book, so users don't need to rotate the product during disassembly, see Figure 47.

Differentiating by colour

While both the book and the design on the headphone heavily rely on transparency, transparency alone isn't enough to clarify the internal layout, especially when users aren't familiar with electronic components. A clear example of this are the headphones by MONDO By Defunc, see Figure 45. These headphones have a transparent housing, but its all-black components visually blend together, making it hard to identify them.

To clearly distinguish components in both the book and the headphones, six different bright colours are used, see Figure 46 and Figure 47. These colours ensure that individual parts remain visible through the transparent sheets, even with multiple sheets stacked on top of each other. In the headphones, the colour coding creates visual clusters that prevent components from blending together, making it easier to identify and locate parts, and understand their relationships.

Visible instead of hidden fasteners

A key part of intuitive disassembly is showing users where and how to open the product. In this design, connectors are deliberately made visible, especially the connectors for the earcup housing, which are usually hidden in headphones. Here, the shell is held in place with visible snap fits, so users can immediately understand how the housing is attached and feel confident in their ability to open the product, see Figure 48.

This emphasis on visibility is also reflected in the book, where each component page includes a 1:1 scale illustration of all fasteners used for that component, see Figure 50. This not only helps users recognise what fasteners to expect during disassembly, but also supports correct reassembly by making it easier to identify and match the correct fasteners.

Figure 45. Difficult to identify internal components in the transparent Freestyle and Over-Ear headphones by MONDO by Defunc (Amazon, n.d.; Tweakers, n.d.).

Figure 46. The transparent pages in the book show the headphones in the correct orientation for disassembly. The use of different colours stops the components from blending together.

Figure 47. The orientation of the headphones for disassembly is the same as the headphone orientation in the book. The use of different colours creates visual clusters, guiding the user..

Figure 48. Visible snap fits keep the two halves of the earcup housing together.

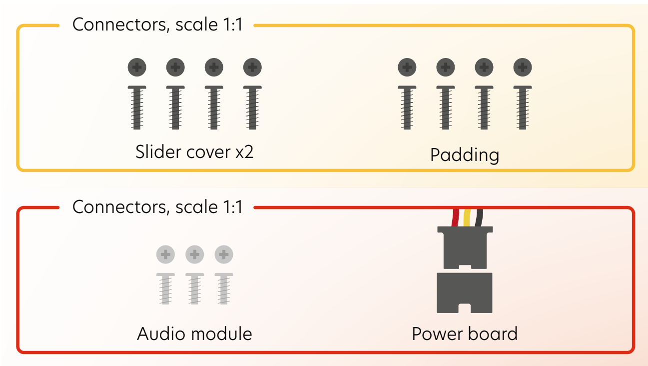


Figure 50. Information on the used fasteners of the headband and battery, as shown in the Page by Page book.

8.7 Eliminating the black box: transparency & clarity

The headphone and the accompanying book are designed to make all components and systems visible and understandable from the start. Transparency is used both visually and structurally to give users insight into the product from the moment they unbox it.

The book as an X-ray

Each page of the book features a cut-out with a transparent polyester sheet with the component, or cluster of components. Because the prints themselves are semi-translucent, the full stack creates an almost X-ray-like view of the entire headphone, where all components are visible, see Figure 51. This allows the user to see inside their headphones, without physically opening them.

The same idea of transparency and component visibility is applied in the headphones. Visible snap-fits in the housing show how to open the headphone, transparent structural parts reveal components that would typically be hidden and strategic cut-outs in the components reveal underlying components and fasteners.

Colour-coding by function

To make the headphones more understandable to users, the book provides information about the headphones as a whole, its subsystems, and individual components. Each subsystem, or function, is assigned a colour, which is used consistently across all related pages and components, see Figure 52. This same colour-coding is used in the headphones, helping users visually identify the function of each part at a glance, see Figure 53.

Information supply

The component pages in the book offer in-depth explanations of how different parts work, how they relate to one another, and background information that goes beyond just listing component names and functions. For example, the audio module page includes a description of how speaker drivers function, see Figure 54. This helps users gain a clearer understanding of the inner workings of their product as a whole. In addition, the pages contain information on common errors, their potential causes, and tips for proper care and maintenance.

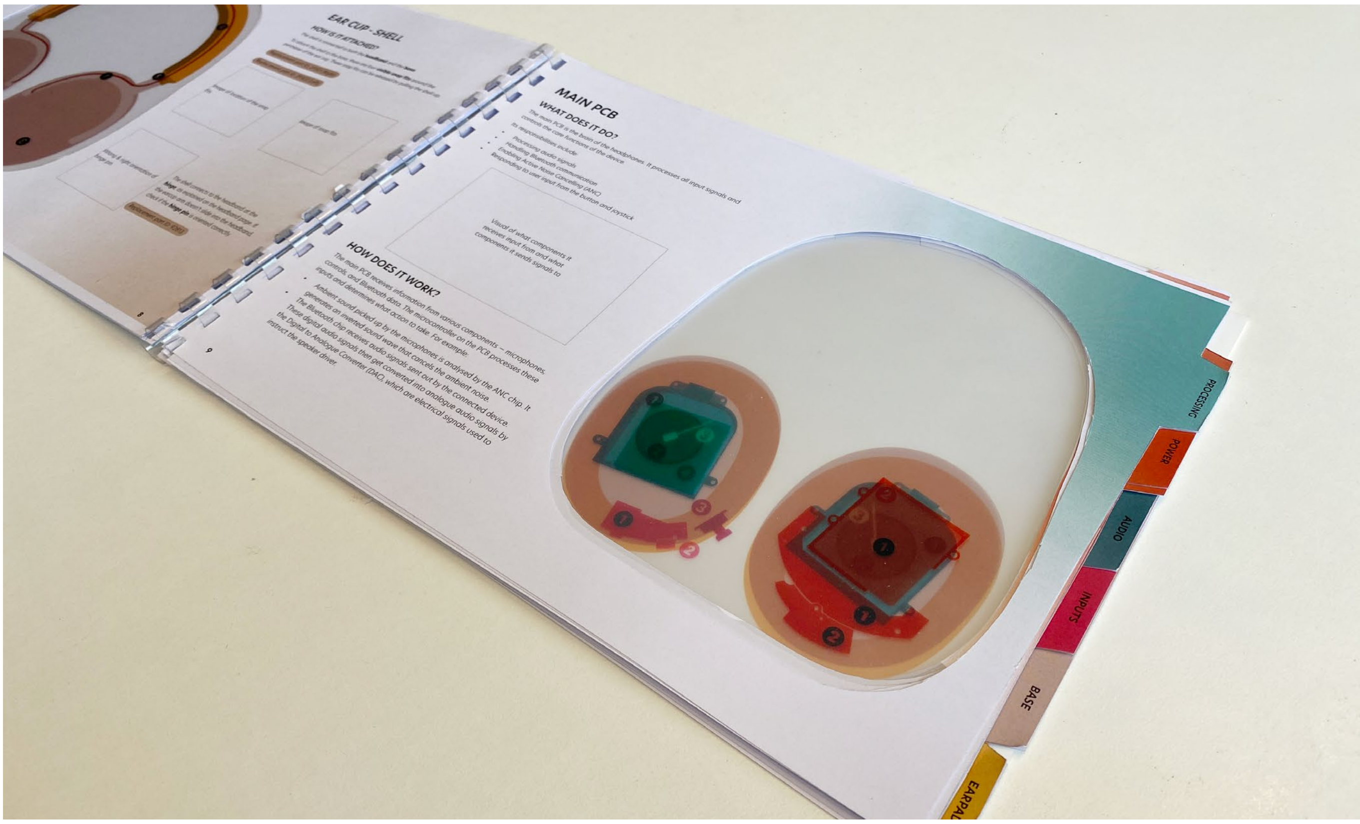


Figure 51. An X-ray like view of the headphones is created by the semi-translucent components in the cut-outs.

OVERVIEW

The headphone can be divided into 6 different functions: **Comfort**, **Structural**, **Power**, **Processing**, **Audio**, and **Sensing**.

Comfort ensures the correct fit of the headphones and that you can wear them for prolonged periods of time. It consists of the **headband** and the **earpads**.

Structural ensures the structural integrity of the headphone and protection of internal components. It consists of the **shell** and the **base**.

Processing is the brain of the headphones. It receives all the information, and gives commands to the drivers so you hear your music. It consists of the **main PCB**.

Power ensures all electrical components get the energy they need to fulfil their function and enables wireless use. It consists of the **battery**, the **power board**, and the **USB-C PCB**.

Audio transforms the electrical signals given by the main PCB get transformed into sound waves. It includes the **audio module**.

Sensing ensures that you as a user can control your headphones. It consists of the **input PCB** and the **joystick PCB**.

4

Figure 52. Colour-coding by function in the book makes components visually distinct from each other..

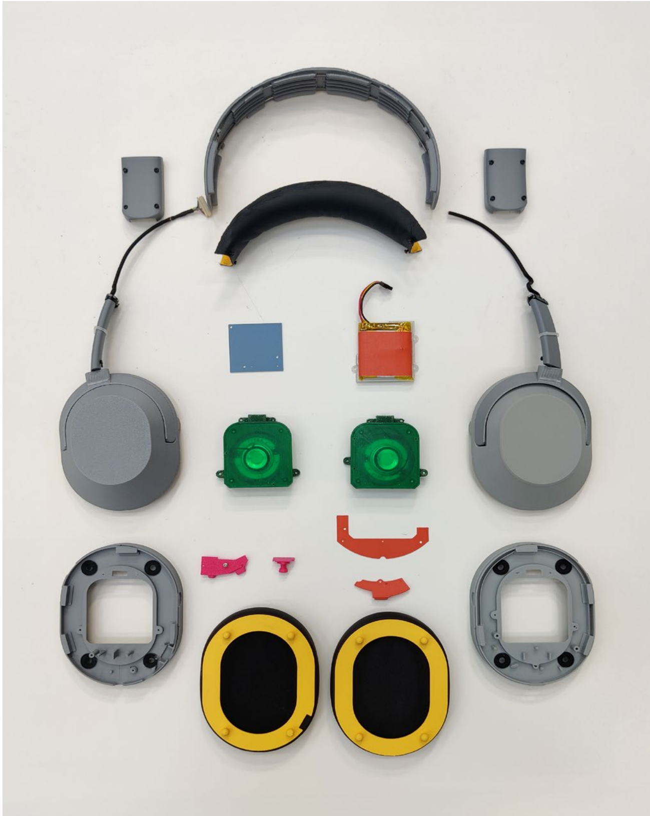
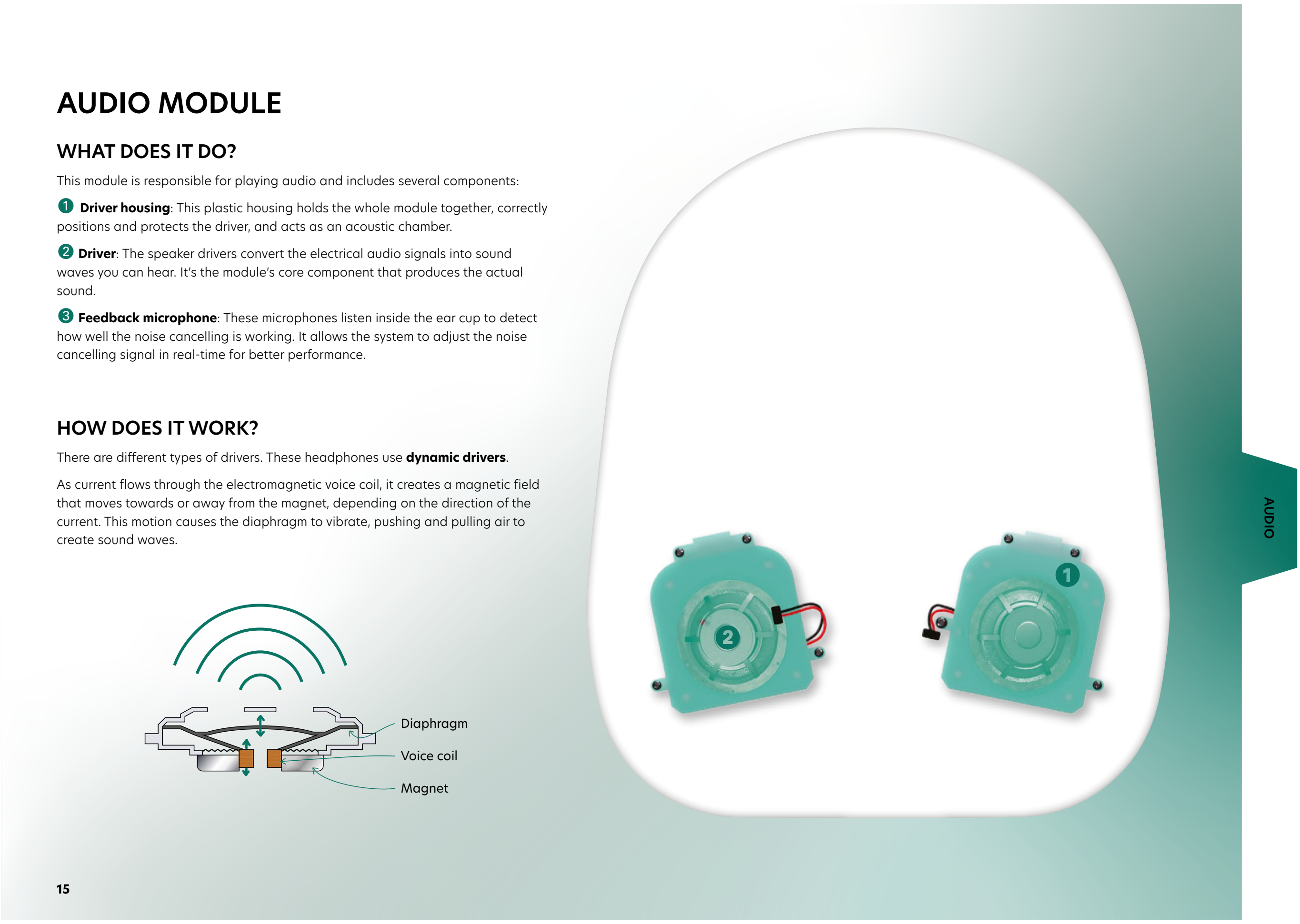


Figure 53. The same colour-coding as in the book is used throughout the headphones.



AUDIO MODULE

WHAT DOES IT DO?

This module is responsible for playing audio and includes several components:

1 **Driver housing**: This plastic housing holds the whole module together, correctly positions and protects the driver, and acts as an acoustic chamber.

2 **Driver**: The speaker drivers convert the electrical audio signals into sound waves you can hear. It's the module's core component that produces the actual sound.

3 **Feedback microphone**: These microphones listen inside the ear cup to detect how well the noise cancelling is working. It allows the system to adjust the noise cancelling signal in real-time for better performance.

HOW DOES IT WORK?

There are different types of drivers. These headphones use **dynamic drivers**.

As current flows through the electromagnetic voice coil, it creates a magnetic field that moves towards or away from the magnet, depending on the direction of the current. This motion causes the diaphragm to vibrate, pushing and pulling air to create sound waves.

15

Figure 54. The page for the audio module, containing in-depth information about speaker drivers.

8.8 More than modularity

While the concept builds on modularity, it takes it a step further by putting the relationship between the user and their product at the centre. Modularity becomes one of several tools—alongside transparency, clarity, and information supply—to support this relationship. The concept not only aims to make parts easy to replace, but also emphasises care, maintenance, and the end-of-life of both individual components and the headphones as a whole.

Guidance for the end-of-life

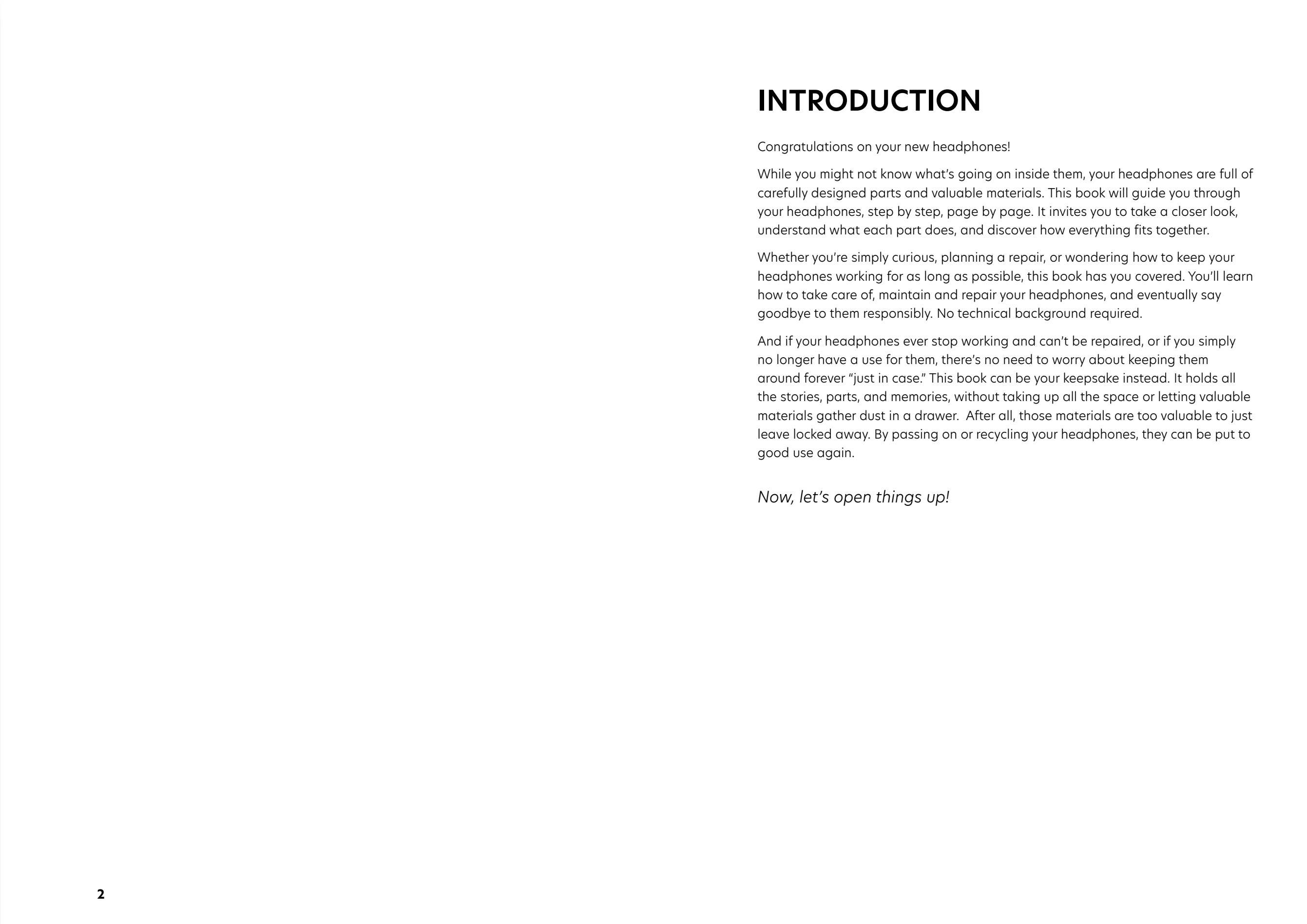
The book provides guidance on proper end-of-life actions and emphasises that headphones should not end up collecting dust in a drawer, see Figure 56. Instead, it invites users to give the product, or its materials and components, a second life. It starts off with explaining where and how to discard components responsibly and gives users links to order replacement parts, see Figure 57.

Smarter use of modularity

The headphones themselves still use modularity as a key strategy, but do so with more nuance. Instead of combining all critical components into a single earcup module, the design divides these across smaller, more accessible modules. This reduces the chance that a failure in a single part will require replacing multiple functioning, valuable electronic components. Figure 55shows all individually replaceable components and modules.

Together, the headphones and the book promote a more layered, thoughtful interpretation of modularity—one that enables maintenance and repair at a smaller scale, while also guiding users through the full lifecycle of their product.

Figure 55. The headphone separated into all its individually replaceable parts and modules .



INTRODUCTION

Congratulations on your new headphones!

While you might not know what's going on inside them, your headphones are full of carefully designed parts and valuable materials. This book will guide you through your headphones, step by step, page by page. It invites you to take a closer look, understand what each part does, and discover how everything fits together.

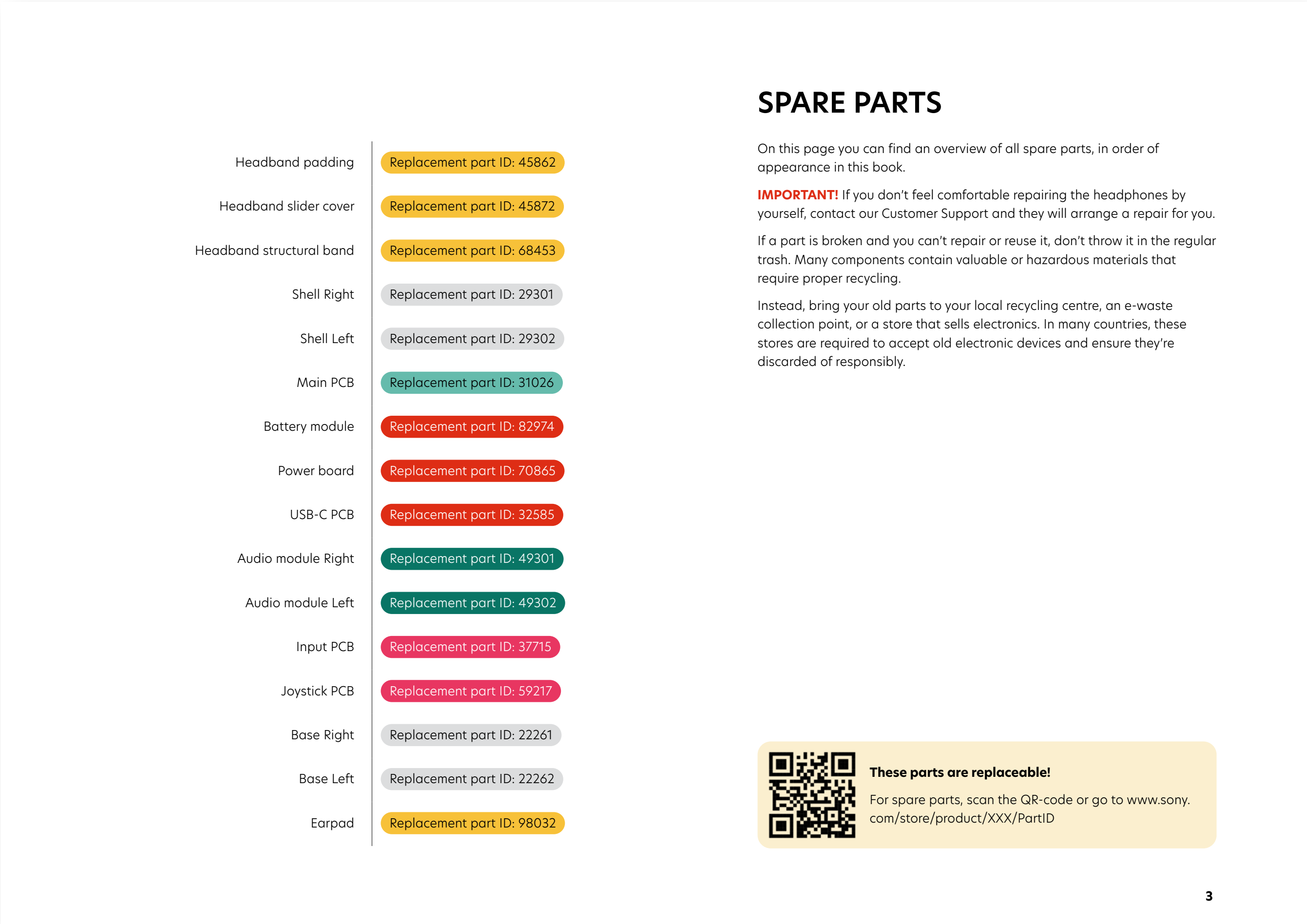
Whether you're simply curious, planning a repair, or wondering how to keep your headphones working for as long as possible, this book has you covered. You'll learn how to take care of, maintain and repair your headphones, and eventually say goodbye to them responsibly. No technical background required.

And if your headphones ever stop working and can't be repaired, or if you simply no longer have a use for them, there's no need to worry about keeping them around forever "just in case." This book can be your keepsake instead. It holds all the stories, parts, and memories, without taking up all the space or letting valuable materials gather dust in a drawer. After all, those materials are too valuable to just leave locked away. By passing on or recycling your headphones, they can be put to good use again.

Now, let's open things up!

2

Figure 56. The introduction page of the book encouraging users to give their headphones a second life.



Headband padding	Replacement part ID: 45862
Headband slider cover	Replacement part ID: 45872
Headband structural band	Replacement part ID: 68453
Shell Right	Replacement part ID: 29301
Shell Left	Replacement part ID: 29302
Main PCB	Replacement part ID: 31026
Battery module	Replacement part ID: 82974
Power board	Replacement part ID: 70865
USB-C PCB	Replacement part ID: 32585
Audio module Right	Replacement part ID: 49301
Audio module Left	Replacement part ID: 49302
Input PCB	Replacement part ID: 37715
Joystick PCB	Replacement part ID: 59217
Base Right	Replacement part ID: 22261
Base Left	Replacement part ID: 22262
Earpad	Replacement part ID: 98032

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On this page you can find an overview of all spare parts, in order of appearance in this book.

IMPORTANT! If you don't feel comfortable repairing the headphones by yourself, contact our Customer Support and they will arrange a repair for you.

If a part is broken and you can't repair or reuse it, don't throw it in the regular trash. Many components contain valuable or hazardous materials that require proper recycling.

Instead, bring your old parts to your local recycling centre, an e-waste collection point, or a store that sells electronics. In many countries, these stores are required to accept old electronic devices and ensure they're discarded of responsibly.

These parts are replaceable!

For spare parts, scan the QR-code or go to www.sony.com/store/product/XXX/PartID

3

Figure 57. The book includes a page containing an overview of all spare parts and what to do with your broken components.

Evaluate

9. Concept validation

9.1 Expert validation

This chapter addresses *RQ6.1 What are the potential pain points of the concept?* To identify weak spots in the design, both the headphones and the accompanying book were critically reviewed by a person with extensive experience in disassembling and repairing small electronics. Their feedback provides insight into areas where the concept could be improved, particularly with regard to user experience, clarity and reassembly.

Tool compatibility

The concept uses small screws that are standard in small electronics but not compatible with the tools most users typically have at home, a flathead and Phillips 1 screwdriver. This means they likely won't be able to open the product without buying additional tools. Since using larger screws isn't feasible due to the size of the components, one potential solution is to include the correct screwdriver with the product. Torx screws are preferred due to their lower risk of stripping.

Screw differentiation

Although the 1:1 illustrations in the book already support users in screw recognition, it was suggested to further improve clarity by implementing visual strategies such as colour coding screws by length or providing an overview that shows all screw types and where they belong.

Cable connectors

The use of ribbon cables was flagged as a potential issue due to their fragility and tendency to bend when inserting them. Replacing them with connectors that produce a tactile 'click' when inserted could help users feel more confident that components are correctly reconnected. However, as ribbon cables are often hard to avoid in small electronic products, it is recommended to use zero insertion force (ZIF) connectors when they are used. These connectors reduce the risk of damage.

Button reassembly

The fact that the button is mounted using the same screw as the PCB is a positive point. However, during reassembly the button tends to rotate, making it difficult to position correctly. Adding a keyed feature to the button (e.g., a flat side or notch) would keep it in place and oriented properly while the screw is being tightened.

Keying of parts

Just like with the button, the feedback emphasized the importance of keying throughout the design. Users often operate on autopilot, and mistakes should be prevented by design. Similar to how printer cartridges are keyed by color, modules should only fit one way to reduce error.

Visual boundaries between modules

For modules that are not intended to be opened by users, a smooth continuous surface and using the same material and colour can help signal this. This reduces the impression that the parts can come apart.

Book structure and layout

It was not immediately clear that spreads in the book did not correspond to the same part. Stronger visual separation could reduce misinterpretation. Additionally, the expert instinctively tried to begin disassembly as soon as they reached the first page of the component, while the disassembly information is on the back of the page.

Orientation of illustrations

For the illustration about the controls, showing the headphones as they are worn and describing their function in relation to how the user wears them (e.g., front/back or facing toward/away from face rather than left/right) could help overcome confusion about orientation and make it easier to apply in practice.

Conclusion

Overall, the expert validated the concept's potential. However, their observations also point to small usability flaws that could impact the reassembly experience or confuse users. Many of these pain points can be addressed through relatively minor design changes, such as improved keying, clearer orientation cues, and minor layout adjustments in the book.

9.2 Comparing to requirements

This chapter evaluates to what extent the final design meets the requirements defined in Chapter 6.4. Each requirement is assessed based on whether it is fulfilled by the concept, with a short explanation as to why it is or isn't met. The assessment can be found in Table 7.

Most requirements are met, particularly those concerning ease of disassembly, component accessibility and visibility, and user guidance. This is largely thanks to the book. However, some aspects, such as product attachment and user confidence, are difficult to evaluate without extensive user testing. This means it is unclear whether some of the requirements have been met.

Table 7. Evaluation of the concept according to the requirements defined in Chapter 6.4.

ID	Requirement	Met?	Explanation
KF1.1	The product should clearly communicate which components are meant for self-repair and which require professional repair services.	Yes	The book only contains disassembly information and replacement part IDs for components intended for self-repair.
KF2.1	Critical components should be individually replaceable.	Partially	All PCBs can be individually replaced. The battery and drivers are both the only critical component in a module. However, the hinge and cable are part of the same module.
KF3.1	Critical components should be accessible within 5 disassembly steps.	Partially	Disassembly depth of the battery and USB-C PCB is 2, and of the drivers 3. That of the module containing the hinge and headband cable is 6.
KF3.2	The headband padding and earpads should be individually replaceable.	Yes	
KF3.3	The headband padding and earpads should be accessible within 1 disassembly step.	Yes	Both have a disassembly depth of 1 and can be removed without removing other components.
KF4.1	The maximum disassembly depth should be ≤ 20.	Yes	Maximum disassembly depth is 7
KF4.2	Once the shell has been removed, components inside the earcups should not be dependent on the removal of more than two other components.	Partially	When considering disassembly at a module level, only the base requires more than two components to be removed (5 left, 4 right).
KF5.1	Users should be able to disassemble the headphones without the use of heated tools.	Yes	The only tool needed is a screwdriver.

ID	Requirement	Met?	Explanation
KF5.2	Critical components should use reversible and reusable fasteners.	Partially	The modules that critical components are part of do, but the battery and speaker drivers are glued to their module's housing.
KF5.3	Critical components should be reachable without having to undo non-reusable connectors.	Yes	There are no non-reusable connectors at a module level.
KF6.1, KF7.4 & B1.2	Connectors should be visible or clearly indicated.	Partially	All connectors that users would need to undo are visible, connectors not meant for self-repair are not.
KF6.2 & B1.1	Components should not hide or obscure other components.	Yes	Strategic cut-outs, component placement, and transparent structural components make components visible.
KF6.3	The use of cantilever snap fits should be avoided.	Yes	
KF6.4	The number of total parts should be reduced.	Yes	The original WH-1000XM5 has 87 parts, the redesign 52.
KF6.5	The number of different tools required for disassembly should be reduced.	Yes	The original WH-1000XM5 used 7 tools, including two different screwdrivers, the redesign only requires one screwdriver.
KF6.6	The number of screws should be reduced.	Yes	The original WH-1000XM5 used 46 screws, the redesign uses 42
KF6.7	Users should be guided through the disassembly process	Yes	The book guides users through the disassembly, but users do have to consult it.
KF7.1	Information about the headphones' components, disassembly, and repair should be easily accessible .	Yes	The book contains information about all three points.
KF7.2	The product should educate users about its product architecture and how it functions.	Yes	The book contains in-depth information, but users must seek it out.
KF7.3	The product should encourage user involvement to foster product attachment.	Unknown	User involvement through the interaction with the book and possibilities for self-repair, but effect on product attachment is not proven.
KF8.1	Users should be educated on end-of-life steps.	Yes	End-of-life instructions are included in the book.
KF8.2	Modules should contain a limited number of components and no more than one critical component.	No	The earcup shell module contains 4 components, including the hinge and cable.
V1	The products should provide information about care, repair, and end-of-life steps.	Yes	All covered in the book.
V2	The products should make basic repairs feasible for people without repair experience.	Unknown	Not yet tested, but the book is likely to provide enough guidance.
V3	The products make the product architecture, functioning, and disassembly understandable to non-technical users.	Unknown	Not yet tested
V4	The products encourage regular care and maintenance.	Unknown	Not yet tested
B2.1	The headphone should allow parts to be disassembled in the same order as the book.	Yes	Largely sequence-independent disassembly structure allows for components to be removed in various orders.
B3	All parts should be accessible from one side, without product manipulations.	Yes	Only parts that are not intended for self-repair are not accessible from the orientation used in the book.
B4	There should be a clear visual distinction between parts.	Yes	Parts are colour-coded by function.

9.3 Disassembly map

This section answers *RQ6.2 What is the ease of disassembly of the concept?* Ease of disassembly plays a key role in making the product understandable to users and in circularity as a whole. This chapter evaluates the new headphone concept by comparing its disassembly map to that of the current Sony WH-1000XM5.

Figure 59 shows the disassembly map of the new headphone concept, which was redesigned according to the principles and requirements stemming from the book. For easy comparison, Figure 58 includes both the original Sony WH-1000XM5 disassembly map and that of the redesign.

Some components in the redesigned headphones are grouped into modules. The disassembly of the modules into their individual components is shown in lighter areas in the disassembly map. For this evaluation, only the steps required to reach the modules themselves are considered, as further disassembly is not something that needs to be done by users themselves.

Structure and disassembly depth

Compared to the Sony WH-1000XM5, the disassembly map of the concept is noticeably shallower and more horizontal. The structure is largely sequence-independent, reducing interdependencies between parts compared to the original. This is reflected in the redesign's maximum disassembly depth, which. at 7, is significantly lower than that of the original Sony WH-1000XM5, see Table 8. There are also significant improvements in the disassembly depth of the critical components, meaning components are more accessible and disassembly is easier.

Tool use

Only two tools are needed to disassemble the redesigned headphones, and one of these is only required for accessing internal components within the modules, which users are not expected to do. In contrast, the WH-1000XM5 requires six different tools.

Penalties

The redesign significantly reduces disassembly penalties. It requires fewer product manipulations, such as flipping or reorienting the headphones during disassembly, as all components can be accessed from one side. Non-reusable connectors are avoided entirely when disassembling the modules from the main structure, and are only present within the modules themselves when disassembling them further into individual components.

Conclusion

The disassembly map of the redesigned headphones shows significant improvements in ease of disassembly compared to that of the Sony WH-1000XM5. The reduction in disassembly depth, tools, adhesives, and the more sequence-independent disassembly structure contribute to a product architecture that is easier to understand and disassemble, making it more repair-friendly.

Table 8. Comparison of the disassembly depth of critical parts for the original design of the Sony WH-1000XM5 and the redesign.

	Max. disassembly depth	Battery	Charging port / USB-C PCB	Drivers	Headband hinge	Headband cable	Headband cover
Original Sony WH-1000XM5	46	5	8	10	26	46	28
Redesign	7	2	2	3	6	6	1

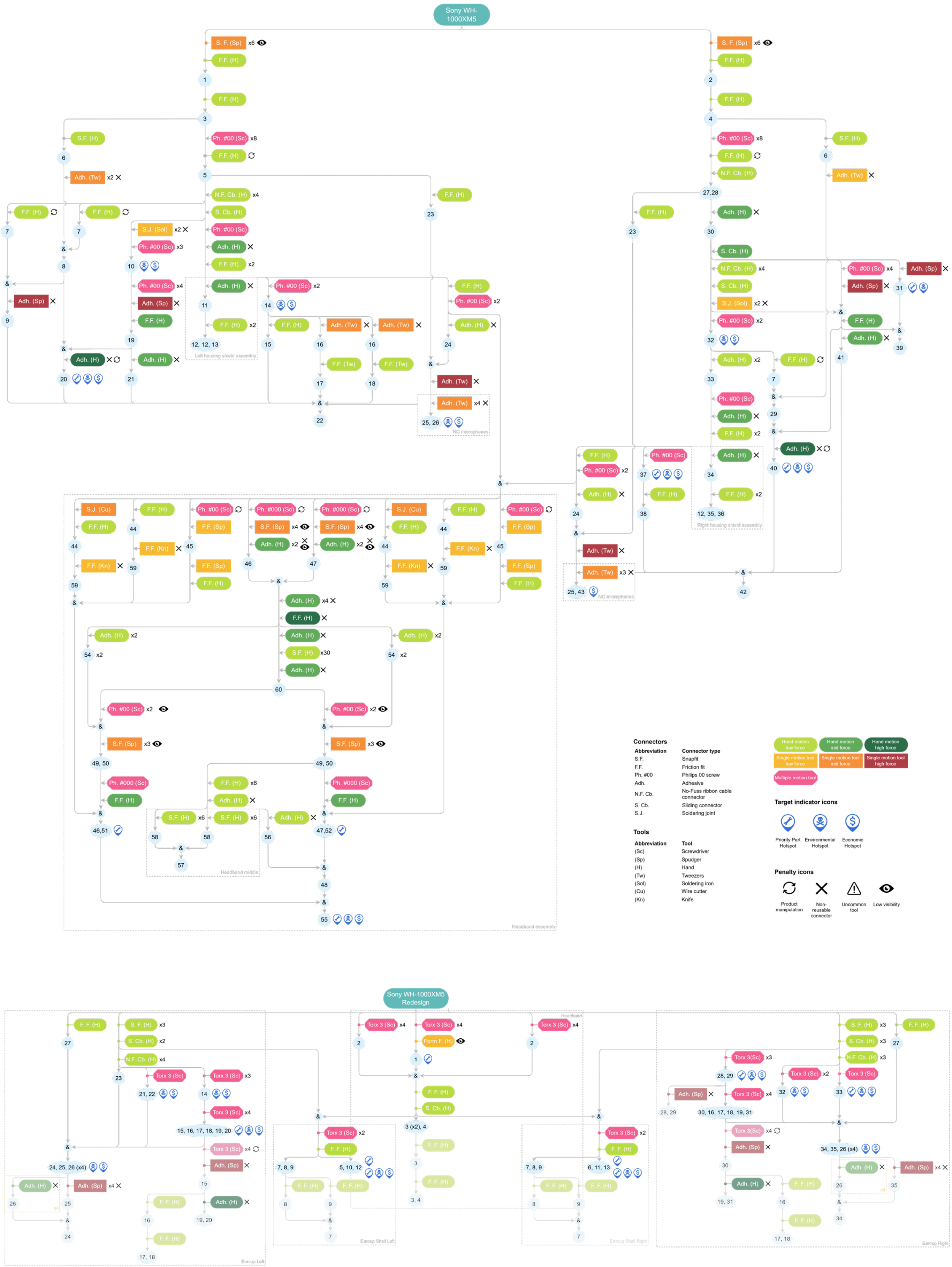
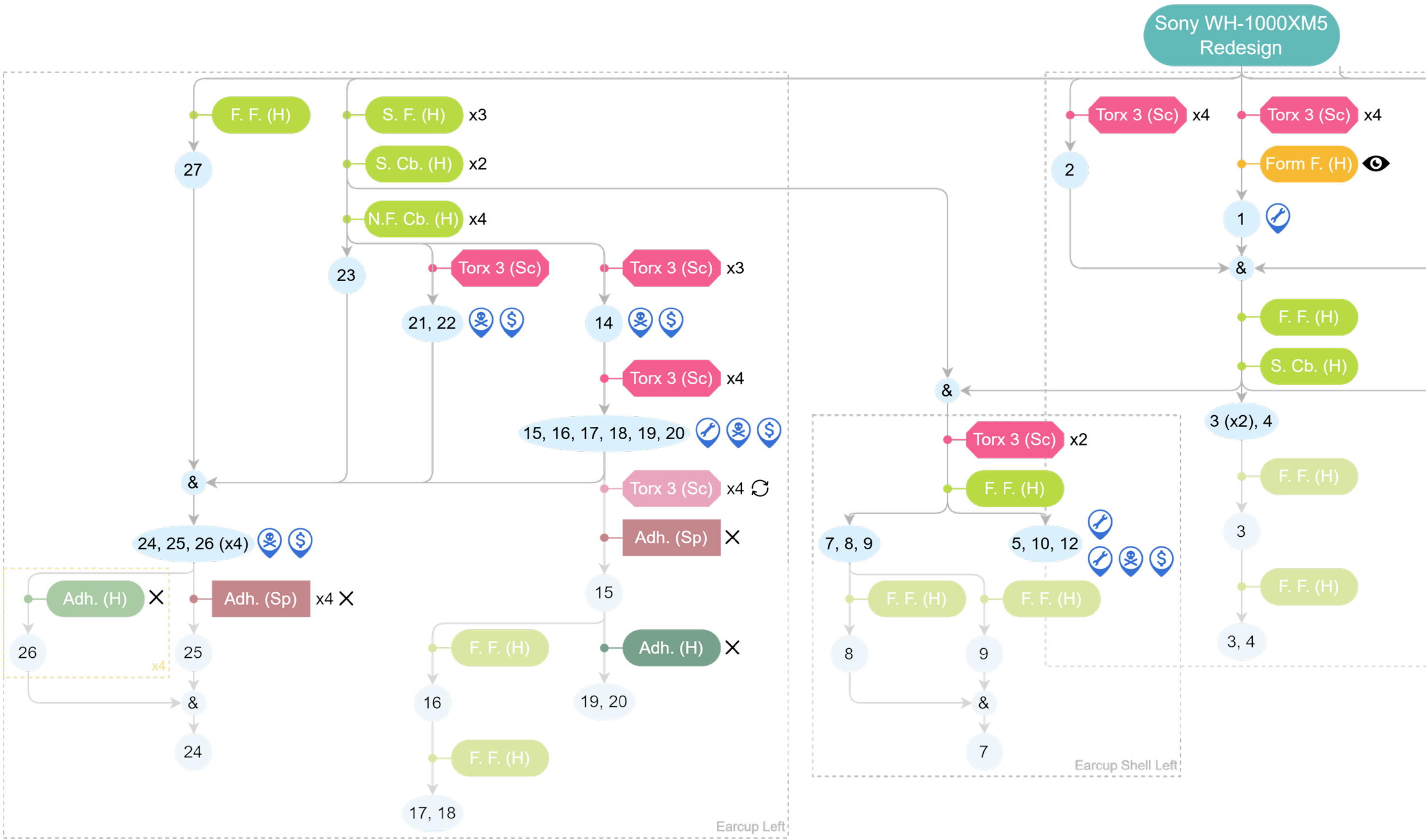
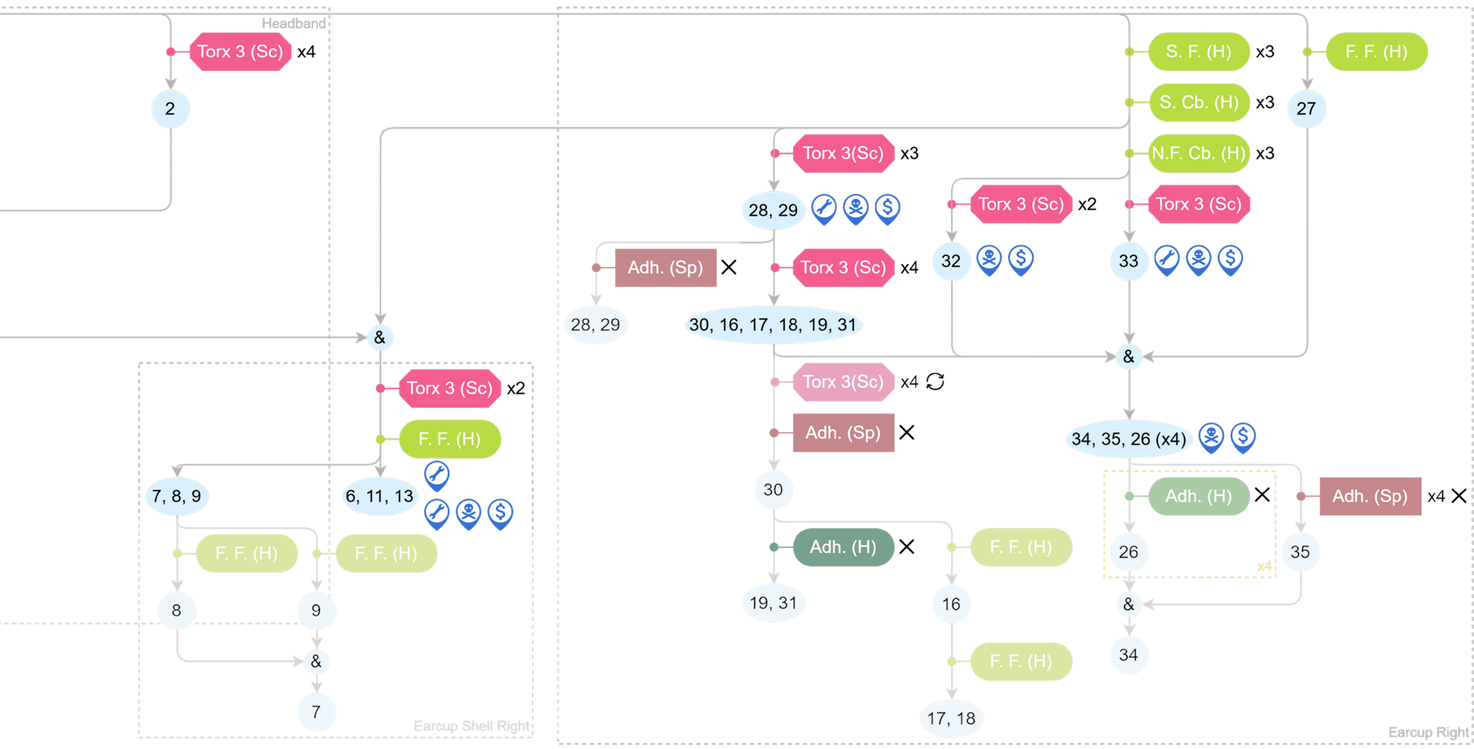


Figure 58. Comparison of the disassembly maps of the original design of the Sony WH-1000XM5 headphones (top) and the redesign optimised for the book (bottom).



1. Headband padding
2. Headband slider cover (x2)
3. Spring steel wire (x2)
4. Headband top band
5. Earcup housing shell Left
6. Earcup housing shell Right
7. Slider (x2)
8. Slider ring (x2)
9. Slider stopper (x2)
10. Headband arm Left
11. Headband arm Right
12. Headband cable Left
13. Headband cable Right
14. Main PCB
15. Driver top housing Left
16. Feedback microphone (x2)
17. Microphone sleeve (x2)
18. Microphone stopper (x2)
19. Driver (x2)
20. Driver bottom housing Left
21. Input PCB
22. Button
23. Joystick PCB
24. Earcup housing base Left
25. Microphone array Left
26. Earpad attachment gasket (8x)
27. Earpad (2x)
28. Battery
29. Battery plate
30. Driver top housing Right
31. Driver bottom housing Right
32. Power board
33. USB-C PCB
34. Earcup housing base Right
35. Microphone array Right

Figure 59. Disassembly map of the redesigned Sony WH-1000XM5 headphones.



Connectors

Abbreviation	Connector type
S.F.	Snapfit
F.F.	Friction fit
Form F.	Form fit
Torx 3	Torx 3 screw
Adh.	Adhesive
N.F. Cb.	No-Fuss ribbon cable connector
S. Cb.	Sliding connector

Hand motion low force | Hand motion mid force | Hand motion high force

Single motion tool low force | Single motion tool mid force | Single motion tool high force

Multiple motion tool

Target indicator icons

Priority Part Hotspot | Environmental Hotspot | Economic Hotspot

Tools

Abbreviation	Tool
(Sc)	Screwdriver
(Sp)	Spudger
(H)	Hand

Penalty icons

Product manipulation | Non-reusable connector | Uncommon tool | Low visibility

10. Conclusion

10.1 Implications for Sony

The findings of this thesis and the resulting concept have several implications for Sony.

Proactive approach to circularity

Although Sony is currently a pioneer in areas such as user experience and technical performance of its products, it has a traditional approach to circularity. This concept demands a shift in mindset that prioritises circularity, even if this means moving away from today's highly complex and feature-rich products toward more simplified and comprehensible product architectures. Rather than waiting for legislation or market pressure, Sony should be proactive and treat circularity as a source of innovation.

Logistical flow

Introducing a range of different spare parts that are directly available to customers would require changes to Sony's current logistics system. A system would need to be established for selling, stocking and shipping parts. This could be via Sony's existing webshop or a dedicated repair platform. However, this would require new infrastructure and a new approach to parts accessibility.

Trusting the user

Designing a product optimised for repair also involves trusting the user and their abilities. To achieve this, Sony would need to move away from delivering closed systems and adopt a more supportive role instead. This would involve providing additional guidance and clear information via online manuals, customer support, and repair services.

These implications go beyond design and touch on Sony's brand identity and how the company relates to its users. Embracing these changes could establish Sony as a leader in sustainable consumer electronics.

10.2 Limitations & recommendations

This thesis proposes a concept for a more circular and repairable pair of headphones and an accompanying book that showcases a different approach to circular design by adapting the product to the way information is supplied. While it covers many key areas, several aspects offer room for further development and validation. This chapter outlines these areas and suggests directions for future work.

User testing and validation

The concept's vision hinges heavily on building user confidence, product understanding and attachment. However, these outcomes are difficult to assess without extensive user testing. As no structured user testing was conducted with the target group, it is unclear whether these goals have been achieved. Additionally, the evaluation session with an expert revealed some unexpected interactions with the book.

Recommendation: Future development should include user testing to assess the book's understandability, its encouragement of circular behaviour, and the effectiveness with which the interaction between product and book supports the project's vision. This testing could also help to address aspects of the book's layout and order that could cause misunderstandings.

Technical detailing

Some technical aspects of the headphone still need to be explored and detailed further.

Currently, the placement and routing of the cables connecting the electronics have only been roughly outlined, even though this has a significant impact on how cluttered the product architecture appears.

While the mechanical fastening solutions in the earcup housing and padding have been prototyped, further testing is required to ensure durability and a secure fit.

The headphones themselves have also been simplified for the feasibility of this project, with certain features (e.g. the proximity sensor) left out, despite Sony positioning itself as a company that focuses on high-end products incorporating the latest technical advancements.

Recommendation: Explore and validate the technical and mechanical details through a more thorough embodiment, including cable routing, fasteners, and incorporating all the components found in existing Sony headphones.

Manufacturability

The scope of this project ended at the prototyping stage. This means that the plastic components and custom electronics of the headphones have not yet been designed with large-scale manufacturing in mind. In addition, while a small batch of the book was professionally printed, the production logistics and scalability of the book still need to be explored.

Recommendation: Apply design for manufacturing principles and assess production feasibility for both the headphones and the book.

Division into modules

The current division of the headphones into 16 replaceable parts and modules may raise questions about necessity, user convenience and feasibility within Sony's existing systems.

Additionally, while I set out to make all critical components individually replaceable, the hinge and headband cable have been grouped into the same module for the sake of simplification in this book.

Recommendation: Re-evaluate the modular breakdown with input from users and Sony stakeholders. Investigate whether certain components could be grouped differently, or whether fewer modules would still effectively support repair and sustainability goals.

Cost and perceived value

A cost breakdown was not within the scope of this project. As a result, the cost of the concept remains unknown, as does whether users perceive the book to offer added value.

Recommendations: To evaluate commercial viability, future work could assess production costs and conduct user studies on willingness to pay for the headphones and book.

Product flow and logistics

The concept focused on the physical product and its support system. However, the practicalities of ordering and distributing spare parts for both Sony and users have not yet been mapped out.

Recommendations: Investigate logistical models for spare parts supply, user interfaces for ordering and back-end systems.

Environmental impact assessment

The aim of adding the book is to encourage more circular user behaviour. However, introducing an additional product inevitably has an environmental impact. It has not yet been evaluated whether the total impact would be net positive compared with standalone headphones.

Recommendation: Conduct a comparative life cycle assessment to evaluate the environmental trade-offs of the concept. This would help determine whether the addition of support materials, such as the book, has a positive overall impact.

Brand alignment

The final concept was founded on the principle of circularity. Although the design was based on an existing pair of Sony headphones, the brand itself played a smaller role.

Recommendation: To better align with Sony's brand identity and strategies, future research should focus specifically on Sony products.

Visual identity

The concept took the current design of the Sony WH-1000XM5 headphones as a starting point, with the aim of improving clarity, structure and repairability. While some elements have been changed, such as the addition of snap fits or the repositioning of the headband arm outside the earcup, there has been little exploration into creating a cohesive design language or using product aesthetics to set the concept apart.

Recommendation: Investigate how product aesthetics can complement and support the overall concept and create a cohesive design.

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11. Appendix

Appendix A – Project brief

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Circular redesign of over-ear wireless headphones

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

We are consuming resources at a rate that exceeds the earth's capacity to regenerate them, making sustainability and circularity increasingly important topics. Consumer electronics, in particular, contain valuable and critical raw materials such as raw-earth metals and precious minerals, with only a small percentage being properly recycled. The lifecycle of consumer electronics is predominantly linear: products are typically bought new and rarely repaired before being thrown away. In Europe, e-waste amounts to 17.6 kg per capita, with the majority coming from small electronics (Baldé et al., 2024).

Adopting circular models in consumer electronics can reduce their environmental impact by retaining as much value as possible and extending product lifecycles. The Value Hill model by Achterberg et al. (2016) provides a visual overview of the circular strategies involved in value retention. Achieving full circularity involves not only product design (micro level) but also business strategy (meso level) and product flow (macro level). Over-ear wireless headphones, the focus of this project, have seen less progress in circular design compared to other small electronics like smartphones and tablets.

Circularity is also becoming more important for Sony, partially due to (impending) legislations and consumer demand. Circular business models present new opportunities, such as offering spare parts to ensure long-term customer relationships. Additionally, more circular products can benefit consumers by lasting longer and offering greater modularity and customisability. However, to ensure customers actually choose more circular products, it is crucial that the experience, ease of use, and quality are not affected.

Sources:
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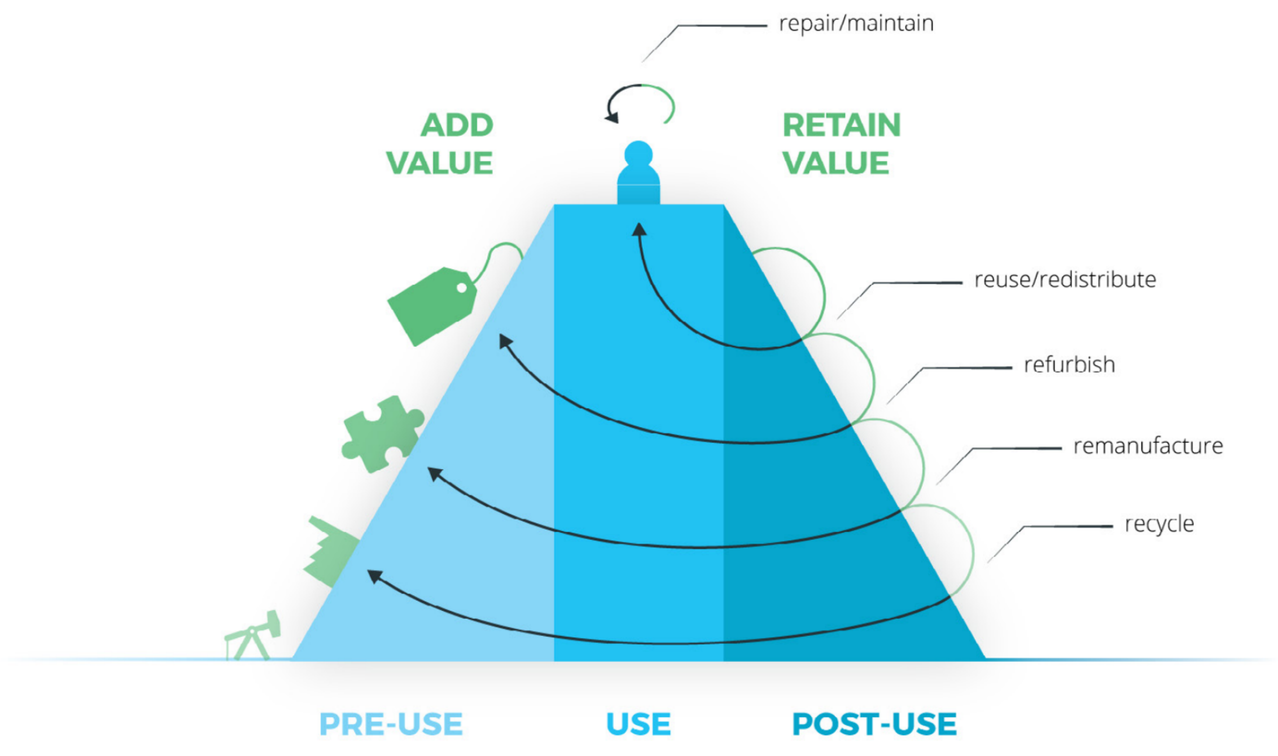

image / figure 1 The Value Hill in a circular economy. (Achterberg et al., 2016)

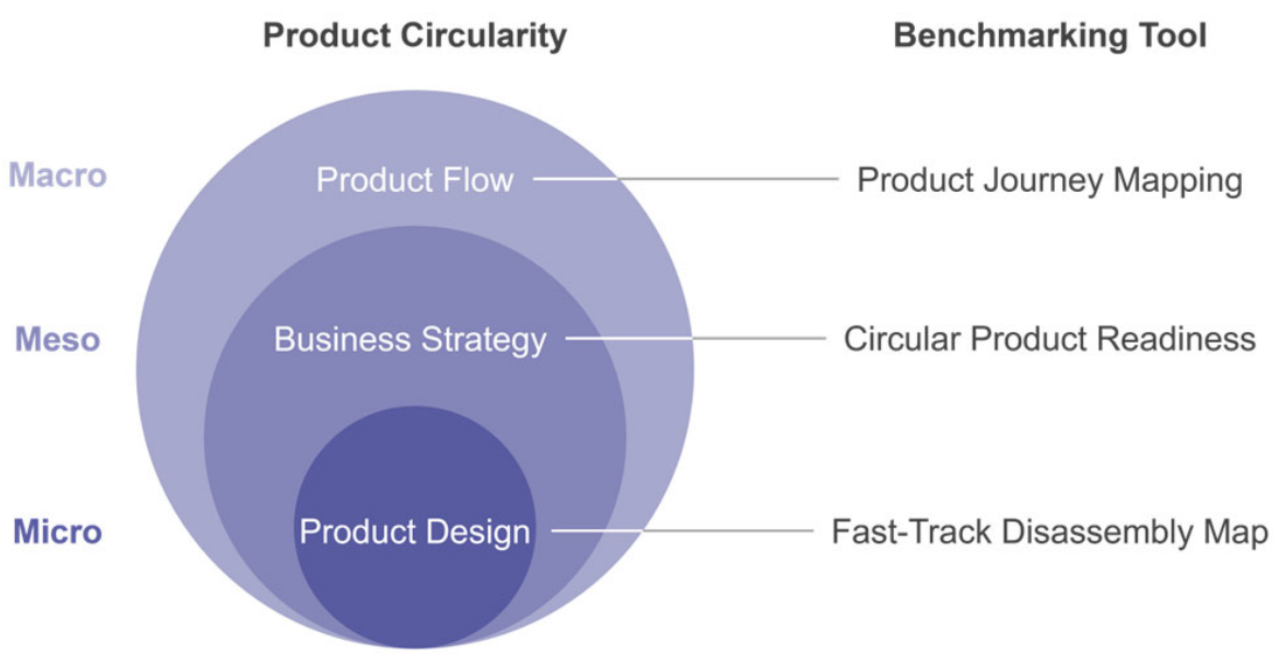

image / figure 2 Circularity toolset for benchmarking consumer electronics: circularity levels & tools (Sekijima et

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The problem with current Sony headphones is that they are difficult to repair, and valuable parts are hard to separate for reuse or recycling. This is due to the amount of disassembly steps required and several irreversible or hard-to-remove connections, such as glue or solder. Additionally, the only spare parts available are the ear cushions. So far, Sony hasn't strongly focused on circularity. This project aims to show that a shift to more circular products is possible.

The main focus will be on a product design level. However, each circular strategy, as outlined in the Value Hill model, brings its own design requirements. For example, self-repair has different needs than remanufacturing, and professional repair and recycling also have their own requirements. It is important to find a balance among these strategies and define the differences between them, especially self and service repair.

To create added value for Sony, the product should also have a value proposition for customers who are not necessarily interested in sustainability and ideally fit within Sony's current logistics system, to help keep the implementation timeline within a 4-5 year range.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

(Re)design a concept for a pair of circular over-ear wireless headphones for Sony.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will roughly follow a double diamond approach. The first phase will focus on researching design for circular economy and analysing existing headphones to define key problem areas and identify possible solutions and design strategies and a product narrative. The starting point is the benchmarking results of existing headphones done by Keita Sekijima, using the circularity toolset for benchmarking consumer electronics, supplemented by more in-depth tools such as disassembly maps and hotspot analyses. Additionally, a reference book will be created to track inspiring solutions. The main focus will be on a product design level, but also on how choices at this level affect higher levels. Research and prototyping should go hand in hand.

The second phase will focus on developing and combining insights and solutions from the first phase into an integrated prototype that fits within Sony. As stated in the introduction, the redesign should not negatively affect the experience, ease of use, and quality of the headphones.

Throughout both phases, ideas and concepts will be tested against the benchmarking baseline of existing headphones.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	12 sept 2024
Mid-term evaluation	21 nov 2024
Green light meeting	20 feb 2025
Graduation ceremony	1 apr 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✔
For how many project weeks	20
Number of project days per week	4

Comments:
The full project will be part time, 4 days a week. Next to that, I have a TA job in week 2 (Jan. 6-10) so I will only work 2 days that week.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

Motivation:
My interested in circular design began with the Repair! elective, but I have only scratched the surface and want to learn a lot more about what it means to design circular products. Sustainability in product design is crucial. I believe we should all aim to leave the world a better place, and as designers, we must play our part. I enjoy the challenge of a hands-on project. I believe I work best when I can prototype. It allows me to think more clearly and reflect, and this project lends itself very well to a lot of prototyping, making it exciting. Next to that, I want to both demonstrate and further develop my skills in embodiments design and creating integrated solutions.

Personal learning ambitions:
1. Show up to every meeting with new prototypes (or something physicial), both to foster discussion and to develop my prototyping skills.
2. Ask for help from my supervisory team, other students, and additional experts whenever I think it could benefit me or my project. A useful tool for this are regular (weekly) reflection moments to find points of friction.
3. Develop my knowledge of electronics in products. I want to be able to effectively design with and for electronics and design simple PCBs.

Appendix B — Legislation

Ecodesign for Sustainable Products Regulation

This is a replacement of the Ecodesign Directive (Directive 2009/125/EC), which regulates the energy use of appliances/products, with the aim of lowering the energy consumption and their overall environmental impact. It also includes providing information to consumers. It establishes a framework for setting ecodesign requirements for specific energy-related product categories to improve their environmental performance by regulating their design. Its primary goal is energy efficiency.

In April of 2024, the new Ecodesign for Sustainable Products Regulation (ESPR) was adopted (Regulation 2024/1781). Here the scope is expanded to all physical goods placed on the EU market and it addresses the entire life cycle of the products, including manufacturing, use, and end-of-life disposal, covering aspects such as durability, reusability, repairability, and recyclability. In general, it pushes for more circular product design. It is a regulation instead of a direction, which means that it is directly applicable in all member states without needing member states to transpose it into national legislation. This ensures a more uniform and immediate application across the EU. The exact requirements differ per specific product group, and can be found in the group's ecodesign requirements regulation.

The new Ecodesign for Sustainable Products Regulation builds upon the old Ecodesign Directive by:

- Expanding the scope to cover a wider range of products beyond just energy-related ones.
- Emphasising circularity, durability, and broader environmental impacts.
- Introducing the Digital Product Passport for better transparency and information sharing.
- Prohibiting the destruction of unsold goods and enhancing market surveillance.
- Establishing a regulation rather than a directive, ensuring more consistent application across the EU.

European Green Deal

The European Green Deal includes a directive on the repair of goods. Adopted on 13 June 2024, entered into force on 30 July 2024 (Directive 2024/1799). Member states have to apply it from 31 July 2026. It aims at encouraging customers to use their goods for longer thus preventing premature disposal of repairable goods. Currently it applies only to a selection of product categories, which doesn't yet include headphones, but this will be updated on an annual basis. It establishes a number of measures to promote repair:

- **Obligation to repair**: manufacturers will have to repair products within a reasonable time and for a reasonable price, and information on their repair services (including prices) should be easily accessible to customers. There is product-specific legislation for specific repairability requirements, these include disassembly requirements and can be found in the ecodesign requirement regulation of that product category. For smartphones (2023/1670) this includes:
  - Spare parts cannot be assemblies (with a few exceptions).
  - Replacement should be able to be carried out in a workshop environment by a generalist, with commercially available tools.
  - Fasteners should be removable, resupplied, or reusable.
  - Battery replacement should be able to be carried out by a non-expert in a use-environment, with no tools, supplied tools, or basic tools.
  - Design for reliability: resistance to accidental drops.
  - Recyclability requirements: instructions to get to batteries & PCBs >10cm2 (2012/19/EU).
  - Manufacturers cannot use contractual clauses, hardware or software techniques that hinder the repair of goods. In other words, users should be able to replace broken components with spare parts.
  - Manufacturers have to provide access to spare parts at reasonable prices, information about this should be easily available.
- **European Online Platform for repair**: consumers can find repairers easily through an online platform, which will become operational in 2027.
- **Extension of legal guarantee after repair**: as an amendment to Sale of goods Directive

(EU) 2019/771, consumers get an extra year of legal guarantee if they choose to repair the product instead of replacing it under the legal guarantee.

- **National measures promoting repair**: member states will have to take at least on measure promoting repair within their country. This can be both financial, e.g. repair funds, or non-financial, e.g. campaigns, vouchers, trainings in repair skills, measures.
- **European Repair Information Form**: repairers can offer consumers information about their repair services via a standardised form. This allows customers to easily compare different repair offers.

Directive on waste electrical and electronic equipment (WEEE)

This directive is mainly about the collection & processing of disposed electronic products **(2012/19/EU)**, but there also one article about product design. This article says that member states "encourage cooperation between producers and recyclers and measures to promote the design and production of EEE, notably in view of facilitating re-use, dismantling and recovery of WEEE, its components and materials. In this context, Member States shall take appropriate measures so that the ecodesign requirements facilitating re-use and treatment of WEEE established in the framework of Directive 2009/125/EC are applied and producers do not prevent, through specific design features or manufacturing processes, WEEE from being re-used"

Other noteworthy aspects are that the following components need to be removed:

- Batteries
- PCBs > 10 cm2

Appendix C – Hotspot Mapping Datasheet Sony WH-1000XM5

HotSpot Mapping Datasheet

General project information

Brand name	Sony
Product category	Headphones
Authors	Iza Bosch
Date	okt-24
Location	Delft

Overall HotSpot Results

Total:		**Average:**		
- time to disassemble	?105 sec	- time per step	18,8 sec/step	
- number of tasks	217	- force	2	[1=low .. 5=high .. 10=extreme]
- number of steps	112	- accessibility	2	[1=clear .. 5=moderate .. 10=difficult]
- number of tools	6	- positioning	4	[1=easy .. 5=moderate .. 10=difficult]

General | Activity | Accessibility | Functional | Material | HotSpot Indicators

Step number	Name	Subasssembly?	Part of ...	Type of activity	Required tool	Tool size	Task frequency	Total time to disconnect (sec)	Force	Accessibility	Positioning	Failure Likelihood	Functinoal relevance	Material group	Weigth (g)	Time	Activity	Priority part	Environmental	Economic	Notes
1	Right ear cushion	no	main assembly	Disconnec	Lever / Prybar		6	23	level 1 -	level 2 -	level 1 -	Moderate precision					⚐				
2	Right ear cushion	no	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 1 -	level 1 -	Mixed materials mainly	12				⚐	⚐	
3	Left ear cushion	no	main assembly	Disconnec	Lever / Prybar		6	23	level 1 -	level 2 -	level 1 -	Moderate precision					⚐				
4	Left ear cushion	no	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 1 -	level 1 -	Mixed materials mainly	12				⚐	⚐	
5	Left foam insert	no	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Foam	0,52						
6	Right foam insert	no	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Foam	0,47						
7	Screws	no	main assembly	Unscrew	Screwdriver	Ph00	8	98	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,84	⚑					
8	Left earcup shell	no	main assembly	Remove	Hands		1	3	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Thermoplastic	17,9				⚐	⚐	
9	Screws	no	main assembly	Unscrew	Screwdriver	Ph00	8	98	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	No-to-low relevant	0,84	⚑					
10	Right earcup shell	no	main assembly	Unplug	Hands		1	3	level 0 -	level 0 -	level 0 -	No-to-low precision									
11	Right earcup shell	no	main assembly	Remove	Hands		1	3	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Mixed materials mainly	19,8				⚐	⚐	Incl. touch sensor
12	Fabric battery tape	no	main assembly	Peel off	Hands		1	4	level 1 -	level 0 -	level 1 -	level 0 -	level 0 -	Mixed materials mainly	0,07						
13	Battery	no	main assembly	Unplug	Hands		1	5	level 1 -	level 0 -	level 1 -	Moderate precision									
14	Battery	no	main assembly	De-glue	Hands		1	8	level 2 -	level 0 -	level 1 -	Moderate precision					⚐				
15	Battery	no	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 2 -	level 2 -	Rechargeable	22,8			⚑	⚑	⚑	
16	Power PCB	no	main assembly	Unplug	Hands		4	20	level 0 -	level 0 -	level 1 -	Moderate precision									
17	Power PCB	no	main assembly	De-solder	Soldering iron		2	79	level 0 -	level 0 -	level 2 -	High precision				⚑	⚐				Time incl. warm up time (54sec)
18	Screws	no	main assembly	Unscrew	Screwdriver	Ph00	2	18	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,14						
19	Power PCB	no	main assembly	Remove	Hands		1	6	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	PCB	2,6				⚑	⚑	
20	Thermal padding	no	main assembly	Peel off	Hands		2	5	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Thermoset	1,61						
21	Screws	no	main assembly	Unscrew	Screwdriver	Ph00	1	7	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,07						
22	Right housing shield assembly	yes	main assembly	Peel off	Hands		1	17	level 1 -	level 0 -	level 1 -	Moderate precision									
23	Right housing shield assembly	yes	main assembly	Other	Hands		2	4	level 0 -	level 0 -	level 0 -	No-to-low precision									Pull the 2 ribbon cables out of the gaskets
24	Cable gasket	no	Right housing shiel	Remove	Hands		2	4	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Rubber	0,22						
25	Right housing shield seal	no	Right housing shiel	De-glue	Hands		1	6	level 1 -	level 0 -	level 0 -	level 0 -	level 0 -	Mixed materials mainly	0,48						
26	Right housing shield	no	Right housing shiel	Other	Hands		0	1				level 0 -	level 1 -	Mixed materials mainly	1,3						Left over when you peel off the seal. Has a copper coloured sticker on it
27	Screws	no	main assembly	Unscrew	Screwdriver	Ph00	2	15	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,14						
28	Right speaker housing assembly	yes	main assembly	Remove	Hands		1	3	level 0 -	level 0 -	level 0 -	No-to-low precision									
29	Silicone NC PCB stopper	no	Right speaker hous	Remove	Hands		1	2	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Rubber	0,07						
30	Felt NC PCB cover	no	Right speaker hous	Peel off	Hands		1	3	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Mixed materials mainly	0						
31	Right NC microphones	yes	Right speaker hous	De-glue	Lever / Prybar		3	167	level 2 -	level 0 -	level 2 -	High precision				⚑	⚐				
32	Right NC microphones	yes	Right speaker hous	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	No-to-low precision									
33	NC microphone housing	no	Right NC micropho	De-glue	Pliers		3	114	level 1 -	level 0 -	level 2 -	level 0 -	level 1 -	Mixed materials mainly	0,81	⚑	⚐				
34	Right NC microphone PCB	no	Right NC micropho	Remove	Hands		0	1				level 0 -	level 1 -	PCB	0,5				⚐	⚐	Part freed at same time as previous step
35	Screws	no	Right speaker hous	Unscrew	Screwdriver	Ph00	1	7	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,07						
36	USB-C PCB	no	Right speaker hous	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 2 -	level 2 -	PCB	1,43			⚑	⚑	⚑	
37	Right LED diffuser	no	Right speaker hous	Remove	Hands		1	4	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Thermoplastic	0,08						
38	Microphone cover	no	Right speaker hous	Remove	Hands		1	8	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Rubber	0,13						
39	Silicone cable plug	no	Right speaker hous	Unplug	Hands		1	3	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Rubber	0,12						
40	Right speaker microphone	no	Right speaker hous	De-glue	Lever / Prybar		1	4	level 0 -	level 0 -	level 1 -	Moderate precision									
41	Right speaker microphone	no	Right speaker hous	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Other Electronics	0,07						
42	Screws	no	Right speaker hous	Unscrew	Screwdriver	Ph00	4	33	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,27	⚐					
43	Right speaker-cover	no	Right speaker hous	De-glue	Lever / Prybar		1	68	level 2 -	level 1 -	level 2 -	High precision				⚑	⚑				
44	Right speaker-cover	no	Right speaker hous	Other	Hands		1	3	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Mixed materials mainly	5						Pull speaker cable out
45	Right speaker seal	no	Right speaker hous	Peel off	Hands		1	6	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Mixed materials mainly	0,19						
46	Right speaker-driver	no	Right speaker hous	De-glue	Hands		1	12	level 2 -	level 0 -	level 0 -	level 2 -	level 2 -	Other Electronics	11			⚑	⚑	⚑	
47	Right speaker shell	no	Right speaker hous	Remove	Hands		0	1				level 0 -	level 1 -	Mixed materials mainly	20,4				⚐	⚐	ABS, but still contains some stickers, adhesive double sided tape, and felt
48	Main PCB	no	main assembly	Unplug	Hands		4	11	level 0 -	level 0 -	level 1 -	Moderate precision									
49	Screws	no	main assembly	Unscrew	Screwdriver		3	29	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,21	⚐					
50	Main PCB	no	main assembly	De-solder	Soldering iron		2	48	level 0 -	level 0 -	level 2 -	High precision				⚐	⚐				Time: excl. warm up time
51	Main PCB	no	main assembly	Remove	Hands		1	2	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	PCB	3,7				⚑	⚑	
52	Screw	no	main assembly	Unscrew	Screwdriver	Ph00	1	7	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,07						
53	Left housing shield assembly	yes	main assembly	Peel off	Hands		1	13	level 1 -	level 0 -	level 1 -	Moderate precision									
54	Left housing shield assembly	yes	main assembly	Other	Hands		2	4	level 0 -	level 0 -	level 0 -	No-to-low precision									Pull the 2 ribbon cables out of the gaskets
55	Cable gasket	no	Left housing shield	Remove	Hands		2	4	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Rubber	0,24						
56	Left housing shield seal	no	Left housing shield	De-glue	Hands		1	4	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Mixed materials mainly	0,48						
57	Left housing shield	no	Left housing shield	Other	Hands		0	1				level 0 -	level 1 -	Thermoplastic	1,32						Left over when you peel off the seal
58	Headband assembly	yes	main assembly	Unplug	Hands		1	3	level 0 -	level 0 -	level 1 -	Moderate precision									Pull cable out of strain relief
59	Screws	no	main assembly	Unscrew	Screwdriver	Ph00	2	17	level 0 -	level 1 -	level 1 -	level 0 -	level 0 -	Steel	0,14						
60	Headband assembly	yes	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	No-to-low precision									
61	Left speaker housing assembly	yes	main assembly				0	1													Comes free at the same time as the headband assembly
62	Screws	no	Left speaker housi	Unscrew	Screwdriver	Ph00	2	18	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,14						
63	AUX PCB	no	Left speaker housi	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 2 -	level 1 -	PCB	1,63			⚐	⚑	⚑	Also contains the on-off button
64	Left LED diffuser	no	Left speaker housi	Remove	Hands		1	2	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Thermoplastic	0,05						
65	Button padding	no	Left speaker housi	De-glue	Pliers		2	10	level 1 -	level 0 -	level 1 -	level 0 -	level 0 -	Foam	0,05		⚐				
66	Power button	no	Left speaker housi	Remove	Pliers		1	24	level 0 -	level 0 -	level 2 -	level 0 -	level 2 -	Thermoplastic	0,1	⚐	⚐				
67	NC button	no	Left speaker housi	Remove	Pliers		1	7	level 0 -	level 0 -	level 1 -	level 0 -	level 1 -	Mixed materials mainly	0,15						
68	Silicone NC PCB stopper	no	Left speaker housi	Remove	Hands		1	3	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Rubber	0,05						
69	Felt NC PCB cover	no	Left speaker housi	Peel off	Hands		1	6	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Mixed materials mainly	0						
70	Left NC microphones	yes	Left speaker housi	De-glue	Lever / Prybar		4	61	level 2 -	level 0 -	level 2 -	High precision				⚑	⚐				

71	Left NC microphones	yes	Left speaker housi	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	No-to-low precision								
72	NC microphone housing	no	Left NC microphon	De-glue	Pliers		4	152	level 1 -	level 0 -	level 2 -	level 0 -	level 1 -	Mixed materials mainly	1,08	🚩	⚐			
73	Left NC microphone PCB	no	Left NC microphon	Remove	Hands		0	1				level 0 -	level 1 -	PCB	0,66				🚩	🚩	Part freed at same time as previous step
74	Microphone cover	no	Left speaker housi	Remove	Hands		1	3	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Rubber	0,13					
75	Silicone cable plug	no	Left speaker housi	Unplug	Hands		2	5	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Rubber	0,23					
76	Left speaker microphone	no	Left speaker housi	De-glue	Pliers		2	8	level 0 -	level 0 -	level 1 -	Moderate precision								
77	Left speaker microphone	no	Left speaker housi	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Other Electronics	0,08					
78	Speaker sensor ring	no	Left speaker housi	De-glue	Lever / Prybar		1	4	level 2 -	level 0 -	level 1 -	Moderate precision					⚐			
79	Speaker sensor ring	no	Left speaker housi	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Other Electronics	1,24					⚐	
80	Screws	no	Left speaker housi	Unscrew	Screwdriver	Ph00	4	33	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,27	⚐					
81	Left speaker cover	no	Left speaker housi	De-glue	Lever / Prybar		1	39	level 2 -	level 1 -	level 2 -	High precision				⚐	🚩				
82	Left speaker cover	no	Left speaker housi	Other	Hands		1	31	level 1 -	level 0 -	level 0 -	level 0 -	level 1 -	Mixed materials mainly	4,8	⚐					Pull speaker cable out, this one took longer because it had a bit more solder on the end
83	Left speaker seal	no	Left speaker housi	Peel off	Hands		1	6	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Mixed materials mainly	0,15						
84	Left speaker driver	no	Left speaker housi	De-glue	Hands		1	16	level 2 -	level 0 -	level 0 -	level 2 -	level 2 -	Other Electronics	11			🚩	🚩	🚩	
85	Left speaker shell	no	Left speaker housi	Remove	Hands		0	1				level 0 -	level 1 -	Mixed materials mainly	20,3				⚐	⚐	Left over after you remove speaker. ABS, but also has a sticker, some adhesive, and felt pads stuck to it
86	Headband arm clips	no	Headband assembl	Unplug	Hands		4	24	level 0 -	level 0 -	level 1 -	level 0 -	level 1 -	Thermoplastic	1,62	⚐					
87	Screws	no	Headband assembl	Unscrew	Screwdriver	Ph000	2	20	level 0 -	level 0 -	level 2 -	level 0 -	level 0 -	Steel	0,06						
88	Headband cover clamps	no	Headband assembl	Disconne	Lever / Prybar		8	26	level 1 -	level 2 -	level 2 -	High precision				⚐	🚩				
89	Headband cover clamps	no	Headband assembl	De-glue	Hands		4	12	level 1 -	level 0 -	level 0 -	No-to-low precision									Tiny bit of adhesive on there
90	Screws	no	Headband assembl	Unscrew	Screwdriver	Ph00	2	9	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,12						
91	Headband cable covers	no	Headband assembl	Remove	Lever / Prybar		2	8	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Thermoplastic	0,34						
92	Headband cable	no	Headband assembl	Cut	Wire cutter		2	4	level 1 -	level 0 -	level 1 -	Moderate precision					⚐				Cut off connector
93	O-ring	no	Headband assembl	Cut	Knife		4	6	level 0 - Light resistance			level 0 -	level 0 -	Rubber	0,06						
94	Headband cover	no	Headband assembl	De-glue	Hands		4	119	level 1 -	level 2 -	level 1 -	Moderate precision				🚩	⚐				
95	Headband cover	no	Headband assembl	Remove	Hands		1	107	level 2 -	level 0 -	level 1 -	Moderate precision				🚩	⚐				Basically peeling back
96	Foam headband topper	no	Headband assembl	Peel off	Hands		1	52	level 1 -	level 0 -	level 0 -	level 0 -	level 0 -	Mixed materials mainly	3,8	🚩					
97	Foam cushioning + cable	yes	Headband assembl	Peel off	Hands		1	18	level 0 -	level 0 -	level 1 -	Moderate precision									
98	Tape	no	Headband assembl	Peel off	Hands		4	48	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Mixed materials mainly	0,2	⚐					
99	Screws	no	Headband assembl	Unscrew	Screwdriver	Ph00	4	26	level 0 -	level 2 -	level 1 -	level 0 -	level 0 -	Steel	0,22	⚐	⚐				
100	Headband slider outside covers	no	Headband assembl	Disconne	Lever / Prybar		6	24	level 1 -	level 2 -	level 1 -	Moderate precision				⚐	⚐				
101	Headband slider outside covers	no	Headband assembl	Remove	Hands		2	6	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Mixed materials mainly	8,2						
102	Headband slider inside covers	no	Headband assembl	Remove	Hands		2	2	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Thermoplastic	8,8				⚐		
103	Screws	no	Headband assembl	Unscrew	Screwdriver	Ph000	2	12	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	0,08						
104	Headband cable	no	Headband assembl	Unplug	Lever / Prybar		2	4	level 0 -	level 0 -	level 1 -	Moderate precision									
105	Headband cable	no	Headband assembl	Unplug	Hands		2	60	level 1 -	level 0 -	level 1 -	Moderate precision				🚩					Unplugging the cable clamps (attached to headband cable)
106	Earcup arms	no	Headband assembl	Remove	Hands		2	10	level 0 -	level 0 -	level 0 -	level 2 -	level 2 -	Mixed materials mainly	19,2			🚩	⚐	⚐	
107	Headband cover clamps	no	Headband assembl	Remove	Hands		2	4	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Mixed materials mainly	1,32						
108	Headband cover	no	Headband assembl	Remove	Hands		1	6	level 0 -	level 0 -	level 0 -	level 1 -	level 1 -	Textile (synthetic)	5,4						
109	Headband cable guide	no	Headband assembl	Disconne	Hands		12	9	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Thermoplastic	1,8						
110	Headband cushion	no	Foam cushioning +	Peel off	Hands		1	11	level 0 -	level 0 -	level 0 -	level 1 -	level 1 -	Mixed materials mainly	2,5						Foam with double-sided tape stuck to it that cannot be removed without tearing the foam
111	Headband cable	no	Foam cushioning +	Remove	Hands		0	1				level 2 -	level 2 -	Other Electronics	9,5			🚩	🚩	🚩	Leftover after previous step
112	Headband metal wires	no	Headband assembl	Remove	Hands		0	1				level 0 -	level 2 -	Steel	4,3						Leftover after previous step
113																					
114																					
115																					
116																					
117																					
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Figure C-1. Sony Hotspot Map

Appendix D — Results Hotspot analysis

Hotspot analysis has only been done for the Sony WH-1000XM5, with the goal to identify the most critical parts and activities. The logging of activities is based on the video of the gentle dismantle, with more destructive steps, such as desoldering, timed separately afterward.

Overall results

The total disassembly time for the headphones was 2105 seconds, or roughly 35 minutes. This is shorter than the disassembly time from the gentle dismantle video, even though the Hotspot Mapping disassembly went further. The difference is because only the time spent on actual disassembly activities was recorded in the Hotspot Mapping Datasheet. Pauses to change tools or figure out what to do were excluded, whereas they were included in the gentle dismantle video.

In Hotspot Mapping, a step refers to a distinct action, while a task represent the number of times that action is repeated within the step. For example, the step of unscrewing the earcup housing involves eight tasks, as there are eight screws to be unscrewed. In total, disassembling the headphones took 112 steps and 217 tasks, with each step taking an average of 18.8 seconds.

Six different tools were used: a lever/prybar, a screwdriver with a Phillips #00 and a Phillips #000 bit, a soldering iron, pliers, a wire cutter, and a knife. Most tasks could be done using just your hands, Table D-1 shows for how many steps and tasks each tool was used. The soldering iron, wire cutter, and knife are all only used for a limited number of steps and tasks, eliminating the need for these three tools would streamline the disassembly process by minimising the number of tools needed.

Critical activities

There are several steps with both of the critical activity hotspot indicators, which means that they either take a long time (Time Hotspot) or that they use a non-standard tool, need a lot of force, precision, and/or the part is hard to access (Activity Hotspot). The parts with both critical activity hotspot indicator are the following:

- De-soldering the right speaker driver from the power PCB and de-soldering the left speaker driver from the main PCB: De-soldering is time-consuming, partly due to the time needed for the soldering iron to warm up. De-soldering the right driver takes 79 seconds, including 54 seconds of warming up. De-soldering the left driver takes 48 seconds, as the soldering iron was already warmed up. Next to it being time-intensive, this step also requires a high level of precision, as the solder joints are small and you need to avoid accidental contact with other components on the PCB.
- **De-glueing the right NC microphones and de-glueing the left NC microphones:** The NC microphones are glued alongside the edge of the earcup with strong adhesive, which requires significant time and force to remove. Next to that, there is limited space around the microphones, which makes removal challenging, as it requires precise positioning of tweezers to act as a lever. Removing the right NC microphones took 167

Table D-1. Tool usage for the disassembly of the Sony WH-1000XM5 headphones.

	Number of steps	*Number of tasks*
No tools (hands)	74	105
Lever/prybar	12	41
Screwdriver	16	48
Soldering iron	2	4
Pliers	6	13
Wire cutter	1	2
Knife	1	4
Total	*112*	*217*

seconds, while the left took 61 seconds, as I had figured out the correct technique.

- **De-glueing the right NC microphone housings and de-glueing the left NC microphone housings**: The NC microphone housings are also attached with a strong adhesive that need a significant amount of force and precision to be removed. The process took 114 seconds for the right, and 152 seconds for the left.
- **De-glueing the right speaker cover and de-glueing the left speaker cover**: It isn't immediately obvious that the speaker covers are glued, as they are also secured with screws. The adhesive used is strong and requires significant force and it is only possible to get a lever under the covers at specific points. De-glueing the right speaker cover took 68 seconds, while the left took 39 seconds.
- **Removing the power button**: The small button needs to be grabbed with tweezers and manoeuvred in a specific way to be removed, taking 24 seconds
- **Disconnecting the snap fits of the headband cover clamps**: The snap fits are not visible, and as the cover clamps are also screwed in place, you do not expect them to be there. This leads to blindly using a lever to try to get the cover clamps off. Each clamp was small but had four snap fits, disconnecting them took 26 seconds.
- **De-glueing the headband cover and removing/peeling off the headband cover**: The headband cover can be removed without the use of tools, though it requires some force. The adhesive is not visible, so it isn't immediately clear that de-glueing is necessary. The cover itself is very tight, so after de-glueing, it has to be peeled back gradually with significant force. De-glueing took 119 seconds, while removing the cover took an additional 107 seconds.
- **Unscrewing the headband slider covers**: The screws are covered by the foam headband topper. When they are revealed, it takes 26 seconds to remove them.
- **Disconnecting the snap fits of the headband slider outside covers**: These snap fits were also hidden from view, leading to unnecessary force during removal. You also don't expect them to be there, as you also need to undo screws and remove two pieces of tape holding the inside and outside covers together.

Appendix E — Repair Data

To identify the priority parts of over-ear wireless headphones, repair data from Repair Cafes worldwide are used. The data is on repairs done between 2017 and Q1 of 2024 (RepairMonitor, 2024). Within this timeframe, 446 (attempted) headphone repairs were documented, this includes both wired and wireless headphones. Table 16 shows an overview of the analysed data.

The most common reason for repair, was issues with the external audio cable. This was good for 187 out of 446 repairs. After this, it was problems with the housing (38), most prominently the hinges connecting the earcups to the headband (23). The internal wiring was the issue for 34 repairs, this includes both the cable connecting the two earcups, and unspecified connections between electronics. Other frequent reasons were broken speaker drivers (21), issues with charging or audio ports (20), and battery issues (19).

In 63 of the 446 attempted repairs (14%), the exact cause of the problem remained unknown. This indicates that error diagnosis can be really hard, even for more experienced repairers.

Conclusion

Based on the RepairMonitor, the following parts can be identified as priority parts for wireless headphones, and should thus be easily accessible:

- Hinges
- Speaker drivers
- Charging and audio ports
- Battery
- Headband cable

However, there are some additional parts that did not come up in the RepairMonitor, but that do adhere to the definition of a priority part:

- Earpads. Ear cushions wear down way before the technical lifetime of the headphones as a whole, and thus have to be replaced (multiple times) during use.
- Headband padding or cover, for similar reasons as the earpads. The headband cover is in constant contact with the users skin, and often wears down before the technical lifetime of the headphones as a whole.

Table E-1. Reasons for repair listed in the RepairMonitor

Earcups/ Housing			38
	Earcups broken off	16	
	Earcup disassembled	3	
	Headband	2	
	Broken headband bracket	2	
	Hinge	5	
	Springs in the headband stretched	1	
	Ear pads	5	
	Broken plastic	4	
Buttons			13
	On/off button broken	7	
	Volume button	5	
	NC switch	1	
Ports			20
	Charging port broken	12	
	Stereojack port	8	
Battery			19
	Battery	19	
External cable			187
	External audio cable	83	
	Plug/jack	64	
	Draadbreuk	35	
	Snoer/contact kapot	4	
	Stekker los	1	
Microphone			4
	Microphone	3	
	Detached microphone	1	
Internal cabling			34
	Internal cable connecting earcups	9	
	Broken soldering connection (unspecified)	8	
	Damaged wires (unspecified)	6	
	Loose wire (unspecified) (assumed internal)	11	
Speaker drivers			21
	Speakers	13	
	Open circuit coil (speaker)	3	
	Broken stator winding (speaker)	1	
	Magnet loose (speaker)	2	
	Soldering connection	2	

Bluetooth			1
	Bluetooth	1	
Other electronics?			24
	SMD PCB	2	
	Broken transformator	2	
	Electronics (unspecified)	3	
	Unspecified short circuit	2	
	Bad contact	15	
Charger			2
	Charger	2	
User error			11
	Empty battery	3	
	Bluetooth disconnected	3	
	User error	5	
Unknown problem			63
	Unknown problem	44	
	Not charging	4	
	Not turning on	1	
	Unclear	14	
Unclear data			9
	Underpowered	1	
	Gescheurd'	1	
	Rubber edge	1	
	Kanaalinstelling	1	
	Adapter	2	
	Pinnetje afgebroken'	3	
		446	

Appendix F – Disassembly maps competitors

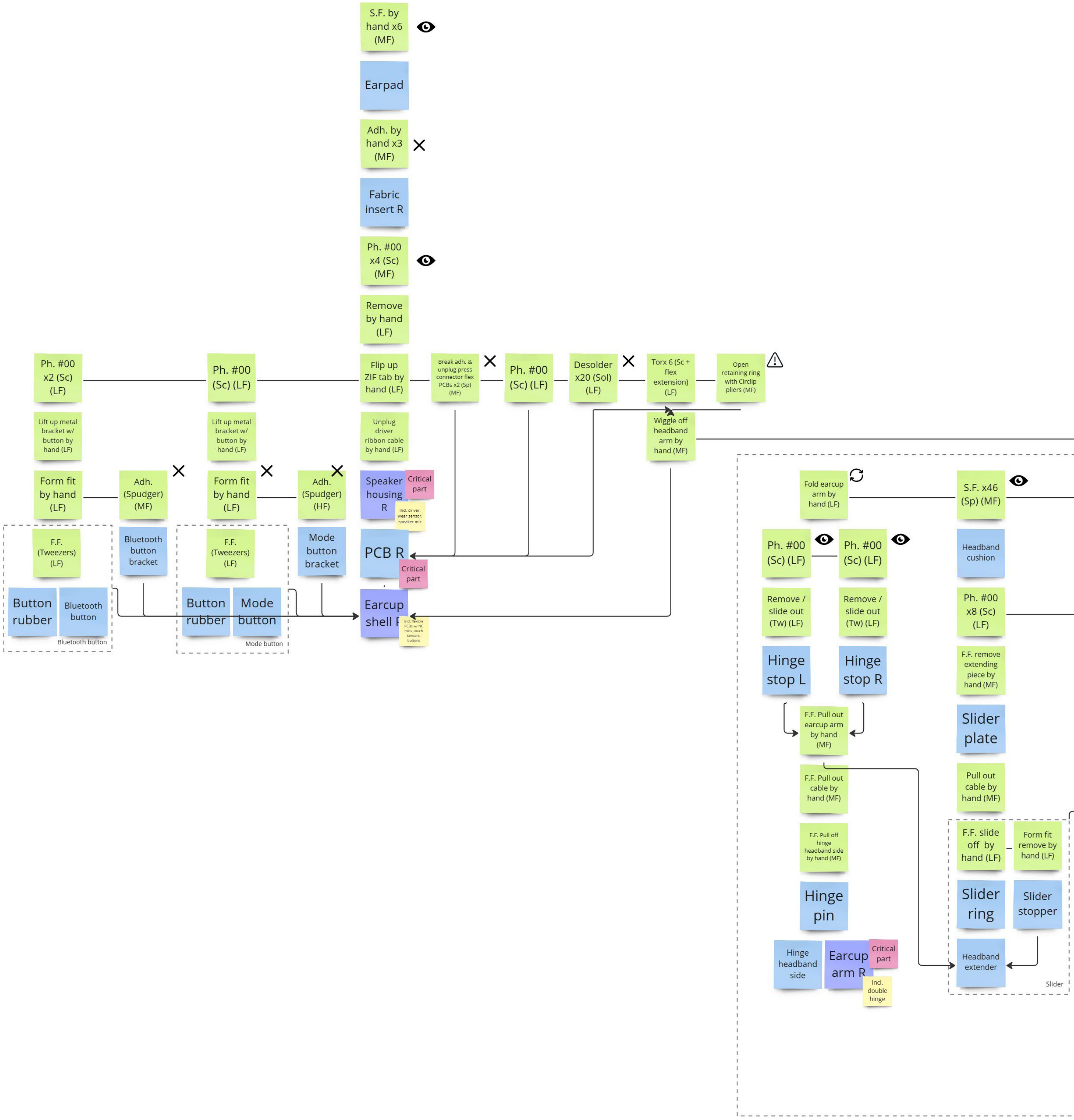
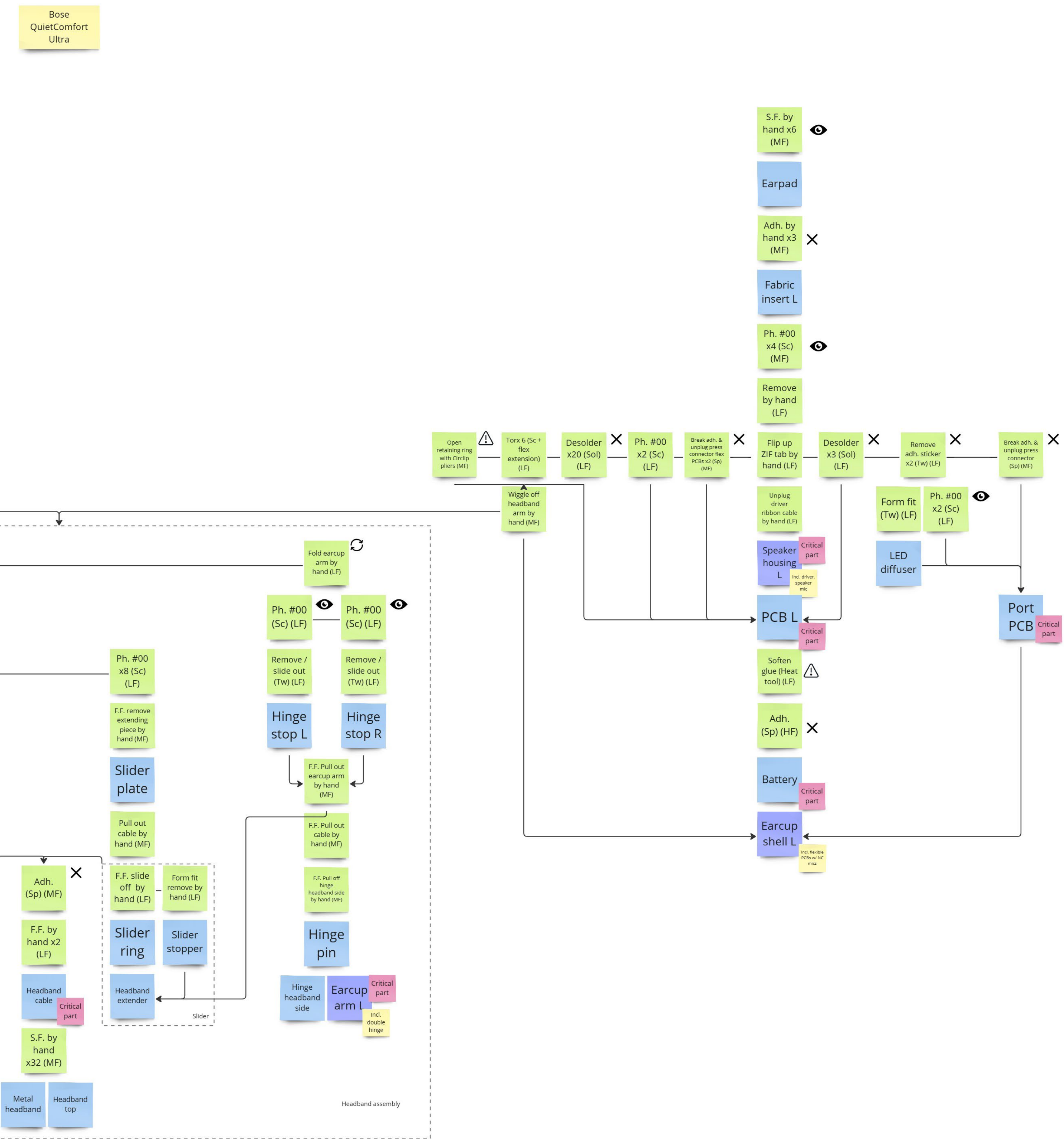


Figure F-1. Disassembly Map Bose QuietComfort Ultra.



Bose QuietComfort Ultra
S.F. by hand x6 (MF)
Earpad
Adh. by hand x3 (MF)
Fabric insert L
Ph. #00 x4 (Sc) (MF)
Remove by hand (LF)
Open retaining ring with Circlip pliers (MF)
Torx 6 (Sc + flex extension) (LF)
Desolder x20 (Sol) (LF)
Ph. #00 x2 (Sc) (LF)
Break adh. & unplug press connector flex PCBs x2 (Sp) (MF)
Flip up ZIF tab by hand (LF)
Desolder x3 (Sol) (LF)
Remove adh. sticker x2 (Tw) (LF)
Break adh. & unplug press connector (Sp) (MF)
Wiggle off headband arm by hand (MF)
Unplug driver ribbon cable by hand (LF)
Speaker housing L
Critical part
Incl. driver, speaker mic
Form fit (Tw) (LF)
Ph. #00 x2 (Sc) (LF)
LED diffuser
PCB L
Critical part
Port PCB
Critical part
Soften glue (Heat tool) (LF)
Adh. (Sp) (HF)
Battery
Critical part
Earcup shell L
Incl. flexible PCBs w/ NC mics
Fold earcup arm by hand (LF)
Ph. #00 (Sc) (LF)
Ph. #00 (Sc) (LF)
Remove / slide out (Tw) (LF)
Remove / slide out (Tw) (LF)
Hinge stop L
Hinge stop R
F.F. Pull out earcup arm by hand (MF)
F.F. Pull out cable by hand (MF)
F.F. Pull off hinge headband side by hand (MF)
Hinge pin
Hinge headband side
Earcup arm L
Critical part
Incl. double hinge
Ph. #00 x8 (Sc) (LF)
F.F. remove extending piece by hand (MF)
Slider plate
Pull out cable by hand (MF)
F.F. slide off by hand (LF)
Form fit remove by hand (LF)
Slider ring
Slider stopper
Headband extender
Slider
Adh. (Sp) (MF)
F.F. by hand x2 (LF)
Headband cable
Critical part
S.F. by hand x32 (MF)
Metal headband
Headband top
Headband assembly

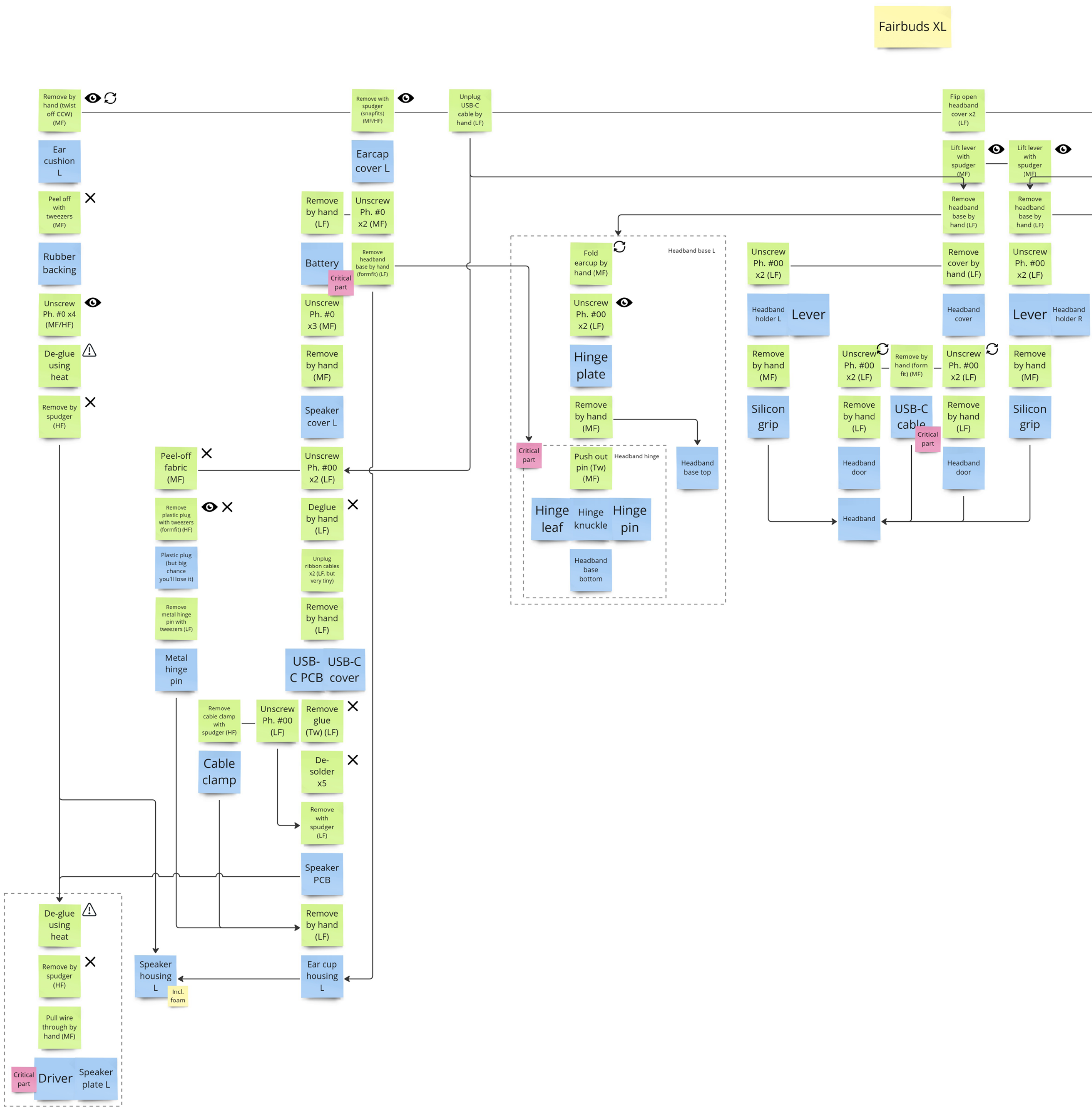
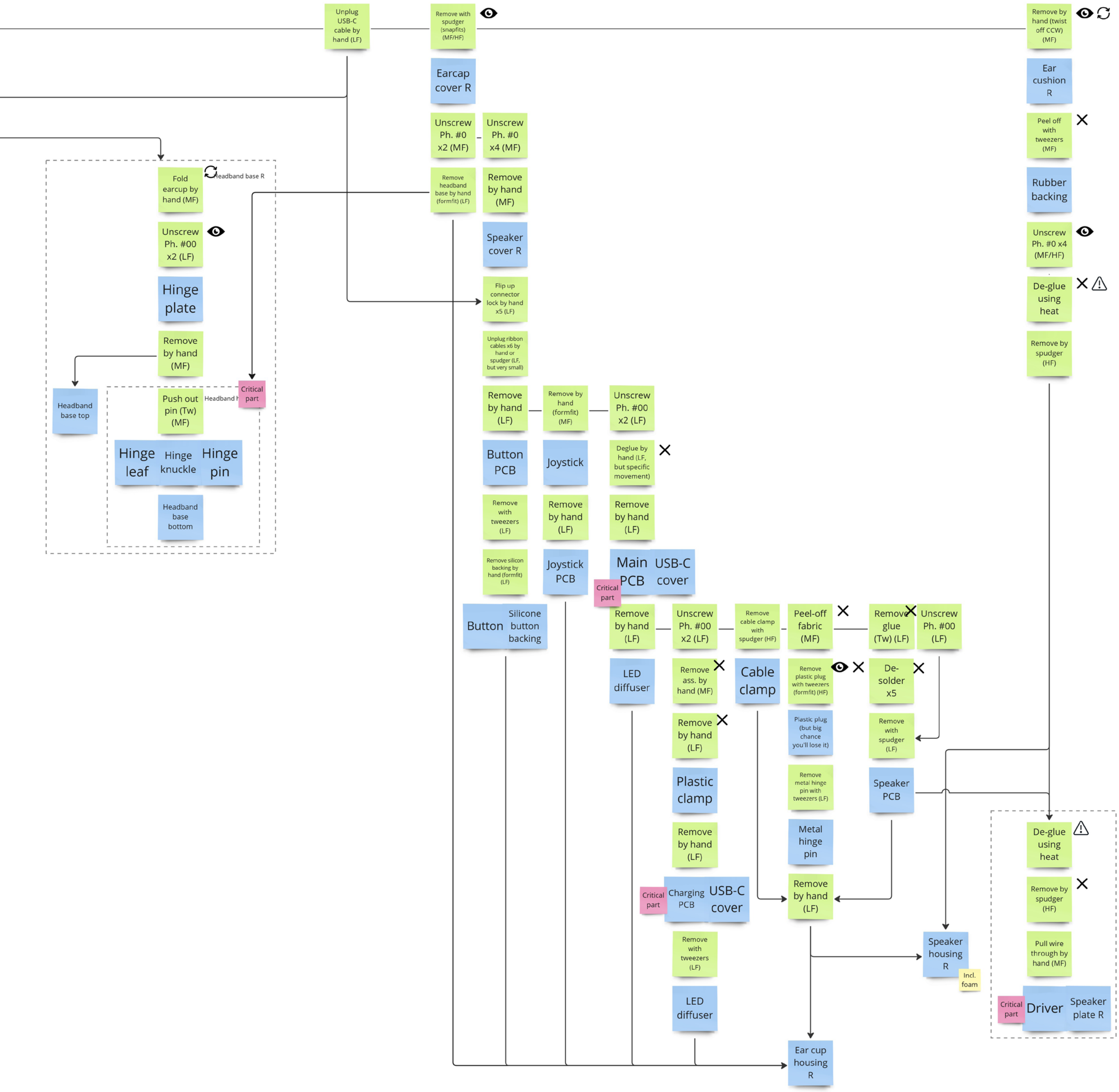


Figure F-2. Disassembly Map Fairphone Fairbuds XL.



Unplug USB-C cable by hand (LF)
Remove with spudger (snapfits) (MF/HF)
Earcap cover R
Unscrew Ph. #0 x2 (MF)
Unscrew Ph. #0 x4 (MF)
Remove headband base by hand (formfit) (LF)
Remove by hand (MF)
Speaker cover R
Flip up connector lock by hand x5 (LF)
Unplug ribbon cables x6 by hand or spudger (LF, but very small)
Remove by hand (LF)
Remove by hand (formfit) (MF)
Unscrew Ph. #00 x2 (LF)
Button PCB
Joystick
Deglue by hand (LF, but specific movement)
Remove with tweezers (LF)
Remove by hand (LF)
Remove by hand (LF)
Remove silicon backing by hand (formfit) (LF)
Joystick PCB
Main PCB
USB-C cover
Critical part
Button
Silicone button backing
Remove by hand (LF)
Unscrew Ph. #00 x2 (LF)
Remove cable clamp with spudger (HF)
Peel-off fabric (MF)
Remove glue (Tw) (LF)
Unscrew Ph. #00 (LF)
LED diffuser
Remove ass. by hand (MF)
Cable clamp
Remove plastic plug with tweezers (formfit) (HF)
De-solder x5
Remove by hand (LF)
Plastic plug (but big chance you'll lose it)
Remove with spudger (LF)
Plastic clamp
Remove metal hinge pin with tweezers (LF)
Speaker PCB
Remove by hand (LF)
Metal hinge pin
Critical part
Charging PCB
USB-C cover
Remove by hand (LF)
Remove with tweezers (LF)
Speaker housing R
Incl. foam
LED diffuser
Ear cup housing R
Fold earcup by hand (MF)
Headband base R
Unscrew Ph. #00 x2 (LF)
Hinge plate
Remove by hand (MF)
Headband base top
Push out pin (Tw) (MF)
Headband
Critical part
Hinge leaf
Hinge knuckle
Hinge pin
Headband base bottom
Remove by hand (twist off CCW) (MF)
Ear cushion R
Peel off with tweezers (MF)
Rubber backing
Unscrew Ph. #0 x4 (MF/HF)
De-glue using heat
Remove by spudger (HF)
De-glue using heat
Remove by spudger (HF)
Pull wire through by hand (MF)
Critical part
Driver
Speaker plate R

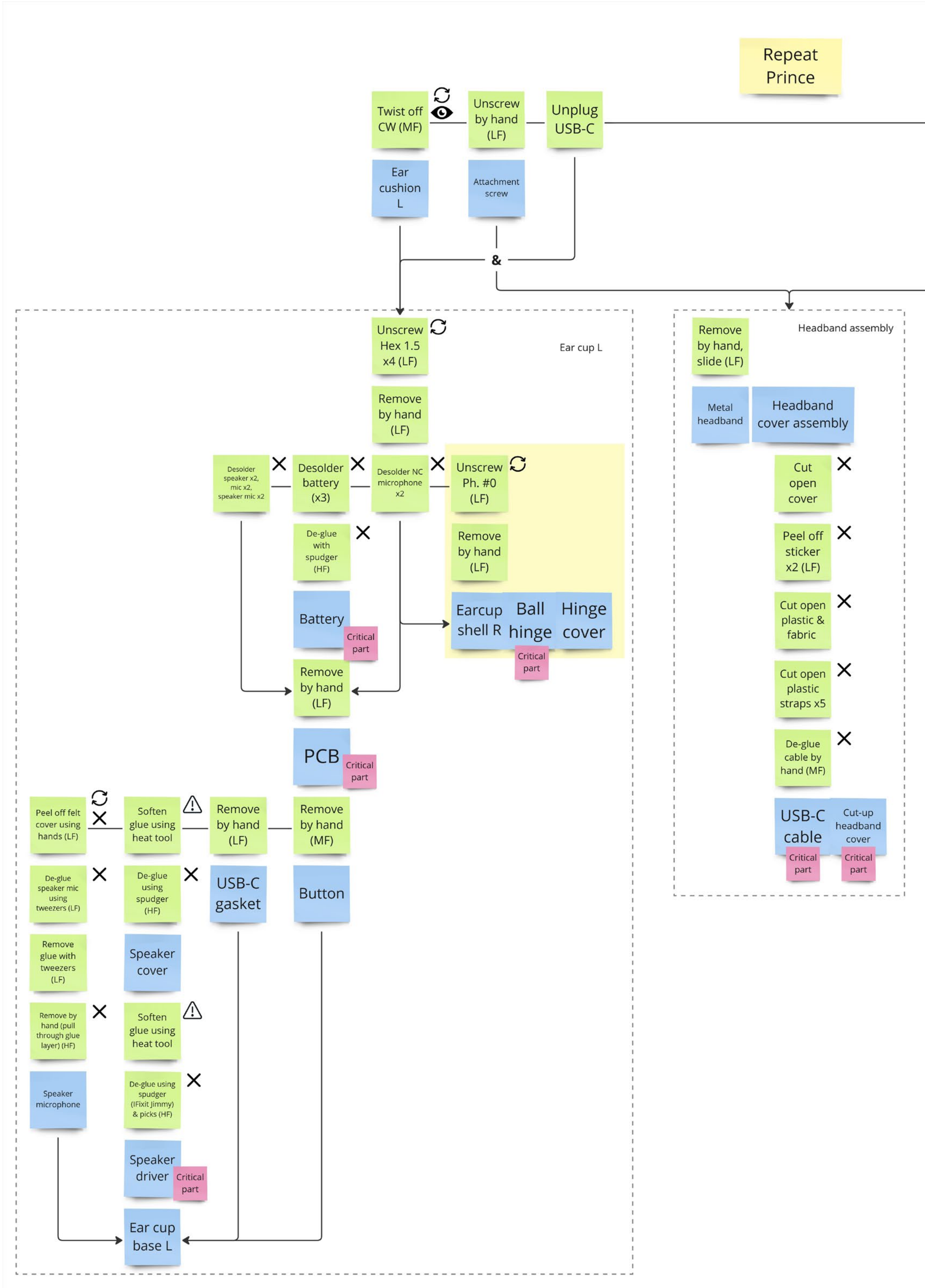
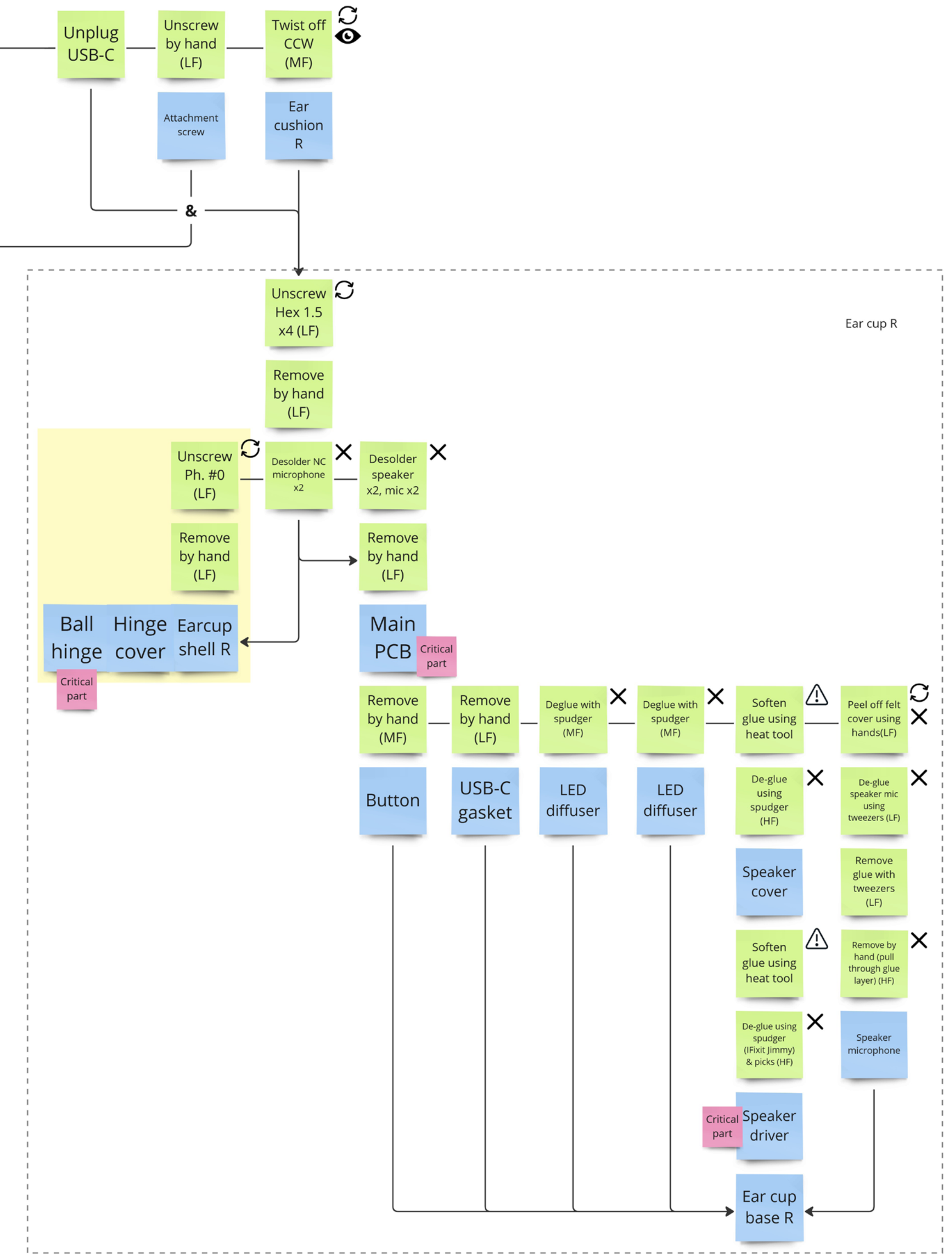


Figure F-3. Disassembly Map Repeat Prince.



Unplug USB-C
Unscrew by hand (LF)
Twist off CCW (MF)
Attachment screw
Ear cushion R
&
Unscrew Hex 1.5 x4 (LF)
Ear cup R
Remove by hand (LF)
Unscrew Ph. #0 (LF)
Desolder NC microphone x2
Desolder speaker x2, mic x2
Remove by hand (LF)
Remove by hand (LF)
Ball hinge
Hinge cover
Earcup shell R
Critical part
Main PCB
Critical part
Remove by hand (MF)
Remove by hand (LF)
Deglue with spudger (MF)
Deglue with spudger (MF)
Soften glue using heat tool
Peel off felt cover using hands(LF)
Button
USB-C gasket
LED diffuser
LED diffuser
De-glue using spudger (HF)
De-glue speaker mic using tweezers (LF)
Speaker cover
Remove glue with tweezers (LF)
Soften glue using heat tool
Remove by hand (pull through glue layer) (HF)
De-glue using spudger (IFixit Jimmy) & picks (HF)
Speaker microphone
Critical part
Speaker driver
Ear cup base R

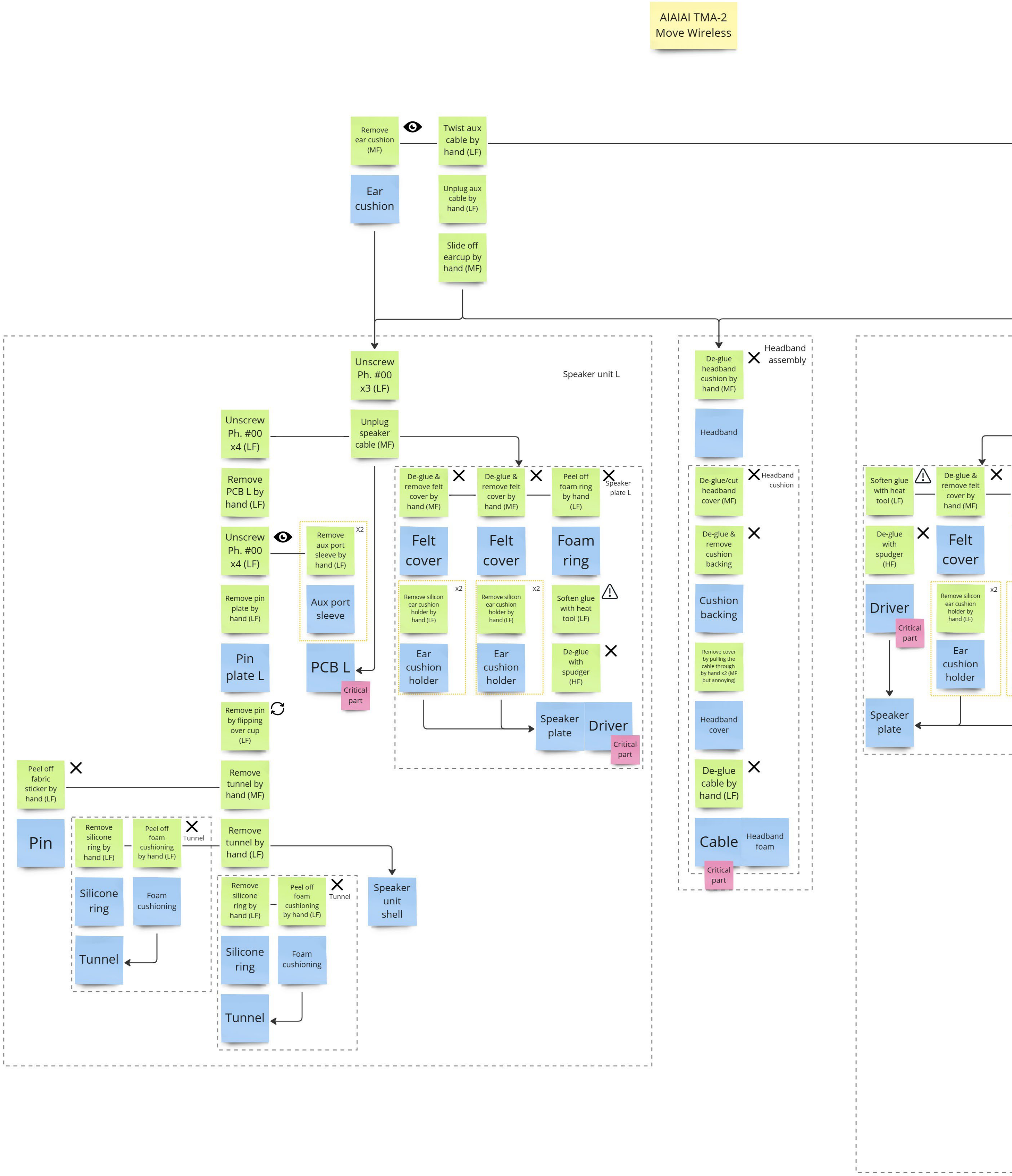
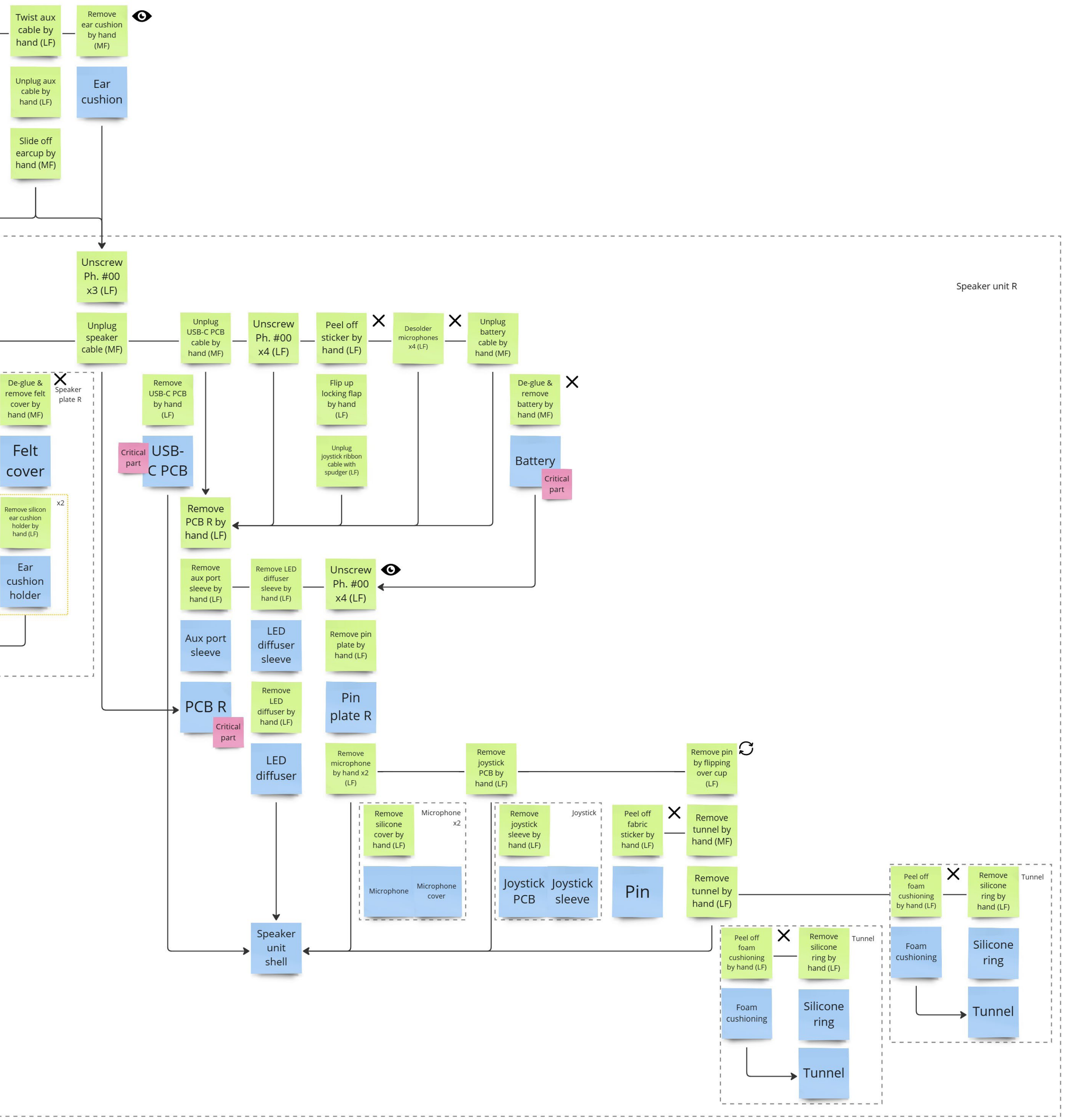


Figure F-4. Disassembly Map AIAIAI TMA-2 Move Wireless.


Twist aux cable by hand (LF)
Remove ear cushion by hand (MF)
Unplug aux cable by hand (LF)
Ear cushion
Slide off earcup by hand (MF)
Speaker unit R
Unscrew Ph. #00 x3 (LF)
Unplug speaker cable (MF)
Unplug USB-C PCB cable by hand (MF)
Unscrew Ph. #00 x4 (LF)
Peel off sticker by hand (LF)
Desolder microphones x4 (LF)
Unplug battery cable by hand (MF)
De-glue & remove felt cover by hand (MF)
Speaker plate R
Remove USB-C PCB by hand (LF)
Flip up locking flap by hand (LF)
De-glue & remove battery by hand (MF)
Felt cover
Critical part
USB-C PCB
Unplug joystick ribbon cable with spudger (LF)
Battery
Critical part
x2
Remove silicon ear cushion holder by hand (LF)
Remove PCB R by hand (LF)
Ear cushion holder
Remove aux port sleeve by hand (LF)
Remove LED diffuser sleeve by hand (LF)
Unscrew Ph. #00 x4 (LF)
Aux port sleeve
LED diffuser sleeve
Remove pin plate by hand (LF)
PCB R
Critical part
Remove LED diffuser by hand (LF)
Pin plate R
LED diffuser
Remove microphone by hand x2 (LF)
Remove joystick PCB by hand (LF)
Remove pin by flipping over cup (LF)
Remove silicone cover by hand (LF)
Microphone x2
Remove joystick sleeve by hand (LF)
Joystick
Peel off fabric sticker by hand (LF)
Remove tunnel by hand (MF)
Microphone
Microphone cover
Joystick PCB
Joystick sleeve
Pin
Remove tunnel by hand (LF)
Peel off foam cushioning by hand (LF)
Remove silicone ring by hand (LF)
Tunnel
Speaker unit shell
Peel off foam cushioning by hand (LF)
Remove silicone ring by hand (LF)
Tunnel
Foam cushioning
Silicone ring
Tunnel
Foam cushioning
Silicone ring
Tunnel

Appendix G — Circular product design strategies

In Products that Last, Bakker et al. (2014) outline six circular product design strategies aimed at prolonging the life span of a product.

Design for Attachment and Trust

User are more likely to keep and care for a product they feel connected to. This strategy focuses on designing products that evoke a sense of attachment and trust, although this is a complex phenomenon and not fully controllable through design.

Design for Durability

Products should both be physically long-lasting and perceived as reliable. Interestingly, a product that frequently requires minor repairs or maintenance may be perceived as more reliable than a product with rare but major failures.

Design for Standardisation and Compatibility

Designing products to work with other products or standardised components, with the goal of either expanding your product, using it for a different function, or repairing it.

Design for Ease of Maintenance and Repair

Maintenance and repair are essential for elongating the life of a product and maintaining its value. These processes must be worthwhile for all the parties involved.

Design for Adaptability and Upgradability

Products should be able to evolve over time, either to keep up with technological developments, add new functionalities, or adapt to its user's changing needs.

Design for Dis- and Reassembly

Easy disassembly is a classic requirement for sustainable products, but reassembly is equally important. You shouldn't only be able to take a product apart, but also put it back together.

Simplicity plays a key role in this.

Appendix H — Guidelines for designing for the end-of-life

The strategies in Appendix G focus on prolonging the use of a product. However designing for the end-of-life is just as important, as products cannot last forever. This is especially the case for small electronic devices, as they contain valuable and critical raw materials.

PolyCE has developed a set of guidelines for designing electronic devices that enable better and easier recycling (Feenstra et al., 2021). Below are the main topics and the guidelines relevant for headphones.

Enable easy access and removal of hazardous or polluting components.

- Avoid permanent fixing methods for batteries. Instead, use click or snap solutions.
- Avoid permanent fixing methods for valuable components (PCBs, cables, wires and motors). Instead use metal screws, click fingers, press fit, shrink foil, selfscrewed/tapering or connectors.
- Avoid magnetic components on PCBs.

Use recyclable materials which will be recycled by WEEE (Waste of Electrical and Electronic Equipment) recyclers.

- Avoid the use of coatings on plastics
- Avoid the use of foam. When foam is necessary, use thermoplastic foam.
- Minimize the use of magnets.

Use material combinations and connections that allow liberation.

- Avoid connections that permanently enclose materials, such as moulding inserts into plastic, rivets, staples, press-fits, bolts and nuts, brazing, welding, or clinching.
- Avoid fixing ferrous metals to non-ferrous metals in either parts or fasteners.

Appendix I — Explored visions

The next pages contain an explanation sheet of each vision, which was the starting point for the corresponding Design in a Day session. The results of the Design in a Day session is included below the explanation sheet.

VISION 1: CLARITY

WHAT

Headphones that foster clarity from the unboxing onward, enabling users to understand the product and feel confident in their ability to use, maintain, repair, and care for their device. By reducing uncertainties around use and upkeep, the headphones elicit a feeling of agency.

HOW IT SUPPORTS CIRCULARITY

By enabling users to understand their headphones and taking away doubt and insecurities surrounding the product architecture, use, maintenance, repair and end-of-life steps, they are less likely to be intimidated by the steps needed to extend the life of their headphones. This knowledge and confidence thus helps reduce the likelihood of early disposal, supporting a more circular product lifecycle.

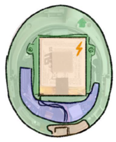
WHY I FIND IT INTERESTING

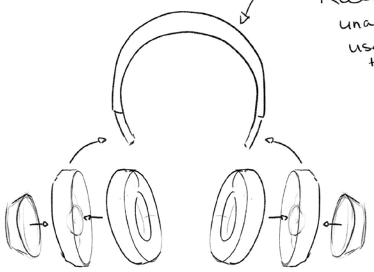
I think user understanding and confidence is key. You can design products to be fully repairable and circular, but without user confidence in how to maintain, repair, or properly dispose of them, these efforts won't have any effect.
During the disassembly of the headphones, I found it really frustrating to be unsure of each component's function and the disassembly steps needed, which emphasized the importance of clarity in the design and product architecture.

IDEATION

Simplistic product architecture

Visual indicators to differentiate different components & functions





Receive the headphones unassembled, so the user has to assemble them

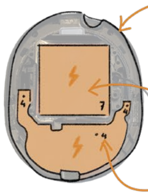
Clear boundaries between self- and service repair

Clear error indication and diagnostics

IMPORTANT FOR ALL:

Accessibility of information, support, and guidance
Easy dis- and reassembly
Comfort (& user experience) shouldn't be negatively affected

1. Clarity



Received unassembled, user can assemble them using just the clamp.

Take-aways

- Interesting duality between wanting users to understand their headphones, but also wanting a certain level of separation between self- and service-repair.
- Vision should go beyond just the product.

Questions

- What parts should be available for self-repair?

VISION 2: PRIORITISING CARE & MAINTENANCE

WHAT

Headphones that incentivise the user to properly care for and maintain them. The product's design and accompanying services are used to transform care and maintenance into a natural, enjoyable part of ownership.

HOW IT SUPPORTS CIRCULARITY

Care and maintenance is the first step to extending a product's life. When users are guided to perform maintenance and view it as an engaging routine, they are more likely to regularly tend to it, ultimately supporting circularity by prolonging use.

WHY I FIND IT INTERESTING

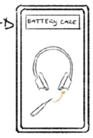
Maintenance is often viewed as a chore, while in reality it is a proactive, preventative measure. By reframing maintenance as a rewarding and relaxing ritual, we can shift this view and help users see maintenance as an integral part of product ownership that enhances their experience, rather than something to dread.

IDEATION

better experience for care, maintenance and repair

Reminders

interactive support guides



Visual indicators for care

like with toothbrush bristles

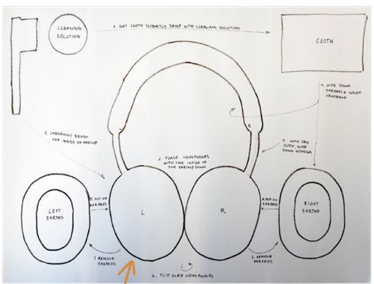
availability of care products/kits

care as a ritual

IMPORTANT FOR ALL:

Accessibility of information, support, and guidance
Easy dis- and reassembly
Comfort (& user experience) shouldn't be negatively affected

2. Maintenance

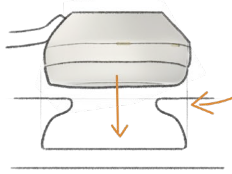


Ridge prohibits moisture from entering the earcup when the headphones are placed correctly on the cleaning station.

Special cleaning station with instructions.

Case with designated spot for cleaning supplies and with a maintenance reminder & info.

Case cleans the earcushions when the headphones are placed inside.



Take-aways

- Not that many parts really need regular maintenance, other than wiping the earpads after every use and cleaning the headphones weekly.
- Not really focused on the product, more on surrounding things like the app, case, information provision, and cleaning kit.

Questions

- How is maintenance defined? Is it just preventative, or also corrective?

VISION 3: HEADPHONES THAT LAST A LIFETIME

WHAT

Headphones designed to last a lifetime, emphasizing durability, modularity, and upgradability. Obsolescence can be prevented by allowing for component upgrades periodically, so the headphones can adapt to technological advancements, while an exererior that ages well ensures you do not feel the need to replace your headphone on aesthetic grounds.

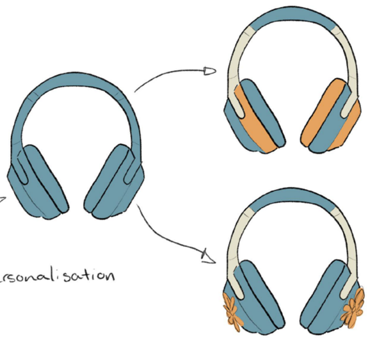
HOW IT SUPPORTS CIRCULARITY

The most sustainable product is the product that lasts the longest. When headphones are built to last, with replaceable components, users can easily update technology without discarding the entire product. This approach extends the product lifecycle and contributes to a circular economy by minimizing the environmental impact of disposal.

WHY I FIND IT INTERESTING

Extending the lifespan of a product has one of the greatest impacts on its sustainability, and while it seems like a straightforward solution, achieving it involves addressing multiple interconnected aspects. Many products today are simply not designed to last; repair is difficult, and upgradability is often overlooked.

IDEATION



ability to easily change the look of the headphones → = personalisation

opposites

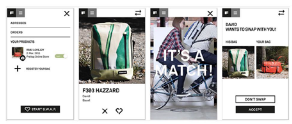
timeless design

option to refinish exterior housing

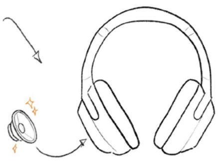
materials that age well

digital market place to swap out parts

Like Freitag's S.W.A.P platform



easily swap out components so your headphone stays up to date



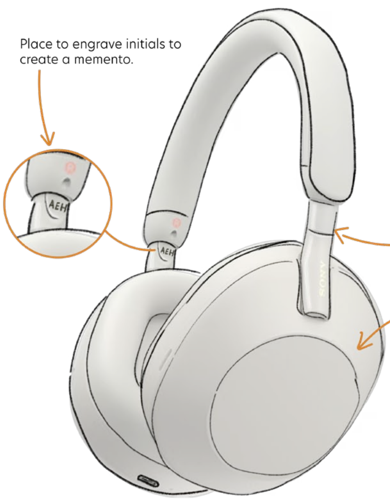
Access business model

↳ subscription-based

IMPORTANT FOR ALL:

Accessibility of information, support, and guidance
Easy dis- and reassembly
Comfort (& user experience) shouldn't be negatively affected

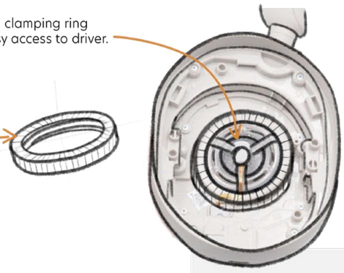
3. Last a lifetime



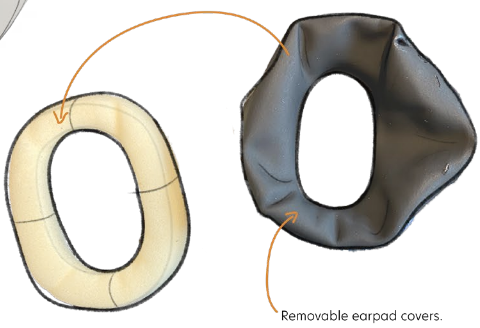
Place to engrave initials to create a memento.

High -end materials.

Swappable covers.



Screw-on clamping ring gives easy access to driver.



Removable earpad covers.

Take-aways

- Vision currently too broad to work with.
- While there were some interesting directions, it was hard to combine them into a cohesive idea.

Questions

- Even if a pair of headphones could last for a lifetime, would people use it for that long?