

# Circular design of electric toothbrushes

Mart Drummen  
Integrated Product Design  
Master Thesis



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Concept design of an electric toothbrush ready for the circular economy.

*Master thesis*

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## Foreword

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*This thesis brought together all my learning from 5 years of studying at TU Delft and I want to thank everyone that was involved in this thesis.*

*I would like to thank Bas and Ruud for their guidance as this result would not have been possible without them. By challenging me to step outside my comfort zone the project yielded a final result that I am truly proud of.*

*I would like to thank Arjan and Moritz for the weekly graduation meetings and tips provided. Doing this together made a big difference.*

*I would like to thank my colleagues for participating in the creative session and providing me with great ideas and I would like to thank all those that provided toothbrushes for the analysis phase of the thesis.*

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*Mart Drummen  
Delft, Juli 13, 2022*

## Abstract

Electric toothbrushes are the most effective method for maintaining oral hygiene (Elkerbout et al., 2019), but also the method with the greatest environmental impact (Lyne et al., 2020). Most of the impact of electric toothbrushes comes from transport, materials and parts (Lyne et al., 2020). This means that by extending the product life and enabling local loops, the environmental impact of electric toothbrushes can be reduced. The circular economy encompasses multiple strategies that can be leveraged to achieve this (Bocken et al., 2016).

So far, there has been little research into designing small waterproof personal care appliances for the circular economy. In this thesis, the challenges and opportunities for transitioning electric toothbrushes to the circular economy are uncovered and a design solution to these challenges and opportunities is proposed. The primary research question for this thesis is:

*How can an electric toothbrush be designed suitable for the circular economy?*

The first two phases of this thesis were dedicated to uncovering the challenges and opportunities for transitioning electric toothbrushes to the circular economy. In the first phase, research into the state of the circular economy of current electric toothbrushes was performed in which the academic, manufacturer and user perspectives were researched. This led to three key insights for the circular design of an electric toothbrush. In the second phase, an analysis was performed of the implementation of circular design strategies in a representative set of current electric toothbrushes. This led to four key insights for the circular design of an electric toothbrush.

In the third phase of the thesis, the key insights were translated to design challenges and a design solution to tackle these design challenges was conceived. This resulted in the Everbrush electric toothbrush concept (see Figure 1).

The battery has been made user replaceable to tackle the primary reason for reaching the end of life, reduced battery performance. An aluminium main body was introduced that aims to increase product attachment by ageing with dignity, which should also increase repair considerations. Another aim of the aluminium main body is to reduce hygiene concerns when purchasing refurbished. The ease of disassembly has been improved significantly which can open up additional opportunities for product life extensions. The amount of elastomers has been reduced by introducing a rotating magnetic power switch, eliminating the need for a power switch seal and increasing high-value recycling performance. Lastly, permanent connections were avoided throughout the design, also increasing high-value recycling performance.



Figure 1: Everbrush circular electric toothbrush concept.

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# Project & context

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*Relevance of the project & Introduction of core elements*

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# 1. Project scope

## 1.1. Goal & context

The goal of this thesis is to uncover challenges and opportunities for transitioning electric toothbrushes to the circular economy and to propose a design solution to these challenges and opportunities. Toothbrushes are chosen as representative products of small waterproof personal care appliances with complex integrated product architectures. This type of product has so far seen little research for implementation in the circular economy. The primary research question of this thesis is:

*How can an electric toothbrush be designed suitable for the circular economy?*

While the use of electric toothbrushes is beneficial for oral hygiene, their environmental impact is comparatively high. There are several types of toothbrushes available, but the electric toothbrush is considered the most effective (Elkerbout et al., 2019). Unfortunately, it also has the greatest environmental impact out of all types (Lyne et al., 2020). In Europe, the use of electric toothbrushes is common, for example in Great Britain (51 million in use)(Kantar Media, 2021a), Spain (31 million in use)(Kantar Media, 2021b) and France (20 million in use)(Kantar Media, 2021c). With an average lifetime of 3 to 5 years (Ordo, 2020), it is expected that over 20 million toothbrushes a year are disposed of in these countries combined.

The circular economy is an effective way of reducing electric toothbrushes' environmental impact and the amount the e-waste generated. Most of the impact generated by electric toothbrushes comes from transport, materials and parts (Lyne et al., 2020), meaning that elongating product lifetime can significantly reduce the environmental impact of using electric toothbrushes. Elongating the product lifetime also reduces the number of toothbrushes disposed of yearly. The circular economy includes several strategies that can be used to elongate product life and retain the material and part value as much as possible throughout product life. These strategies are further elaborated on in chapter 3.

## 1.2. Approach

This thesis is split into three phases: Research, Analysis and Design. Each of these phases has its own research questions that combined serve to answer the primary research question of this thesis.

In order to bring toothbrushes towards the circular economy, it is important to gain insight into the lifecycle of current electric toothbrushes. By uncovering the factors leading to replacement and the circularity efforts currently made, insight can be gained into the challenges and opportunities for implementing a circular economy for electric toothbrushes. Additionally, this can serve as a reference for any gains made to improve the circularity of electric toothbrushes. The research questions for the first phase are:

*RQ1.1: What is the state of the circular economy of current electric toothbrushes?*

*RQ1.2: Which challenges and opportunities for implementing a circular economy for electric toothbrushes are there?*

Existing literature discusses an array of circular design strategies that can be applied in order to design products suitable for the circular economy. Current electric toothbrushes might or might not contain some of these design strategies already. By analysing current electric toothbrush designs for the implementation of these circular design strategies, insight can be gained into the challenges and opportunities for implementing circular design strategies in electric toothbrushes. Additionally, this analysis will provide insight into the design considerations made. The research questions for the second phase are:

*RQ2.1: How are circular design strategies implemented in the design of current electric toothbrushes?*

*RQ2.2: Which challenges and opportunities for implementing circular design strategies in electric toothbrushes are there?*

In the third phase, design solutions will be explored that aim to tackle the challenges and opportunities found in the first two phases. The design solutions will be combined into an integrated design. This design also aims to serve as a guide for designing circular small waterproof personal care appliances in general. The research question for the third phase is:

*RQ3: How can an electric toothbrush be designed that tackles the challenges and opportunities for transitioning electric toothbrushes to the circular economy?*



Figure 2: Disassembled Oral-B iO electric toothbrush (Isakeit, 2020).

## 2. Circular economy

### 2.1. Introduction

The goal of this thesis is to design an electric toothbrush suitable for the circular economy. But what is the circular economy, and how can it help reduce the environmental impact? The remainder of this chapter aims to answer these questions by discussing relevant academic literature.

### 2.2. Definition

The circular economy is a departure from the linear economy in which resources are obtained, used and discarded (Ellen MacArthur Foundation, n.d.). As Geisendorf & Pietrulle (2017) defined:

*“In a circular economy, the value of products and materials is maintained, waste is avoided, and resources are kept within the economy when a product has reached the end of its life.”*

There are several motivations for this switch. Increasing human activity since the Industrial Revolution is driving environmental change and threatening the stability of the earth’s desirable environmental state (Rockström et al., 2009), and there is a strong belief that transitioning to the circular economy is important to stopping this change (Ellen MacArthur Foundation, 2021). Besides addressing environmental issues, there are economic benefits to a closed-loop system such as material savings, reduced supply risks and potential unemployment benefits (Ellen MacArthur Foundation, 2013).

### 2.3. Thinking in loops

The circular economy for products is built upon a rethinking of product life cycles. Contrary to products in the linear economy, the lifecycle for circular products consists of loops. There are three fundamental strategies for optimizing the flow of resources in these loops, introduced by Bocken et al. (2016):

- Slowing resource loops: By keeping products working for a longer period of time, the flow of resources is slowed down.

- Closing resource loops: By using high-value recycling to cycle resources back into the production, resource flows can be closed resulting in a circular system.
- Narrowing resource flows: By using fewer resources per product, the amount of resources in the flow can be reduced.

Additionally to introducing three fundamental strategies to optimize the flow of resources in loops, Bocken et al. (2016) highlight several product design strategies that can be used to enable those fundamental strategies. These strategies are discussed in detail in chapter 3.

### 2.4. Capturing value

By applying these fundamental strategies for optimizing resource flows, a lot of value can be retained. Each step prior to the use of a product, from extracting resources to the sale of a product, is adding value to that product. Each step after the use of a product can be seen as reducing the value of this product. This is captured visually in the value hill introduced by Achterberg et al. (2016). Both the linear (see Figure 3) and circular (see Figure 4) scenarios have been visualized.

The higher up on the value hill, the greater the value of the product. So logically, the higher up on the value hill a loop is created, the more value can be saved. However, there is a cost to creating any loop. For example, in order to sell a refurbished product, it needs to be bought from users that no longer desire the product, checked and thoroughly cleaned and sold again. In order for a loop to make business sense, the cost of all these steps should not exceed the cost of creating the value in another way. This means that in a sense, the value captured when creating a loop at a certain level of the hill can be seen as the budget available for creating that loop (see Figure 5). This is important as it can help determine which circular business model is profitable to apply.

## 2.5. Conclusion

The circular economy is a departure from the linear economy in which “the value of products and materials is maintained, waste is avoided, and resources are kept within the economy when a product has reached the end of its life” (Geisendorf & Pietrulle 2017). In the circular economy resource flows are optimized in three ways: slowing, closing and narrowing loops. By optimizing these resource flows, environmental impact can be reduced and value can be retained, making it economically viable to do so. Several design strategies can be applied in order to optimize resource flows.

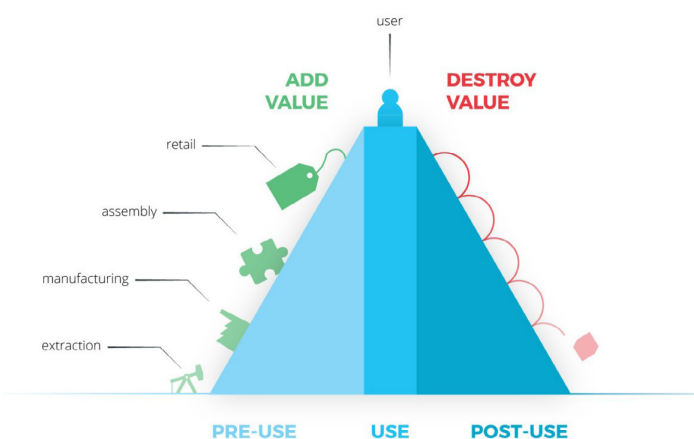


Figure 3: Value hill of Linear scenario (Achterberg et al., 2016).

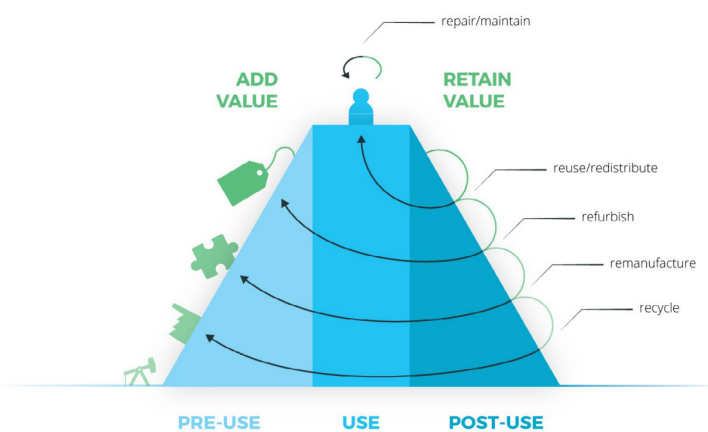


Figure 4: Value hill of Circular scenario (Achterberg et al., 2016).

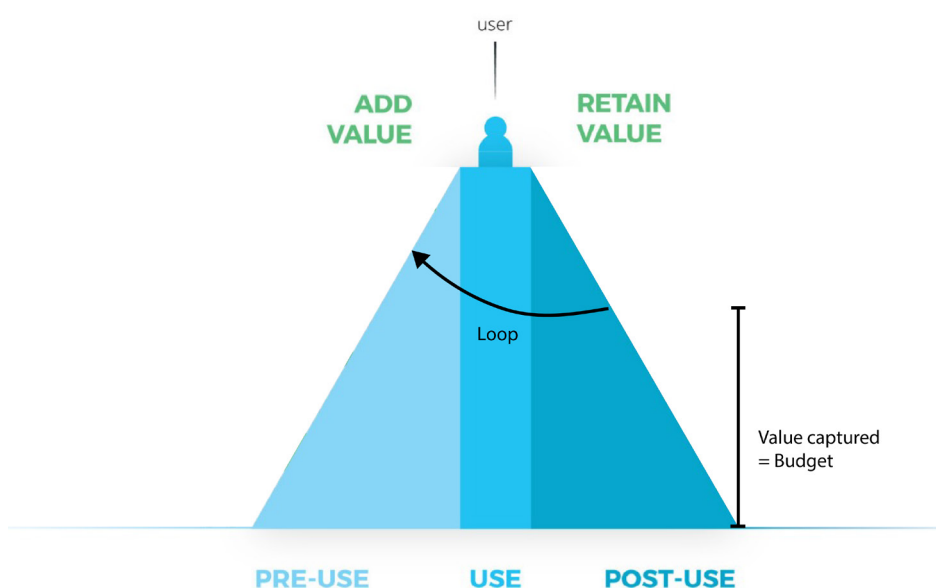


Figure 5: The value captured can be seen as the budget for creating a loop. Image edited from the image by Achterberg et al., (2016).

## 3. Circular design strategies

### 3.1. Introduction

In order to design an electric toothbrush suitable for the circular economy, it is important to gain a deeper understanding of how to design for the circular economy. Bocken et al. (2016) introduce a series of circular design strategies based on three fundamental strategies for optimizing resource flows. This chapter provides an overview of the design strategies and insight into how they can be implemented into a product.

### 3.2. Designing long-life products

The first strategy aimed at slowing resource loops is designing long-life products. When applying this strategy, the goal is to ensure long usage periods by preventing replacement. There are three sub-strategies that can contribute to achieving this.

#### Design for durability

Designing for durability means designing products that are able to perform their functions for an extended period of time without breaking down or obtaining excessive wear (Bocket et al., 2016). Examples are products designed to survive the impact of falling on a floor or being tossed in a backpack along with other goods. There is no single strategy for improving product durability. Attention should be paid both to damage prevention and wear resistance (Mulder et al., 2014). The success of implementation can be evaluated by observing commonly occurring failures (or the lack thereof).

#### Design for reliability

Reliability is different to durability as it does not necessarily relate to physical damage, but specifically to operation for a specified amount of time without failure (Moss, 1985). For this, the design of mechanisms that are unlikely to fail within the desired product life is important. Like with design for durability, no single design strategy is defined for design for reliability. Suggestions for ways to improve reliability are designing out moving parts and over-dimensioning critical components (Mulder et al., 2014).

#### Design for attachment & trust

The topic of designing for attachment has been widely researched (Page, 2014; Odom et al., 2009; Mugge, 2007), resulting in various frameworks aiming to aid designers to design products with stronger user attachment. Mugge lists several design strategies based on four determinants, Page lists several themes, and Odom et al. list categories. For this graduation thesis, the four determinants and related design strategies devised by Mugge will be used as the core framework for design for attachment & trust.

#### Self-Expression

Self-expression can be leveraged by designers using three different design strategies.

The first strategy is matching a product's personality associations with those of the user. This allows the user to use the product for self-expression. Page suggests this can be achieved by adding distinct colours or patterns. A downside to this approach according to Mugge et al. is the ease of replacing such a product with another product with the same personality associations.

The second strategy is allowing product personalisation. There is a positive relationship between the effort required for personalisation and the effect it has on consumer attachment (Mugge, 2007). The downside to requiring more effort is the barrier this can create for users. Odom et al. defined a category called augmentation that is similar but add that personalisation can also occur in reuse or modification, which allows the product to function as a symbol of the user's resourcefulness.

The last strategy is creating unique or exclusive products. Products like this allow users to differentiate themselves from others and are superior for self-expression in that sense. This can be achieved by creating products in limited runs, which causes the product to feel irreplaceable.

### Group Affiliation

Besides the need to distinguish themselves from others, users have a desire to be part of a group. A suggested strategy for achieving this is by designing products for shared use or use in a group setting. Page and Odom et al. also mention this phenomenon. By blending the associations one has with a product with those one has with a group or the shared events, the product becomes harder to replace.

### Memories

When a product is connected to memories, users grow attached to the product. Both Page and Odom et al. also highlight this method of generating product attachment, although Odom et al. calls this category histories. Both Mugge and Page mention that memories are hard to control via product design, but do offer some suggestions for how designers can generate them.

Designing products that age with dignity allows products to gain observable wear and tear to which memories can be connected while keeping the products in a desirable state. An example of this is products made with leather or wood, which can look better over time. Another design strategy suggested by Mugge et al. is implementing odours in products. A potential difficulty of this strategy is finding a good fit between the scent and the product.

### Pleasure

Pleasure originates from a product's superior utility and/or appearance (Mugge, 2007). Page and Odom et al. also name this theme, but Odom et al. call this category engagement and put the focus on tactility and physical engagement. Mugge recognizes that making a product that is simply superior to other competing products is not an easy task, especially in a market in which products are continuously improving.

To achieve a long-lasting feeling of pleasure, designers have to "incorporate pleasure eliciting attributes" that are exclusive to the product. An opportunity to achieve this is creating products that surprise users. Two suggested design strategies for achieving this are using new materials that look like familiar materials and as such can provide a tactile surprise or the other way around, using a new appearance for a familiar product or material.

## 3.3. Design for product life extension

The second strategy that can be utilized for slowing resource loops is designing for product life extension. Product life extension means designing products in such a way that when they do become undesirable to use, there are ways to make the product desirable once again. Within this strategy, four sub-strategies are defined.

### Design for maintenance and repair

Maintenance is the performance of tasks aimed at retaining the functional capabilities of a product. Repair is about restoring a product back to working condition after damage (Bocken et al., 2016). Designing for maintenance and repair means designing products in such a way that the required maintenance or repair can be executed.

The ease with which it is possible to execute maintenance or repair depends greatly on the accessibility of parts that can be expected to wear during use or that are prone to breaking down. As such, the ease of disassembly is of great importance. For further detail on design for dis- and reassembly see chapter 3.6.

### Design for future expansion

Designing for future expansion means designing with future modifications or upgrades in mind. An upgrade is defined as a functional enrichment for a product (Pialot and Millet, 2014), although Aziz et al. (2016) also discussed its potential for changing product aesthetics. While Bocken et al. (2016) categorize this strategy as a method of slowing loops, several other works highlight its potential for successful remanufacturing activities (Aziz et al., 2016; Pialot and Millet, 2014). By enriching a product's functionality it can stay competitive in an evolving market.

The ease with which it is possible to execute upgrades depends greatly on the accessibility of parts that are meaningful to upgrade. Similar to design for maintenance and repair, to achieve this, ease of disassembly is of importance. For further detail on the design for disassembly see chapter 3.6.

### Design for standardization and compatibility

Designing for standardization and compatibility means creating products with parts and interfaces that can fit in multiple products (Bocken et al., 2016). A clear example of this strategy is personal computers, which feature standardized interfaces allowing users to interchange parts and keep their devices in a desirable state. This strategy is in a way complementary to design for future expansion, as designing with interfaces that can fit multiple components can enable future expansion.

### Design for dis- and reassembly

Previously mentioned as important to design for maintenance and repair and design for future expansion, design for dis- and reassembly can be a strategy in itself. Bocken et al. (2016) state that by focussing on the overall ease of dis- and reassembly, future rates of material and component reuse can be increased. For further detail on the design for disassembly see chapter 3.6.

## 3.4. Design for a technological cycle

The first strategy when designing for closing resource loops is designing for a technological cycle. This strategy applies to products of service. Designing for a technological cycle means designing products in a way that allows for high-value recycling (primary or tertiary) at the product's end of life (Bocken et al., 2016).

In order to achieve this, several design for recycling guidelines devised by Balkenende & Bakker (2015) can be implemented. For material selection, only pure materials that can be recycled should be used and the number of different materials should be limited. For connections, fixed connections should be avoided and shredding should result in pieces with uniform composition, ideally with a relatively large size (>1 cm). For electronics, the PCB should be removable in one piece and materials should be detectable easy and fast.

## 3.5. Design for a biological cycle

The second strategy when designing for closing loops, design for a biological cycle, applies to products of consumption (consumables). In product design terms this means any parts of a product that are expected to be used up during the lifetime of the product. In order to close loops for these types of parts, materials have to be biodegradable (Bocken et al., 2016). For this project, design for a biological cycle is considered out of scope as the focus is on a product of service.

## 3.6. Design for dis- and reassembly

The third strategy for closing loops is designing for dis- and reassembly. It is very much interlinked with both other strategies for closing loops and also important for product-life extension.

The ability to disassemble products aids material separation for the technological and biological cycle. The ability to not only disassemble but also reassemble is important for maintenance, reparability and future expansion. Additionally, ease of dis- and reassembly contributes to making end-of-life activities viable (Kwak et al., 2009). The main factors influencing ease of dis- and reassembly are disassembly depth/sequence and disassembly time, the reusability/reversibility of fasteners and the use of common tools (de Fazio et al., 2021).

## 4. Electric toothbrushes

### 4.1. Introduction

An electric toothbrush is an electricity-powered brush that can be used for cleaning teeth. There is a wide variety of electric toothbrushes available on the market today, ranging from 10s to 100s of euros in cost and using varying techniques to achieve the same goal: clean teeth.

In this chapter, the basic product architecture of electric toothbrushes is introduced. Also, an overview of the various brush technologies, battery configurations and other features is provided.

### 4.2. Product architecture

Most electric toothbrushes have a similar basic product architecture. Three parts can be observed: The brush head, handle and charger. These parts can be easily separated from each other by the user.

The handle is the most complex part of the product and it houses most of the electronics. Most (if not all) electric toothbrushes nowadays are battery-powered. Besides the battery, they contain a motor to power the brush movement and a PCB to connect all electronics. Besides these core parts, electric brushes can contain a variety of other parts depending on their exact set of features. Figure 6 shows a disassembled Philips Sonicare Easyclean electric toothbrush, illustrating the variety of parts. A common electric toothbrush weighs between 100 and 150 grams (Love, 2021; Love, 2022).

### 4.3. Brush technology

There are three common brush technologies (Coolblue, n.d.), visualized in Figure 7.

#### 2D rotating

This is the most simple type, as there is rotation over only one axis. It is used mostly in budget toothbrushes with round brushes.

#### 3D rotating

This is a more advanced take on the rotating toothbrush which also adds a pulsating movement. It is used in mid-range and high-end round toothbrushes with round brushes.

#### Sonic

Different to the rotating technologies, the brush head moves from side to side and vibrates. The shape of the brush is often more oblong. Sonic toothbrushes often have a higher number of brush movements, expressed in PPM.

### 4.4. battery

There are varying types of batteries used. Most electric toothbrushes nowadays come with a built-in rechargeable battery, but there are exceptions like the Oral-B Advance Power and Quip Adult electric toothbrush (see Figure 8) that both come with easy user-replaceable AA or AAA batteries. Note that while not all batteries are easy for users to replace, the EU battery directive mandates that batteries need to be removable to ensure separation for recycling (Council directive 2006/66/EC, 2006).



Figure 6: A disassembled Philips Sonicare Easyclean electric toothbrush.

## 4.5. Extra features

Additionally to variations in brush technology, electric toothbrushes can offer a range of features. The overview below is based on the features highlighted on product pages by Coolblue (n.d.-a).

Some electric toothbrushes allow users to select various types of brush settings, for example, one optimized for sensitive teeth. In most cases, these settings just vary the number of brush movements.

Besides offering users control over brush settings, there are electric toothbrushes that aim to improve users' brushing behaviour and technique by adding a timer, pressure sensor and/or smartphone connectivity. These features provide the user with feedback on their brushing to optimize results.

Lastly, most electric toothbrushes are made waterproof for use in the shower and for ease of cleaning. Not every company specifies an IP rating, but both Oral-B and Philips state their electric toothbrushes are safe for use in the shower (PG consumer support, n.d.; Philips, n.d.-a). This would be about IPX5. Boombush does specify the rating at IPX7 (Boombush, n.d.), which means it can be submerged to depths of up to 1 meter for 30 minutes.

## 4.6. Conclusion

Electric toothbrushes are integrated pieces of consumer electronics. While the basic setup of most toothbrushes is quite similar, there can be variations in brush technology, battery configuration and features. The impact of these features on the circularity of electric toothbrushes could vary.



Figure 7: Brush technologies visualized. Top: 2D rotating; Middle: 3D rotating; Bottom: Sonic. (Coolblue, n.d.).



Figure 8: Quip Adult electric toothbrush with its AAA battery removed (Strietelmeier, 2017).



# Research

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*State of the circular economy of current electric toothbrushes*

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## 5. Phase 1 - Relevance, scope & objectives

### 5.1. Relevance

The first phase of this thesis aims to uncover the state of the circular economy of current electric toothbrushes. The state of the circular economy of current electric toothbrushes serves as an important framework on which to base the re-design to be made later in this thesis.

Gaining insight into the lifecycle of current electric toothbrushes will uncover the factors currently leading to replacement and the circularity efforts currently made. This insight will serve to uncover challenges and opportunities for the application of circularity for electric toothbrushes and guide the selection of design strategies to improve the circularity. Additionally, the current state of the circular economy will serve as a reference to measure any gains made to improve the circularity of electric toothbrushes.

### 5.2. Scope

The scope of this first project phase is limited to the overall status of the circular economy of current electric toothbrushes, thus excluding any insight on the design of specific toothbrushes. The design of specific electric toothbrushes will be researched in phase 2 of this thesis.

### 5.3. Research questions

The primary research questions for the first phase are:

- RQ1.1: What is the state of the circular economy of current electric toothbrushes?
- RQ1.2: Which challenges and opportunities for implementing a circular economy for electric toothbrushes are there?

The implementation of the design strategies discussed in chapter 3 is analysed in phase two, but to evaluate the state of the circular economy several performance metrics related to the design strategies have to be considered.

Based on these metrics, some additional secondary research questions can be formulated (RQ1.1.1 - RQ1.1.5). Also, two research questions for informing design were formulated based on RQ1.2 (RQ1.2.1 & RQ1.2.2).

#### Slowing resource Loops

Analysing how well design for long-life products is implemented requires finding out how long the average product life is, as well as what is causing EoL. For design for product-life extension, user acceptance of extension strategies such as maintenance, repair and refurbishment is a good indicator. For these extension strategies, collection rates are of great importance. As such, the following four research questions were defined:

- RQ1.1.1: How long is the product life for current electric toothbrushes?
- RQ1.1.2: What factors are currently leading to the EoL of electric toothbrushes?
- RQ1.1.3: Which efforts are currently made to extend the product life of electric toothbrushes?
- RQ1.1.4: How high are collection rates for current electric toothbrushes?

#### Closing resource loops

In order to close resource loops, electric toothbrushes need to be disposed of and recycled properly. Having dedicated collection programs for toothbrushes at end of life can help achieve this, but other efforts could also be made. As such, the following research question was defined:

- RQ1.1.5: Which efforts are currently made to close resource loops of electric toothbrushes?

#### Informing design

- RQ1.2.1: Which challenges for implementing a circular economy for electric toothbrushes are there?
- RQ1.2.2: Which opportunities for implementing a circular economy for electric toothbrushes are there?

## 6. Academic & industry perspective

### 6.1. Introduction

As discussed in chapter 2, the circular economy is built upon a rethinking of product life cycles. Toothbrush manufacturers can have a big impact on the product life cycles through the systems they put in place to slow or close the loops. This chapter aims to provide insight into the systems put in place by manufacturers to promote circularity and the performance of these systems, and relates those insights to academic literature.

The insight is gained through studying manufacturers' websites and contacting manufacturers. This dual approach of studying manufacturers' websites and contacting manufacturers was chosen as information on manufacturers' websites was often incomplete or absent. Relevant academic literature was studied to complement or relativize the manufacturers' claims.

All five research questions regarding the state of the circular economy for current electric toothbrushes were investigated (RQ1.1 to RQ1.5).

### 6.2. Product-life

No data on the product life of current electric toothbrushes was provided by manufacturers, but there are several clues for how long electric toothbrushes last. According to Cooper (2004), small work or personal care appliances last for four years. This is in line with the duration of three to five years mentioned across the internet and by toothbrush manufacturer Ordo (2020). While product-life is similar for mobile phones, most other types of electronics last longer (Cooper, 2004). According to Cooper, four years is two years short of what is considered reasonable by consumers.

Most of the impact is generated by the materials used and the transport of the toothbrush (Lyne et al, 2020) and not during product life. This means that locally looping the materials with the most impact (CO<sub>2</sub> eq.) can significantly decrease environmental impact.

### 6.3. End of Life

When trying to understand why products are reaching their EoL, it is important to understand the concept of obsolescence. There are two types of obsolescence to take into account when evaluating the end of life: absolute obsolescence and relative obsolescence (Granberg, 1997).

Absolute obsolescence is obsolescence due to a product ceasing to function. Relative obsolescence occurs when the currently owned product no longer has enough perceived value for the owner in comparison to new products. Relative obsolescence can be split into three categories. Psychological obsolescence (product attraction or satisfaction), economic obsolescence (financial factors) and technological obsolescence (functional qualities)(Cooper, 2004).

Harmer et al. (2019) explored the end of life of a vacuum cleaner and found that psychological obsolescence can play a big role in the premature disposal of vacuum cleaners, with vacuum cleaners that are perceived as dirty needing only minor defects to trigger disposal. Similar effects could be leading to the disposal of toothbrushes.

No quantitative data on the reasons for the replacement of electric toothbrushes was provided by manufacturers or could be found. Boombbrush was willing to provide some insight into the reasons for the absolute obsolescence of their toothbrushes, naming various occurring defects (motor, battery, power button and charging port)(K. Hiemstra, personal communication, March 23, 2022). No data could be provided for the frequency of occurrence of these defects. The reasons for replacement are further investigated in chapter 7.

## 6.4. Current efforts - Extending product life

### Maintenance

Maintenance can help extend product life by keeping the product in a desirable state for longer. Oral-B provides users with several basic instructions on the maintenance of their electric toothbrushes (OralB, n.d.), such as:

- Cleaning with running water
- Cleaning with a cloth once in a while
- Storing the electric toothbrush upright (promote air drying)
- Not charging continuously
- Replacing electric toothbrush heads every 3 months

No data is available for how well users follow these maintenance instructions or how effective they are for extending product life.

### Repair

No toothbrush manufacturer offers proprietary repair manuals. Philips even specifically states the batteries in their electric toothbrushes cannot be replaced (Philips, n.d.-c). However, instructions for the repair of several electric toothbrush models by Oral-B and Philips can be found on iFixit (Goldheart, n.d.). Note that not all instructions are by iFixit, as several are user-submitted.

Looking into the availability of these instructions and the difficulty of the repairs provides at least some insight into the current state of reparability of electric toothbrushes. See Table 1 for an overview of the availability of repair instructions and the difficulty of the repairs on iFixit.

While the availability of instructions in total is limited, at least most of the toothbrushes that do have instructions have them for battery replacement. Most toothbrushes require soldering for at least some repairs, inhibiting the accessibility to repair by users. It also stands out that very few of the repairs are deemed easy. Altogether it appears both Philips and Oral-B have not put too much effort into reparability for most of their models.

While none of the manufacturers offers proprietary repair manuals, most do at least have a repair service that users can send their toothbrushes to for repair. Depending on the type of repair, it is free in the warranty period of two years. But with electric toothbrushes lasting for about four years, this period is likely inadequate to cover most repair requests. This means users have to pay for repairs, which could prove problematic as López Dávila et al. (2021) found the cost of repair is the factor most likely to impede repair. According to Boombrush primary factors contributing to repair costs are transport and wages (K. Hiemstra, personal communication, March 23, 2022). Boombrush does offer users the option to get their battery replaced after 5-7 years (Boombrush, n.d.), but it is unclear whether there are costs associated with this offer.

Brand	Number of models that have repair instructions			Soldering required for one of the instructions		Repair difficulty (number of instructions with a certain difficulty)		
	Total	For battery	For other parts	Yes	No	Easy	Medium	Hard
Oral-B	6	6	3	5	1	3	1	8
Philips	7	5	6	6	1	4	11	7

Table 1: Overview of the availability of repair instructions and the difficulty of the repairs.

## Refurbishment

No manufacturer currently offers refurbished toothbrushes. They can be purchased from some other retailers online (Back Market, n.d.). Research by Mugge et al. (2017) indicated about 44% of consumers are willing to purchase refurbished toothbrushes. A hurdle to the refurbishment of electric toothbrushes is that they are 'in the user' products, which results in the highest level of repulsion among consumers (Abbey et al., 2015).

## Other strategies

No manufacturer offers options for future expansion. One interesting finding for standardization and compatibility is that there are Oral-B compatible brush heads made by other manufacturers that claim to be more sustainable (LiveCoco, n.d.; TIO, n.d.). A similar product exists for Philips brushes (Ecomondo, n.d.).

No information on dis- and reassembly could be found beyond the previously discussed repair manuals.

## 6.5. Current Efforts - Collection & closing Loops

Some smaller companies in the electric toothbrush industry are making efforts to increase circularity. Boombbrush collects used electric toothbrush heads as well as broken electric toothbrushes and has a dedicated recycling partner (Boombbrush, n.d.). Happybrush says to be collecting all toothbrushes with a defect and examines them for possible refurbishment (M. Van Doorn, personal communication, March 17, 2022). The two largest manufacturers haven't put in place systems for collection.

Philips allows users to hand in electric toothbrush heads via TerraCycle (Philips, n.d.-d), however, it should be noted that TerraCycle accepts electric toothbrush heads from any brand. For electric toothbrush handles Philips suggest recycling via generic e-waste recycling streams. Oral-B does not specify recycling options, so it is assumed it is similar to that of Philips.

Generic e-waste recycling streams have their limitations. The Dutch national average e-waste collection rate for small appliances is 44% (Baldé et al., 2020). The recycling rate of plastics in generic e-waste collection is in the order of 4 to 5% (NVMP, n.d.).

## 6.6. Conclusion

From the academic & industry perspective, some observations regarding the state of the circular economy for current electric toothbrushes can be made. Product-life is around four years. The reasons for reaching EoL are unclear. When further researching EoL, both absolute and relative obsolescence should be investigated.

Current efforts for extending product life are limited. Some generic maintenance instructions are provided by manufacturers. None of the manufacturers provides repair instructions to users. For some models, instructions can be found on iFixit. From these instructions, it appears that the repair procedures for most models have not been optimized for repair.

Collection rates could not be defined with the information found. Two smaller manufacturers, Boombbrush and happybrush, state they collect defective electric toothbrushes to either recycle or refurbish them. Philips and Oral-b do not have a dedicated collection and rely on generic e-waste collection instead. As such, the overall collection rate is likely low.

## 7. User perspective

### 7.1. Introduction

In order to gain insight into the state of the circular economy of current electric toothbrushes, a quantitative user study was conducted by means of a survey. The user perspective of the state of the circular economy is important. Selvefors et al. (2019) state that while several design strategies can be applied in an attempt to extend product life-cycle, the actual extension of product life-cycle “depends on the people using them”. Users decide what to purchase, how to use and when to replace their electric toothbrushes. Their views and efforts on maintenance, repair and refurbishment all affect circularity.

Additionally to investigating the five research questions regarding the state of the circular economy for current electric toothbrushes (RQ1.1.1 to RQ1.1.5), several relations discussed in literature were evaluated. These were the relation between purchase motivations and reason for replacement (Harmer et al., 2019), continuous charging and reduced battery performance as a reason for replacement (Sweda et al., 2017) and product-life and user expectations about product-life (Cooper, 2004). The full report on the quantitative user study can be found in appendix B.

### 7.2. Setup

The survey was conducted using an online survey tool. The survey was distributed via the researcher’s personal LinkedIn and Whatsapp. Receivers in the researcher’s network were encouraged to share the survey. The participants in this study were 121 (n = 121) adults ranging from 19 to 76 years old. 68 were male, 52 female (1 unspecified). All participants were volunteers recruited because they own electric toothbrushes.

The survey consisted of a combination of multiple-choice and Likert scale questions. Depending on the answer selected, several multiple-choice options allowed users to specify or elaborate on their answers. The questions were split over three themes: purchase, replacement and product-life extension efforts.

### 7.3. Results & insights

#### Purchase motivations

In order to gain insight into users' purchase motivations, participants were asked to rate the importance of factors when deciding which electric toothbrush to purchase on a five-point Likert scale ranging from not at all important (1) to extremely important (5) (see Figure 9).

*Cleaning performance* is by far the most important factor when choosing an electric toothbrush (M = 4,18), followed by *ease of cleaning* (M = 3,60) and *price* (M = 3,59). From this, it appears that functional aspects and value for money dominate purchase motivations.

*Smartphone connection* is by far the least important factor when choosing an electric toothbrush (M = 1,16), followed by *color & design* (M = 2,32) and *brand* (M = 2,41). While participants stated brand is not important when choosing an electric toothbrush, the *availability of brush heads* was the most frequently named other factor that is important when choosing an electric toothbrush (n=15). This is related to brand and thus brand will indirectly affect the purchase decisions more than the rated importance might suggest.

Participants rate *sustainability* as the fourth most important factor for choosing an electric toothbrush (M = 3,25). There was no relationship between participants that do make efforts for lifetime extensions and those that do not and the importance of sustainability as a factor when buying an electric toothbrush.

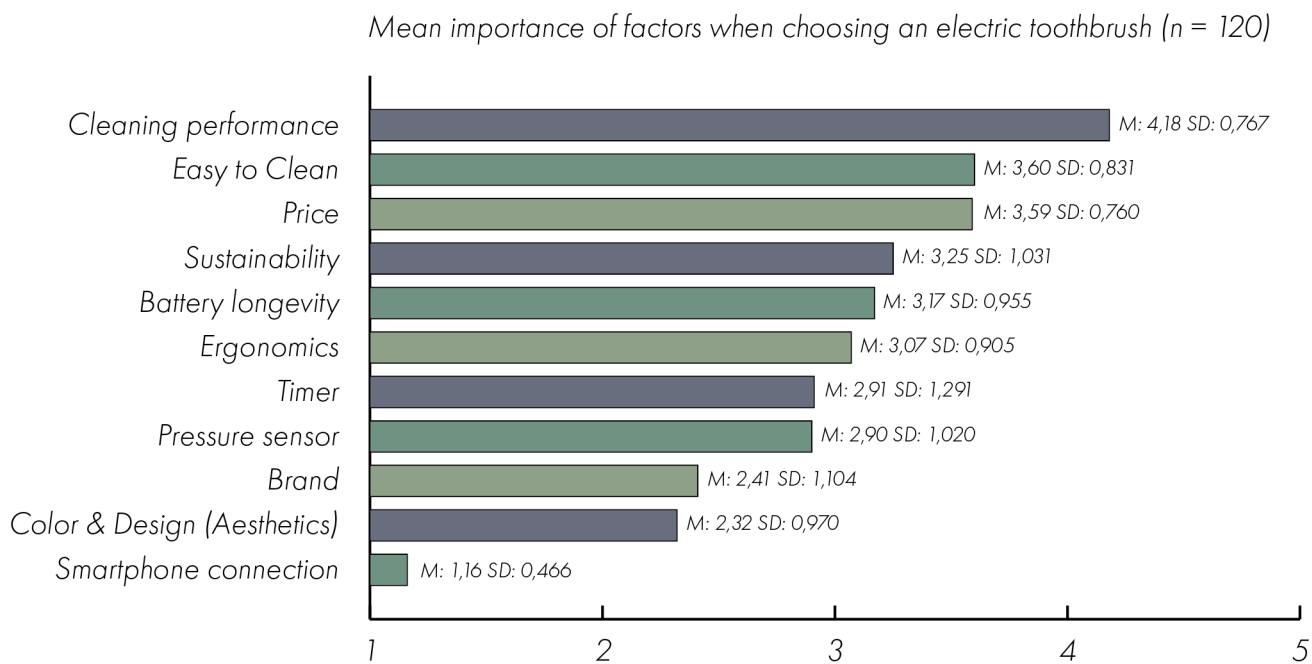


Figure 9: Mean importance of factors when choosing an electric toothbrush. Rated on a 1 (Not at all important) to 5 (Extremely important) scale.

### Product life

The average number of years used prior to replacement appears to be in line with the 3 - 5 years mentioned in chapter 6.2. About 20% of electric toothbrushes were replaced after just 1-2 years of use (see Figure 10). Looking into the mean values of the duration of use meeting participants' expectations, it can be observed that a lifetime of 5-6 years or more is meeting participants' expectations. This is in line with earlier research by Cooper (2004). As basic logic would suggest, the longer the use the more likely the duration of use is to meet or even exceed expectations.

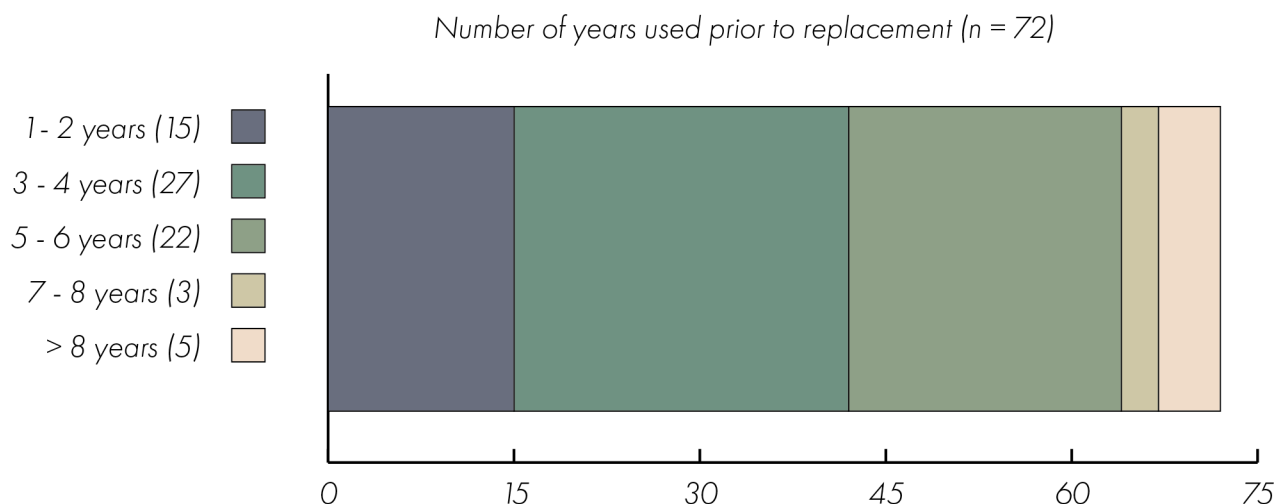


Figure 10: Number of years participant's last electric toothbrush was used prior to replacement.

### End of life

Reduced performance (n=39) and reduced battery performance (n=33) are by far the two most frequently occurring reasons for the replacement of electric toothbrushes. While separated as answer options for the survey, it is highly likely that the reduced performance of the product overall is strongly related to reduced battery performance, as a degrading battery will experience both capacity fade and power fade (Edge et al., 2021).

Only 12,5% of the participants state broken as the reason for replacement, making relative obsolescence the dominant type of obsolescence of electric toothbrushes. Even so, improving ease of repair is still an effective way of reducing relative obsolescence as it can solve reduced performance and reduced battery performance.

When evaluating the reason for replacement split by the duration of use prior to replacement (see Figure 12), it stood out that even for disposal after only 1-2 years of use, reduced performance and reduced battery performance are by far the most occurring reason for replacement, meaning they are also the dominant factors leading to an early end of life. Improving the repairability of parts related to these factors is not only important for extending the product's life beyond the expected life, but also for preventing premature disposal.

Contrary to what was expected based on the work of Harmer et al. (2019), no strong evidence for a correlation between motivations for purchase and reasons for replacement was found.

### Current efforts - Extending product-life

Maintenance actions of cleaning with running water and storing upright are widely accepted (see Figure 11). Once in a while cleaning with a cloth is done by less than half of the users (42,5%), however, as only 6 participants named unhygienic (dirty) as a reason for replacement better cleaning is unlikely to have a big effect on extending product life.

Charging behaviour was mixed, with 57% of participants not continuously charging. No significant relation could be found between not continuously charging and reduced battery performance as a reason for replacement. This empirical evidence is not in line with the commonly accepted principle of overcharging causing battery degradation (Sweda et al., 2017).

Of the participants with a broken product, just over 20% considered repairing. In total, under 2% of broken products are successfully repaired. Of the users considering repair, most users do not attempt repair. In 66% of cases, the reason for not attempting the repair is related to ease of repair (Too much effort (2x), Too time-consuming, Battery not replaceable, Risk of failure, Not repairable). The parts considered for repair most often are the battery (n=5) and casing (n=2) (see Figure 14). Making these parts easier to repair could increase repair success among participants considering repair from 8% to 58%.

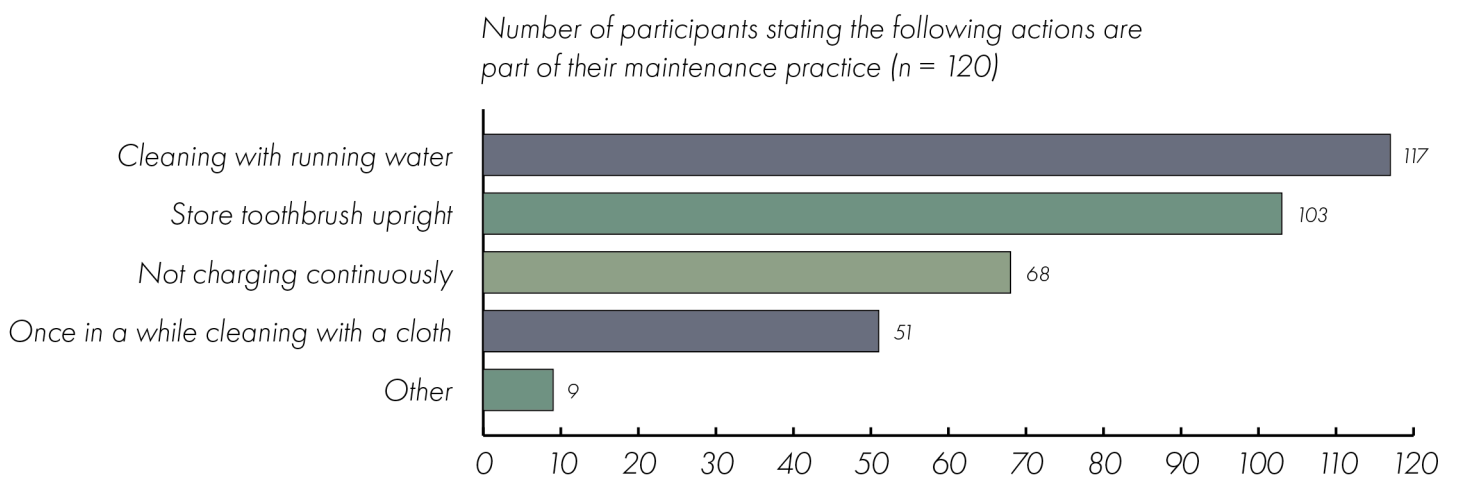


Figure 11: Number of participants stating specified actions are part of their maintenance practice.

Percentage of times a reason for replacement is named,  
Split by number of years using prior to replacement

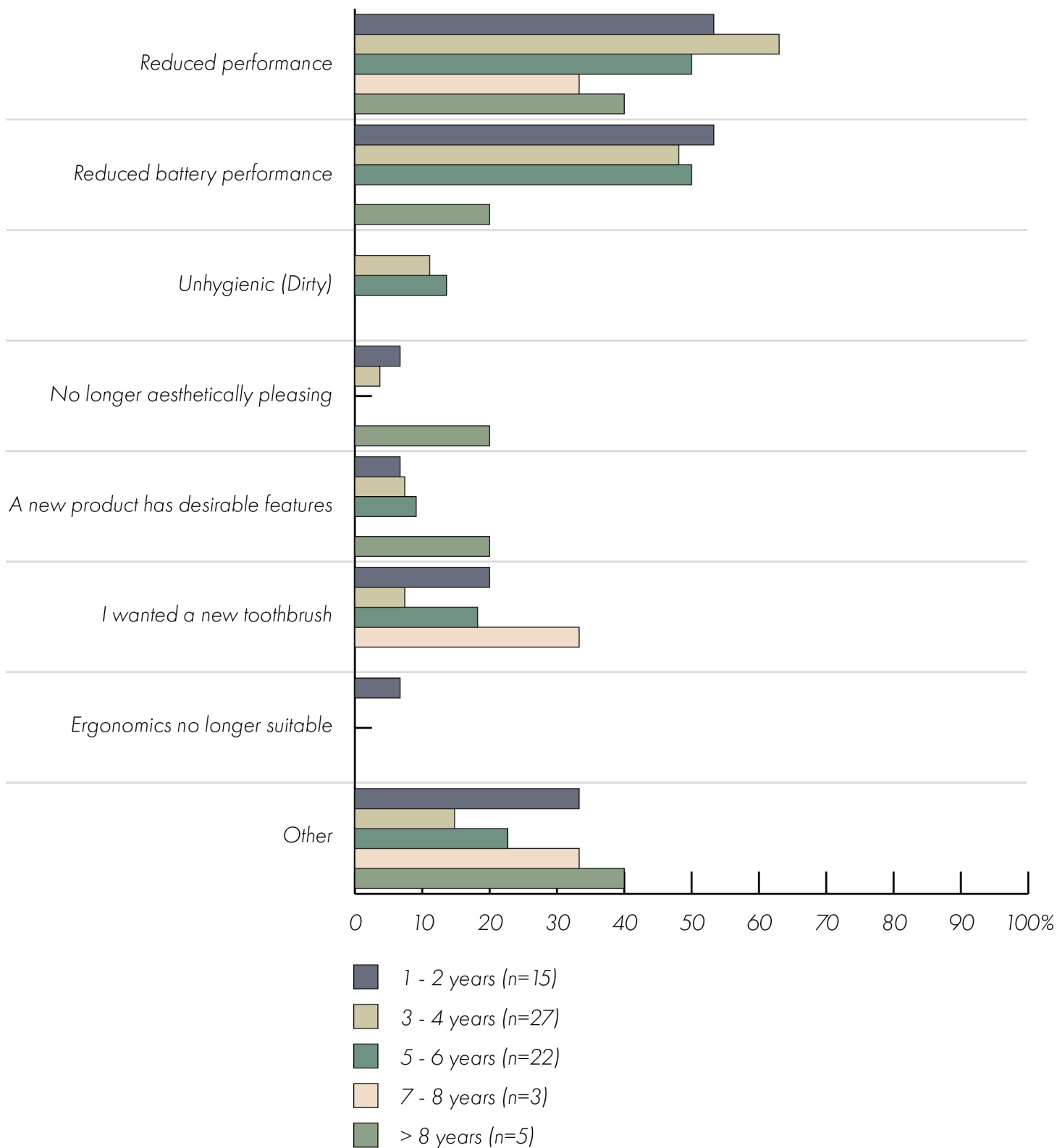


Figure 12: Reasons for replacement of electric toothbrushes with a new model split by the number of years the electric toothbrush was used prior to replacement.

Acceptance of refurbished toothbrushes is low, with only 17,5% of participants saying they would buy a refurbished electric toothbrush (see Figure 13). Including the participants that indicated *maybe*, the number goes up to 48%, very similar to the 44% Mugge et al. (2017) found.

The most named reasons for not wanting to buy a refurbished electric toothbrush were *unhygienic* (23x), *contaminated* (10x), *lower expected longevity* (9x) and *it is a personal hygiene product* (6x) (see Figure 15). If refurbishment is to be used as a resource loop for electric toothbrushes, alleviating concerns about hygiene and contamination is key. Achieving this will be tricky, as several participants stated being aware that there is probably no reason to be concerned about hygiene, but still getting an uncomfortable feeling about it (see Quote from participant 23).

*Participant 23 - "With products like this I prefer if they have not been used by someone else previously. Of course, this is just in my head, but it does (unfortunately) affect my experience a lot."*

#### Current efforts - Collection & closing loops

Only 1 participant stated returning their electric toothbrush to the manufacturer (for warranty). All other toothbrushes (> 98%) enter general waste streams, meaning manufacturer collection rates are near zero.

Once replaced, most participants dispose of the old toothbrush (see Figure 16). A bit under 15% of participants specified taking their old electric toothbrushes to a dedicated e-waste collection point. This is quite a bit below the Dutch national average. A possible reason for this big difference is that participants consider this regular disposal.

## 7.4. Conclusions

From the user perspective, several observations on the state of the circular economy for current electric toothbrushes can be made. Product life is confirmed to be around four years by users. However, worryingly 20% of electric toothbrushes do not last over 2 years. The primary causes for EoL are reduced product performance and reduced battery performance. These two factors are likely strongly related.

The performance of maintenance efforts by users is high, but the effectiveness of these maintenance efforts is unclear. There was no correlation between *cleaning once in a while with a cloth* and *unhygienic* as a factor for replacement, and between *not continuously charging* and *reduced battery performance* as a factor for replacement.

Repair efforts are limited among participants. Only 20% of participants considered repair in the first place. Of all broken products, only 2% were repaired successfully. Most reasons for not attempting repair are related to ease of repair. The parts users most frequently attempt to repair are the battery and casing. Improving the ease of repair for these parts could increase repair success among users considering repair from 8 to 58%.

Collection of replaced electric toothbrushes is nearly not happening, with only 1 participant stating returning their old electric toothbrush to the manufacturer. This is likely the effect of the two most commonly used electric toothbrush brands (Oral-B & Philips) making limited efforts to collect the old electric toothbrushes (see chapter 6.5).

Acceptance of refurbished electric toothbrushes is low, with only 17,5% of participants stating they would buy refurbished. The most frequently named reasons for not wanting to buy refurbished are related to users being worried about the product being used previously by other users.

Would you buy a refurbished electric toothbrush (n = 120)

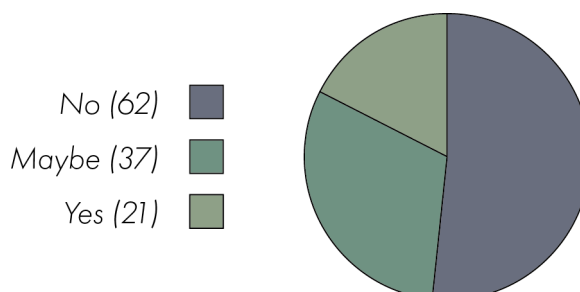


Figure 13: Overview of participants (not) willing to buy refurbished electric toothbrushes.

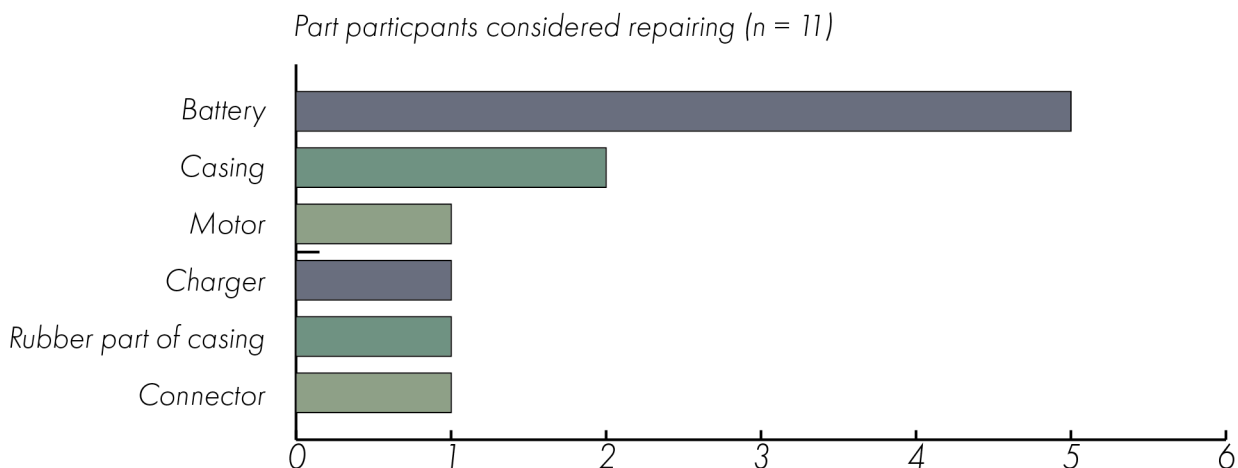


Figure 14: Overview of parts that are being considered for repair.

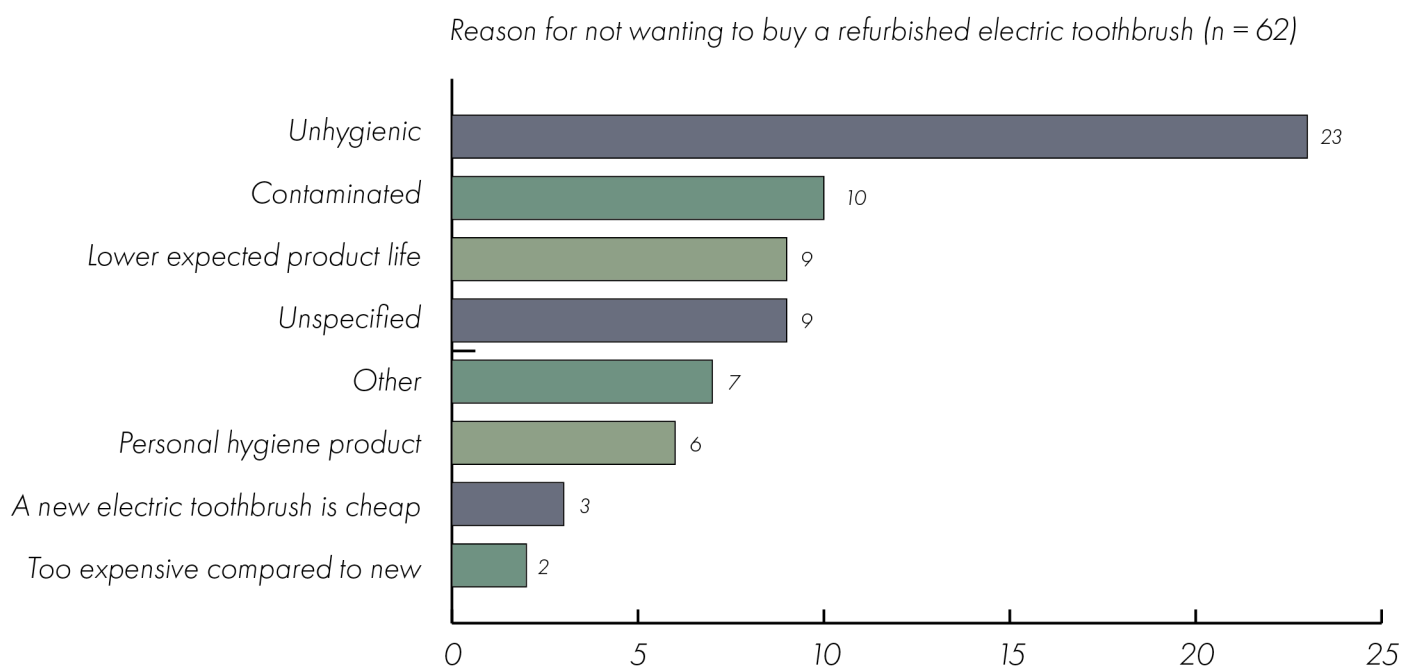


Figure 15: Stated reasons for not wanting to buy refurbished electric toothbrushes.

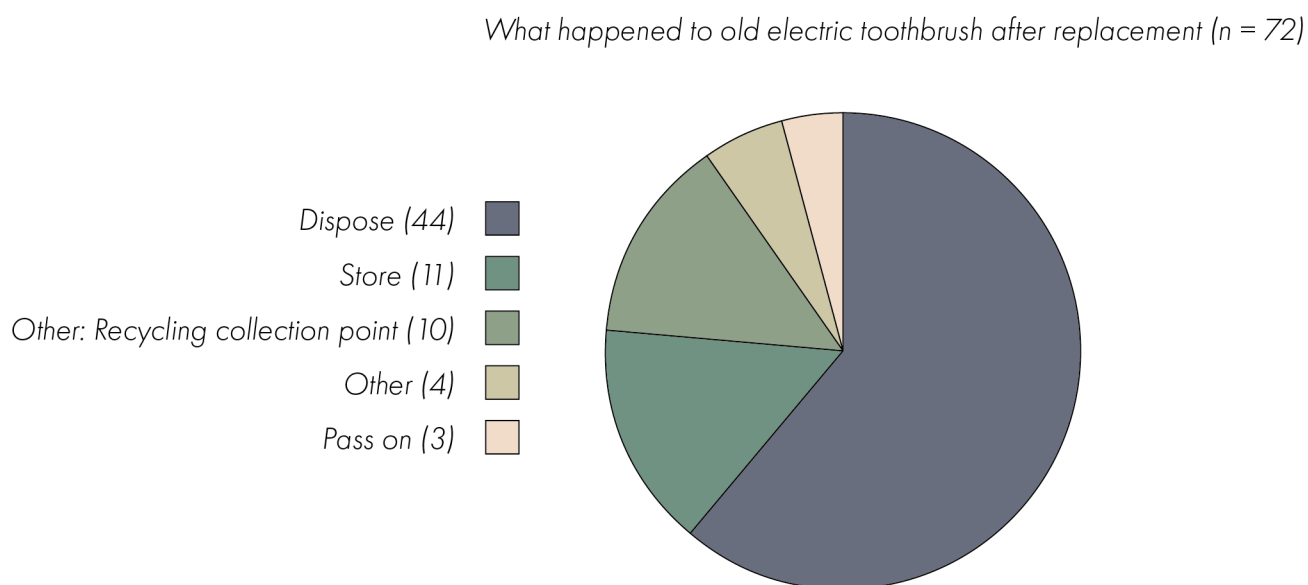


Figure 16: What happened to the old electric toothbrush after replacement.

## 8. Phase 1 - Conclusion

### 8.1. Introduction

Combining the academic, industry and user perspectives provides a view of the state of the circular economy of current electric toothbrushes and the challenges and opportunities for implementing the circular economy for electric toothbrushes. In this chapter, first, the conclusions regarding the state of the circular economy for current electric toothbrushes are summarized. After that key insights regarding challenges and opportunities for implementing a circular economy for electric toothbrushes are presented.

### 8.2. State of the circular economy for current electric toothbrushes

There is no large-scale implementation of the circular economy for electric toothbrushes.

#### Slowing Resource Loops

With reasonable certainty, it can be concluded that the average product life of electric toothbrushes is around four years. A more shocking discovery was that about 20% of electric toothbrushes do not last over 2 years.

Regardless of the number of years used before replacement, the primary causes for EoL are reduced product performance and reduced battery performance. These two factors are likely strongly related.

Current efforts for extending product life are limited. Some generic maintenance instructions are provided by manufacturers. While users generally follow these instructions quite well, their effectiveness for extending product life is unclear. No significant correlations were found between the performance of maintenance practice and related reasons for replacement.

None of the manufacturers provides repair instructions. For some models, instructions can be found on iFixit. From these instructions, it appears that the repair procedures for most models have not been optimised for repair. Companies do offer repairs, but as the average product life exceeds the warranty the pricing of these programs can prove a barrier.

In practice, under 2% of products are successfully repaired. Most reasons for not attempting repair are related to ease of repair, indicating users who consider repair mainly consider self-repair. The parts users most frequently attempt to repair are the battery and casing. Improving the ease of repair for these parts could increase repair success among users considering repair from 8 to 58%.

#### Closing Resource Loops

Collection of replaced electric toothbrushes is nearly not happening. Only small manufacturers (Boombush & happybrush) state they collect defective brushes. Only 1 participant stated returning their old brush to the manufacturer. The few brushes that are collected, are intended for recycling or refurbishing.

Acceptance of refurbished electric toothbrushes is low, with only 17,5% of participants stating they would buy refurbished. The most frequently named reasons for not wanting to buy refurbished are related to users being worried about the product being used previously by other users.

### 8.3. Key insights

One opportunity and two challenges for implementing a circular economy for electric toothbrushes were identified.

**1 Batteries are the key reason for replacement, but battery repairs are not happening. Battery replacement has to become a maintenance practice, not a repair.**

Extending the product life of electric toothbrushes is mainly dependent on providing a solution to the reduction of battery performance. For any number of years used before replacement, reduced performance and reduced battery performance are the most frequently occurring reasons for replacement. Shockingly this includes replacements after just 1 to 2 years of use. This offers an opportunity, as a targeted change to the battery replacement can result in big gains.

To tackle this opportunity, battery replacement should become part of a maintenance practice and no longer be a repair. Boombush stated repair costs are driven by transport costs and wages. By enabling users to replace the batteries by themselves, battery replacements can be made more attractive by significantly reducing costs as less shipping is required.

**2 Only 2% of broken electric toothbrushes are successfully repaired. Increasing repair considerations and improving ease of repair can lead to extended product life.**

The first challenge is that only 2% of broken toothbrushes is successfully repaired. There are two factors contributing to this low number.

Just over 20% of users consider repairing a broken product in the first place. A possible solution is improving product attachment, which can significantly increase consumer tendency to repair (Scott and Todd Weaver, 2015).

Besides low repair considerations, only 8% of users considering repair actually successfully completed a repair. The most named reasons for not attempting or succeeding repairs are all related to the ease of repair. Improving the ease of repair will also be an important part of increasing repair success.

**3 Only 17,5% of users would buy refurbished electric toothbrushes. Improving the acceptance of refurbished electric toothbrushes can open up circular business opportunities.**

The second challenge is the low acceptance of refurbished electric toothbrushes. The most frequently named reasons for not wanting to buy refurbished are related to users being worried about the product being used previously by other users. Users state this is an issue specifically for this type of product.

Refurbishment is the loop with the highest potential for capturing value. Finding a way to improve consumer acceptance of refurbished electric toothbrushes could thus unlock a lot of value capture potential, enabling circular business models. Mugge et al. (2017) suggest design for ease of cleaning and promoting cleaning efforts in order to improve acceptance by consumers. However, more radical strategies, like a full replacement of the outer casing, might be required in this case.

# Analysis

*Application of circular design strategies in current electric  
toothbrushes*

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## 9. Phase 2 - Relevance, scope & objectives

### 9.1. Relevance

The second phase of this thesis aims to generate in-depth insight into the application of circular design strategies in current electric toothbrushes. By generating insight into the application of circular design strategies in current electric toothbrushes, challenges and opportunities for the application of the strategies in a future redesign can be uncovered.

### 9.2. Scope

The scope of the second project phase is limited to the analysis of the design of a selected set of current electric toothbrushes by means of full, preferably gentle, disassembly. The selected set represents the market by including toothbrushes with varying brush techniques and features. Outliers, like the Foreo Issa 3 and Goodwell Be.Brush, have been excluded from the analysis due to budget and time constraints.

### 9.3. Research questions

The primary research questions for the second phase are:

- RQ2.1: How are circular design strategies implemented in the design of current electric toothbrushes?
- RQ2.2: Which challenges and opportunities for implementing circular design strategies in electric toothbrushes are there?

To answer research question 2.1, it is necessary to evaluate if and how the design strategies discussed in chapter 3 are applied. The two design strategies discussed for slowing resource loops are design for long-life products and design for product-life extension. Both strategies have several sub-strategies. The three strategies for closing resource loops are design for a technological cycle, design for a biological cycle and design for dis- and reassembly. A summary of the circular design (sub-)strategies and how they can be observed in a product can be found in Table 2.

Based on these design (sub-)strategies several secondary research questions were formulated (RQ2.1.1 - RQ 2.1.9). Also, two research questions for informing design were formulated based on RQ2.2 (RQ2.2.1 & RQ2.2.2). Note that while design for dis- and reassembly is a design strategy for slowing and closing resource loops, only one research question for this strategy was formulated (2.1.7).

#### Slowing Resource Loops

Designing long-life products:

- RQ2.1.1: How is design for durability implemented in current electric toothbrushes?
- RQ2.1.2: How is design for reliability implemented in current electric toothbrushes?
- RQ2.1.3: How is design for attachment & trust implemented in current electric toothbrushes?

Design for product-life extension:

- RQ2.1.4: How is design for maintenance and repair implemented in current electric toothbrushes?
- RQ2.1.5: How is design for future expansion implemented in current electric toothbrushes?
- RQ2.1.6: How is design for standardization and compatibility implemented in current electric toothbrushes?
- RQ2.1.7: How is design for dis- and reassembly implemented in current electric toothbrushes?

#### Closing Resource Loops

- RQ2.1.8: How is design for a technological cycle implemented in current electric toothbrushes?
- RQ2.1.9: How is design for dis- and reassembly implemented in current electric toothbrushes?

#### Informing Design

- RQ2.2.1: Which challenges for implementing circular design strategies in electric toothbrushes are there?
- RQ2.2.2: Which opportunities for implementing circular design strategies in electric toothbrushes are there?

Circular design strategy	Sub-strategy	How can it be observed in a product?
Design for long-life products	Design for durability	Material selection (resistant to wear) Construction (resistant to damage)
	Design for reliability	Limited amount of moving parts Over-dimensioned critical components
	Design for attachment & trust	Self-Expression (Design to match user's personality associations, Design for product personalisation, Exclusive products) Group Affiliation (Design for shared use, Design for use in group setting) Memories (Designed to age with dignity, Designed with odour) Pleasure (Designed to surprise)
Design for product-life extension	Design for maintenance and repair	Disassembly depth/sequence for parts that are likely to fail or degrade in quality during use, Disassembly time for parts that are likely to fail or degrade in quality during use, Reusability/reversibility of fasteners, Use of common tools
	Design for future expansion	Disassembly depth/sequence for parts that are meaningful to upgrade, Disassembly time for parts that are meaningful to upgrade, Reusability/reversibility of fasteners, Use of common tools
	Design for standardization and compatibility	Standard interfaces Intercompatibility of components
	Design for dis- and reassembly	Disassembly depth/sequence, Disassembly time, Reusability/reversibility of fasteners, Use of common tools
Design for a technological cycle	-	Material selection (Pure materials, Recyclable materials, Limited number of materials) Connections (No fixed connections, Shredding results in uniform large pieces) Electronics (PCB is removable in one piece, Materials are detectable easy and fast)
Design for a biological cycle (out of scope)	-	Material selection
Design for dis- and reassembly	-	Disassembly depth/sequence, Disassembly time, Reusability/reversibility of fasteners, Use of common tools

Table 2: Summary of circular design (sub-)strategies and how their implementation can be observed in a product.

## 10. Toothbrush selection

### 10.1. Introduction

To gain a complete image of the application of circular design strategies in current electric toothbrushes, a representative selection of electric toothbrushes was made. A representative selection should include toothbrushes with a variety of characteristics like brush technologies and features. In this chapter, an overview of the selection of toothbrushes used for analysis and the representativeness of this selection are discussed.

### 10.2. Criteria

As discussed in chapter 4, there is a range of brush technologies and features that can be used for electric toothbrushes. Table 3 provides an overview of the key characteristics of electric toothbrushes and the options available for these characteristics. In order to create a representative selection, the combined selection should include all options.

### 10.3. Selection

Due to the unavailability of budget for purchasing new electric toothbrushes, old toothbrushes were collected that were no longer used. Additionally, several manufacturers were contacted with a request to provide a toothbrush for analysis. Four electric toothbrush models were provided by people that no longer

used them. One electric toothbrush was provided by a manufacturer. One electric toothbrush (Oral-B IO) was provided by iFixit but arrived too late to be included in the analysis. A quick analysis of the Oral-B IO toothbrush can be found in appendix C.

It was decided based on product characteristics and time constraints to exclude the Oral-B Vitality 100 from the analysis. All of its product features already appear in the other toothbrushes in the selection. Table 4 shows the five electric toothbrushes provided and their characteristics.

The provided selection of electric toothbrushes covers most characteristics in the market. However, there are some limitations to the selection.

Two variations of characteristics are missing; toothbrushes without timers and toothbrushes with smartphone connectivity. It is assumed that the product architecture of electric toothbrushes without timers varies little from those with timers, except for minimal added complexity to the PCB. However, toothbrushes with smartphone connectivity might have additional priority parts due to added electronics.

The age of several of the electric toothbrushes in the selection could mean that their architectures are outdated. With regulations regarding the reparability of products on the horizon, it could be that several manufacturers have already started making improvements to their designs.

Characteristic	Options		
Brush technology	2D rotating	3D rotating	Sonic
Battery type	Built-in	User-replaceable	
Brush settings	One	Multiple	
Timer	Yes	No	
Pressure sensor	Yes	No	
Smartphone connectivity	Yes	No	

Table 3: Overview of key characteristics of electric toothbrushes.

Provided by		Users				Manufacturer
Type & Price	Brand	Oral-B	Oral-B	Philips	Oral-B	Boombrush
	Model	Advance Power	Vitality 100	Sonicare Easyclean	Professional Care 3000	Boombrush
	Year	2018		2016	2012	2020
	Price	€13	€30	€60	€90	€90
Technology	Brush technology	2D rotating	2D rotating	Sonic	3D rotating	Sonic
	Number of brush settings	1	1	1	3	5
	Weight (g)	136		129	130	134
Battery	Battery type	Replaceable AA batteries	Built-in Ni-MH battery	Built-in Lithium-ion battery	Built-in Ni-MH battery	Built-in Lithium-ion battery
	Claimed duration	-	20 minutes	56 minutes	45 minutes	360 minutes
Extra Features	Timer	Yes	Yes	Yes	Yes	Yes
	Pressure sensor	No	No	No	Yes	No
	Smartphone Connectivity	No	No	No	No	No
	Waterproofing	Shower safe, not recommended to submerge	Shower safe, not recommended to submerge	Shower safe, not recommended to submerge	Shower safe, not recommended to submerge	IPX7 (submersible)
Sources		Tandenborstels.com, (n.d.); Tweakers (n.d.-a); (PG consumer support, n.d.)	Coolblue (n.d.-c); (PG consumer support, n.d.)	(Philips, n.d.-a); Philips, (n.d.-b); Coolblue, (n.d.-d); (Tweakers, n.d.-c)	Coolblue, (n.d.-b); Tweakers (n.d.-b); (PG consumer support, n.d.)	Coolblue (n.d.-a) (Boombrush, n.d.-a)

Table 4: Overview of toothbrushes available for selection.

# 11. Analysis of current electric toothbrushes

## 11.1. Introduction

The implementation of circular design strategies in current electric toothbrushes was analysed by performing gentle disassemblies on a representative set of electric toothbrushes (see chapter 10) and carefully studying the designs. In order to analyse the disassembly procedure in a structured and informed way, two tools for assessment and visualisation of assembly procedures were used; Hotspot Mapping (HSM) and Disassembly Mapping.

In this chapter, first, the methodology used for analysing each of the circular design strategies is discussed. Next, the research setup, the Hotspot Mapping method and the Disassembly Mapping method are introduced. Finally, an extensive analysis of each of the selected toothbrushes based on this methodology is presented.

All nine research questions regarding the implementation of circular design strategies in current electric toothbrushes were investigated (RQ2.1 to RQ2.9).

## 11.2. Circular design strategies

### Durability and reliability

As discussed in chapter 3, there is a difference between durability and reliability. However, as they are somewhat related they are grouped under one header for this analysis. The best way to evaluate how well a design has been optimized for either durability or reliability is to document real-life failures of a product. Unfortunately, such data is not available. As such, the analysis has been performed based on engineering sense and some guiding principles.

To evaluate durability, the construction and material of the main body part of each of the brushes were analysed. This part is the most important to preventing damage from outside factors. Additionally, known weaknesses of a design are reported. These weaknesses are not based on statistics but rely on a manufacturer statement or consumer complaints. It should be noted neither of these can be seen as evidence for a non-durable construction.

To evaluate reliability, the number of moving parts was analysed. Mostly these are the parts used for the brushing mechanism, but some other features might introduce moving parts as well. Here also, engineering sense is used to evaluate if a construction is built well. Like with durability, it should be noted neither of these can be seen as evidence for a non-reliable construction.

### Attachment and trust

For this thesis the application of design for attachment and trust has been based on the work by Mugge (2007). Four determinants and their related design implementations were presented in chapter 3. However, there are some limitations to note. Not all of these implementations can be analysed just by looking at designs. Also, several implementations were found in none of the brushes.

Three implementations were presented for the determinant self-expression. Personalisation options is the only implementation discussed in this chapter. Personality associations cannot be evaluated separately from the user's personality. Product exclusivity is applied in none of the brushes in this analysis.

The determinant group affiliation was not evaluated as all of the brushes analysed are for personal use in a personal setting. Some use might occur in a group setting, but none of this is by design and as such not relevant for this analysis.

Two implementations were presented for the determinant memories. The ability to age with dignity has been evaluated based on material selection. Design with odour is not used in any of the products, and as such will not be further discussed in this chapter.

The determinant pleasure was not evaluated as none of the brushes analysed applied design for surprise.

### Dis- and reassembly

The main factors contributing to ease of disassembly are disassembly depth/sequence, disassembly time, the reusability of fasteners and the use of common tools. The disassembly depth/sequence and disassembly time have been evaluated using HSM

and disassembly mapping. Non-reusable fasteners are noted in the disassembly map and uncommon tools are noted both in the HSM and disassembly maps.

To gain insight into priority parts for disassembly, both HSM and a separate bill of materials (BOM) were used. The BOM allows for the creation of a visual representation of the hotspots.

Hotspots in the disassembly procedure, like the use of uncommon tools and steps requiring a lot of time, are discussed separately as well to provide deeper insight into what is causing them.

### **Maintenance and repair**

From phase one of this project it was concluded that the parts most frequently requiring replacement are the parts related to performance and battery performance. Due to this, the motor and battery were assumed to be the parts most frequently requiring maintenance or repairs.

Insights into the disassembly depth/sequence and time for both the battery and motor are presented based on the HSM and Disassembly map. The use of non-reversible fasteners and/or uncommon tools is also highlighted.

### **Future expansion, standardization & compatibility**

The parts that are meaningful to upgrade are parts able to enhance the functionality of the product or parts that significantly influence the product's aesthetics. As such the motor, PCB, battery and main body were selected as parts that could be meaningful to upgrade. Insights into the disassembly of the battery and motor are already presented in the paragraph maintenance and repair.

Insights into the disassembly depth/sequence and time for both the PCB and main body are presented in this paragraph based on the HSM and Disassembly map. The use of non-reversible fasteners and/or uncommon tools is also highlighted.

For the strategy of standardization & compatibility, the availability and interchangeability of the battery used are evaluated.

### **Technological cycle**

Three implementations for design for the technological cycle were presented in chapter 3.

For materials selection, a BOM was made in which all parts and their materials are mapped. All BOMs can be found in appendix D. Recyclability of the materials was assessed using Granta Edupack 2020. For each product, the number of different materials was determined. As specific material identification for all parts was deemed both too time-consuming and not relevant, materials that could not be identified have been reported as unidentified. Unidentified materials have been assumed unique (contributing to the number of different materials) or the same as already identified materials (not contributing to the number of different materials) based on their look and feel.

Permanent connections were evaluated in the disassembly procedures and logged in the disassembly maps. It should be noted that for ease of disassembly permanent connections relate to part separation, while for the technological cycle permanent connections relate to material separation. As such, multi-material parts are mentioned as well.

For electronics, the removability of the PCB and functional identifiability of parts was assessed. The removability of the PCB was evaluated based on the disassembly map, while the functional identifiability of parts has been assessed based on the researcher's insight.

## **11.3. Methods**

In this chapter, the setup used for disassembly and the application of the HSM and disassembly mapping methods are discussed.

### **Setup**

To accurately document the disassembly procedure for each toothbrush model, the disassembly procedure was filmed using a phone camera from a side view. While performing the disassembly, the researcher applied thinking aloud (Lewis, 1981) to ensure any insights were documented. This also helped in situations where the side view was not able to capture the full detail of a situation.

An iFixit Essential Electronics Toolkit, a mini screwdriver set and pliers (see Figure 17) were kept in reach during the disassembly procedure. Most of the disassembly steps could be performed using these tools. However, for the disassembly of the Philips Sonicare EasyClean, several spot welds could not be disconnected using these tools. A small angle grinder (Dremel) was used to disconnect them. When possible, soldering connections were loosed using the iFixit tweezers to save time. When not possible to do so, a soldering iron located at the IDE faculty was used. Filming at IDE faculty was possible, but audio recording was not due to ambient noise.

It should be noted that products can not always be fully disassembled by gentle disassembly. In order to disconnect certain parts, other parts have to be destroyed or permanent connections have to be loosened forcefully. This was considered within the scope of the analysis, as understanding factors that hinder the disassembly was of importance.

The original video footage that supports the findings of this study is available from the corresponding author, M. Drummen, upon reasonable request.

### Hotspot mapping

The Hotspot Mapping (HsM) method (Flipsen et al., 2020) was developed "to help designers in (re) designing their product for ease of disassembly". The HsM method provides designers with a spreadsheet that "indicates the ease of disassembly by flagging five 'hotspot' indicators" based on several metrics about product disassembly that have to be entered into the spreadsheet.

Two of the five hotspot indicators are related to ease of access of parts (time & force required, difficulty of access). The other three hotspot indicators help determine critical parts for which good accessibility is most important. Critical parts are the parts most likely to fail and/or require maintenance, as well as parts with high economic and high environmental value.

After performing the disassembly procedures, the video footage was reviewed to fill out the HSM sheets. As mentioned in setup, not all desoldering actions were done using a soldering iron. For these actions, 60 seconds per soldering action has been assumed.

The HsM sheet automatically provides overall results, stating the total time to disassembly, number of tasks, number of steps and number of tools required. For this thesis, an extra result section called priority part accessibility was added, in which the number of steps and time required to reach four predetermined priority parts (motor, battery, PCB & main body) was added.

The full sheets can be found in appendix E.

### Disassembly mapping

Like HsM, the Disassembly Mapping method (de Fazio et al., 2021) was developed to assess the ease of disassembly of household products. Complementary to the HsM, disassembly maps provide a visual representation of the disassembly process in which dependencies and depth of components can quickly be observed. In the disassembly map, parts that are determined to be critical using HsM are called target components and receive a visual marking.

The disassembly maps were made based on the videos and sheets made for HsM, but the toothbrushes were (partly) dis- and reassembled several times again to evaluate dependencies. Parts that during the first disassembly appear locked in by other parts might actually be removable without the removal of other parts upon further inspection.

In the following paragraphs, a basic summary for reading disassembly maps is presented. For a detailed description of disassembly maps, please refer to de Fazio et al. (2021).

Dependencies are shown in the disassembly map by the sequence of parts. The disassembly map starts with the complete assembly at the top, from which arrows point toward the first parts that can be removed. From those parts, new arrows originate indicating the next parts that can be removed. The further down the map a part is, the deeper into the disassembly procure it is. These parts are harder to reach as more parts have to be removed and steps performed to reach these parts.

When multiple arrows originate from a single part, that means multiple parts can be removed after the removal of that part. If prior to a part a '&' sign is seen, it indicates that multiple parts need to be removed to remove that part. If multiple ways of removing a part are possible, the fastest way is shown.

On the arrows between parts, actions can be found. Every action in the map can contain up to six categories of information that together describe the action: motion type, force intensity, type of connector, type of tool, frequency and penalties. A legend of the information categories can be found in Figure 18. Example actions are shown in Figure 19 and Figure 20.

The disassembly maps for the Oral-B Professional Care 3000 and Philips Sonicare EasyClean were split over two disassembly maps. A main map and a motor/gearbox assembly map. This was done to improve the readability of the maps.



Figure 17: Basic tools for disassembly.

Legend		Force intensity		
Motion type		Low	Mid	High
	= Hand motion			
	= Single motion tool			
	= Multiple motion tool			
Type of connector		Type of tool		
S. F.	= Snap Fit	(H)	= Hand	
F. F.	= Friction Fit	(Sc)	= Screwdriver	
N.F.	= Not Fixed	(Sp)	= Spudger	
Sold.	= Soldered	(Pl)	= Pliers	
R.	= Recessed	(Si)	= Soldering iron	
Weld	= Welded	(Ag)	= Angle grinder	
Glue	= Glued			
Scr.	= Screwed			
Tape	= Taped			
Target components		Penalties		
	Failure Indicator		= Product manipulation	
	Environmental Indicator		= Low visibility/identifiability	
	Economic Indicator		= Uncommon tool	
			= Non-reusable connector	

Figure 18: Legend of the information categories in the disassembly maps.

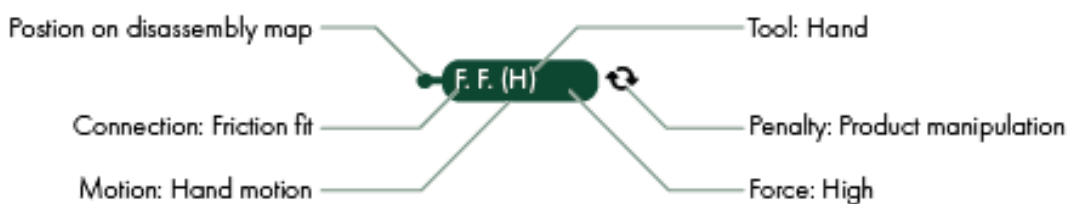


Figure 19: Example action for a high force intensity disconnection of a friction fit, with a penalty for product manipulation.

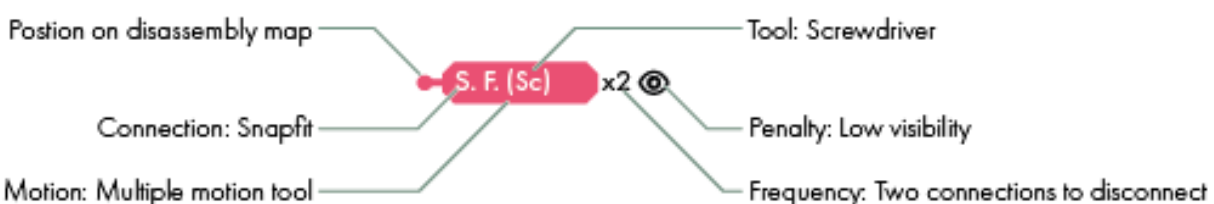


Figure 20: Example action for a multiple motion disconnection of two snap fits using a screwdriver, with a penalty for low visibility.

## 11.4. Boombrush

### Durability and reliability

No special efforts were observed for design for durability in the Boombrush.

The Boombrush's main body is made out of a single part of ABS. This material has good impact and scratch resistance (GRANTA EduPack, 2020). No major weak points were identified when observing the construction of the main body.

The sonic brushing mechanism of the Boombrush consists of the smallest amount of movable parts of any of the brushes in this analysis, as the motor and brush axis is a single part (see Figure 22). This makes the brush axis the only observable moving part of the Boombrush. In practice, this probably means that inside the Boombrush's e-motor, there are several additional moving parts. A benefit to this approach is that there is less chance of damaging or wrongly assembling moving parts.

One drawback in the Boombrush design is the connection between the brush head and the brush axis. The brush head and brush axis fit together in one orientation only and in order to remove the brush head, the user should simply pull the brush head off the axis. This requires some force. According to Boombrush, users tend to try and rotate the brush head during removal and this can damage the motor, requiring replacement.



Figure 21: Boombrush electric toothbrush (Boombrush, n.d.-b).

While the large battery in the Boombrush (7.2Wh) is probably mainly there as a unique selling point (90-day battery life), it also functions to over-dimension one of the critical components of the toothbrush. The Boombrush might be able to have acceptable battery life for longer simply by starting with a much higher capacity.

By reducing complexity and over-dimensioning the battery, design for reliability appears to have been well considered in the Boombrush's design.

### Attachment and trust

No effort appears to be put into design for attachment & trust. The Boombrush does not offer users the option to personalize their product. The materials used for the Boombrush's exterior are unlikely to show the desirable effects of ageing with dignity. While it is made of scratch-resistant material and should keep looking good for quite some time, any scuffs that do appear will deteriorate the product's aesthetics.

### Dis- and reassembly

By some metrics, the Boombrush is one of the best brushes in the analysis for disassembly. At 24 minutes the disassembly time is on the lower end, as is the number of tasks at only 29. The number of tools required is average at 5, but unfortunately like all toothbrushes, a soldering iron is required to completely remove the electronics.



Figure 22: Boombrush motor. The brush axis is fixed directly in the motor.

The Boombrush consists of the fewest number of unique parts of all the brushes in the analysis. The battery, PCB, motor and main body make up over 90% of the CO2 impact of the materials used, making them crucial to any efforts to reduce the impact. The battery, PCB and motor account for over 95% of the economic value of the materials, making them the most important for the economically viable implementation of circularity. The large battery used in the Boombrush in specific makes up almost 40% of the CO2 and 80% of the economic value (see Figure 23).

Specific pain points in the disassembly procedure are removing the main body and PCB.

To remove the main body, two snap fits have to be disconnected that are obstructed visually and hard to access. Simultaneously, pressure has to be applied to the brush axis to remove the main body. This results in the step costing a lot of time.

The PCB is both glued to the internal carriage (see Figure 24) and soldered through the carriage to the battery. In order to remove the PCB, an opening pick has to be pried between the PCB and the carriage, and then the soldered connections between the PCB and battery have to be desoldered. This results in the step costing a lot of time.

Besides the glue on the PCB, in order to access any of the parts with high economic value, 4 strips of tape have to be removed (see Figure 25). The purpose of these tapes is expected to be ease of assembly. Once removed, the tapes have to be handled with care or replaced for reassembly.

Boombrush - Part contribution to mass, CO2 (primary production) and economic value

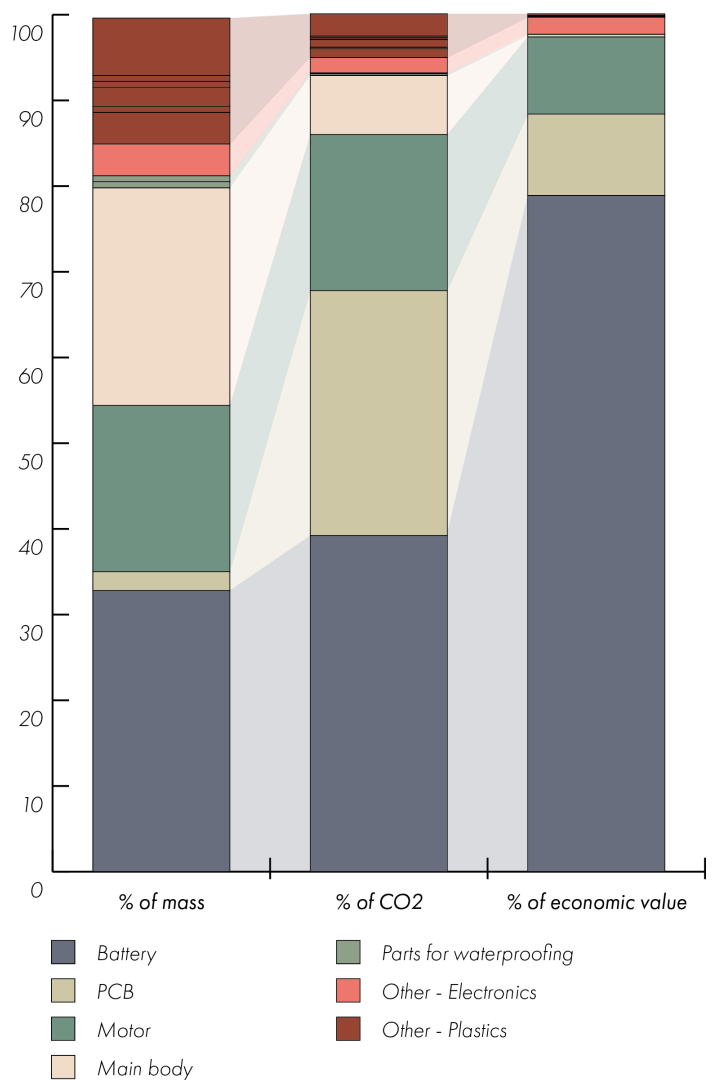


Figure 23: Contribution of materials in the Boombrush to the mass, impact (CO2 primary production) and economic value.



Figure 24: Boombrush uses glue to fix the PCB to the internal carriage.



Figure 25: The four tapes that have to be removed prior to accessing the electronics of the Boombrush.

### Maintenance and repair

The battery and motor in the Boombrush are hard to replace. When looking at the disassembly map of the Boombrush (see Figure 26), it can be observed that both the battery and the motor are relatively deep into the disassembly procedure. While the simple product architecture reduces the number of steps required, the steps that are required are not quick and easy to perform. Both take a similar amount of time to reach (12 - 14 minutes)(see Table 5). For both repairs, a soldering iron is required. Most of the fasteners are reusable, except for the tape.

### Future expansion, standardization & compatibility

The main body of the Boombrush can be removed in five steps (see Table 5). However, as described before some of these steps are complicated. Added to that is a concern over the reusability of the snap fits keeping the internal carriage in the main body. When reassembling the brush, these seem to fit less tight than originally.

The PCB is glued to the internal carriage and soldered to all the other electronics. The four tapes have to be removed as well. As such, upgrading the PCB is a time-consuming task with a disassembly time of about 23 minutes (see Table 5).

The battery used in the Boombrush is a standard size 18650 lithium-ion cell. While standardized in size, this battery type is not commonly available in stores and has to be ordered online. The cell cannot be interchanged by just any cell of the same size. There are differences in discharge current and capacity that can affect user experience and the functioning of the device.

### Technological cycle

Some mixed materials are used in the Boombrush. The motor cap and internal carriage are made out of a mix of PC and ABS. This mix is considered a common plastic for which there is an established recycling stream (PolyCE, 2021).

Several types of elastomers are used for waterproofing. Their exact type is unknown, but it is unlikely all of them are recyclable due to the overall poor recyclability of elastomers (PolyCE, 2021). Besides elastomers used for waterproofing, two elastomer parts are used to damp the vibrations of the sonic motor. In total, 8 different materials are used (excluding electronics)(see Table 6). This is the lowest number of any brush in the analysis.

Part	Steps to reach	Time to reach (s)	Number of tools required	Reversible connections
Motor	20	700	4	No
Battery	12	820	4	No
PCB	17	1405	4	No
Main body	5	370	2	Yes

Table 5: Number of steps and time required to reach components important for maintenance, repair & future expansion.

Number of materials	Polymer	Elastomer	Metal
Identified	4	0	1
Unidentified, assumed unique	0	3	0
Unidentified, assumed same as identified (do not count for total)	0	0	0
Total	4	3	1

Table 6: Boombrush - Unique material count.

Unfortunately, Boombrush uses glue in several places to fix parts. While the glue used for the PCB is relatively easy to pry loose, the charging port and power button have been glued to the bottom cap and main body using a tough glue, likely to ensure waterproofing. These do not separate easily and will be problematic for shredding large pieces of uniform material.

All parts in the brush are easy to identify functionally, and there is a material ID on some of the polymer parts.

## **Conclusion**

To summarize, the Boombrush approach of keeping things simple has some great potential for a more circular design. Challenges for a more circular Boombrush are the lithium-ion battery and glue used for waterproofing. The battery is currently used as a unique selling point, but the lacking availability to consumers and interchangeability with other similar-size batteries complicate maintenance. The glue used is not a major barrier to disassembly but inhibits reaching full circularity via the technological cycle.

*Disassembly map shown on next pages. Chapter continues after the disassembly map.*

# Disassembly Map

Electric Toothbrush

BoomBrush

Mart Drummen

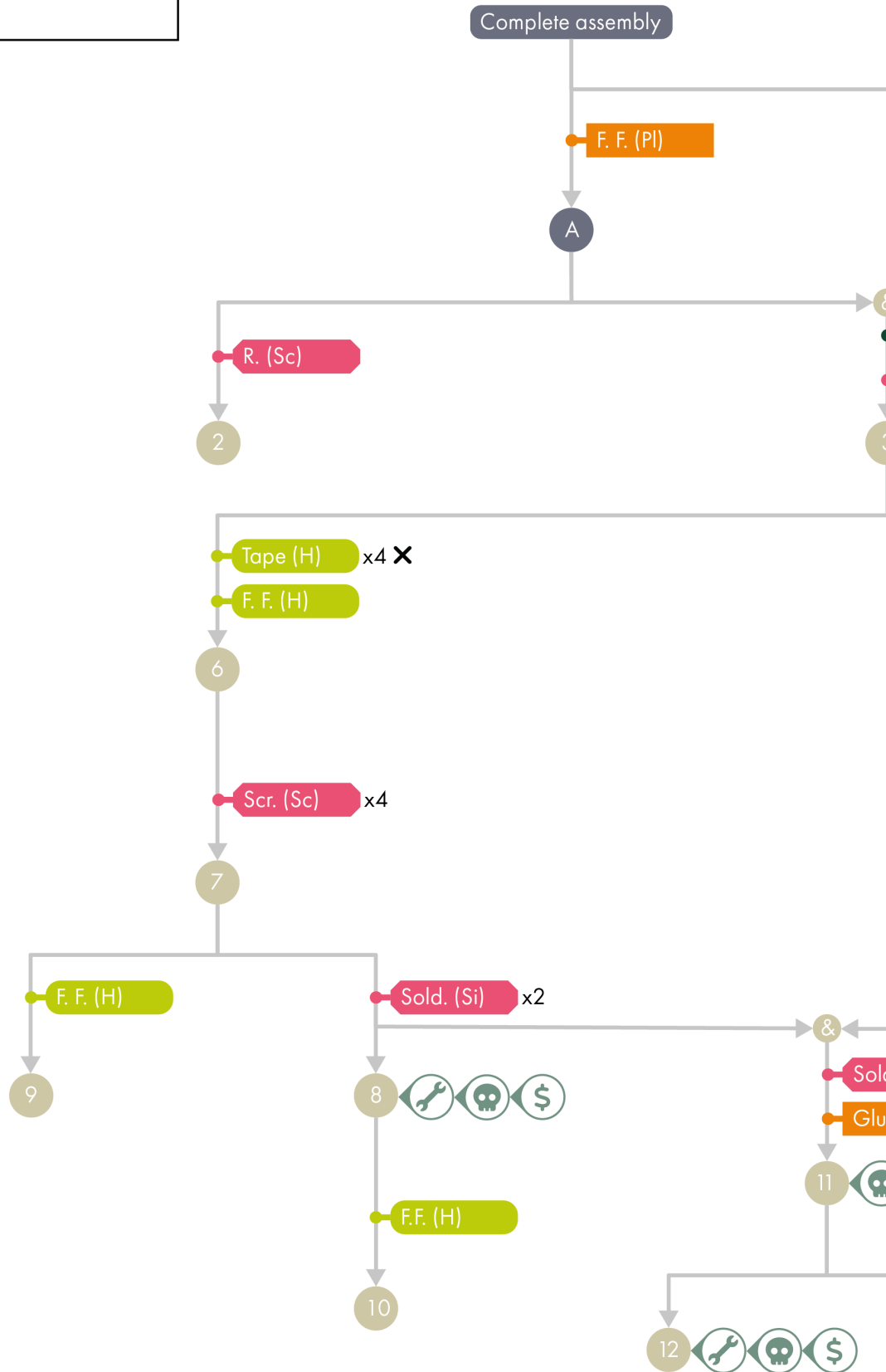
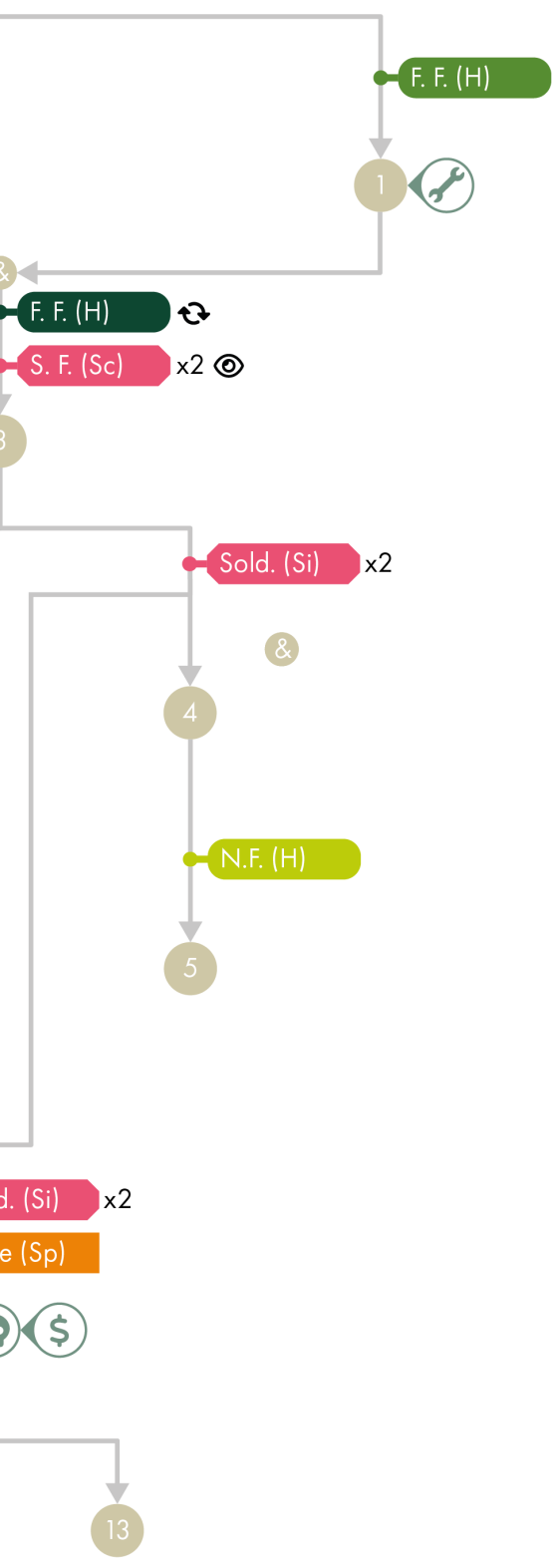


Figure 26: Disassembly map of the Boombrush.



**Components**

- A. Bottom cap assembly
- 1. Brush head
- 2. Seal ring (A)
- 3. Main body
- 4. Bottom cap / Charging port (A)
- 5. Bottom cap ring (A)
- 6. Top seal
- 7. Motor cap
- 8. Motor
- 9. Motor top damper
- 10. Motor bottom damper
- 11. PCB
- 12. Battery
- 13. Internal carriage

**Legend**

**Motion type**

- = Hand motion
- = Single motion tool
- = Multiple motion tool

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Target components**

- Failure Indicator
- Environmental Indicator
- Economic Indicator

**Force intensity**

- Low
- Mid
- High

**Type of tool**

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Penalties**

- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

## 11.5. Oral-B Advance Power

### Durability and reliability

No special efforts were observed to design for durability or reliability in the Oral-B Advance Power.

The Oral-B Advance Power main body is made of 2k moulded ABS and TPE. The ABS has good impact and scratch resistance (GRANTA Edu-Pack, 2020).

The 2D rotating brushing mechanism used has several moving parts (see Figure 28). These are required to translate the rotating movement from the motor to the oscillating movement made by the brush. The brush axis itself is made from steel, however, the parts connecting the brush axis to the motor are all thermoplastics. The mechanism is not known to be prone to failure.

### Attachment and trust

Little effort appears to be put into design for attachment & trust. The brush heads used for the Oral-B Advance Power feature a small ring that can be interchanged by rings of a different colour. This is a very low-effort method of personalisation, mainly meant for users that share their electric toothbrush. Due to the low physical and mental effort, it is unlikely this contributes significantly to product attachment (Mugge, 2007).

The materials used for the Oral-B Advance Power's exterior are unlikely to show the desirable effects of ageing with dignity. While it is made of scratch-resistant material and should keep looking good for quite some time, any scuffs that do appear will deteriorate the product's aesthetics. A known is-



Figure 28: The 2D rotating brush technology, from the motor to the brush axis.



Figure 27: Oral-B Advance Power electric toothbrush (Blokker, n.d.).

sue of the textured grips on the main body is that they are prone to build up dirt over time that is hard to clean.

### Dis- and reassembly

By some metrics, the Oral-B Advance Power is one of the best brushes in the analysis for disassembly. At 17 minutes the disassembly time is the lowest of all the analysed brushes, as is the number of tools required at just 3. A major hurdle however is that both a soldering iron and a saw (uncommon) are required for complete disassembly.

The Oral-B Advance Power consists of 20 unique parts. The battery, PCB, motor and main body



Figure 29: The Oral-B Advance Power was sawn open for complete disassembly.

make up 90% of the CO2 impact of the materials used, making them crucial to any efforts to reduce the impact. The battery, PCB and motor account for over 95% of the economic value of the materials, making them the most important for the economically viable implementation of circularity. Contrary to the other brushes in this analysis the batteries in the Oral-B Advance Power are non-rechargeable (although the user could opt to instal rechargeable AA batteries) making their contribution to both the impact and value much lower at around 15% (see Figure 30).

Specific pain points in the disassembly procedure are removing the main body and PCB. The main body is fixed to the internal components by means of two non-reversible snap fits. The only way to remove the body is thus to destroy it. For this analysis, the main body was carefully sawn into pieces so that it could be removed (see Figure 29). Another major hurdle is desoldering the PCB, which is fixed with seven different soldered connections, four of which are only used for the power button.

**Maintenance and repair**

The Oral-B Advance Power has an advantage over its competitors in the accessibility of the batteries, which can be done without the use of any tools, requires just two steps and is done in just 10 seconds (see Table 7). A big contributor to this advantage is the easy-to-remove bottom cap. In all the other brushes, some tools and force are required, but the Oral-B Advance Power makes this very easy to do. This shows that an easy user-replaceable battery in an electric toothbrush is not impossible.

Unfortunately, no efforts for design for maintenance and repair have been made beyond the batteries, as the main body has to be destroyed in order to access any other priority parts. This directly results in extra tools and time being required. Removing the motor requires 19 steps and costs 16 minutes (see Table 7).

Oral-B Advance Power - Part contribution to mass, CO2 (primary production) and economic value

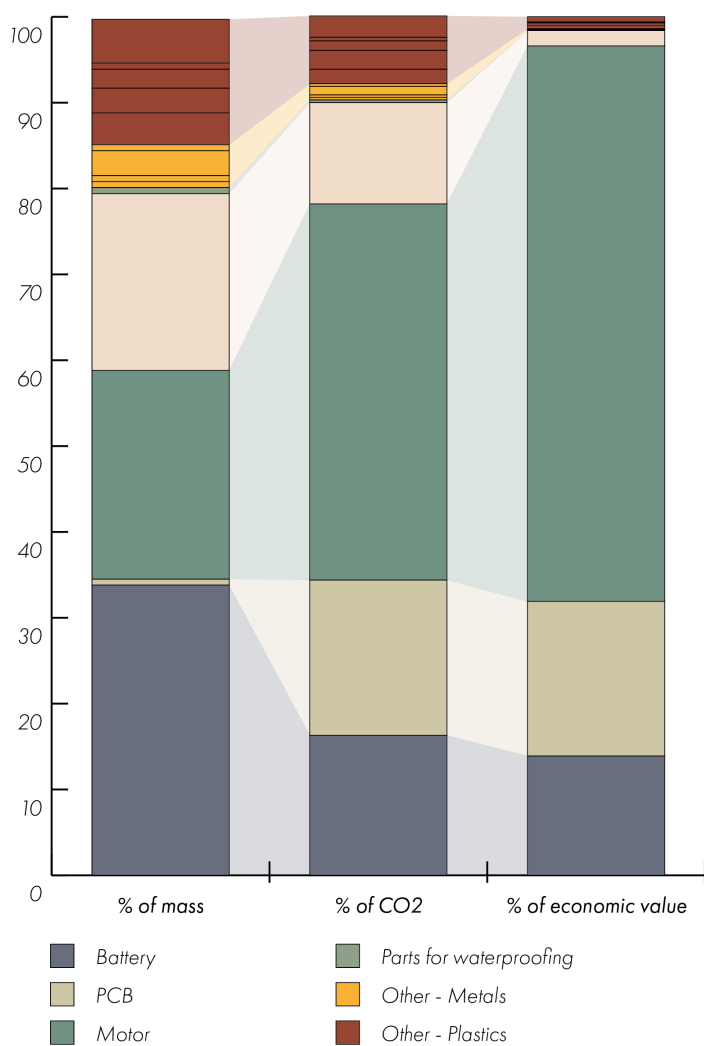


Figure 30: Contribution of materials in the Oral-B Advance Power to the mass, impact (CO2 primary production) and economic value.

Part	Steps to reach	Time to reach (s)	Number of tools required	Reversible connections
Motor	19	950	3	No
Battery	2	10	0	Yes
PCB	14	925	3	No
Main body	6	590	2	No

Table 7: Number of steps and time required to reach components important for maintenance, repair & future expansion.

**Future expansion, standardization & compatibility**

As mentioned previously, the main body has to be destroyed in order to be removed. Should future expansion be desirable, this means that any time the PCB or motor are upgraded a new main body has to be used. An additional problem is that the sawing has to be done carefully in order to not damage any of the internals. Once open, the PCB is soldered to all the other electronics, making it almost as time-consuming as the motor to remove (see Table 7).

A positive aspect that can be noted when looking at the disassembly map (see Figure 32) is that besides the main body and soldering, the connections used in the Oral-B Advance Power offer good potential for disassembly. Most connections used require low force and can be disconnected using hands or a simple flathead screwdriver.

The batteries used in the Oral-B advance power are commonly available for users to purchase either online or in stores, and any brand of the battery can be used.



Figure 31: Top seal used in the Oral-B Advance Power.

**Technological cycle**

The Oral-B Advance Power is poorly optimized for the technological cycle. The main body of the Oral-B Advance Power is made of two different materials that are 2K moulded, which is non-recyclable (PolyCE, 2021). Like the Boombbrush, several types of elastomers are used and it is unlikely all of them are recyclable due to the overall poor recyclability of elastomers (PolyCE, 2021). The other thermoplastics and metals used are all recyclable. In total, 12 different materials are used (excluding electronics)(see Table 8).

While the use of ABS for housing parts and POM for internal components is a common configuration, the use of ASA for the bottom cap is disappointing from a technological cycle perspective. The amount of polymers is high at seven.

The top seal is made out of metal and an elastomer that cannot be separated (see Figure 31). The irreversible snap fits used for the main body are likely not a problem for separation in shredding, but due to the difficulty of removing the main body, the PCB cannot easily be removed for recycling.

All parts in the brush are easy to identify functionally, and there is a material ID on most of the polymer parts.

Number of materials	Polymer	Elastomer	Metal
Identified	3	0	1
Unidentified, assumed unique	4	3	1
Unidentified, assumed same as identified (do not count for total)	0	0	0
<b>Total</b>	<b>7</b>	<b>3</b>	<b>2</b>

Table 8: Oral-B Advance Power - Unique material count.

## Conclusion

To summarize, the Oral-B Advance Power's user-replaceable battery setup is a big benefit to design for maintenance, as this allows users to use commonly available batteries and interchange them without a lot of effort. Interestingly, none of the more expensive brushes uses this approach, possible because this is perceived as less convenient by users. Figuring out how to balance ease of replacement and user perception is going to be a challenge for a more circular toothbrush. Besides its battery configuration, the Oral-B Advance Power shows practically no implementation of circular design strategies.

*Disassembly map shown on next pages. Chapter continuous after the disassembly map.*

**Disassembly Map**  
 Electric Toothbrush  
 Oral-B advance power battery  
 Mart Drummen

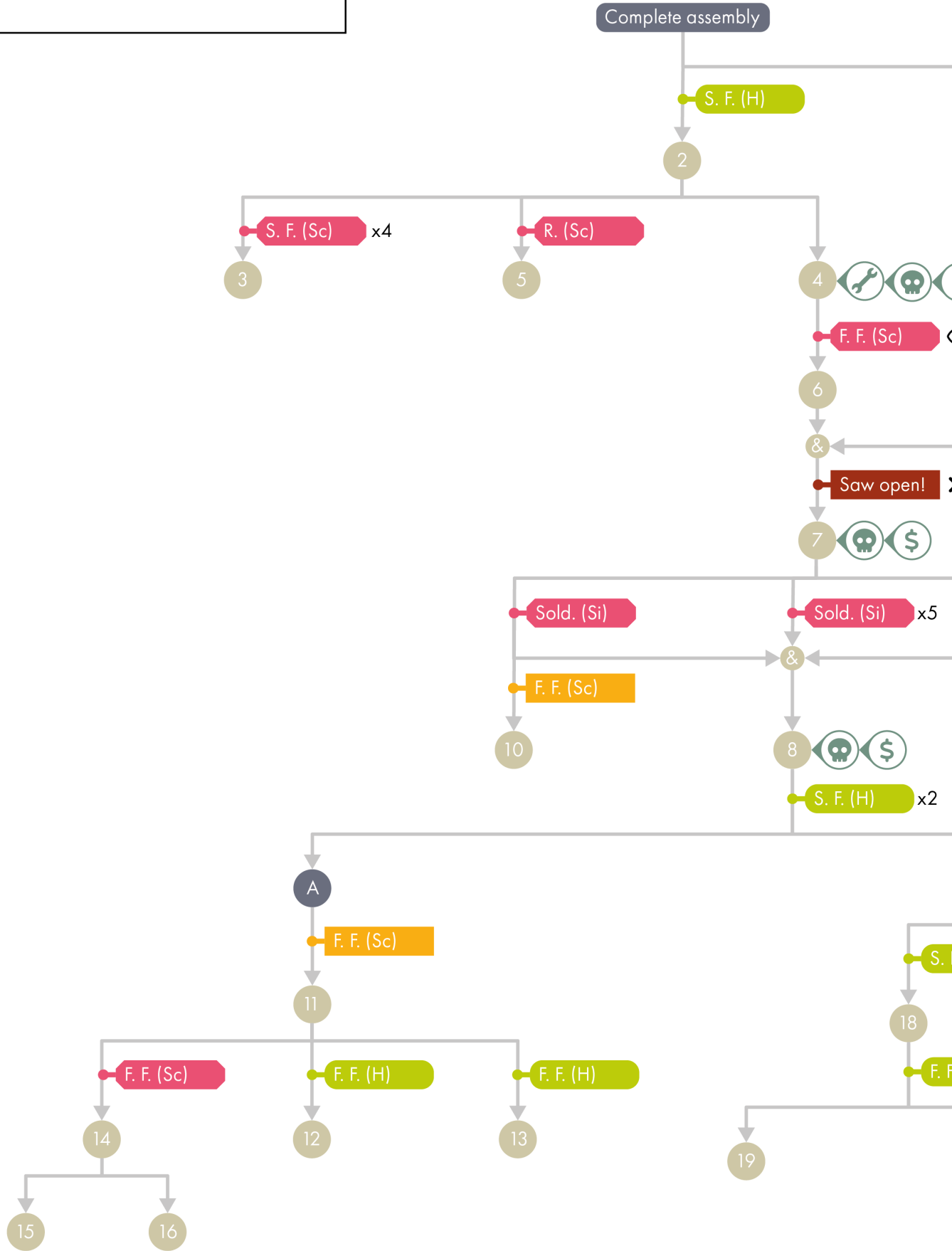
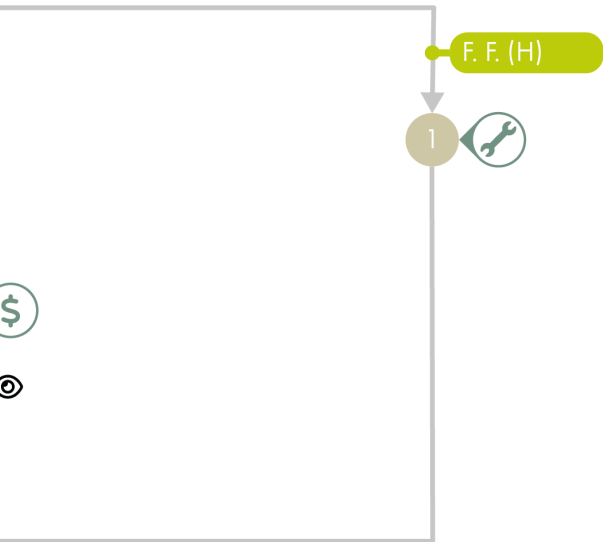
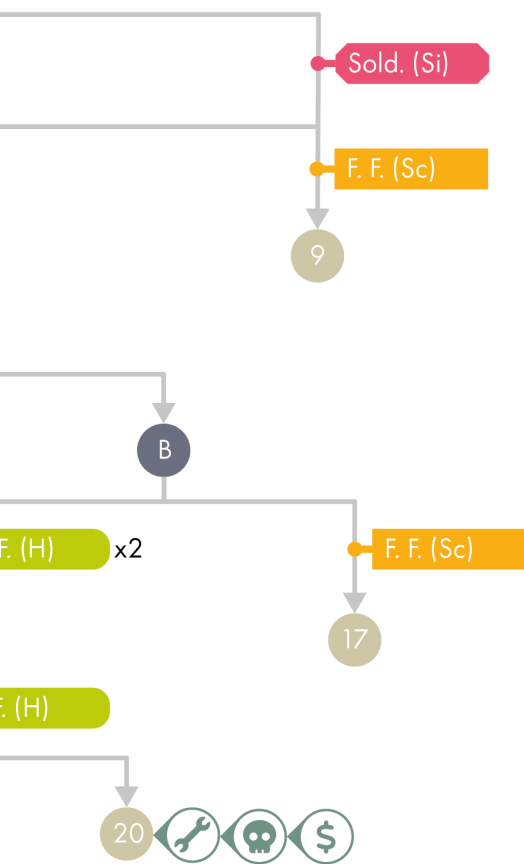


Figure 32: Disassembly map of the Oral-B Advance Power.



✗ Part 7 is destroyed.



### Components

- |                        |                                    |               |
|------------------------|------------------------------------|---------------|
| A. Brush axis assembly | 9. Battery contact short           | 20. Motor (B) |
| B. Motor assembly      | 10. Battery contact long           |               |
| 1. Brush head          | 11. Gearbox cover (A)              |               |
| 2. Bottom cap          | 12. Motor axis connector (A)       |               |
| 3. Bottom cap spring   | 13. Power button (A)               |               |
| 4. AA batteries        | 14. Top seal (A)                   |               |
| 5. Seal ring           | 15. Axis / Power button holder (A) |               |
| 6. Seal spring         | 16. Axis (A)                       |               |
| 7. Main body           | 17. Motor off centre axis (B)      |               |
| 8. PCB                 | 18. Motor bracket (B)              |               |
|                        | 19. Motor spring (B)               |               |

### Legend

#### Motion type

- = Hand motion
- = Single motion tool
- = Multiple motion tool

#### Type of connector

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

#### Target components

- Failure Indicator
- Environmental Indicator
- Economic Indicator

#### Force intensity

- |     |     |      |
|-----|-----|------|
| Low | Mid | High |
|     |     |      |
|     |     |      |

#### Type of tool

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

#### Penalties

- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

## 11.6. Oral-B Professional Care

### Durability and reliability

No special efforts were observed for design for durability or reliability in the Oral-B Professional Care 3000.

The Oral-B Professional Care 3000's main body is made of 2k moulded ABS and TPE. The ABS has good impact and scratch resistance (GRANTA EduPack, 2020). A known issue of the TPE on the main body is that it is prone to separating from the ABS.

The 3d rotating brushing mechanism used has several moving parts (see Figure 34). These are required to translate the rotating movement from the motor to the oscillating movement made by the brush. The brush axis itself is made from steel, however, the parts connecting the brush axis to the motor are mostly thermoplastics. Compared to the 2d rotating mechanism, the 3d rotating mechanism in the Oral-B Professional 3000 adds an additional gear that lowers the rpm. The mechanism is not known to be prone to failure.

More additional moving parts are added in to implement the pressure sensor mechanism (see Figure 35). The entire gearbox and brush axis hinge around an axis. When pressure is applied during brushing, two springs positioned at the motor side compress. When compressed enough, contact is made and the pressure indicator LED lights up. While this system adds significant complexity which could be a reliability concern, the implementation appears well thought out and no major weak spots were identified. In total, the addition of the pressure sensor adds eight additional parts to the product.



Figure 33: Oral-B Professional Care 3000 electric toothbrush (LookFantastic, n.d.).



Figure 34: The 3D rotating brush technology, from the motor to the brush axis.

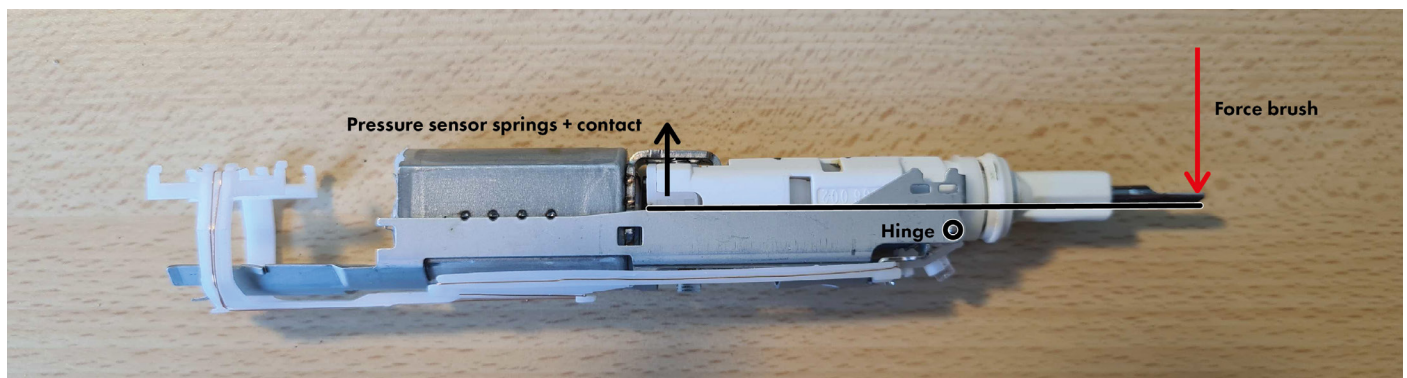


Figure 35: The pressure sensor mechanism used in the Oral-B Professional Care 3000.

### Attachment and trust

Little effort appears to be put into design for attachment & trust. The brush heads used for the Oral-B Professional Care 3000 feature a small ring that can be interchanged by rings of a different color. This is a very low-effort method of personalisation, mainly meant for users that share their electric toothbrush. Due to the low physical and mental effort, it is unlikely this contributes significantly to product attachment (Mugge, 2007).

The materials used for the Oral-B Professional care 3000's exterior are unlikely to show the desirable effects of ageing with dignity. While it is made of scratch-resistant material and should keep looking good for quite some time, any scuffs that do appear will deteriorate the product's aesthetics. A known issue of the textured grips on the main body is that they are prone to build up dirt over time that is hard to clean.

### Dis- and reassembly

The Oral-B Professional Care 3000 is significantly more complex than both the Boombbrush and the Oral-B Advance Power, featuring a total of 28 unique parts. The result is a significantly longer disassembly time of 39 minutes. 6 tools are required for disassembly, including a soldering iron.

Like with Boombbrush and Oral-B Advance Power, 90% of the CO2 impact of the materials used is made up by the battery, PCB, motor and main body (see Figure 36). Interesting to see is that contrary to the Boombbrush, where these parts make up about 80% of the product's mass, for the Oral-B Professional Care this is only 67%. There are two factors that contribute to this difference.

First, the total weight of the Oral-B Professional Care 3000 is a bit lower, at 130 grams compared to the Boombbrush's 134 grams. This might seem insignificant, but the weight of the PCB, the most impact-sensitive component, is the same. This means that with just a 0,1% increase in mass contribution, the impact contribution of the PCB increases by 4%.

Second, the TPE material used in the main body of the Oral-B professional care causes it to be more environmentally sensitive (co2/kg) than the pure ABS housing of the Boombbrush. This means that while the Boombbrush's housing is significantly heavier and makes up 25,4% of the Boombbrush's mass, the contribution to the impact is exactly the same at 6,9%.

Oral-B Professional Care 3000 - Part contribution to mass, CO2 (primary production) and economic value

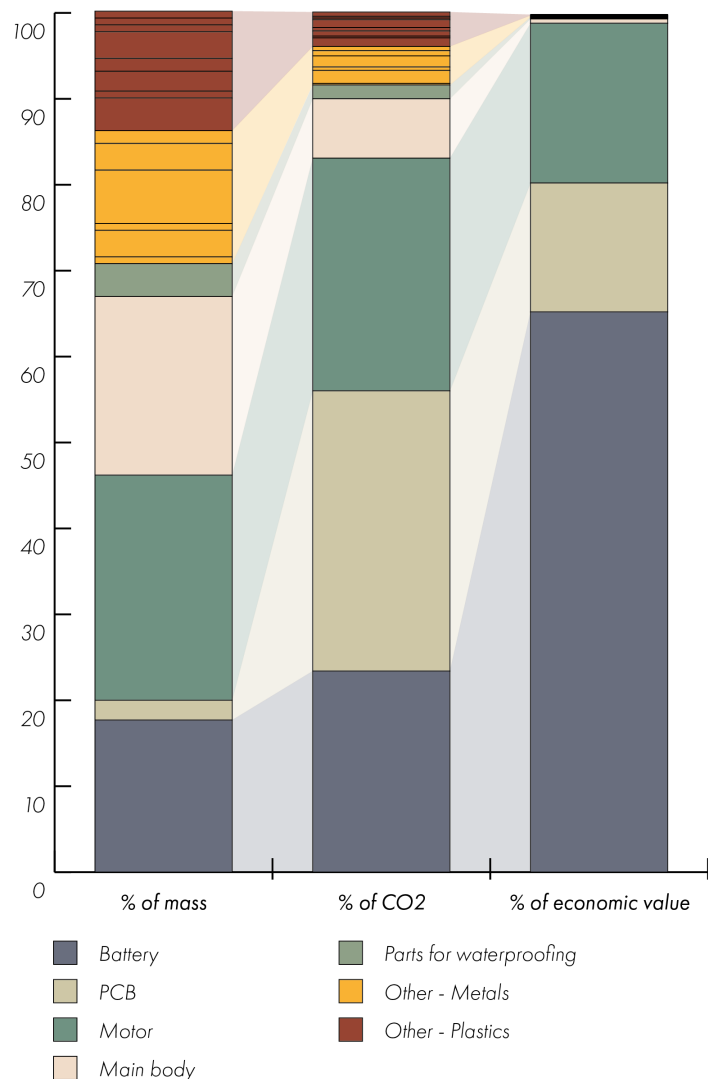


Figure 36: Contribution of materials in the Oral-B Professional Care 3000 to the mass, impact (CO2 primary production) and economic value.



Figure 37: Removing the bottom cap with the charger (Toothbrushbattery.com, n.d.-b).

The Oral-B Professional Care 3000 uses induction charging, adding a copper coil that gets marked for CO2 impact and value by the hotspot mapping sheet.

To open the Oral-B Professional Care 3000, the original charger has to be used (see Figure 37). This is an elegant ‘tool-free’ solution that is promising compared to the prying required for the Boombbrush and Philips Sonicare Easyclean. Unfortunately, for this analysis, the original charger was not provided with the toothbrush. This made removing the bottom cap hard to do and the part was damaged in the process.

Specific pain points in the disassembly procedure are removing the motor/gearbox bracket and the motor/gearbox connector. Both the motor/gearbox bracket and the motor/gearbox connector have to be removed in order to remove the motor. The issue with this is that both parts are attached to the motor by means of spot welding (see Figure 38). The motor/gearbox bracket can be removed by prying open 8 spot welds, but this is both a time-consuming and irreversible process. The welds used for the motor/gearbox connector are so strong that they were not broken. Instead, the metal hook keeping the motor/gearbox connector in place was bent out of the way using pliers. This requires a lot of force and is time-consuming.

**Maintenance and repair**

When looking at the disassembly map of the Oral-B Professional Care 3000 (see Figure 39 and Figure 40), it can be observed that the battery requires a lot of soldering work to be removed. This is because the battery is part of the battery / PCB assembly, meaning that the PCB has to be separated from the rest of the product first.

The motor is located deep into the disassembly sequence. This can be seen in the number of steps (28) and time (28 minutes) it takes to reach (see Table 9). The motor is the only priority part that is harder to replace due to the implementation of the pressure sensor.

For both repairs, a soldering iron is required. Most of the fasteners are reusable. However, as discussed prior to the removal of the motor several spot weld have to be destroyed.

**Future expansion, standardization & compatibility**

The main body of the Oral-B Professional Care 3000 can be removed in four steps (see Table 9). The only issue is that the original charger is required to do this without damage. As described before, the battery and PCB are fixed together in an assembly. This means their time to reach is similar, as is the number of steps (see Table 9). All connections used for the main body and PCB are reversible.

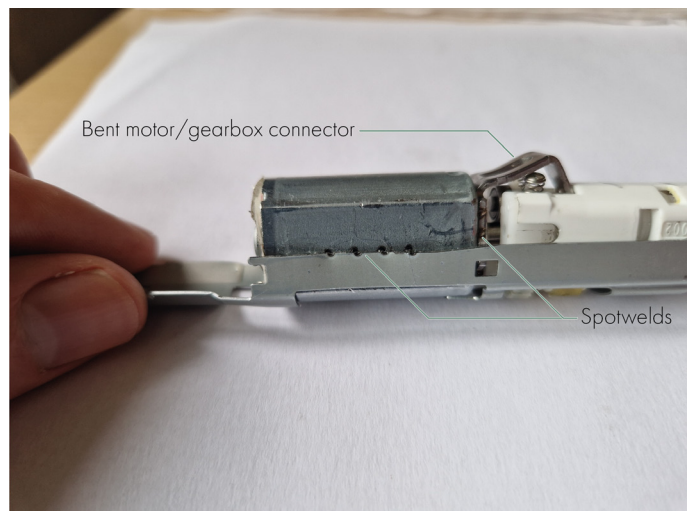


Figure 38: The motor of the Oral-B Professional Care 3000 is welded into place, making it time-consuming to remove.

Part	Steps to reach	Time to reach (s)	Number of tools required	Reversible connections
Motor	28	1695	5	No
Battery	17	1015	2	Yes
PCB	19	1060	2	Yes
Main body	4	395	1	Yes

Table 9: Number of steps and time required to reach components important for maintenance, repair & future expansion.

The battery used in the Oral-B Professional Care 3000 is a rechargeable  $\frac{4}{5}$  AA-size 1.480V Ni-MH battery. While a replacement can be found on the internet (123accu.nl, n.d.), it is much more expensive than regular AA batteries.

### Technological cycle

The Oral-B Professional Care 3000 is poorly optimized for the technological cycle. The main body and bottom cap of the Oral-B Professional Care 3000 are made of two different materials that are 2K moulded, which is non-recyclable (PolyCE, 2021). Like the Boombbrush, several types of elastomers are used and it is unlikely all of them are recyclable due to the overall poor recyclability of elastomers (PolyCE, 2021). No elastomers are used to damp motor vibrations, but there is a spring in the bottom of the brush that possibly damps vibrations somewhat. The other thermoplastics and metals used are all recyclable. In total, 12 different materials are used (excluding electronics)(see Table 10).

While the use of ABS for housing parts and POM for internal components is a common configuration, the use of ASA for the bottom cap is disappointing from a recycling perspective, as is the addition of a single PA part for the charging coil. Another notable downside to the charging solution used is the charger. The charger is potted for waterproofing, making the separation of electronics and other materials in the charger impossible.

Several welded connections are used on the motor that might the separation of the metals harder. The top seal is made out of metal and an elastomer that cannot be separated. The PCB can be removed easily.

All parts in the brush are easy to identify functionally, and there is a material ID on most of the polymer parts.

### Conclusion

To summarize, the Oral-B Professional Care 3000 is a long way from being a circular electric toothbrush. Its design mixes significant barriers to circularity with some promising solutions to key challenges. The charging solution does not use glue for waterproofing the charging port, which is beneficial for the technological cycle. But the charger is filled with material making the separation of electronics in this part impossible. The overall disassembly procedure takes a long time, many steps and requires soldering for all electronics, but the removal procedure of the bottom cap is an interesting concept. Like the Oral-B Advance Power, the 2k moulded body solves the button waterproofing challenge but complicates the technological cycle.

*Disassembly map shown on next pages. Chapter continues after the disassembly map.*

Number of materials	Polymer	Elastomer	Metal
Identified	4	0	3
Unidentified, assumed unique	2	2	1
Unidentified, assumed same as identified (do not count for total)	1	0	0
Total	6	2	4

Table 10: Oral-B Professional Care 3000 - Unique material count

# Disassembly Map

Electric Toothbrush

Oral-B Professional Care 3000

Mart Drummen

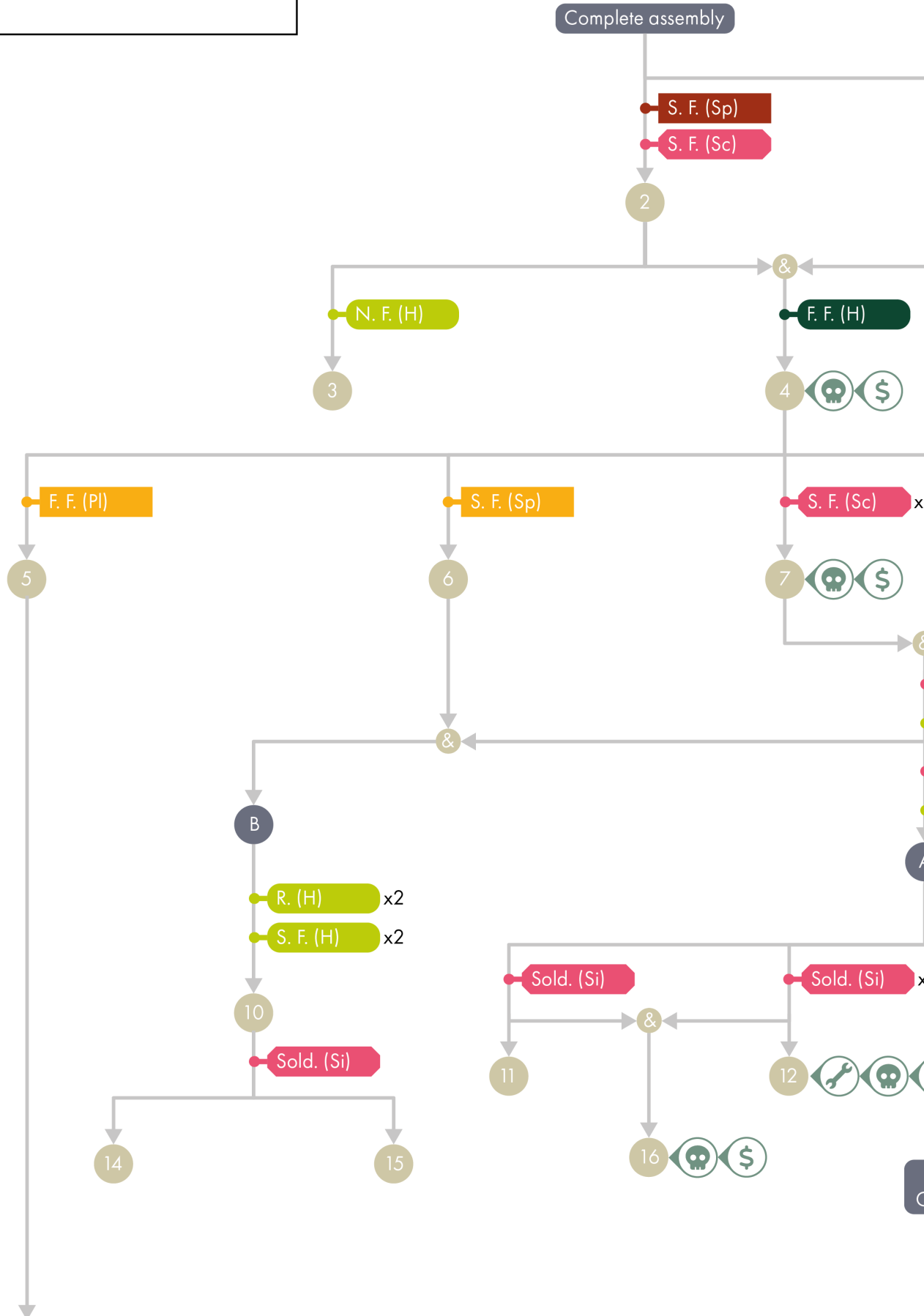
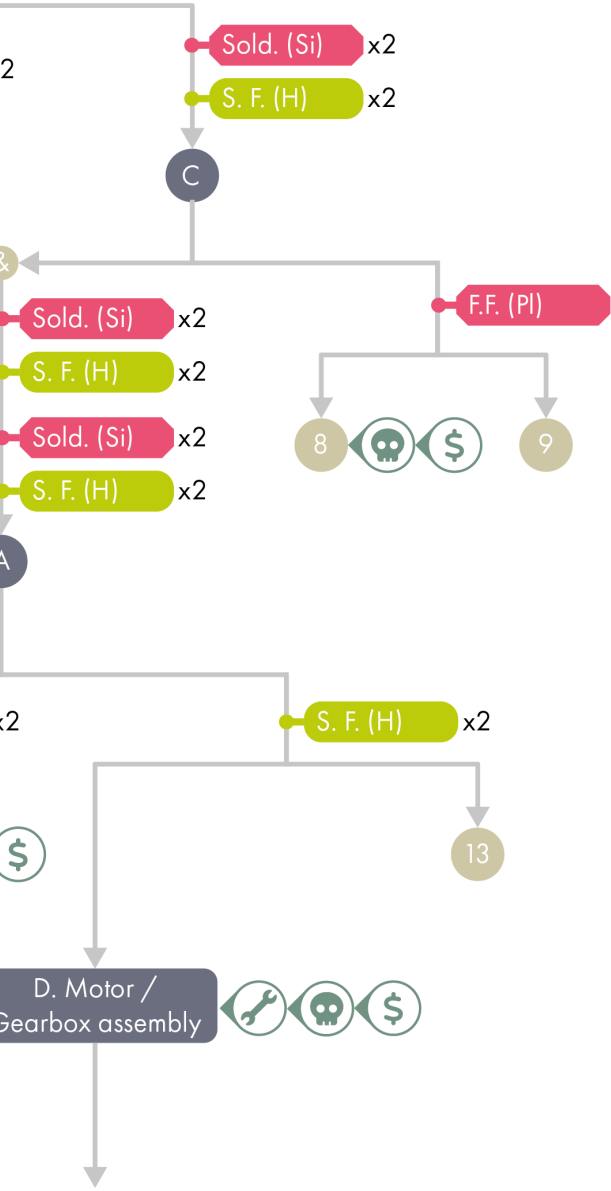
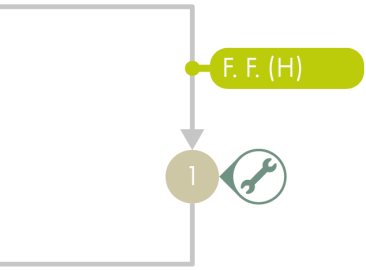


Figure 39: Disassembly map of the Oral-B Professional Care 3000.



**Components**

- A. Battery / PCB assembly
- B. LED assembly
- C. Charging coil assembly
- D. Motor / Gearbox assembly
- 1. Brush head
- 2. Bottom cap
- 3. Spring
- 4. Main body
- 5. Pressure sensor axis
- 6. LED bracket lock ring
- 7. Power button pressure plate
- 8. Charging coil (C)
- 9. Charging coil bracket (C)
- 10. LED bracket (B)
- 11. Pressure sensor PCB connector (A)
- 12. Battery (A)
- 13. Battery holder
- 14. LED wires (B)
- 15. LED (B)
- 16. PCB (A)

**Legend**

- Motion type**
- = Hand motion
  - = Single motion tool
  - = Multiple motion tool
- Force intensity**
- |  |  |  |
|--|--|--|
| Low  | Mid  | High   |
| <span style="display: inline-block; width: 15px; height: 10px; background-color: #C8E6C9;"></span> | <span style="display: inline-block; width: 15px; height: 10px; background-color: #FFCCBC;"></span> | <span style="display: inline-block; width: 15px; height: 10px; background-color: #FF8A65;"></span> |
- Type of tool**
- (H) = Hand
  - (Sc) = Screwdriver
  - (Sp) = Spudger
  - (Pl) = Pliers
  - (Si) = Soldering iron
  - (Ag) = Angle grinder

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Penalties**

- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

**Target components**

- Failure Indicator
- Environmental Indicator
- Economic Indicator

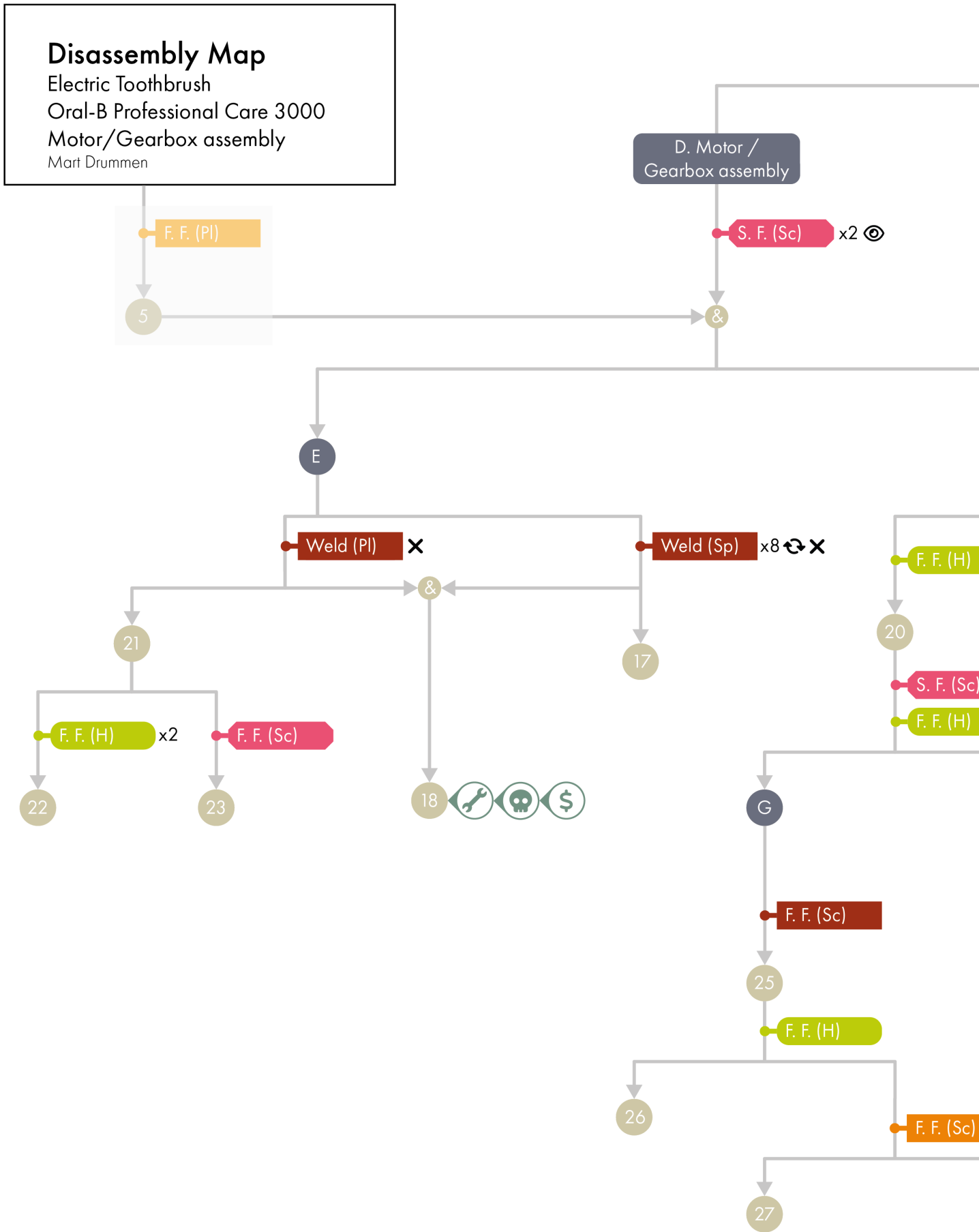
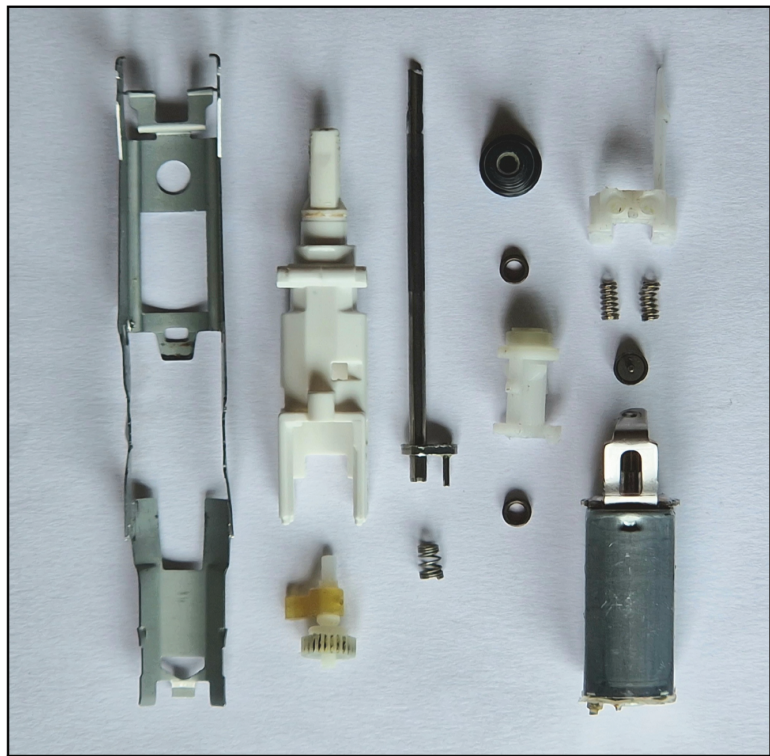
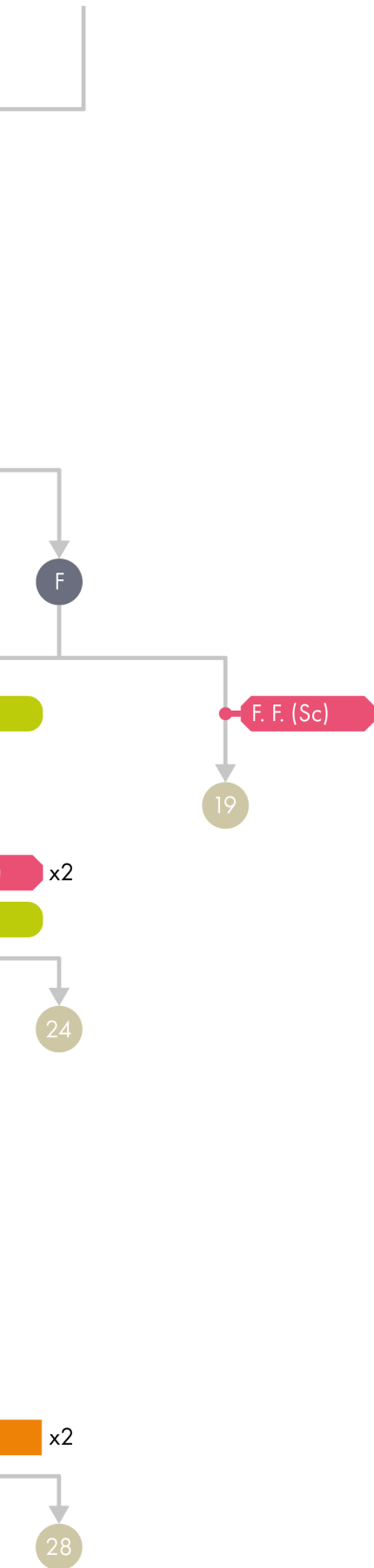


Figure 40: Disassembly map of the motor/gearbox assembly of the Oral-B Professional Care 3000.






### Components

- |                               |   |
|-------------------------------|---|
| D. Motor / Gearbox assembly   | 20. Rotating oscillating converter gear (F) |
| E. Motor assembly (D)         | 21. Motor/Gearbox connector (E)             |
| F. Gearbox assembly (D)       | 22. Pressure sensor springs (E)             |
| G. Brush axis assembly (F)    | 23. Pressure sensor contact (E)             |
| 5. Pressure sensor axis       | 24. Brush axis housing (F)                  |
| 17. Motor/Gearbox bracket (E) | 25. Top seal (G)                            |
| 18. Motor (E)                 | 26. Brush axis (G)                          |
| 19. Brush axis spring (F)     | 27. Axis spacers (G)                        |
|                               | 28. Axis holder (G)                         |

### Legend

#### Motion type

-  = Hand motion
-  = Single motion tool
-  = Multiple motion tool

#### Type of connector

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

#### Target components

- |   |  |  |
|---|--|--|
|  Failure Indicator |  Environmental Indicator |  Economic Indicator |
|---|--|--|





#### Force intensity

- |   |   |   |
|---|---|---|
| Low   | Mid   | High  |
|  |  |  |

#### Type of tool

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

#### Penalties

-  = Product manipulation
-  = Low visibility/identifiability
-  = Uncommon tool
-  = Non-reusable connector

## 11.7. Philips Sonicare Easyclean

### Durability and reliability

No special efforts were observed for design for durability or reliability in the Philips Sonicare Easyclean.

The Philips Sonicare Easyclean's main body is made out of a single part of PA + ABS. This material has better impact resistance but less scratch resistance than regular ABS (GRANTA EduPack, 2020). No major weak points were identified when observing the construction of the main body.

Contrary to the single-part configuration in the Boombush, the sonic brushing mechanism of the Philips Sonicare Easyclean consists of 10 parts (see Figure 42). It is also significantly heavier than the Boombush mechanism at a total of 41 grams (vs 26 g). Unlike the Oral-B rotating toothbrushes, none of the parts rotate. Instead, they are there to pass on the sonic vibrations in a controlled manner.

### Attachment and trust

No effort appears to be put into design for attachment & trust. The Philips Sonicare Easyclean offers no options for personalisation. The materials used for the Philips Sonicare Easyclean's exterior are unlikely to show the desirable effects of ageing with dignity. While it is made of scratch-resistant material and should keep looking good for quite some time, any scuffs that do appear will deteriorate the product's aesthetics.



Figure 42: Brush mechanism of the Philips Sonicare Easyclean.



Figure 41: Philips Sonicare Easyclean electric toothbrush (Handleidi.ng, n.d.).

### Dis- and reassembly

The Philips Sonicare Easyclean is of similar complexity as the Oral-B Professional Care 3000, featuring the same total of 28 unique parts. While the disassembly time is quite a bit lower at 29 minutes, the amount of steps required for a full disassembly is the highest of all electric toothbrushes compared at 65. Six tools are required for disassembly, including a soldering iron.

The Philips Sonicare Easyclean is the only brush analysed in which the battery, PCB, motor and main body make up less than 90% of the CO<sub>2</sub> impact of the materials used. This can be attributed to these parts making up a significantly lower percentage of the total mass of the product. This however doesn't change the distribution of value in the product, with the battery, PCB and motor still accounting for almost 99% of the value, making them the most important for the economically viable implementation of circularity (see Figure 43). Like the Oral-B Professional Care 3000, the Philips Sonicare Easyclean uses induction charging, adding a copper coil that gets marked for CO<sub>2</sub> impact and value by the hotspot mapping sheet.

Specific pain points in the disassembly procedure are several desoldering actions and removing the top (motor) bracket and a magnet lock.

The soldering actions that cost by far the most time were those required to remove the charging coil (240 s). The main reason for this was the design of the contact patches, which are situated on two metal pins fitted through the PCB / battery carriage.

In order to reach the motor and magnet, the top bracket has to be removed. The top bracket is fixed to the bottom (motor) bracket using 10 spot welds, each of which is much stronger than those used in the Oral-B Professional Care 3000. This means that prying the welds loose does not work. Due to this, a small angle grinder was used to disconnect the welds. This method permanently damages the part and requires high precision, an uncommon tool and several minutes to do.

The magnet lock needs to be removed in order to reach the magnet. This lock consists of a small metal piece and a screw with a Philips #1 head. However, since the screw is not the strongest and a lot of Loctite has been applied to it, it could not be removed using a standard Philips #1 screwdriver. Instead, a small angle grinder was used to make room for a 3mm flat head screwdriver. This allowed enough force to be applied in order for the screw to be removed (see Figure 44).

While there appears to be little thought about performing maintenance, repair or future expansion of priority parts, the Philips Sonicare Easyclean has one advantage over its competitors. Looking at the disassembly map of the Philips Sonicare Easyclean (see Figure 47 and Figure 48), it can be observed that the disassembly map is much wider on the top than that of other toothbrushes. This is because contrary to Oral-B's approach, many components are directly accessible after removing the main body, meaning that several parts can be accessed directly and independently from each other.

Philips Sonicare Easyclean - Part contribution to mass, CO2 (primary production) and economic value

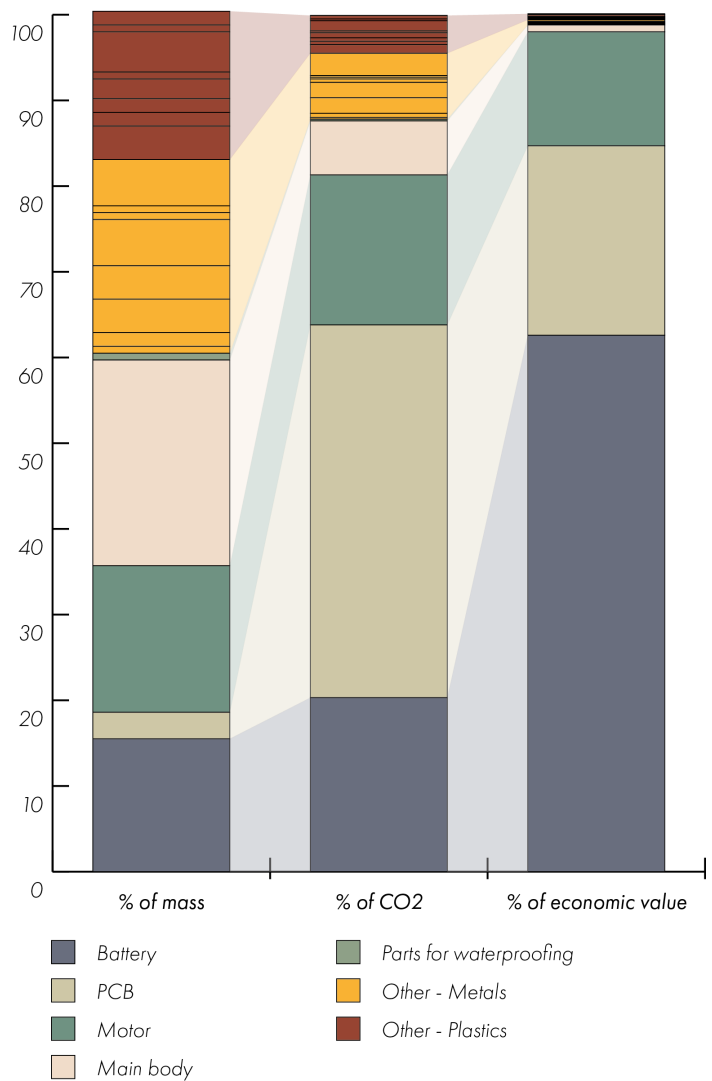


Figure 43: Contribution of materials in the Philips Sonicare Easyclean to the mass, impact (CO2 primary production) and economic value.



Figure 44: The screw used in the magnet lock of the Philips Sonicare Easyclean is fixed using Loctite. To apply enough force to remove the screw, the screw had to be destroyed.

### Maintenance and repair

The battery in the Philips Sonicare can be replaced quicker than the other brushes with a built-in battery, but it still requires soldering to remove. The battery is only covered by an easy-to-remove elastomer cover. In order to desolder the battery, the same type of cover has to be removed from the PCB. In total, the removal costs 8 steps and 5 minutes to do (see Table 11).

The motor is located deep into the disassembly procedure. This can be seen in the number of steps (39) and time (18 minutes) it takes to reach (see Table 11). Removing the motor is impossible without either permanently damaging the brush, or replacing a large number of parts.

For both repairs, a soldering iron is required.

### Future expansion, standardization & compatibility

The main body of the Philips Sonicare Easy-clean can be removed in just three steps (see Table 11) and 2 minutes, making it the quickest to remove of all brushes compared. Like the other brushes, removing the PCB is quite time-consuming due to the soldering work required. This means this requires significantly more time to remove than the battery (see Table 11). All connections used for the main body and PCB are reversible.

The battery used in the Philips Sonicare Easy-clean is a 14 x 49 mm 3.7 V lithium-ion battery. Like the lithium-ion battery in the Boombrush, this battery type is not commonly available in stores and has to be ordered online and the cell cannot be interchanged by just any cell of the same size. There are differences in discharge current and capacity that can affect user experience and the functioning of the device. The battery used is more expensive than a regular AA battery (Toothbrushbattery.com, n.d.-a).

Part	Steps to reach	Time to reach (s)	Number of tools required	Reversible connections
Motor	39	1095	5	No
Battery	8	320	3	Yes
PCB	17	710	3	Yes
Main body	3	125	1	Yes

Table 11: Number of steps and time required to reach components important for maintenance, repair & future expansion.

Number of materials	Polymer	Elastomer	Metal
Identified	1	0	3
Unidentified, assumed unique	5	4	1
Unidentified, assumed same as identified (do not count for total)	1	0	0
Total	6	4	4

Table 12: Philips Sonicare Easyclean - Unique material count.

## Technological cycle

The Philips Sonicare's main body is the best design for material separation. It isn't 2K Moulded like the Oral-B brushes, but also does not have glued-on parts like that of the Boombush. To achieve this an elastomer power button with snapfits is used (see Figure 45).

Like the Oral-B Professional Care 3000, a notable downside to the charging solution used is the charger itself. The charger is potted for waterproofing, making the separation of electronics and other materials in the charger impossible (see Figure 46).

The Philips Sonicare Easyclean has the largest amount of elastomer parts (7 g), which are unlikely to all be recyclable due to the overall poor recyclability of elastomers (PolyCE, 2021). No elastomers are used to damp motor vibrations, but there is a spring in the center of the brush that appears to damp vibrations. Elastomer covers are applied to the PCB and battery. The other thermoplastics and metals used are all recyclable. In total, 14 different materials are used (excluding electronics)(see Table 12).

Spot welding is used to connect the top (motor) bracket and bottom (motor) bracket, but as both are made of stainless steel this is unlikely to be problematic. The PCB can be removed easily.

All parts in the brush are easy to identify functionally, but almost none of the polymer parts have a material ID.

## Conclusion

To summarize, the Philips Sonicare Easyclean does not apply many circular design strategies in a meaningful way. What it does right is having a wide disassembly tree and reducing the replacement time of the battery. This removal of dependencies in the disassembly map is a great strategy to improve ease of dis- and reassembly. It also has some interesting features that can aid the technological cycle, like the main body that is neither 2k moulded nor glued. The charging solution does not use glue for waterproofing, but the charger is filled with material making the separation of electronics in this part impossible.

*Disassembly map shown on next pages. Chapter continues after the disassembly map.*



Figure 45: The power button of the Philips Sonicare Easyclean is an elastomer part with snapfits.



Figure 46: The charger of the Philips Sonicare Easyclean is filled, making the separation of electronics impossible.

# Disassembly Map

Electric Toothbrush

Philips Sonicare Easyclean

Mart Drummen

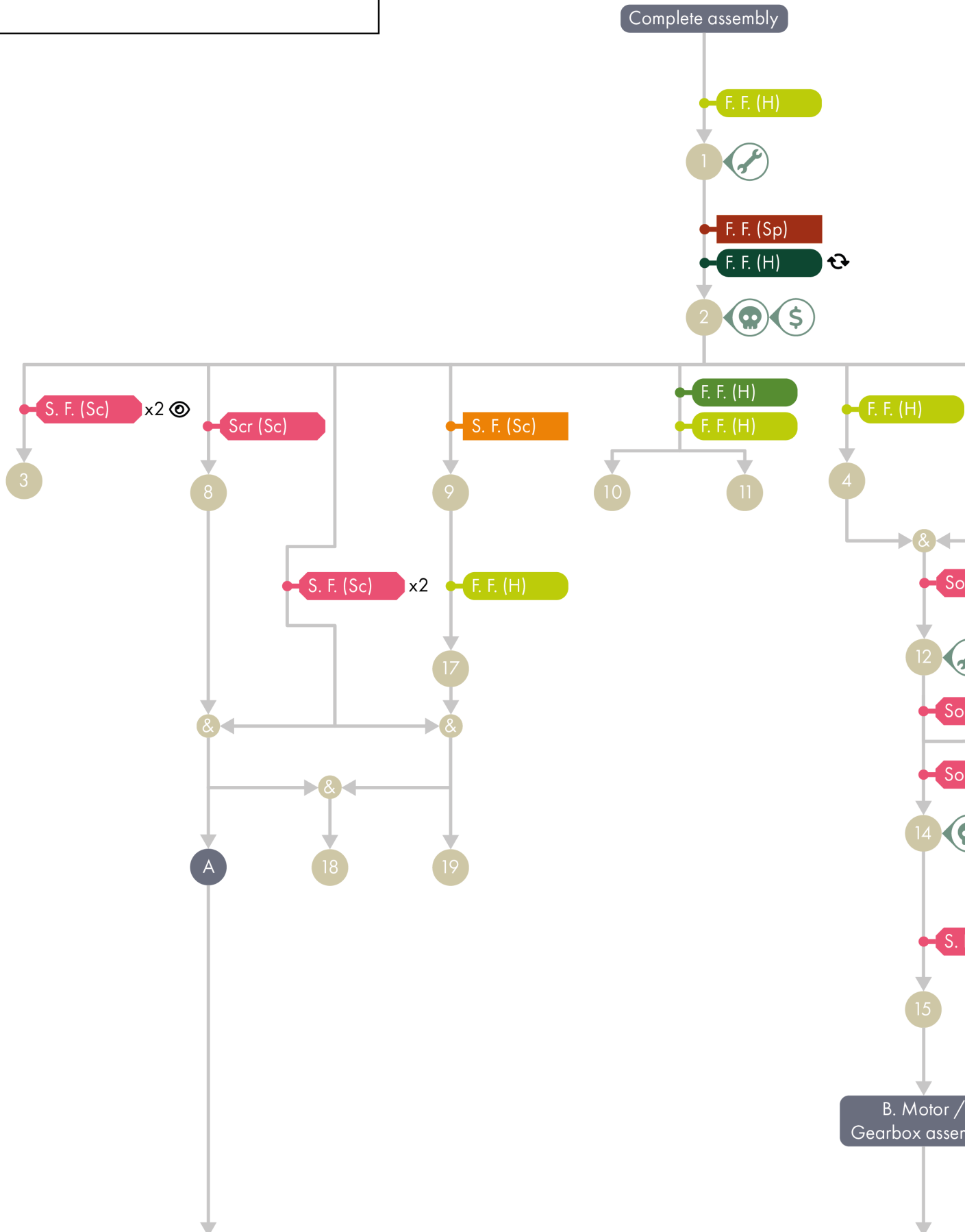


Figure 47: Disassembly map of the Philips Sonicare Easyclean.



**Disassembly Map**  
 Electric Toothbrush  
 Philips Sonicare Easyclean  
 Motor/Gearbox assembly  
 Mart Drummen

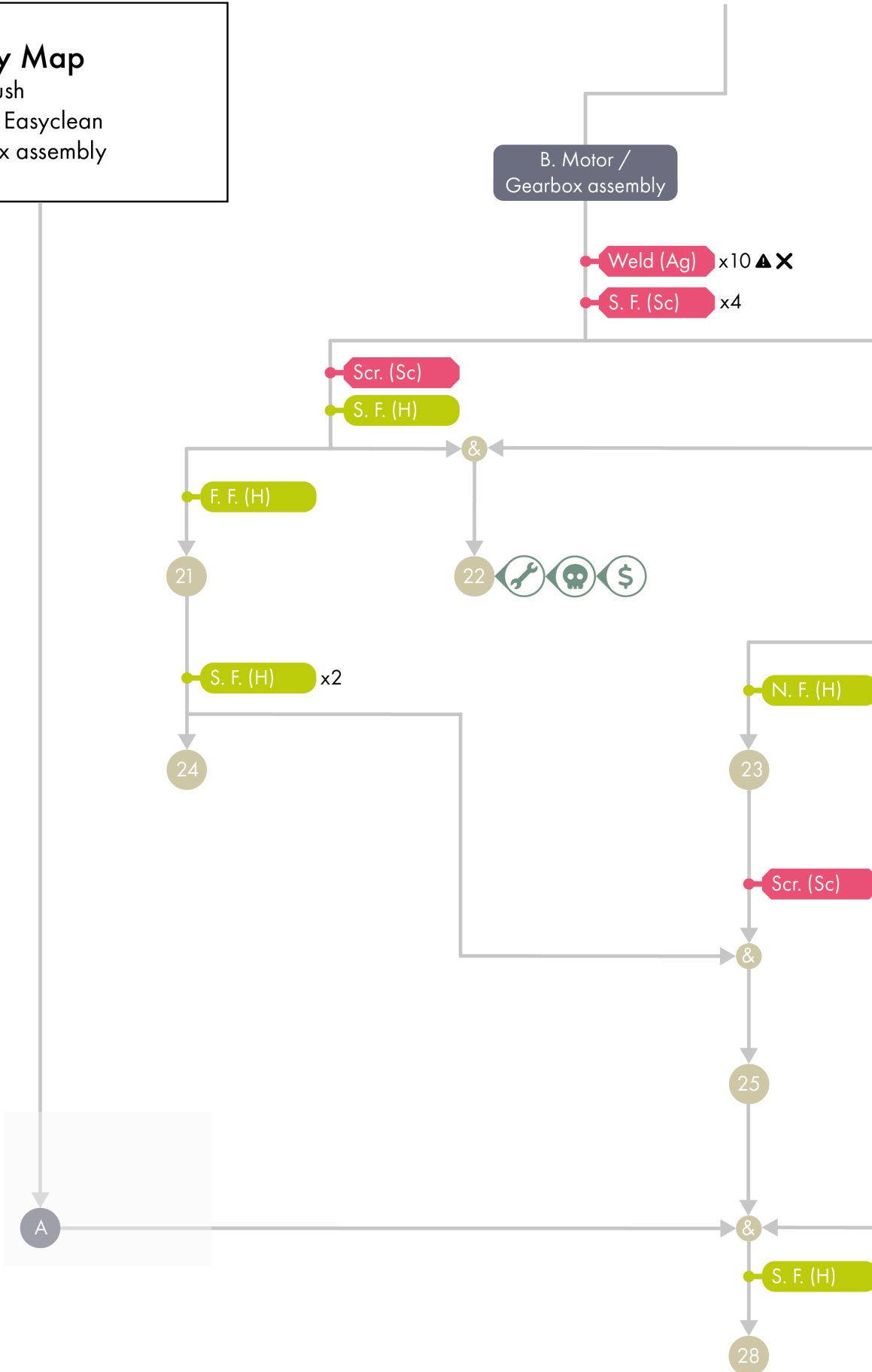
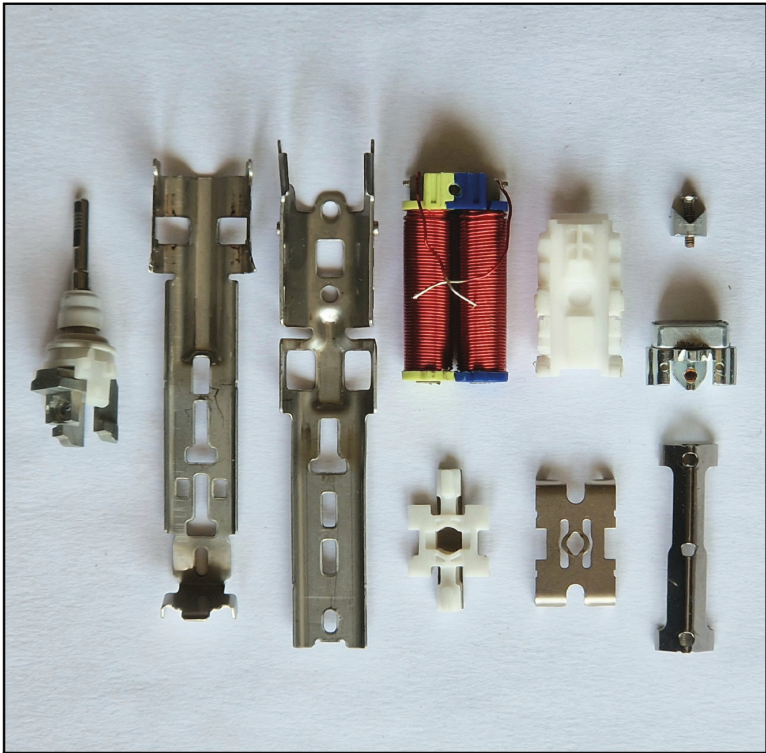
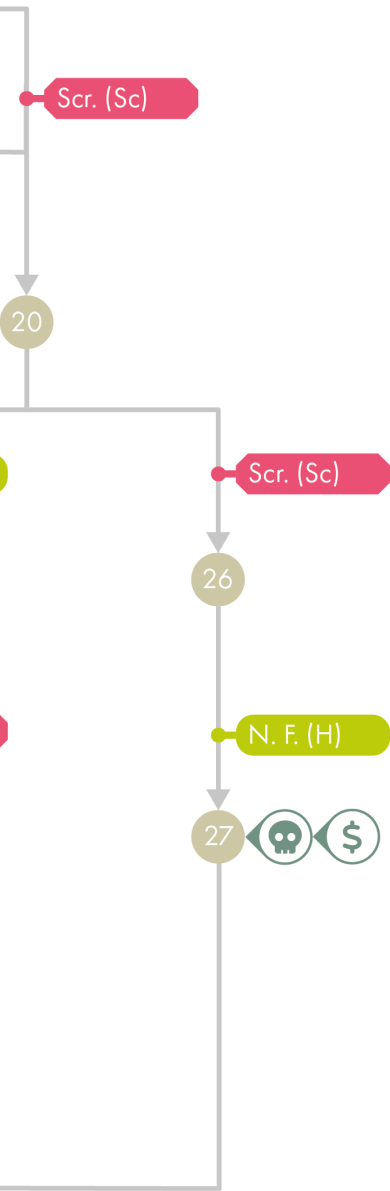


Figure 48: Disassembly map of the motor/gearbox assembly of the Philips Sonicare Easyclean.



**Components**

- A. Front axis assembly
- B. Motor / Gearbox assembly
- 20. Top bracket (B)
- 21. Bottom bracket (B)
- 22. Motor (B)
- 23. Top axis holder (B)
- 24. Bottom axis holder (B)
- 25. Axis bracket (B)
- 26. Magnet lock (B)
- 27. Magnet (B)

28. Axis (B)

**Legend**

**Motion type**

- = Hand motion
- = Single motion tool
- = Multiple motion tool

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Target components**

- Failure Indicator
- Environmental Indicator
- Economic Indicator

**Force intensity**

- Low
- Mid
- High

**Type of tool**

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Penalties**

- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

## 12. Phase 2 - Conclusion

### 12.1. Circular design strategies in current electric toothbrushes

#### Slowing resource loops

##### *Designing long-life products*

None of the analysed toothbrushes appeared to have special efforts for design for durability. While no data for durability was available, some noteworthy weaknesses are the brush axis fragility of the Boombbrush and the 2K moulded Oral-B housings that are prone to material separation. These specific issues can be taken into account for a brush specially designed for the circular economy, but such design defects are more likely to be the result of design error than a lack of attention to durability.

The lack of data on reliability meant that the reliability of the current toothbrushes can only be evaluated based on system complexity. In this regard, the Boombbrush is the clear winner with its motor and brush axis integrated into a single part. Figure 49 shows all the brush technology configurations side by side.



Figure 49: Overview of the four analysed brushes' brush technologies. From left to right: Boombbrush (sonic), Oral-B Advance Power (2d rotating), Oral-B Professional Clean (3d rotating), Philips Sonicare Easyclean (sonic).

None of the electric toothbrushes appears to have strategies for attachment or trust applied. The only personalisation option found was the coloured ring on the brush heads used by the Oral-B brushes. These rings are most likely too low effort to generate product attachment and limited to the brush heads, which require replacement every few months anyway.

##### *Design for product-life extension*

Except for the replacement of brush heads, which is an easy one-step procedure for all brushes, the only electric toothbrush with clear effort for ease of maintenance is the Oral-B Advance Power. The user-replaceable batteries can be removed in just two steps.

For repair, the Boombbrush is the best brush. While the tapes used in the Boombbrush add a barrier, the value of these tapes is low and replacement should not be a big problem. All other brushes require parts to be permanently damaged in order to replace the motor.

While the Boombbrush is the best current electric toothbrush for repair, it seems none of the brushes is particularly optimized for this strategy. All repairs for the motor and battery require soldering, which significantly increases the time required (see Figure 50).

None of the brushes appears to have design for future expansion implemented. The PCB, like the battery and motor, is not optimized for interchanging in any of the brushes. Except for the Oral-B Advance Power, it is possible to change the main body relatively quickly. Important here is however that the main body is always a heavily integrated part that has to align to the PCB and top and bottom seals for waterproofing. This is likely an unavoidable characteristic.

All of the battery cells used in the toothbrushes are standard sizes. That does not mean they are commonly available or guarantee compatibility with similarly sized cells. The best implementation of design for standardization and compatibility are the AA batteries in the Oral-B Advance Power. AA batteries are commonly available and interchangeable with any brand. The other batteries used are harder to acquire and need to be purchased online. They also are not easily interchangeable.

**Closing resource loops**

None of the brushes appears to have all design principles for design for a technological cycle applied. The Boombrush has the least amount of different materials but uses glue in several spots. The Oral-B brushes are probably the worst in this regard, as they use both permanent connections and a lot of different materials. The Philips Sonicare Easyclean is the best brush for materials separation, but also uses a lot of different materials.

As discussed, design for maintenance and repair and design for future expansion are not well implemented in the brushes. The main cause for this is a lack of design for dis- and reassembly. This makes the current electric toothbrushes unfit for leveraging circular economy loops like refurbishment and remanufacturing. The biggest barriers are several irreversible connections and the soldering required.

Some positive aspects regarding the design for disassembly are the bottom caps of both Oral-B toothbrushes. Neither requires prying to open. The Oral-B Advance Power has by far the easiest to remove bottom cap, which requires almost no force and can be done in a few seconds. The system used by the Oral-B Professional Care 3000 that leverages the included charger as a tool for opening is a smart method of creating a strong seal while not requiring users to own tools.

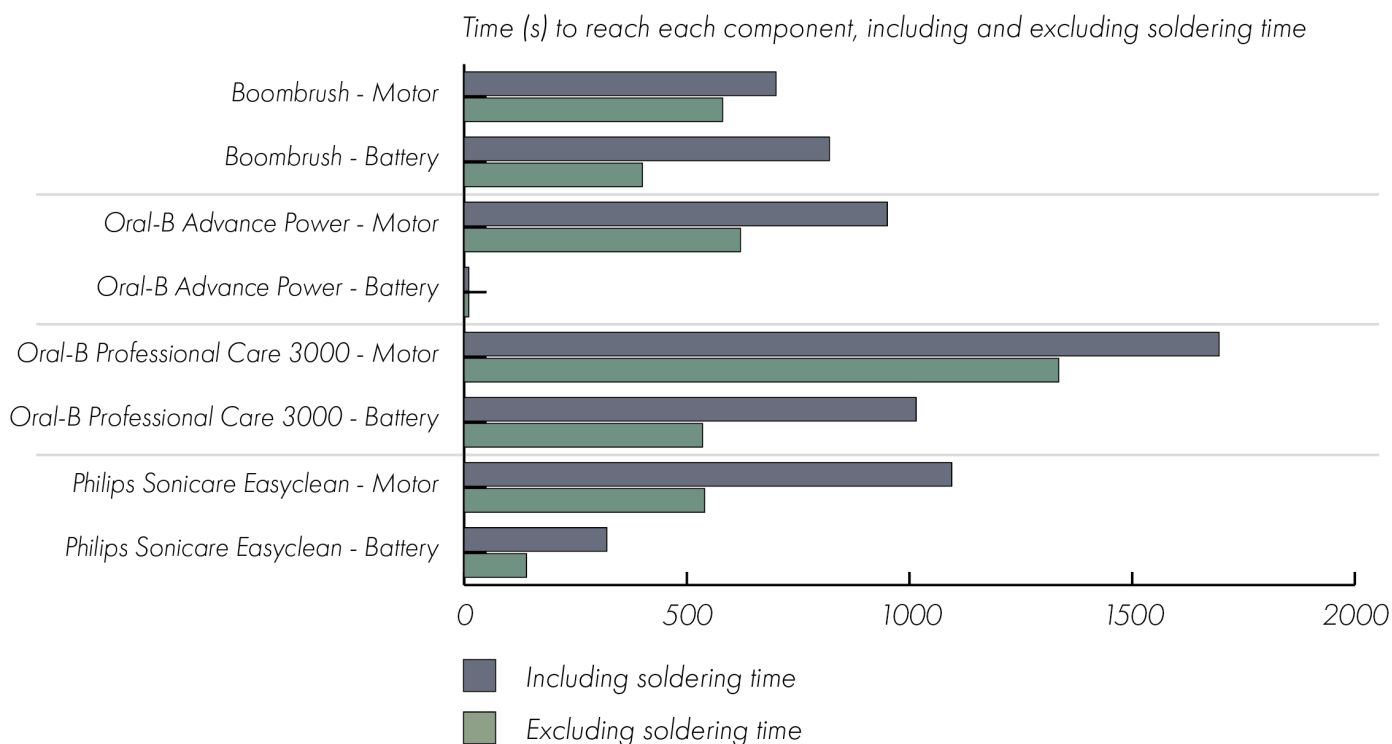


Figure 50: Overview of disassembly times of motor and battery, including or excluding soldering time.

## 12.2. Key insights

Three opportunities and one challenge for applying circular design strategies for electric toothbrushes were identified.

### **1 Design for attachment strategies are not implemented in current electric toothbrushes. Implementing design for attachment could extend product life.**

The first opportunity is implementing designing for attachment. Design for product attachment is not implemented on current electric toothbrushes. Some strategies for increasing consumer attachment, like designing for surprise or designing with odour, might be a bad fit for electric toothbrushes. But other strategies like product personalisation, creating unique or exclusive products and designing products that age with dignity are feasible to apply.

Scott and Todd Weaver (2015) found product attachment was significant to consumer tendency to repair. This indicates that increasing product attachment might improve repair consideration, which was found to be lacking in phase 1 of this thesis.

### **2 Current electric toothbrushes are not optimized for disassembly. Improving the ease of disassembly for priority parts can open up opportunities for product life extension.**

For all analysed electric toothbrushes the battery, motor and PCB make up about 80% of the material value. This makes these parts key for a successful implementation of circular business models. Unfortunately in current electric toothbrushes the disassembly procedure for accessing these parts often takes many steps and is time-consuming. This increases the costs of part replacement and recovery, reducing repair considerations. As such, the second opportunity is to improve the ease of disassembly for priority parts.

While the accessibility of these parts is important for value capture, the battery motor and PCB typically also make up about 95% of the CO<sub>2</sub> impact of the materials. Lyne et al. (2020) found material to be the second greatest contributor to the total impact of the toothbrush over its lifetime. Locally cycling these materials and retaining them for as long as possible is a good strategy for reducing environmental impact.

### **3 Permanent connections are used unnecessarily in current electric toothbrushes. Avoiding permanent connections used can increase high-value recycling performance.**

Various permanent connections, like 2k moulding, welding and glueing, are used in the design of current electric toothbrushes which impedes material liberation. When looking at the architectures of all brushes it can be observed the permanent connections are for different parts in different brushes. This means that there are solutions to fix each of those parts without permanent connections. As such, the third opportunity is avoiding permanent connections.

An important side note for avoiding permanent connections is the charging technology that is selected. The induction chargers that come with current electric toothbrushes are made waterproof by potting them, which makes it impossible to separate the materials in the charger properly.

### **4 Elastomers are required for waterproofing. Reducing the amount of elastomer used can increase high-value recycling performance.**

All of the brushes use several elastomer parts for waterproofing. These parts are detrimental to high-value recycling as they pollute material streams. By reducing the amount of elastomer the high-value recycling performance can be increased, but reducing them will be a challenge as they are required for waterproofing. All elastomers that are used should be easy to remove from the product.



# Design

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*Design of an electric toothbrush suitable for the circular economy*

<b>Objectives</b>	<b>80</b>
<b>Ideation &amp; conceptualisation</b>	<b>82</b>
<b>Concept development - Everbrush</b>	<b>87</b>
<b>Concept validation</b>	<b>96</b>

# 13. Objectives

## 13.1. Introduction

The goal of the third and final phase of this master thesis is to come up with design solutions that tackle the key insights found in phases one and two. These design solutions will then be combined into one integrated design concept that is feasible, desirable and viable.

Based on the key insights of phases one and two seven design challenges were identified for designing an electric toothbrush for the circular economy. These design challenges are the key aspects that require improvement over current electric toothbrushes in order to make the electric toothbrush suitable for the circular economy.

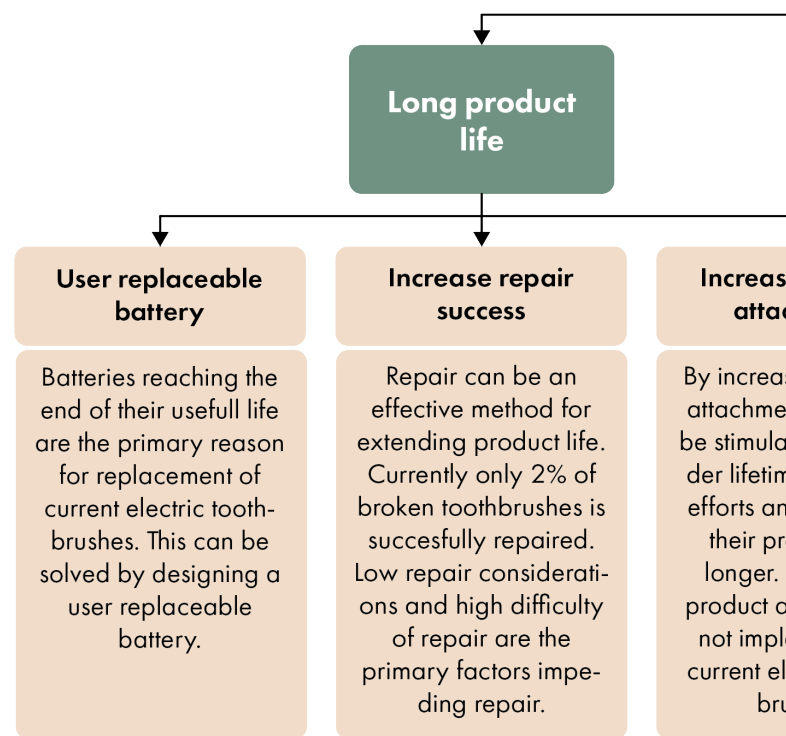
The functionality of the designed concept is kept in line with current electric toothbrushes by using the Boombbrush electric toothbrush as the starting point. As such, the Boombbrush motor and PCB will have to fit in the new design.

## 13.2. Design challenges

To organize the gained insights and translate them into design challenges, the creative problem-solving (CPS) method (van Boeijen et al., 2014) was used. CPS was chosen as it helps redefine design problems to come up with breakthrough ideas. CPS consists of three steps. First, the design objectives should be defined. Second, facts should be gathered. The facts were gathered in phases one and two and were coupled to the design objectives. Third, the problems (design challenges) that require solving in order to achieve the objectives should be defined.

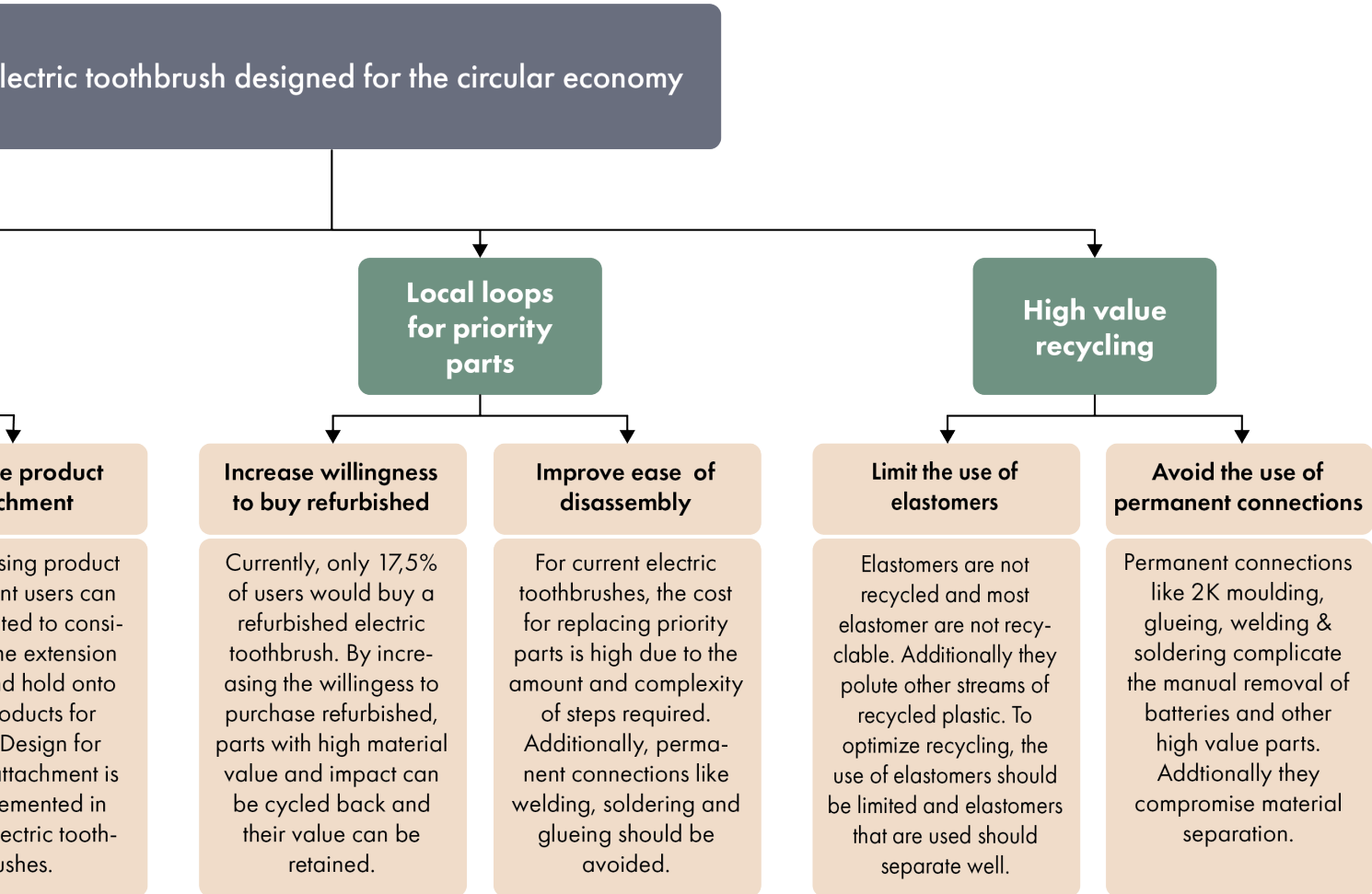
The primary research question of this master thesis is: *how can an electric toothbrush be designed suitable for the circular economy?* As such, the primary design objective was defined to be an electric toothbrush designed for the circular economy. The three sub-design objectives, otherwise called the three pillars of this design, are based on the fundamental circular design strategies discussed in chapter 2. The design challenges are grouped under the pillars and based on the key insights of phases 1 and 2.

The results are organized into a diagram (see Figure 51).



- Primary design objective
- Sub design objective / Pillar
- Design challenge

Figure 51: Design objectives and related design challenges base



based on the creative problems solving method.

## 14. Ideation & conceptualisation

### 14.1. Introduction

Based on the design challenges discussed in chapter 13, three concepts for an electric toothbrush for the circular economy were developed. First, ideas were generated for the design challenges individually. Second, these ideas were combined into concepts based on a philosophy picked for each concept. Last, one of the concepts was selected based on several key performance indicators (KPIs).

The selection of a battery technology was done separately from the generation of concepts. The battery technology selection is discussed in chapter 14.3.

### 14.2. Idea generation

Ideas were generated in multiple ways. The disassembly maps of current electric toothbrushes were used to find promising product architecture directions for reducing the cost of part replacement and limiting the use of permanent connections (see Appendix F). A brainwriting session was organized with three other industrial design graduates on three topics (Easy & intentional battery replacement; Alleviating concerns about buying refurbished; Increasing product attachment)(see Appendix G) to increase the breadth of ideas. Additionally, several brainstorms were performed by the designer individually to find new solutions for challenges found while improving the product architectures.

One idea that deserves a specific mention came from the brainwriting session on alleviating concerns when buying refurbished. The idea is to challenge what it means for a product to be refurbished by only selling products that can contain refurbished parts. This way, the difference between new and refurbished is blurred. This is hypothesised to increase acceptance of refurbished electric toothbrushes. As this idea can in theory be implemented with any of the concepts described in chapter 14.4, the hypothesis will be tested with the selected concept during the concept validation.

### 14.3. Battery technology selection

From the analysis performed in phases one and two it became apparent that the battery is an important part of the electric toothbrush, especially from a circular perspective. It is the primary reason for electric toothbrushes reaching their end of life and is one of the biggest contributors to material impact and value.

All the electric toothbrush concepts that were developed feature easily user-replaceable batteries. This makes the considerations for selecting a battery technology mostly similar for all the brushes. For this chapter, the considerations were split into two categories: battery longevity and end of life. For both categories, literature was evaluated to make an informed decision about the battery technology.

Morris (2012) lists all common commercial and many investigational rechargeable battery types. From the types listed, a selection of promising technologies was made. Technologies excluded from the selection can currently only be implemented on a 'large' scale (not toothbrush sized) or are prohibited for this application by EU legislation (Council directive 2006/66/EC, 2006).

Nickel-Zinc is introduced by Morris as a promising alternative to Ni-MH, but according to Morris achieving enough cycles for commercial success is an issue for this type of battery. Other sources echo these longevity concerns (Thomas, 2018). As such, Ni-Zn was also excluded.

Additionally to rechargeable batteries, primary cell (non-rechargeable) alkaline batteries were considered but deemed undesirable due to their larger environmental impact (Dolci et al., 2016). The remaining selection matches the rechargeable batteries found in current electric toothbrushes.

Important to battery longevity are the battery technology's specific energy, energy density and cycles. These describe how long a battery can last on a single charge and how often it can be charged. The combination of these specifications indicates how long the battery will last. The battery life in years is also important, as this can pose a different limit to bat-

tery longevity. The characteristics of the considered battery technologies can be found in Table 13.

Battery end of life is considered important as improper collection and recycling “increases the risk of releasing hazardous substances and constitutes a waste of resources” (European Commission, n.d.).

Determining the recycling rates for the different battery technologies is tricky, as the EU does not record statistics on collection and recycling efficiency for these technologies individually. The general EU battery collection rate is 51,3% and the recycling efficiency of ‘other batteries’ (which contains both considered technologies) is 68,9%, both figures are for 2019. Based on the figures for Sweden, it can be assumed that the actual collection rates for NiMH and Li-ion in Europe are much lower. However, NiMH and Li-ion batteries are often not user-removable and can be shipped away from where they were sold. As such collection rates are skewed (Melin, 2019).

While the more specific figures for NiMH recycling were not found, there are some interesting figures for Li-ion recycling. The recycling volume of lithium-ion batteries in the world is expected to nearly double from 2022 to 2025 to nearly 400.000 tons. The amount of lithium-ion batteries reaching the end of life in 2025 is expected to be around 700.000 tons (Melin, 2019). That would be a recycling rate of over 55%. While most of the capacity growth up until 2025 is expected in Asia, the capacity in Europe is expected to reach 277.000 tons by 2030 (Bockey, 2022).

Based on the two considerations, li-ion batteries are deemed the best choice. They have the highest specific energy, number of cycles, and years of life and as such will be effective at reducing the need for battery replacement. The difference at end of life between the two battery technologies is not fully clear, as figures for NiMH could not be obtained. While an

advantage for NiMH is the greater profitability for recycling in Europe (Zhao et al., 2021), the European recycling capacity for Li-ion batteries is expected to increase significantly by 2030 which is expected to increase profitability (Zhao et al., 2021).

## 14.4. Concept elaboration

Three concepts were developed from the ideas generated based on the design challenges. Table 14 shows the three concepts and elaborates their core philosophy and how the design challenges are tackled. A more detailed description of the concepts and how they work can be found in appendix H.

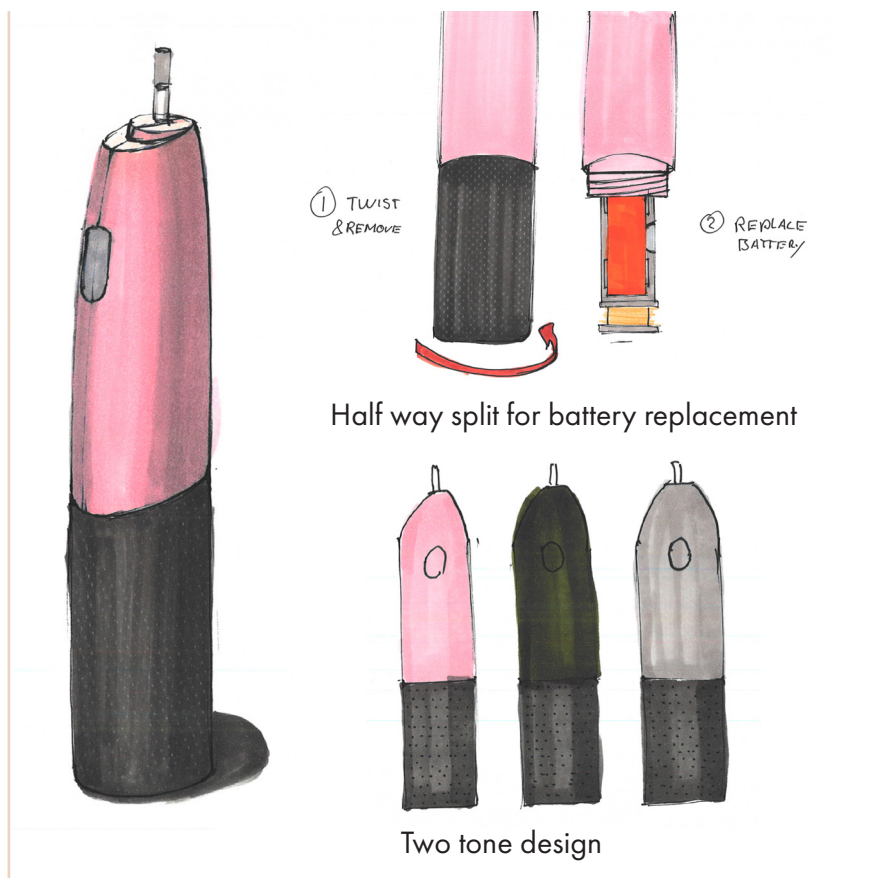
In the table, the challenges increase repair success and increase product attachment have been grouped. Repair success is increased by increasing product attachment as well as by reducing the difficulty of repair. The difficulty of repair is reduced by improving the ease of disassembly. The way this is achieved is discussed under the challenge improve ease of disassembly.

## 14.5. Concept selection

To select one of the concepts for further development, a KPI was created for each design challenge. The resulting set of KPIs can be found in Table 15. Each concept was rated for each of the KPIs based on the criteria listed in the table and scored on a 1-5 scale (higher is better) according to the designer’s insight. The scores for each concept on each KPI can be found in Table 16. A more extensive justification for the scores given can be found in appendix I.

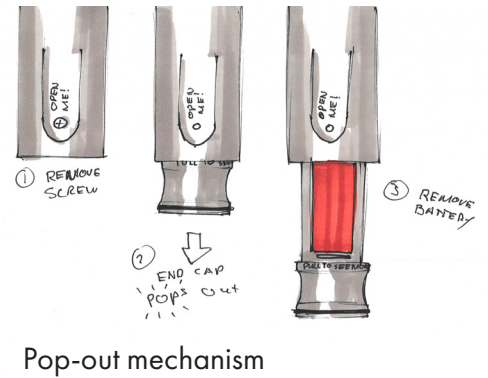
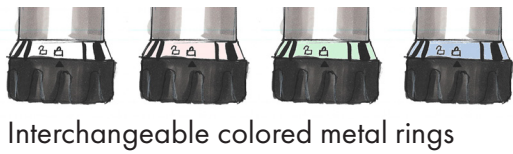
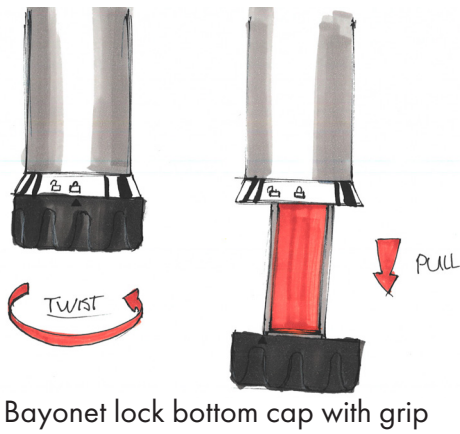
Technology	NiMH	Li-Ion
Specific energy (Wh/kg)	75	150
Energy density (Wh/L)	240	400
Life - Cycles	400-500	1000
Life - Years	4-6	5+

Table 13: Characteristics for the considered battery technologies (Linden et al., 2002).



Concept	Concept 1 - Half split	Concept 2 - High cap
Concept philosophy	Splitting the main body in the middle instead of at the bottom makes access to the battery easier.	Take the good parts from them further.
User-replaceable battery	The main body consists of two halves held together by a screw thread. The battery can be removed immediately after screwing off the bottom half.	The bottom cap uses a Oral-B IO toothbrush knob to improve the grip, allowing the user to easily remove the cap.
Increase repair success	The two-tone design comes in multiple colours. This increases product attachment slightly.	The toothbrush features a ring that can be swapped out for different colors.
Increase product attachment		This ring can be swapped out for different colors.
Increase willingness to buy refurbished	No features included. Potentially, the top half of the body could be replaced as standard to relieve contamination concerns.	User concerns about a broken ring as an unbroken seal on the brush.
Improve ease of disassembly	The number of steps for reaching the priority parts has been minimized. The motor cap is fixed with screws, other parts are mostly fixed using snap fits. The half-split design allows the snap fits holding the inner carriage in place to be extended, making the removal of the inner carriage easier.	The number of steps for reaching the priority parts has been minimized. A motor lock inspired by the Oral-B IO toothbrush is implemented. This is a single step that also fixes the inner carriage.
Limit the use of elastomers	Using a transparent power button means no seals are required for LEDs.	A capacitive button is used instead of a physical one, eliminating the need for a seal. The LED is placed directly into the main body.
Limit the use of permanent connections	No permanent connections are used. The charging solution currently implemented used induction charging. This is a major downside to the concept if the charger design is not optimized for recycling.	No permanent connections are used. The charging solution currently implemented used induction charging. For this, the charger is made out of two parts.

Table 14: Summarized overview of the developed concepts and how they tackle the design challenges.



<p>Capacity</p>	<p><b>Concept 3 - Full metal</b></p>
<p>From the Boombbrush and Oral-B IO and improve</p>	<p>Using a metal housing to change how people view the product and stimulate people to hold onto their product for longer.</p>
<p>bayonet-style closing mechanism, similar to the The cap has been made into a larger textured grip. The cap is attached to the inner carriage to easily slide the inner carriage out.</p>	<p>The battery replacement procedure requires the use of a screwdriver. After unscrewing the seal screw, the inner carriage pops out slightly at the bottom of the brush. The part that pops out is grip shaped and allows the user to pull out the inner carriage.</p>
<p>As a coloured metal ring above the bottom cap. Designed by the user, increasing product attachment.</p>	<p>The metal product housing is able to age with dignity and this way increases product attachment. Higher perceived value due to the metal product housing, increasing product attachment.</p>
<p>Contamination are reduced by using the metal seal. The ring looks shiny upon receiving the</p>	<p>The metal product housing is expected to alleviate some concerns about contamination. The metal product housing is less likely to show (undesirable) wear. Potentially the housing could be given a brushed finish that is re-brushed for refurbishment.</p>
<p>For reaching the priority parts has been minimized by the Oral-B advance power was implemented the part that attaches to the inner carriage with the PCB and serves as a top seal positioner.</p>	<p>The number of steps for reaching the priority parts has been minimized. The motor cap uses sliding snap-fits to implement the pop-out mechanism. All internal connections are toolless. A tool is only required to release the inner carriage.</p>
<p>That works through the plastic casing removes the LEDs are placed behind transparent parts moulded by.</p>	<p>The power button is replaced by a rotating power switch that works with a magnet through the casing, eliminating the need for a seal. Unfortunately, the full metal concept still has the highest number of elastomer seals.</p>
<p>Connections are used. USB-C charging has been the design of the bayonet-style bottom cap was</p>	<p>No permanent connections are used. USB-C charging has been implemented.</p>

The combined score for the KPIs shows concept 2 as the concept that is currently the least promising, with no maximum score for any of the criteria. Concepts 1 and 3 are evenly matched, ending at just a one-point gap. As the ratings for each of the KPIs are based on the designer's insights and as such not exact, a one-point gap is too small to warrant the selection of a concept. However, a strong argument can be made for selecting concept 3.

Concept 3 is easier to improve as its weaknesses are limited to just two KPIs that can be improved without changing the fundamental concept. Concept 3 scores well on most KPIs and receives low scores for KPIs 1 and 6 only. These KPIs are the battery re-

placement procedure and the use of elastomers. It is feasible for both of these areas to be significantly improved in further development. Meanwhile, concept 1 receives low scores on 4 KPIs, including the KPIs related to product attachment, repair success and refurbishment. These areas are much harder to improve in further development as the advantage concept 3 has on these KPIs comes from its metal housing.

For this reason, it was decided to continue work on concept 3. In the further development of the concept, the use of elastomers and the ease of battery replacement should receive special attention. For these challenges, inspiration could be taken from concept 1.

#	Indicator	Evaluated by
K1	Ease of replacing the battery	Evaluate the number of steps and complexity of battery replacement. Fewer steps and less complexity are better.
K2	Increase in repair success	Evaluate the number of features that aim to increase the product attachment and the expected effectiveness of these features as well as the number of steps and complexity of disassembly. Fewer steps and less complexity are better.
K3	Increase in product attachment	Evaluate the number of features that aim to increase the product attachment and the expected effectiveness of these features.
K4	Increase in willingness to purchase the product refurbished	Evaluate the number of features that aim to increase the willingness to purchase refurbished and the expected effectiveness of these features
K5	Reduction in cost of part replacement	Evaluate the number of steps and complexity of disassembly. Fewer steps and less complexity are better.
K6	Amount of elastomers used	Less is better.
K7	Number of permanent connections	Fewer is better.

Table 15: Overview of the seven KPIs derived from the design challenges.

KPI	Concept 1	Concept 2	Concept 3
K1	5	4	3
K2	3	3	5
K3	2	2	4
K4	2	2	4
K5	5	4	4
K6	5	4	1
K7	3	4	5
Combined score	25	23	26

Table 16: Overview of scores of each concept on each of the KPIs.

## 15. Concept development - Everbrush

### 15.1. Introduction

In this chapter the further development of the chosen concept, now called the Everbrush (see Figure 52), is elaborated. The chapter starts with an overview of the assumptions made during the initial development of the concept. These assumptions require further development in order to evaluate the feasibility, desirability and viability of the concept.

The remainder of the chapter will discuss the design of the concept related to the design challenges discussed in chapter 13.

### 15.2. Assumptions

An overview of the key assumptions related to the design challenges can be found in Table 17. For each assumption, the related design objective and concept features have been listed.

Note that not all assumptions require further development at this stage. These assumptions (2, 3, 4 & 9) have to be validated in user research. This user validation step is discussed in chapter 16.



Figure 52: The Everbrush electric toothbrush concept.

#	Design objective	Assumption	Concept features
1	Long product life	The battery replacement procedure enables users to perform battery replacements.	Pop-out mechanism; seal screw; snap-fit battery; User testing required
2		The metal housing increases product attachment by ageing with dignity.	Material; User testing required
3	Local loops for priority parts	The metal housing increases the willingness to purchase refurbished	Material; User testing required
4		The 'everything is refurbished' strategy increases the willingness to purchase refurbished*	User testing required
5		The ease of disassembly of priority parts is improved	Low number of steps; Minimal tools required
6	High-value recycling	The number of elastomers can be limited	Magnetic power switch
7		No permanent connections have to be used	No soldering; No other types of permanent connections
8	Other	The brushing experience is not negatively affected by the metal housing	User testing required
9		Manufacturing costs do not increase significantly due to the metal housing	Manufacturing method;

Table 17: Overview of assumptions made during the initial development of the concept. (\*this assumption was not made during initial concept development but during ideation. See chapter 14.2).

### 15.3. Everbrush - Fundamentals

The Everbrush is in many ways similar to the Boombrush, as it has been used as the starting point of the design. This was done in order to ensure the Everbrush is able to perform similarly to current electric toothbrushes when it comes to cleaning performance. The motor and PCB are assumed to be the same size as those in the Boombrush, however, PCB connections are assumed to be flexible in location.

### 15.4. Long product life

The battery replacement procedure was further optimized from the original concept. While the amount of steps remains the same at four (see Figure 53), all of the steps are now toolless. To implement this change, some changes were required to the spring pop-out mechanism.

The pop-out mechanism in the original concept used a spring between a sliding motor cap and the battery. This moving part has been eliminated in the new design by implementing a larger spring at the top of the brush (see Figure 54), improving the design for reliability.

The o-ring was originally placed as low as possible in the toothbrush to ensure its path was as short as possible, minimizing the required spring force. In order to make the procedure toolless, the o-ring had to be moved up.

By performing measurements with the Boombrush, the force required for moving the o-ring was determined to be about 12 N (see appendix J). Several springs able to provide the required force and fitting the other limitations were found (see appendix K), which require between 54 and 45 N to fully compress. This amount of force was checked with a scale and deemed reasonable. The spring selection should be given attention in further development, but it is deemed feasible to find or produce a spring meeting all requirements.

The seal screw was replaced by a snap-fit style release button. While the exact design of the snap-fit should be optimized, several concepts were already tested using 3d printing for the prototype (see Figure 55).

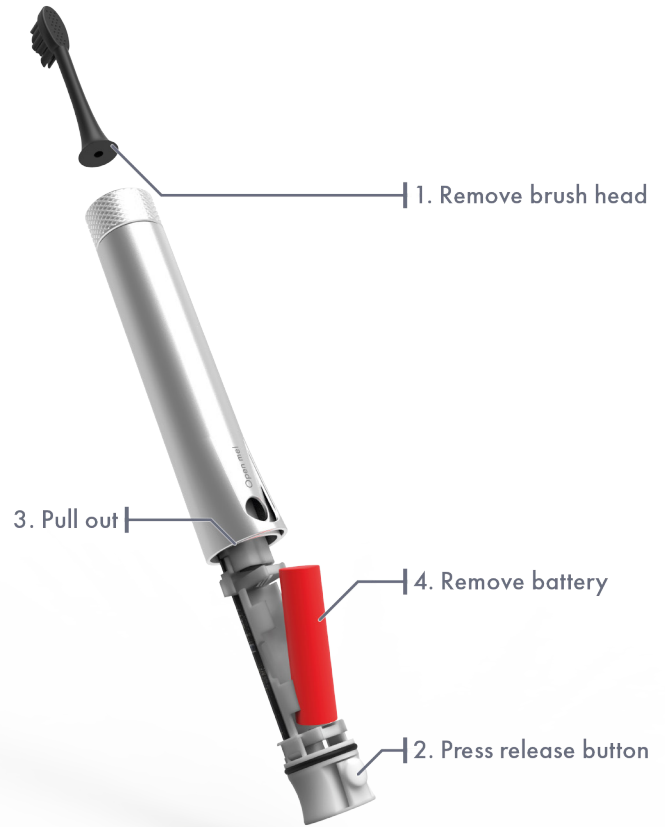


Figure 53: The battery replacement procedure for the Everbrush takes 4 steps.

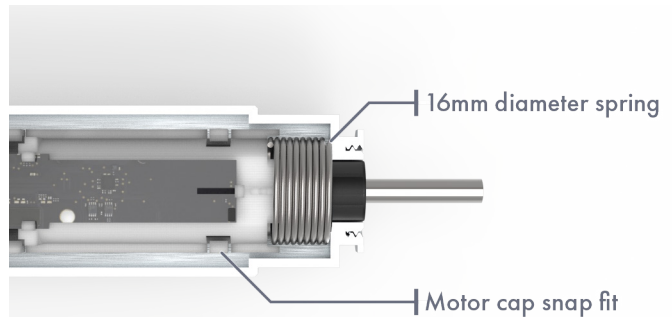


Figure 54: Section view of the large spring placement in the Everbrush.



Figure 55: 3d printed test models of the snap-fit style release button on the bottom cap.

The battery in the Everbrush is a protected Li-ion 14500 cell, which is just a bit taller than a regular AA battery (NKON, n.d.). This prevents users from using the Li-ion cell in other devices that do not have the right circuitry required for safe operation.

The textual cue from the original concept was retained to strengthen the user empowerment character of the product (see Figure 56).

The core of the Everbrush concept is its metal main body. For the initial concept, the metal selected was aluminium based on its use in the Apple Macbook Pro and this has been retained for the final concept due to aluminium's low density, high-quality appeal and corrosion resistance. Other metals identified as suitable were stainless steel and magnesium. Detailed material selection should receive further attention in future development.

The aluminium housing brings several advantages for the circularity of the brush. However, for a successful implementation of the aluminium body, integrating all required functionalities and keeping costs competitive with current electric toothbrushes is important. As such, selecting the right manufacturing technique is important.

The other design elements of the Everbrush concept inform the features that have to be integrated into the main body. Figure 57 shows the proposed main body part, and highlights four features informed by other design elements:

1. The top of the brush requires a staggered, sharp-angled design for the implementation of the rotating power switch.
2. The Philips power button style LED panel requires a complex cut-out.
3. The extending feature at the bottom of the brush prevents accidental pressing of the release button.
4. The release button requires a hole.

Three manufacturing techniques were considered; CNC machining, aluminium die casting and impact extrusion.

CNC machining was the first option considered as it is also used for the Macbook Pro's aluminium body, but the combination of the small diameter, relatively large depth and complex features make the main body impossible to produce this way (A. Chen, personal communication, June 22, 2022).



Figure 56: Users are encouraged to open the Everbrush by a textual cue.



Figure 57: The main body part of the Everbrush concept.

Impact extrusion was considered, but due to time constraints not enough information on this method of production could be obtained. Initial findings show that the asymmetry of the main body and the extending feature at the bottom could prove challenging to achieve. However, the advantages of this manufacturing technique are low tool costs and high material efficiency (GRANTA Edupack, 2020). Further investigation into impact extrusion should be done when further developing the concept.

The third and chosen method of production is aluminium die casting. With this manufacturing method, most of the features can be made in a single forming step. However, the decision between a more complex mould design with less post-processing required or making some of the features in post-processing depends on the batch size and should be further investigated when further developing the concept.

A cost estimate for the part was made using the [custompartnet.com](http://custompartnet.com) cost estimator (CustomPartNet, n.d.). The settings used can be found in appendix L. Dimensions were taken from the CAD model. It should be noted that no draft angles have been applied to the CAD model yet. A quantity of 10.000 was assumed for the calculation. The cost estimate comes in at 5,84 euros per part for 10.000 units. A quote was obtained from a Chinese supplier, which came in at 4,47 euros per part (J. Zhang, personal communication, June 23, 2022).

As most parts in the brush are the same or similar to those in the Boombrush, the total cost of the Everbrush has been estimated by calculating the expected increase in the cost of the main body, multiplying this increase by five and adding it to the sales price of the Boombrush. This is not an accurate estimation of the costs, but merely an indication of whether costs are within an acceptable range. The estimate comes in at just over 100 euros, about 10 euros higher than the Boombrush.

Besides the integration of features and the cost, the ergonomics and weight are important considerations for the main body. To ensure good ergonomics, the size of the brush has been kept similar to the Boombrush. Further testing should be performed for optimizing the ergonomics.

The aluminium main body comes in at a weight of 54 grams, 20 grams more than the Boombrush’s main body. However, due to the move to a smaller Li-ion cell, the weight of the Everbrush is actually lower than the Boombrush at just 123 grams (vs 135 grams).

### 15.5. Local loops for priority parts

The aluminium product housing is assumed to increase consumers’ willingness to purchase refurbished. A further strategy to increase the willingness to purchase refurbished is to make the toothbrush suitable for medical-grade sterilisation techniques. Note that this thesis will not investigate the economics of implementing a sterilisation step in the refurbishment process.

Three methods of sterilisation are suitable for use with electronics (Maxim Integrated, 2011). Of these three methods, only chlorine dioxide gas sterilization is suitable for integrated batteries, as the other two methods require a vacuum. However, this method is not compatible with aluminium (CP Lab Safety, 2018). Of the three methods, only vaporized hydrogen peroxide is compatible with aluminium. It is also compatible with the other materials in the brush (Quip Laboratories, n.d.). For this method, the battery needs to be removed prior to sterilization. The feasibility of hospital-grade sterilization for refurbishment requires further research.

The ease of disassembly for priority parts in the Everbrush is improved significantly over current electric toothbrushes. The step count for most priority parts has been reduced, the number of tools required is lower and all connections used are reversible (see Table 18).

Part	Steps to reach	Number of tools required	Reversible connections only?
Motor	11	1	Yes
Battery	4	0	Yes
PCB	12	2	Yes
Main body	7	2	Yes

Table 18: Number of steps required to reach components important for maintenance, repair & future expansion.

A conceptual disassembly map (see Figure 60) has been made of the Everbrush. Note the map is called conceptual as the product is not final, and the part count, dependencies, and tools and force required could still vary. Looking at the map, there are some interesting things to highlight.

There is one step that still requires soldering. This step splits the PCB and battery connectors. Removing the PCB with the battery contacts still attached only requires a screwdriver. As the part value of the battery contacts is low, the intention of the design is that they are replaced when the PCB is replaced, making this last step unnecessary to perform.

Another thing that stands out is the width of the map, indicating limited dependencies for removing components which makes part replacement faster.

### 15.6. High-value recycling

The material selection is done in a way that limits the number of different materials used. For a full overview of the parts and material selection, see the BOM in appendix M. Something that stands out at this point is that while the amount of different thermoplastics is limited compared to current electric toothbrushes at just three, the amount of different metals is similar to current electric toothbrushes at four. This is due to the aluminium parts and the spring used for the pop-out mechanism.

The switch to an aluminium product housing has some interesting effects on the contribution of materials to the mass, impact and economic value (see Figure 58). Compared to current electric toothbrushes, the contribution of the body to the mass is high. Combined with aluminium's high CO2 impact (primary production), this makes the main body the largest contributor to CO2 impact.

PolyCE (2021) advises using only SEBS-based TPE for elastomer parts to reduce contamination of recycling streams. As this material is suitable for gaskets (GRANTA Edupack, 2020), it is the material of choice for all elastomer parts in the Everbrush. However, more detailed research on the usability of SEBS-based TPE for all of these parts is required.

Everbrush - Part contribution to mass, CO2 (primary production) and economic value

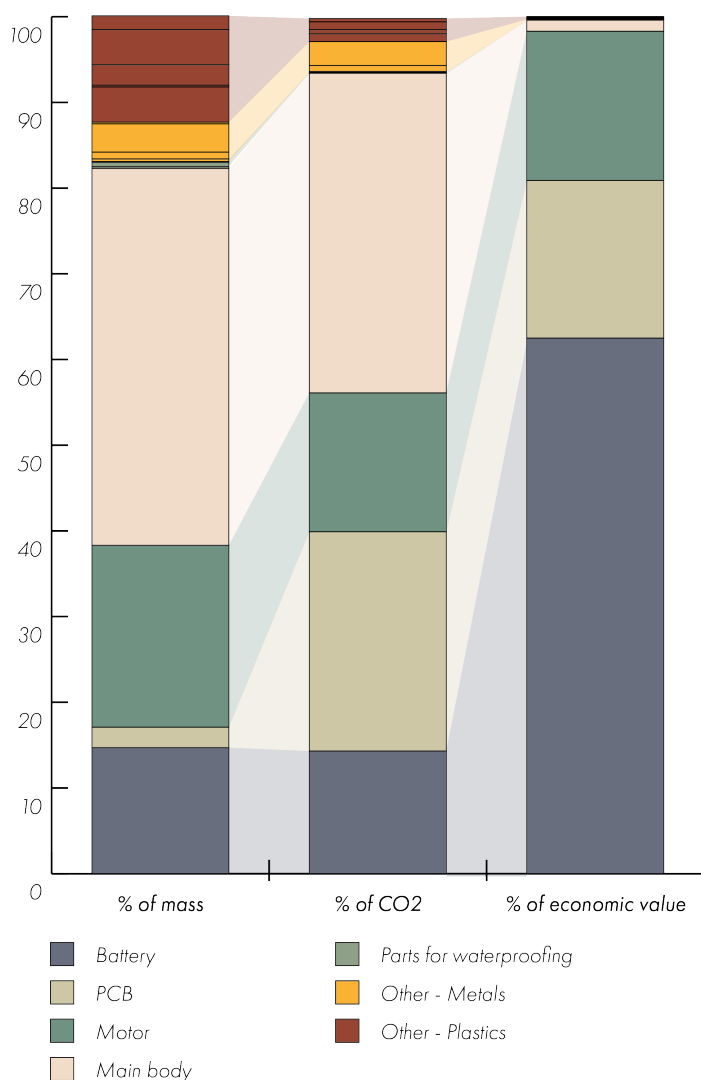


Figure 58: Contribution of materials in the Everbrush to the mass, impact (CO2 primary production) and economic value.



Figure 59: Rotating power switch on the Everbrush concept in the on (left) and off (right) position.

# Conceptual Disassembly Map

Electric Toothbrush

EverBrush

Mart Drummen

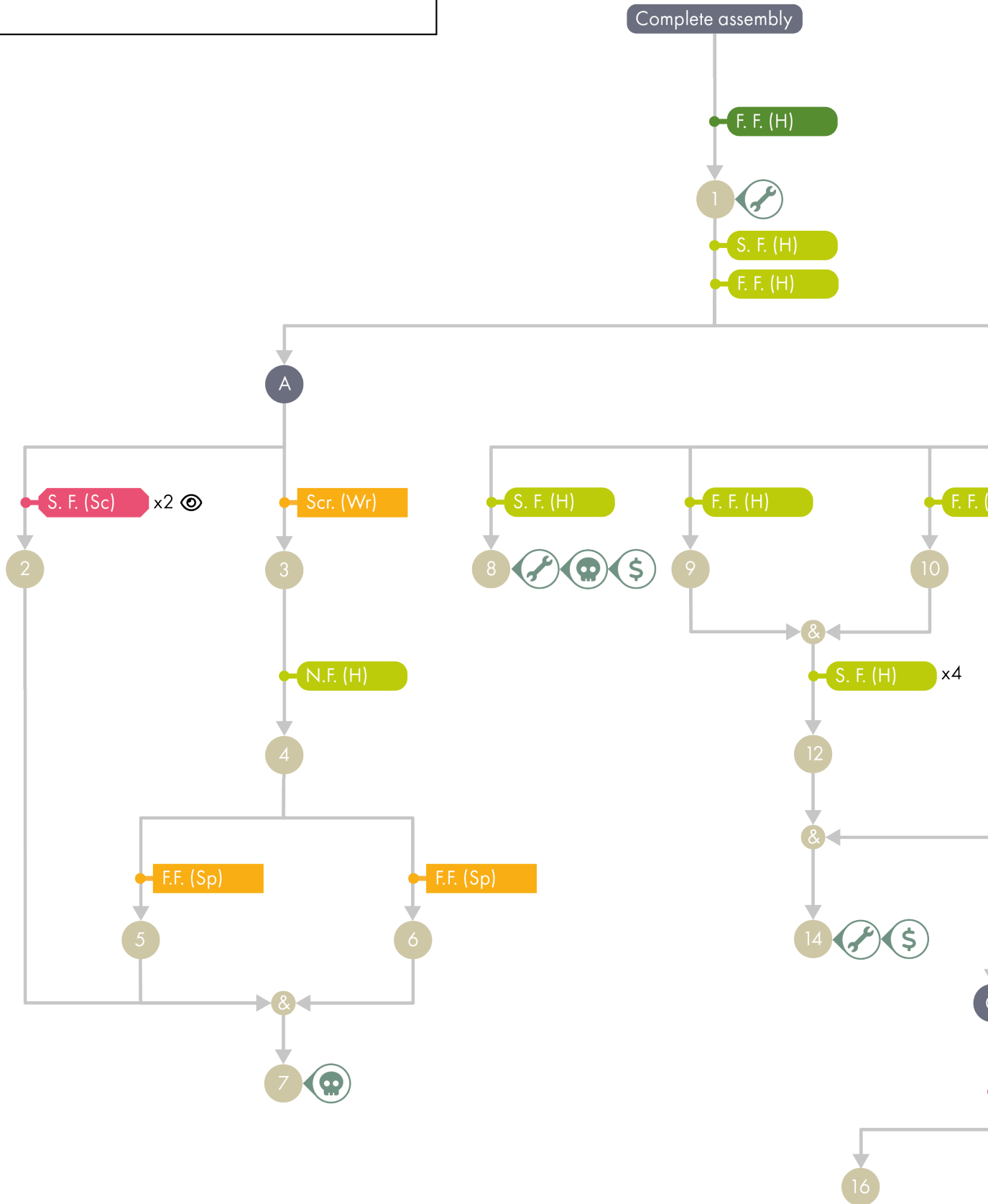
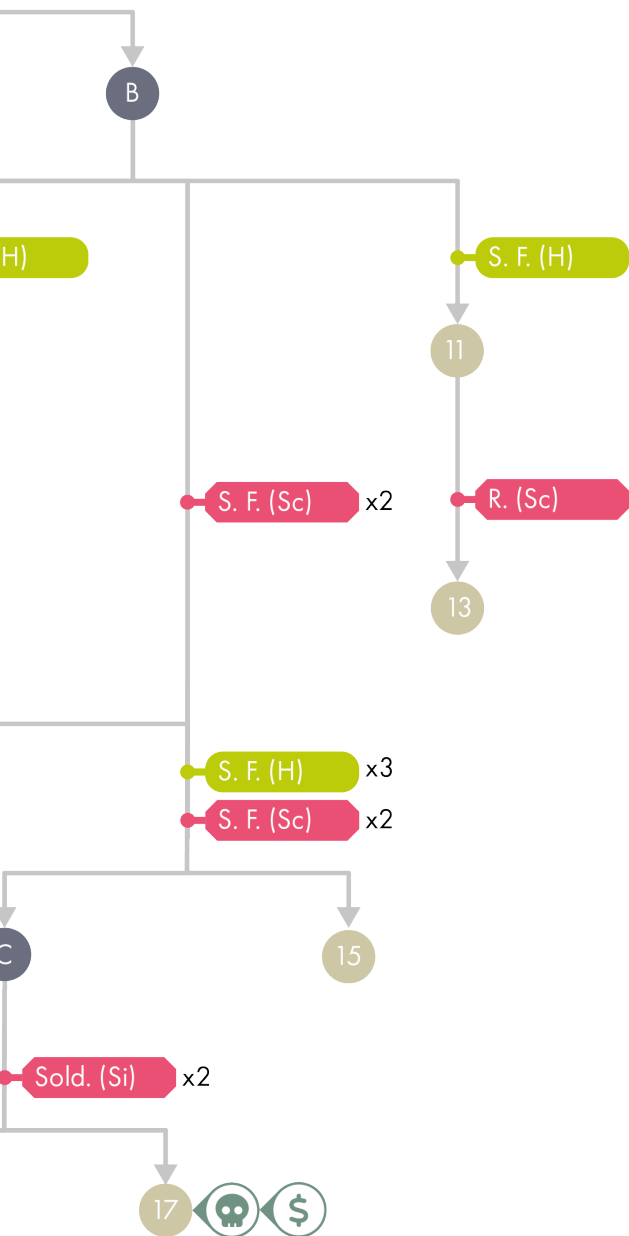


Figure 60: Conceptual disassembly map of the Everbrush.



### Components

- |                                   |                              |
|-----------------------------------|------------------------------|
| A. External assembly              | 7. Main body (A)             |
| B. Internal assembly              | 8. Battery (B)               |
| C. PCB assembly (B)               | 9. Spring (B)                |
| 1. Brush head                     | 10. Top seal (B)             |
| 2. LED panel (A)                  | 11. Bottom cap (B)           |
| 3. Power switch lock (A)          | 12. Motor cap (B)            |
| 4. Power switch (A)               | 13. Seal ring (B)            |
| 5. Magnet (A)                     | 14. Motor (B)                |
| 6. Power switch position lock (A) | 15. Internal carriage (B)    |
|                                   | 16. Battery contacts (2x)(B) |
|                                   | 17. PCB (B)                  |

### Legend

#### Motion type

- = Hand motion
- = Single motion tool
- = Multiple motion tool

#### Type of connector

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

#### Target components

- Failure Indicator
- Environmental Indicator
- Economic Indicator

#### Force intensity

- |     |     |      |
|-----|-----|------|
| Low | Mid | High |
|     |     |      |
|     |     |      |
|     |     |      |

#### Type of tool

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Wr) = Wrench

#### Penalties

- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

To limit the number of elastomers required, the Everbrush features a unique rotating power switch. The switch uses a hall sensor on the motherboard to detect the magnetic field of a magnet in the rotating ring. The ring has a textured design to improve grip. There is a line on it that aligns with a line on the main body to indicate whether the toothbrush is on or off (see Figure 59).

No permanent connections are used anywhere in the Everbrush concept, except between the PCB and battery contacts. Nearly all parts are fixed using reversible snap fits (see Figure 61). Compared to current electric toothbrushes, the PCB has been made easier to remove. Instead of being soldered through the inner carriage, the battery contacts can be slid into the carriage from the PCB side and function as snap fits (see detail view in Figure 61). It is assumed that soldering the battery contacts to the PCB does not affect recycling performance if the metal used for the battery contacts can be separated.

The LED panel is fixed similar to the Philips Sonicare EasyClean power button using snap fits through the main body, as such the IP rating of the Everbrush is expected to be IPX5 like the Philips toothbrush. The LEDs behind the panel indicate battery and power status.

As stated previously, the battery contacts are soldered to the PCB. While this was deemed no problem for the battery contacts, the connections for the motor should not be soldered to facilitate ease of disassembly. For the motor, two wires have to be connected. For these wires, several options were considered, but due to the requirement for a very low profile, the Wago SMD PCB terminal block (Wago, n.d.) was selected.

For the charging port, no solution has been decided yet. The Everbrush concept uses a USB-C port for charging, which requires at least six wires. While these could be connected using six Wago connectors, that solution takes up a lot of valuable PCB space. USB-C ports in smartphones are prone to wear and as such the USB-C port in the Fairphone (Fairphone 4 USB-C Port, n.d.) has been made easy to replace. A similar style USB-C port could also work for the Everbrush, but as it is a custom part it is likely an expensive solution. So far, there appears to be no ideal solution. Additionally, while wear on smartphones that are charged daily is high, it is unknown how long a USB-C port in a toothbrush will last.

## 15.7. Packaging

The Everbrush dimensions have been kept similar to that of the Boombush. An advantage of this size is that the Everbrush can fit in a letterbox parcel. This reduces shipping costs, which is beneficial for the collection of broken brushes.

Upon receiving their Everbrush, consumers will find the brush, brush head and battery separately in the package (see Figure 62). The goal of packaging the battery separately is to empower users by showing them they can place the battery easily themselves.

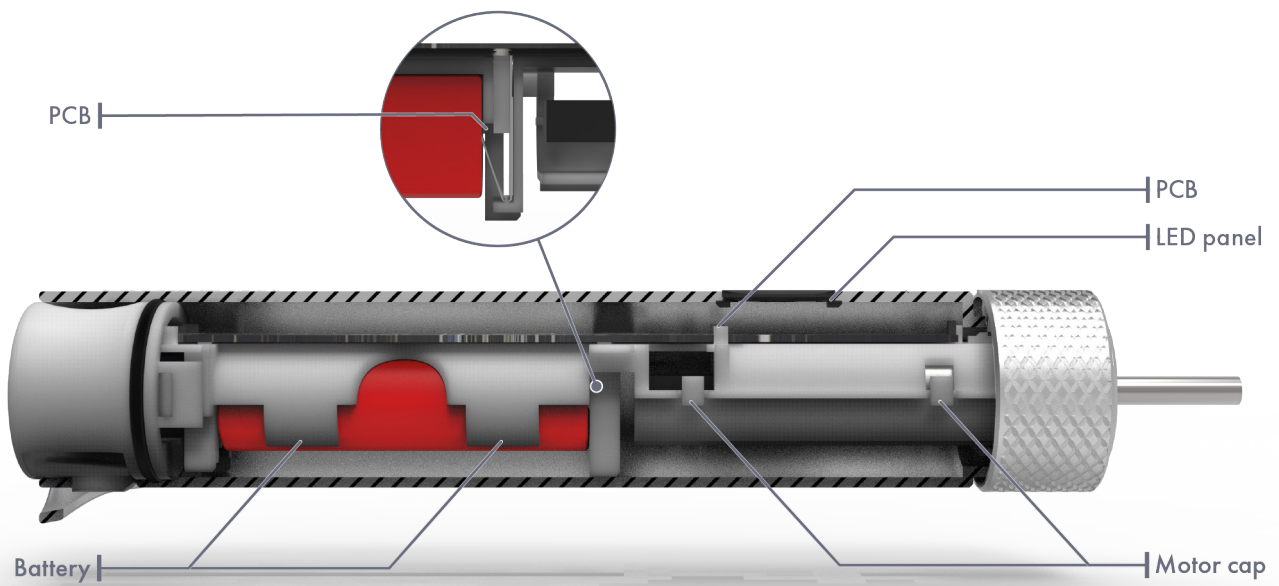


Figure 61: Most connections in the Everbrush are made using reversible snap-fits. The annotations in the image indicate which part the snap-fit fixes.

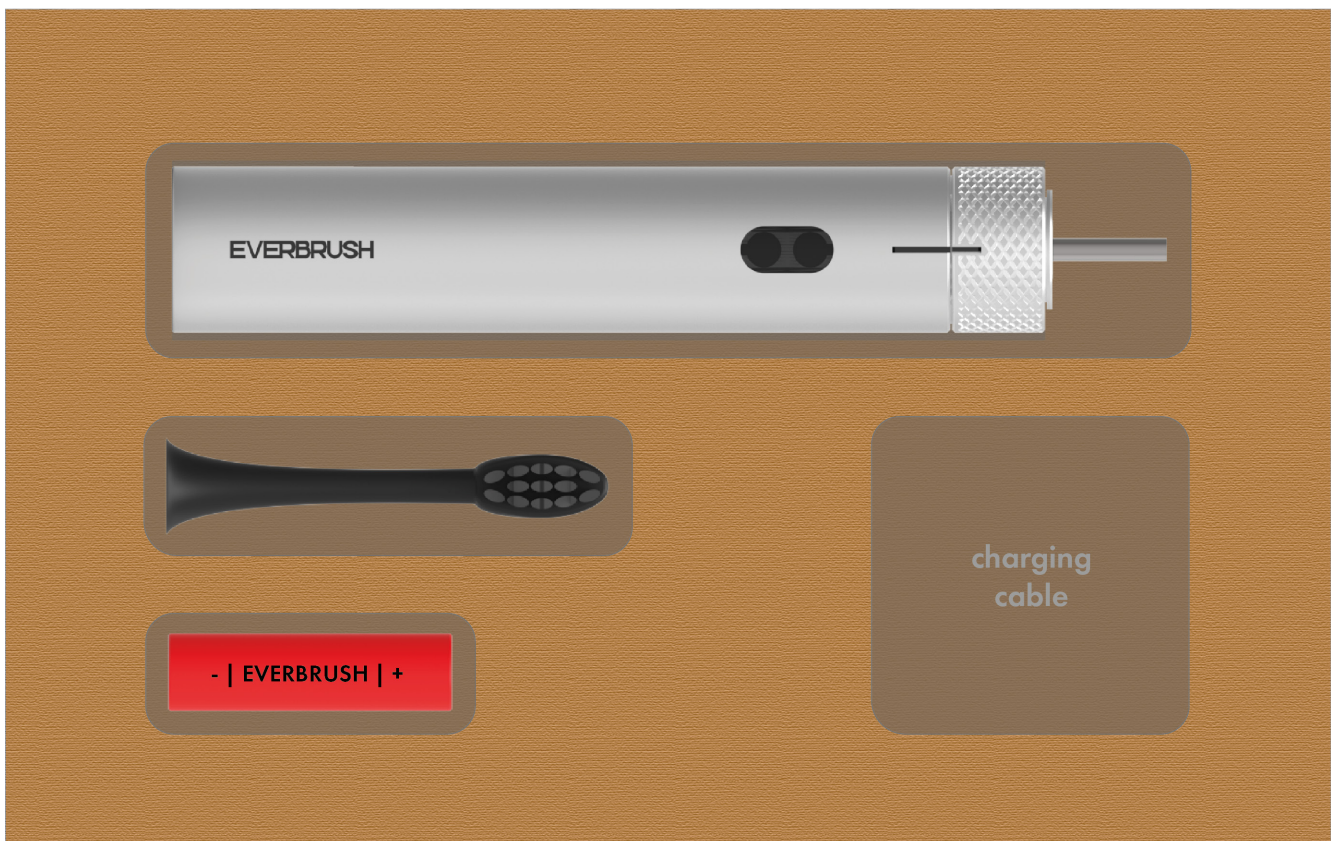


Figure 62: Schematic of the Everbrush in a letterbox parcel.

## 16. Concept validation

### 16.1. Introduction

A concept validation study was performed to test several of the key assumptions made during the development of the concept. Table 19 gives an overview of the key assumptions as presented in chapter 15.2. In the table, it is indicated whether an assumption has been validated by further development or still requires testing. The remainder of this chapter discusses the testing methods and conclusions for the assumptions that have not yet been validated in more detail. The full detailed report of the study can be found in appendix N.

One assumption, assumption 2, has been left unvalidated. In order to validate assumption two, the relation between the ageing of the aluminium main body and users' attachment to the product would have to be evaluated. Prior academic research into increased product attachment through material ageing (Lilley et al., 2016; Ranscombe et al., 2022) encountered a clear limitation in evaluating this relation. The mechanism leading to increased product attachment through material ageing is related to the user's memories, and simulating the creation of memories in short-duration experiments is not feasible. For this reason, the validation of this assumption is considered out of scope.

### 16.2. Setup

The participants in this study were 5 adults ranging from 20 to 25 years old. 3 were male, 2 female. All participants were volunteers recruited via personal contact. Participants were informed about the study procedure and allowed to ask questions prior to the study. When it was ensured everything was clear, participants were asked to fill out an informed consent form. The study was split into three sections.

#### Battery replacement

In the first section, assumption 1 was tested. Participants were asked to perform a battery replacement using a prototype that simulates the battery replacement procedure (see Figure 63) while thinking aloud (Lewis, 1982). Participants were given the battery replacement prototype with the brush head attached to the brush. The procedure was finished once the brush head was re-attached again. Participants were filmed while performing the procedure. Afterwards, the video footage was reviewed and the positive and negative aspects as stated by the participants were noted.

#### Refurbishment

In the second section, assumptions 3 and 4 were tested. Three mock-up webshop interfaces were made to evaluate participants' perception of the toothbrush in a refurbished condition. The first interface shows the toothbrush in a new condition (see Figure 65). The second interface shows a refurbished toothbrush with an additional text box highlighting the cleaning efforts that are made (see Figure 66). The third interface indicates all toothbrushes can contain refurbished parts. In an additional text box, the concept is explained and the high quality of the parts is stressed (see Figure 67).

Participants were first shown the mock-up webshop interface with a new toothbrush. The interface with a new brush was tested first as this served as a reference for the refurbished brushes. A semi-structured interview was conducted in which questions about the participant's perception of product quality and hygiene were asked. These two areas of interest were identified based on the user study in phase 1. Semi-structured interviews were chosen given the exploratory objective of the research (Patton, 2002). The procedure was then repeated with the other two mock-up webshop interfaces. The interviews were recorded. Afterwards, the recording was reviewed and the positive and negative aspects as stated by the participants were noted.

#	Design objective	Assumption	Validated?	Test method or conclusion
1	Long product life	The battery replacement procedure enables users to perform battery replacements.	No	Testing using a battery replacement prototype and the thinking aloud method.
2		The metal housing increases product attachment by ageing with dignity.	No	Not tested due to complexity and time constraint.
3	Local loops for priority parts	The metal housing increases the willingness to purchase refurbished	No	Testing using mock-up webshop interfaces that highlights the refurbishment strategy. The participant's perceptions of the concept are evaluated through semi-structured interviews.
4		The 'everything is refurbished' strategy increases the willingness to purchase refurbished*	No	Testing using mock-up webshop interfaces that highlights the refurbishment strategy. The participant's perceptions of the concept are evaluated through semi-structured interviews.
5		The ease of disassembly of priority parts is improved	Yes	Disassembly map shows a significant decrease in tools, force and steps required.
6	High-value recycling	The number of elastomers can be limited	Yes	The number of elastomers was limited to four. Further development showed the rotating power switch to be feasible.
7		No permanent connections have to be used	Yes	No permanent connections are used in the toothbrush design.
8	Other	The brushing experience is not negatively affected by the metal housing	No	Testing using a brushing experience prototype. The participant's experience is evaluated through semi-structured interviews.
9		Manufacturing costs do not increase significantly due to the metal housing	Yes	Increase by about 10 euros in sales price expected. This is deemed acceptable.

Table 19: Overview of assumptions made during the initial development of the concept and their validation status. (\*this assumption was not made during initial concept development but during ideation. See chapter 14.2).



Figure 63: Prototype for the battery replacement procedure.

### Brushing experience

In the third section assumption 8 was tested. Participants were given a prototype simulating an electric toothbrush with an aluminium housing (see Figure 64). Each participant was provided with a new brush head and toothpaste. Participants were asked to perform a two-minute brushing routine. After completing the brushing routine, participants were asked about the (dis)comfort of the aluminium brush in a semi-structured interview. A semi-structured interview was chosen given the exploratory objective of the research (Patton, 2002). The interview was recorded. Afterwards, the recording was reviewed and the positive and negative aspects as stated by the participants were noted.



Figure 64: Prototype for the brushing experience.

### Webshop



Search 


## Everbrush Electric Toothbrush

Keeping your teeth in shape is easy with this electric toothbrush.

Figure 65: Mock-up webshop interface - New toothbrush.

### Webshop



Search 

## Everbrush Electric Toothbrush

### Refurbished

Keeping your teeth in shape is easy with this electric toothbrush.


#### Carefully refurbished

Everbrush treats refurbishment with extreme care to ensure you receive the highest quality product. The toothbrush has been checked and performs like any of our new brushes. The toothbrush has been sterilized with the medical grade vaporized hydrogen peroxide technique, removing any contaminants.

Figure 66: Mock-up webshop interface - Refurbished toothbrush with cleaning efforts highlighted.

### Webshop



Search 

## Everbrush Electric Toothbrush

Keeping your teeth in shape is easy with this electric toothbrush.

#### Can contain refurbished parts

Every part in the Everbrush is designed to last a lifetime. As such, we don't believe the quality of refurbished parts is inferior. Every Everbrush can contain refurbished parts. If you are unsatisfied with the quality of your toothbrush, you can return it free of charge.

## 16.3. Results & Insights

### Battery replacement (see Figure 68)

No major complications were found in the battery replacement procedure as all of the participants were able to complete the procedure without receiving instructions. However, one hurdle that all participants encountered was that they did not remove the brush head before pressing the release button. A solution to this issue could be to instruct users to remove the brush head first in the packaging used for the batteries.

Another issue that was noted by two participants, but that all participants encountered, was the lack of an indication of how the battery terminals should be oriented. A clear indication for this should

be added and verified in future research. Most participants were able to circumvent the issue in the test as they remembered how the battery was previously oriented.

Some issues only noted once, but potentially interesting for further research were the size of the release button being too small and the lack of a way to check whether the installation of the battery was successful.

Some participants were even impressed by the ease of the procedure, with participant 1 stating the procedure was “very clear” and participant 4 stating “it was almost too easy”.

Aspects named for battery replacement (n = 5)

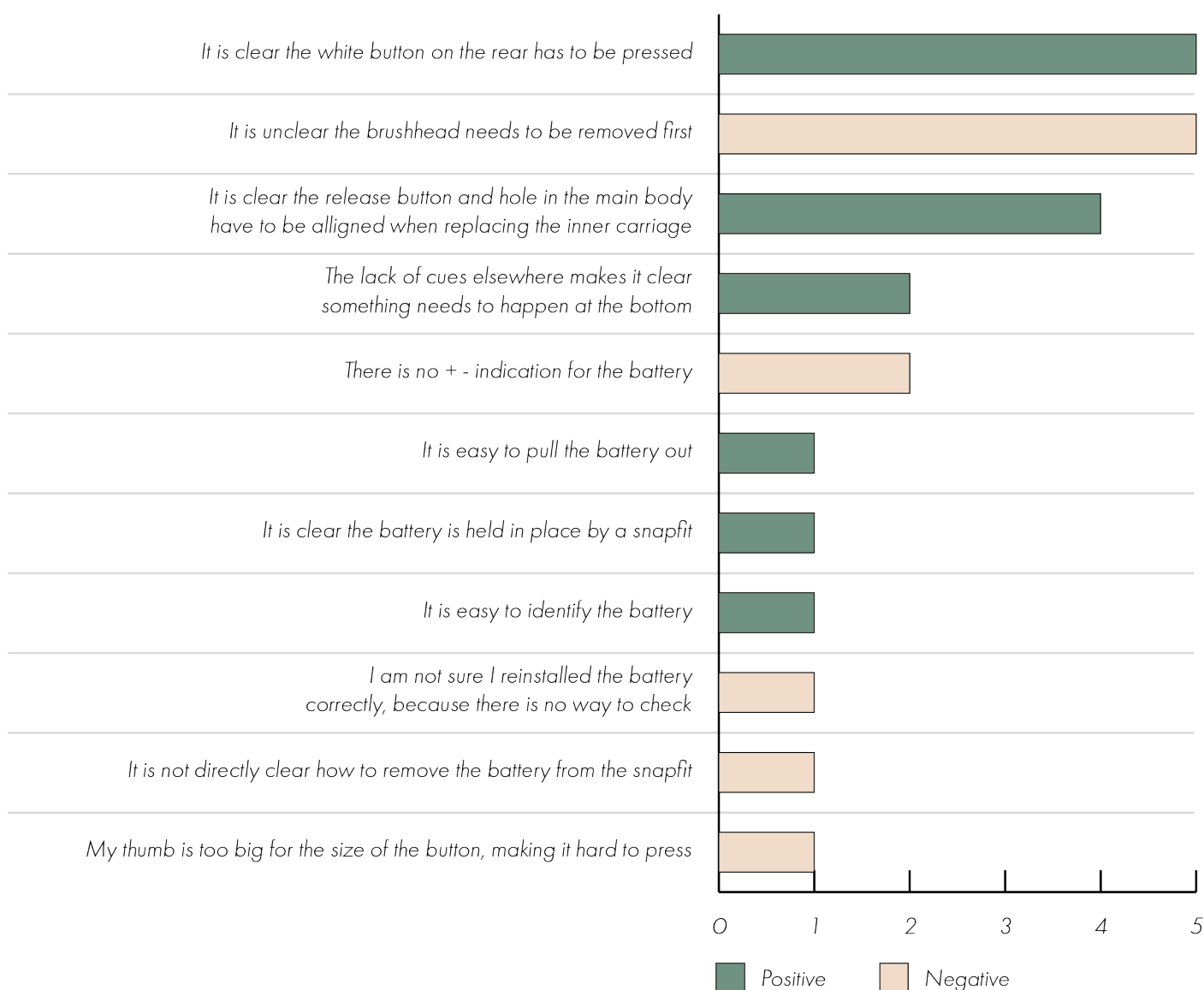


Figure 68: Aspects noted by participants for the battery replacement procedure.

## Refurbishment

### New (see Figure 69)

Responses on the interface showing a new toothbrush were mixed. While most participants made positive remarks about their perception of the quality of the product, two of the participants also expressed their concerns about how the aluminium will hold up over time. Participant 5 made an interesting remark on this, as she was worried about scale building up on the textured rotating power button. The ease of cleaning of the power button texture should receive additional attention in the further development of the brush.

The product's design appeared to have a somewhat positive effect on the participant's perception of hygiene, with participant 5 highlighting the clinical look due to the metal body and participant 2 specifically mentioning the benefit of not having any elastomer grips that get dirty over time. However, as the product is shown as a new product, it would be unlikely for participants to express concerns about hygiene at this stage.

### Cleaning efforts (see Figure 70)

Responses on the interface showing a refurbished brush with the cleaning efforts highlighted were also mixed. Two participants expressed concerns about contamination when purchasing a refurbished electric toothbrush. At 40% of the participants, this number is similar to the findings of the research in phase 1 and as such it appears the metal housing has little effect on concerns about contamination. Testing with more participants is necessary to draw more informed conclusions about this effect.

Aspects named refurbishment - new (n = 5)

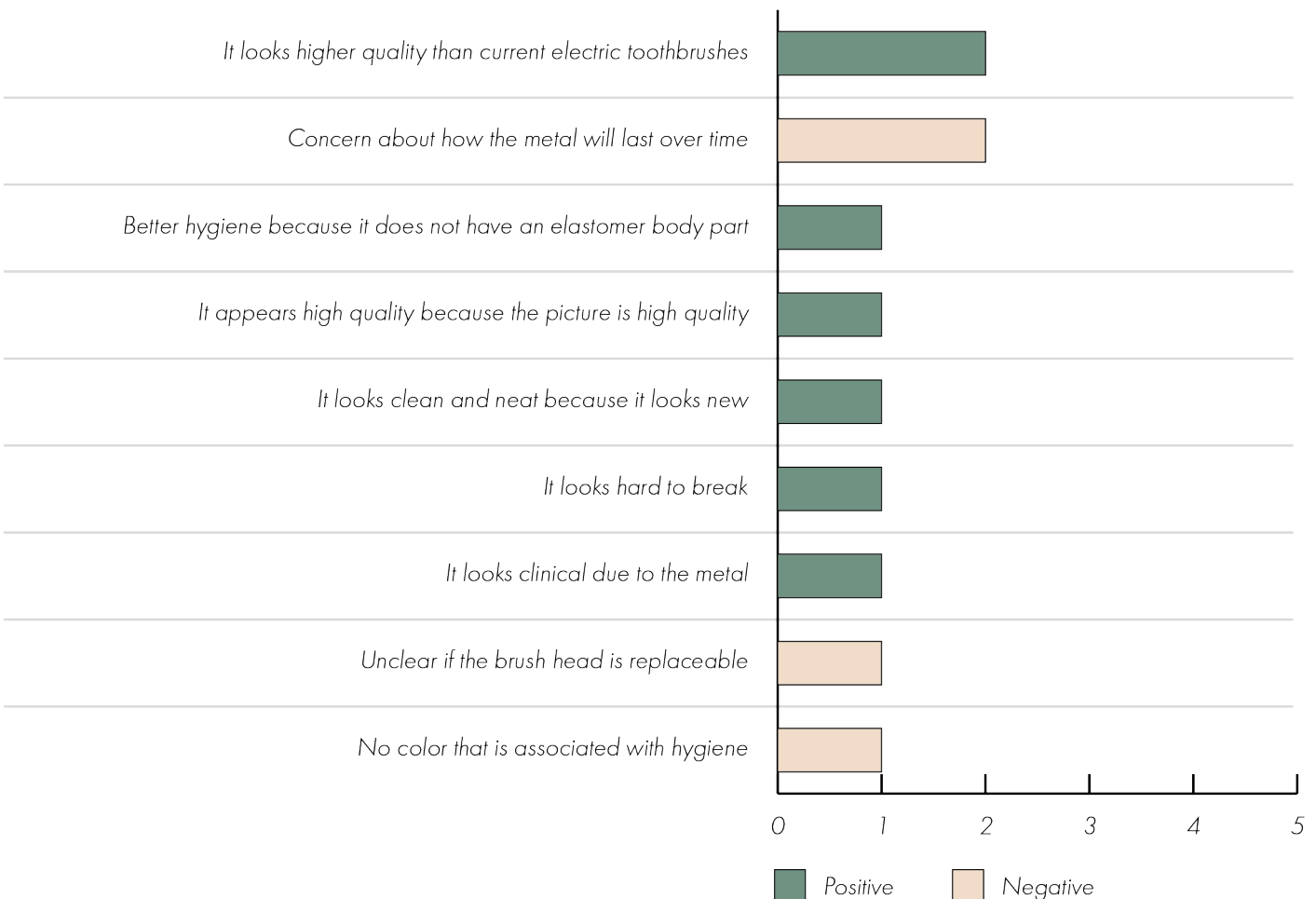


Figure 69: Aspects noted for the mock-up interface with a new toothbrush.

Several participants noted the medical-grade sterile cleaning mentioned in the text did help their perception of the product's hygiene somewhat (n=3), indicating that communicating cleaning efforts indeed could help sell refurbished electric toothbrushes as suggested by Mugge et al. (2017).

None of the participants appeared to doubt the refurbished product's quality, with multiple participants stating the looks of the product positively affected the perception of quality. As such, it does appear that the metal housing has a positive effect on the perception of product quality. However, as three of the participants expressed not relating refurbishment to reduced product quality anyways, the effect of the metal body could be minor.

Aspects named refurbishment - cleaning efforts (n = 5)

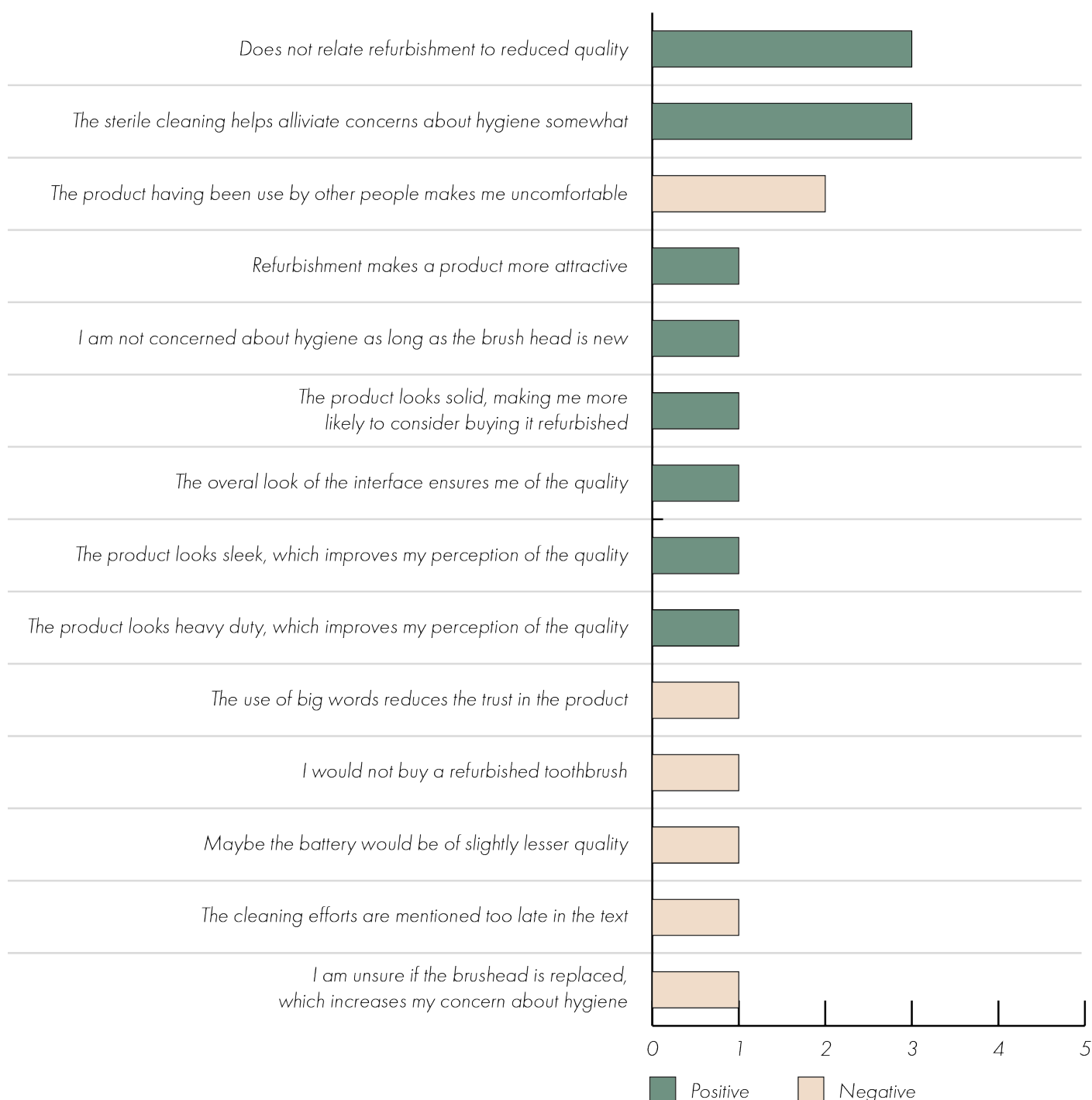


Figure 70: Aspects noted for the mock-up interface with a refurbished toothbrush with cleaning efforts highlighted.

**Everything is refurbished (see Figure 71)**

The interface showing a refurbished toothbrush with the 'everything is refurbished' strategy highlighted consistently got a more negative response than the interface with cleaning efforts highlighted. In general, the lack of information about which specific parts were refurbished appeared to be causing some distrust, which led to a lower perception of the product quality in two participants. For one of these participants, it also caused a knock-on effect on the perception of product hygiene. Another participant noted the absence of an explanation on the cleaning efforts as a reason for perceiving the product hygiene as worse than the other interface.

The specific wording used in the text had a negative effect on the perception of quality among participants, with two participants expressing that the option to return the brush when unsatisfied with the quality lowered their perception of the quality and

one of those participants also mentioned that the number of times it was mentioned some of the parts could be refurbished reduced the perception of quality.

One positive effect of the everything is refurbished strategy is that two participants somehow felt the refurbishment now only related to internal parts, removing their concern about hygiene altogether. Whether this advantage can be kept while providing consumers with the additional information they desire to be ensured of the quality of the product should be further researched.

Aspects named refurbishment - everything is refurbished (n = 5)

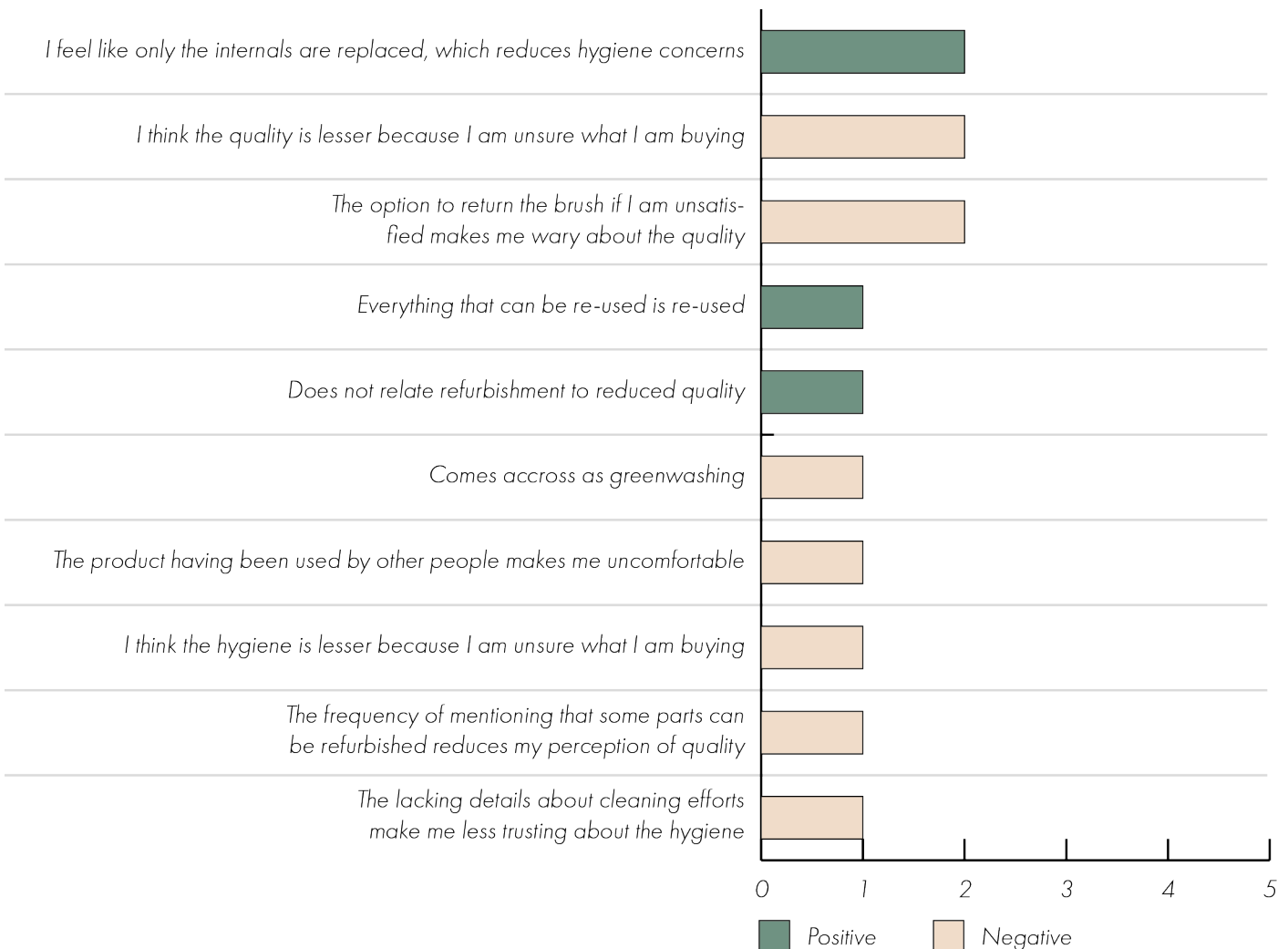


Figure 71: Aspects noted for the mock-up interface with the everything is refurbished strategy.

### Brushing experience (see Figure 72)

No major complications related to the aluminium main body were found during the brushing experience test. None of the participants reported grip issues related to the material and in general participants appreciated the feel in the hand of the brush.

There were two minor concerns expressed by participants. Participant 2 reported minor discomfort related to his specific brushing style. In this style, he tries to reach all the way behind his molars while brushing, causing the main body of the brush to touch his face which he experienced as less comfortable with the aluminium housing. This could partly be caused by the increase in the diameter of the prototype. Participant 3 reported that the uniform shape of the grip did not suit his brushing style in which he sometimes likes to hold the brush with just his fingertips. Both concerns should be considered in the further development of the brush, in which the ergonomics should receive additional attention.

Besides the observations related to the shape and material of the brush, there were some prototype-related observations. The prototype used was both heavier and larger than the actual brush is expected to be, at 197 grams and a diameter of 35 millimetres. The increase in size and weight over current electric toothbrushes received a mixed response, with some participants stating they liked the increase in size ( $n=3$ ) and weight ( $n=2$ ), but others stating it negatively affected their brushing experience ( $n=2$ ). The button on the prototype was tricky to press and this attribute was noted by participants ( $n=3$ ) but is not relevant to the actual concept.

An interesting finding was that some participants noted improved stability when putting down the brush ( $n=2$ ). One of the two participants stated that two toothbrushes had previously broken due to a lack of stability when putting them down. The increase in stability was not intentional in the design and is likely caused by the increase in diameter and weight of the prototype. How to increase the stability intentionally should be a point of attention in the further development of the brush.

Aspects named for brushing experience (n = 5)



Figure 72: Aspects noted by participants for the brushing experience.

## 16.4. Conclusion

While some areas of improvement were found, the battery replacement procedure enables all participants to replace the battery in the product. Some improvements that should be made are adding indications for the correct battery orientation and instructions to remove the brush head prior to performing the battery replacement. An area that could receive further attention is the size of the release button.

No strong evidence was found for the aluminium product housing relieving user concerns about contamination and hygiene when buying refurbished. While some participants made statements indicating that aluminium improved their perception of product hygiene, the number of participants expressing concerns about contamination appears to not have changed significantly from the study in phase 1.

The aluminium product housing did however positively affect participants' perception of the product's quality, with none of the participants expressing concerns about product quality when buying refurbished.

The everything is refurbished strategy appeared to relieve concerns about contamination and hygiene for some users, as they were led to believe refurbishment now only applied to internal parts. This is however untrue (the externals could also be refurbished), so whether this is an acceptable way of alleviating the concerns is debatable.

While alleviating concerns about hygiene and contamination for some participants, the everything is refurbished strategy in its current form negatively affected participants' perception of the quality of the product.

What stood out for both refurbishment tests is that the specific wording, interface and images used strongly affects the participants' perception. As such, further research should be performed to ensure this is optimized.

All participants were able to perform a regular brushing routine without experiencing significant discomfort. However, two participants experienced some minor discomfort related to their specific brushing styles. For one participant, this minor discomfort did originate from the aluminium housing, but the effects were possibly strengthened by the prototype. Further research into brushing styles and the resulting ergonomic requirements should be performed to ensure a satisfying brushing experience for most users.

# **Conclusion & Recommendations**

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**Conclusion**

**108**

**Recommendations**

**112**

## 17. Conclusion

### 17.1. Introduction

The goal of this thesis was to uncover challenges and opportunities for transitioning electric toothbrushes to the circular economy and to propose a design solution to those challenges and opportunities, with the primary research question:

*How can an electric toothbrush be designed suitable for the circular economy?*

To answer this research question, first, the challenges and opportunities for designing an electric toothbrush suitable for the circular economy were researched. After determining these challenges and opportunities, a design solution was proposed.

### 17.2. Challenges & Opportunities

The first two phases of this thesis were dedicated to uncovering the challenges and opportunities for transitioning electric toothbrushes to the circular economy.

In the first phase, research into the state of the circular economy of current electric toothbrushes was performed in which the academic, manufacturer and user perspectives were researched. For this phase the research questions were:

*RQ1.1: What is the state of the circular economy of current electric toothbrushes?*

*RQ1.2: Which challenges and opportunities for implementing a circular economy for electric toothbrushes are there?*

This led to three key insights for the circular design of an electric toothbrush.

1. Degrading batteries are the key reason for replacement, but battery repairs are not happening. By making battery replacement a maintenance practice for the user, most cases of end-of-life could be avoided.

2. Repair success is low, with just 2% of broken toothbrushes getting repaired successfully. This is driven by low repair considerations, with just over 20% of consumers with a broken toothbrush considering repairing their toothbrushes. Among users considering repairs, the difficulty of repair is the primary reason for not attempting or failing a repair.
3. The willingness to purchase refurbished toothbrushes is low, with only 17,5% of consumers stating they would buy a refurbished electric toothbrush. Concerns about contamination and hygiene are the most frequently named reasons for not wanting to purchase refurbished.

In the second phase, an analysis was performed of the implementation of circular design strategies in a representative set of current electric toothbrushes. For this phase the research questions were:

*RQ2.1: How are circular design strategies implemented in the design of current electric toothbrushes?*

*RQ2.2: Which challenges and opportunities for implementing circular design strategies in electric toothbrushes are there?*

This led to four key insights for the circular design of an electric toothbrush.

4. Design for attachment is not implemented in current electric toothbrushes. Implementing design for attachment could extend product lifetime.
5. Current electric toothbrushes are not optimised for disassembly. Improving the ease of disassembly for priority parts can open up opportunities for product life extension.
6. Elastomers are required for waterproofing but reduce high-value recycling performance.
7. Permanent connections are used unnecessarily in current electric toothbrushes. Avoiding permanent connections can increase high-value recycling performance.

### 17.3. Design solution

In the third phase of the thesis, the key insights were translated to design challenges and a design solution to tackle these design challenges was conceived. For this phase the research question was:

*RQ3: How can an electric toothbrush be designed that tackles the challenges and opportunities for transitioning electric toothbrushes to the circular economy?*

This resulted in the Everbrush electric toothbrush concept (see Figure 73).

Core to the concept is its aluminium main body, which tackles multiple challenges simultaneously. Design for product attachment is implemented by using a material that ages with dignity. This in turn also increases repair considerations. The material is also expected to reduce hygiene and contamination concerns when purchasing refurbished, but so far no strong evidence for this effect was found.

Another core feature of the concept is the user-replaceable battery. The replacement procedure takes four steps and can be completed without the use of tools. In initial testing, all participants managed to perform the procedure without major complications. The battery is a rechargeable 14500 li-ion cell, which was selected for its long life and good future recycling potential.

Further improvements included in the concept focus on the ease of disassembly and the high-value recycling potential. Improving the ease of disassembly could open up opportunities for product life extension, but also positively influences repair considerations as the cost of repairs is reduced. Improving the high-value recycling potential is essential for truly closing loops.

The ease of disassembly was improved by reducing the total number of parts, for example by choosing to use a single-part motor. Most connections in the concept are made using reversible snap fits or screwthread. The result is a reduction in the steps required for most priority parts, with the only exception being the main body. All of the connections used are reversible.

The high-value recycling potential has been improved by reducing the number of elastomers used and eliminating the use of permanent connections. The number of elastomers was reduced by implementing a rotating magnetic power switch. The resulting mass of elastomer material is under 1 gram (about 0,75% of the total mass), made up of three parts. In some current electric toothbrushes elastomer parts were also used for damping motor while others appeared to use a spring. It is assumed the spring in the Everbrush can also serve this function, but this has not been validated.

The use of permanent connections was avoided by using reversible snap fits for the PCB, as well as using a Philips Sonicare EasyClean style snap-fit panel as the LED cover. One exception has been made for the permanent connections, which is between the battery contacts and the PCB. It was assumed this does not affect high-value recycling performance as long as the metal used for the battery contacts can be separated in recycling.

### 17.4. Implications

Combined, the aforementioned improvements lead to a concept that has the potential for significantly extended product life and increased cycling of resources when the product reaches its end of life. This is in line with the fundamental circular economy strategies discussed in chapter 2. The Everbrush should serve to guide toothbrush manufacturers and legislators towards a circular future for electric toothbrushes.

While this thesis focussed on the design of circular electric toothbrushes, it was expected the result could serve as a guide for designing circular small waterproof personal care appliances. Not all key insights apply to other appliances to the same extent. Electric toothbrushes pose an extreme case for refurbishment as they are 'in the user' products. However, key insights related to battery replacement, ease of disassembly and waterproofing are almost sure to apply to most common small waterproof personal care appliances and using similar design solutions could help transition other appliances to the circular economy. Further research is required to determine which key insights are relevant and which related design solutions should be applied.

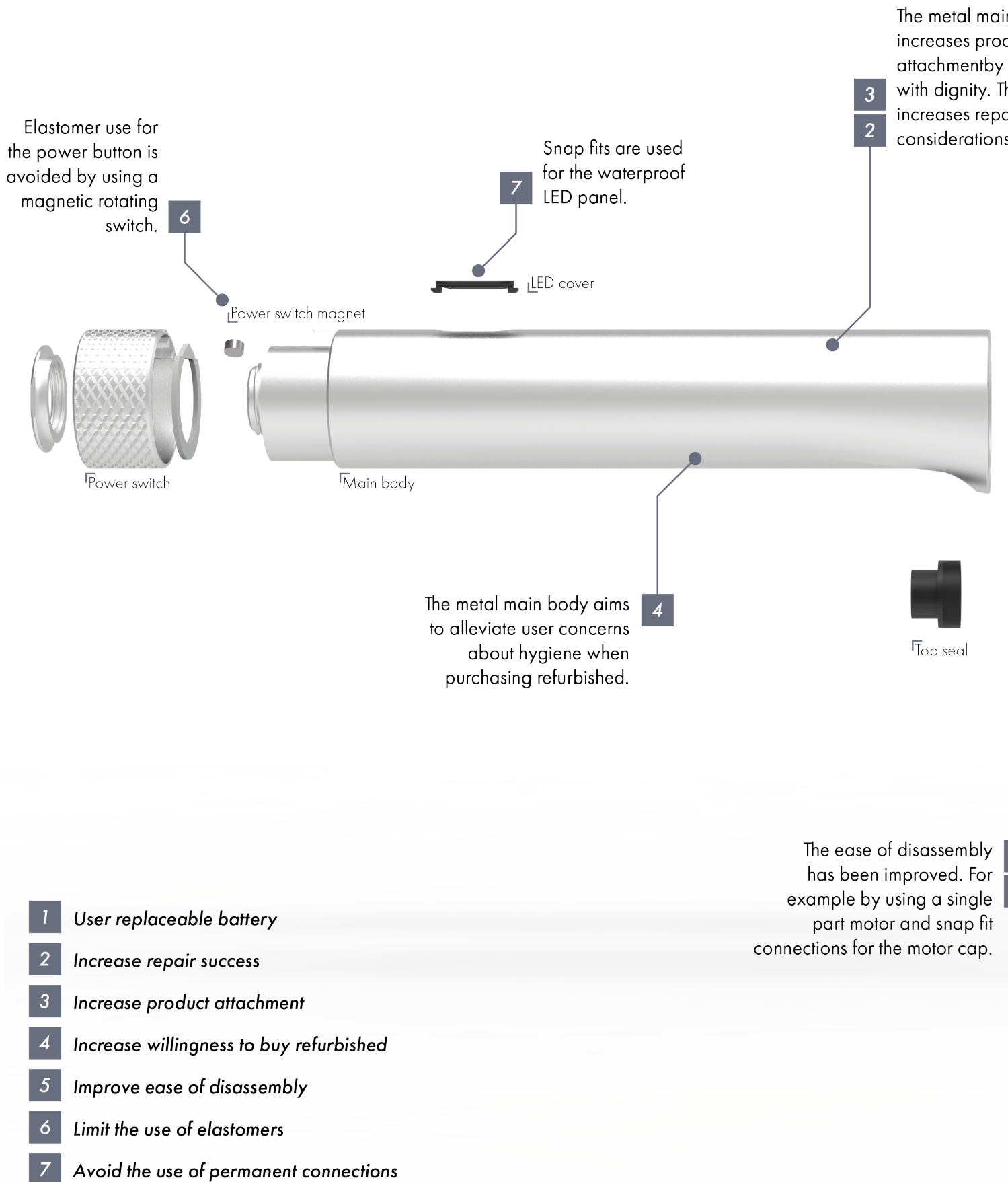
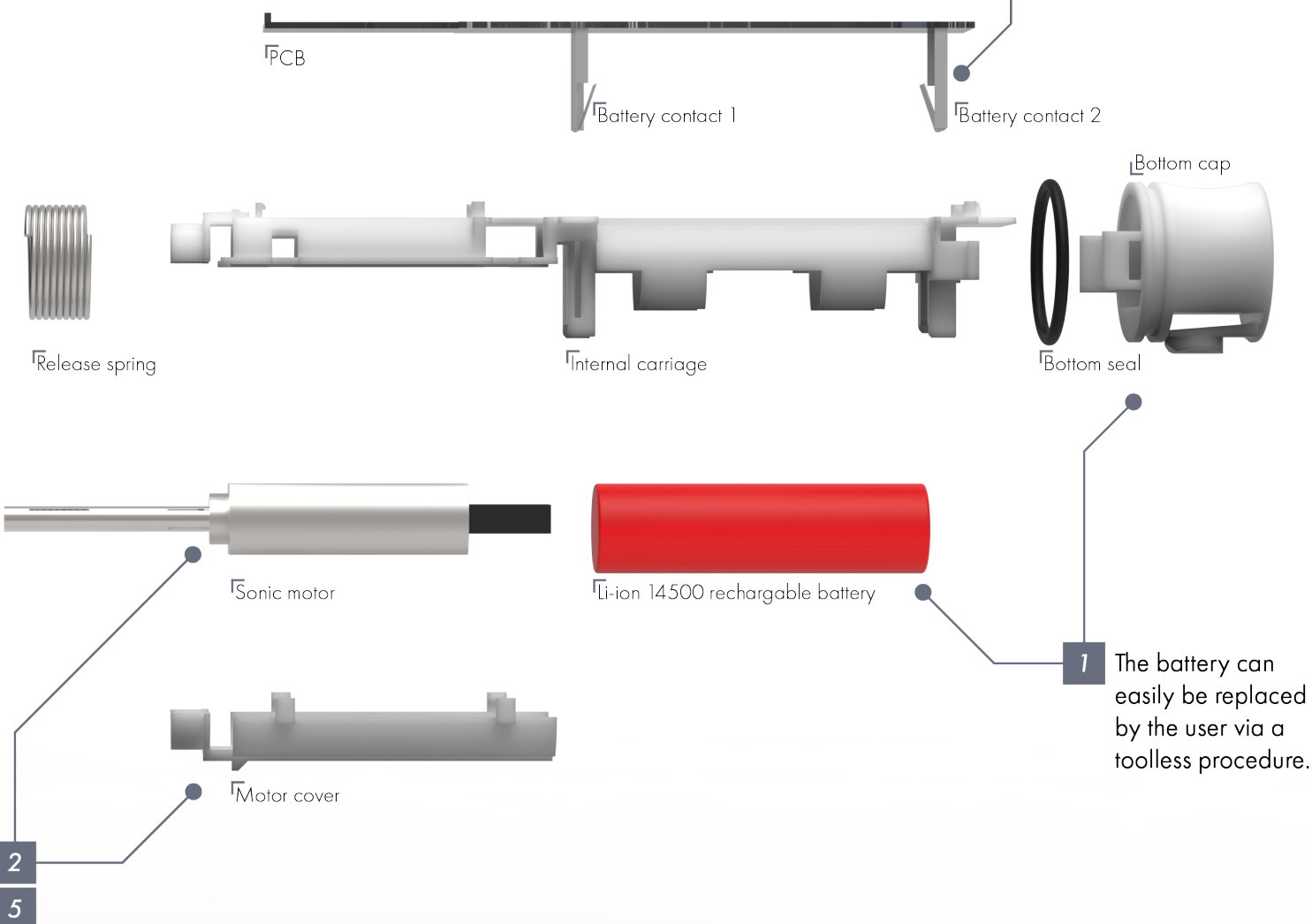


Figure 73: The Everbrush circular electric toothbrush concept with several design solutions for the key design challenges highlighted

h body  
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is also  
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.

The battery is not soldered to the PCB. The battery contacts double as the PCB snapfits, making the PCB easy to disassembly.



The battery can easily be replaced by the user via a toolless procedure.

## 18. Recommendations

### 18.1. Introduction

While the Everbrush concept has shown promise in the further development and initial concept validation performed in this thesis, some areas require attention in further research and development to ensure the product can be a success.

Some specific recommendations regarding the design of the concept have already been made in chapters 15 and 16. The recommendations in this chapter focus on activities that were not part of this thesis but should receive further attention.

### 18.2. Impact

Fundamental to this thesis was the identification that electric toothbrushes are both the most effective and most environmentally impactful method for maintaining oral hygiene. It was assumed that by transitioning electric toothbrushes to the circular economy their environmental impact can be significantly reduced as the majority of the impact is generated by transport and materials.

However, in this thesis, the impact generated by the concept has not been researched. The material selection was informed purely by the desire for circularity and a more detailed material selection should be performed keeping both environmental impact and circularity in mind. No attention has been given to transport yet. When selecting suppliers, attention should be paid to the environmental impact associated with transport.

### 18.3. Brush heads

For this thesis, brush heads were considered out of scope. While the mass of a brush head is only about 5 grams, the mass of all the brush heads used will surpass that of the brush itself in under 7 years. This makes the brush head an important factor in reducing the impact of electric toothbrushes. Having traits of both durables and consumables, designing circular brush heads will be a different challenge.

### 18.4. Viability

It is important to acknowledge that while circular design strategies are extensively implemented throughout the Everbrush concept, the success of a circular product depends on more than the product alone. Further research is required into suitable business models and alterations to the design should be made accordingly.

For this thesis it was assumed that by not letting the costs of the concept exceed that of the brush it is based on (Boombrush) by too much it was plausible that the resulting product is viable. This is an important assumption and should receive attention in the further development of the product. A target audience should be determined and it should be investigated if their willingness to pay and the sales price of the concept match.



Figure 74: Everbrush circular electric toothbrush concept.

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*Note: Dataset, web & Image references are located in separate lists.*

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# Appendices

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## ***Appendix A. Project brief***

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*Appendix on the following pages*



introduction (continued): space for images

image / figure 1: \_\_\_\_\_

image / figure 2: \_\_\_\_\_



**PLANNING AND APPROACH \*\***

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and 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 activities.

start date \_\_\_\_\_ - \_\_\_\_\_ - \_\_\_\_\_ end date

### MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... . Stick to no more than five ambitions.

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### FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

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## ***Appendix B. User study - State of the circular economy***

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*Appendix on the following pages*

# State of the circular economy of current electric toothbrushes - A quantitative study on the user perspective

Author: Drummen, Mart | Date: March 2022

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## Introduction

The main goal of the master thesis *circular design of electric toothbrushes* is to decrease the environmental impact caused by electric toothbrushes by re-designing them for the circular economy. In order to get insight into the state of the circular economy for current electric toothbrushes, a quantitative user study was conducted.

The state of the circular economy for current electric toothbrushes will serve as an important framework on which to base the re-design. Gaining insight into the lifecycle of current electric toothbrushes will provide cues for which aspects of the design are leading to replacement and have to be improved. Additionally, this will serve as a reference for any gains made to improve the circularity of electric toothbrushes.

The user perspective of the state of the circular economy is important. Selvefors et al. (2019) state that while several design strategies can be applied in an attempt to extend product life-cycle, the actual extension of product life-cycle “depends on the people using them.” Users decide what to purchase, how to use and when to replace their electric toothbrushes. Their views and efforts on maintenance, repair and refurbishment all affect product lifetime. The research question for this quantitative research is: *What is the state of the circular economy for current electric toothbrushes from a user perspective?*

## Methods

### **Participants**

The participants in this study were 121 (n = 121) adults ranging from 19 to 76 years old. 68 were male, 52 female (1 unspecified). All participants were volunteers recruited because they own electric toothbrushes.

### **Procedure**

Participants were approached randomly online and asked to fill out the survey. The survey was filled out from the participants' current location. The full survey can be found in Appendix A.

Participants were first asked to provide their age and gender. On the next pages, questions about the purchase, replacement and lifetime extension efforts for their electric toothbrush are presented.

## **Measures**

The measures were divided into three themes: *Purchase*, *Replacement* and *Lifetime extension efforts*.

### ***Purchase***

For purchase, participants were asked to rate the importance of factors when choosing an electric toothbrush on a Likert scale ranging from not at all important to extremely important. Insight into factors leading to purchase was deemed important as Harmer et al. (2019) reasoned that motivations for disposal are linked with the motivations for purchase.

### ***Replacement***

For replacement, participants were first asked if they had ever replaced their electric toothbrushes. Participants that had not replaced their electric toothbrushes yet skipped this section. Participants that had replaced their electric toothbrush multiple times already were asked to refer to the last time they replaced it. Questions in replacement were multiple-choice questions about the reasons for replacement, duration of use prior to replacement, comparison of the duration of use to their expectations and what happened to the old electric toothbrush.

### ***Lifetime extension efforts***

For lifetime extension efforts, multiple-choice questions on three themes based on the circular design strategies were asked. Maintenance practice was evaluated by asking participants which of the maintenance actions advised by Oral-B (n.d.) they performed. For repair, participants were first asked if they have ever considered a repair. If they did, they were asked why, if a repair was attempted and whether it was successful. For refurbishment users were asked if they would consider purchasing a refurbished electric toothbrush. Mugge et al. (2017) previously found that about 44% of people would potentially accept a refurbished toothbrush and it was deemed interesting to see if that is still the case.

## **Pilot results**

Several changes were made to the study based on a pilot conducted with 3 participants (n=3). Several extra options were added for purchase factors based on suggestions made and 'smart features' was split into separate more descriptive options as users found it hard to determine whether a feature was a 'smart feature' or not.

A question was added asking participants if the number of years used met their expectations or not, after a participant of the pilot called 3-4 years long. This showed a difference in expectations between the researcher and participant.

## **Analysis**

### ***Data exclusion***

Pilot results and responses stating no ownership of an electric toothbrush were excluded.

## **Purchase**

To determine the importance of purchase factors, the mean of the importance of each purchase factor was determined. Factors stated as other important factors were paraphrased and grouped. The most frequently occurring factors ( $n \geq 3$ ) were named in the results.

## **Replacement**

Responses were split between participants who said to have replaced their toothbrushes and participants that did not. For replacement, only the group that had replaced their electric toothbrush was used. The frequencies of each answer option were determined for questions about *Reason for replacement*, *Number of years used prior to replacement* and *What happened to the old electric toothbrush after replacement*.

Pairs for analysing the relationship between *Importance of factors for purchase* and *Reason for replacement* were made to analyse the expected link mentioned by Harmer et al. (2019). Not all purchase factors have a related reason for replacement. The pair made can be found in table 1.

Purchase factor	Related reason for replacement
Cleaning performance	Reduced product performance
Battery longevity	Reduced battery performance
Easy to clean	Unhygienic (Dirty)
Color & Design (Aesthetics)	No longer aesthetically pleasing
Smartphone connection	-
Brand	-
Sustainability	-
Price	-
Ergonomics	The ergonomics no longer suit me
Timer	-
Pressure sensor	-

*Table 1: Pairs for analysis or relation between the motivation of purchase and the reason for disposal.*

To analyse the relationship, the dataset was split into the group that stated a certain *Reason for replacement* and the group that did not. The mean values of the importance of the related purchase factor for both groups were compared.

To analyse the relationship between the *Reason for replacement* and *Number of years used prior to replacement*, the dataset was split based on the *Number of years used prior to replacement*. The percentage of participants stating a *Reason for replacement* was determined for each group (e.g. % of participants that have used their toothbrush for 3-4

years prior to replacement stating reduced battery performance as a reason for replacement).

To analyse the relationship between *Number of years used prior to replacement* and *Duration of use meeting participants' expectations* the dataset was split by *Number of years used prior to replacement*. The mean values for *Duration of use meeting participants' expectations* for each number of years were compared. Spearman's rank-order correlation was computed to further assess the relationship.

### **Lifetime extension efforts**

The frequencies of each answer option were determined for questions about *Maintenance practice*, *Repair considered*, *Parts requiring repair*, *Repair attempted*, *Repair success* and *Willingness to purchase a refurbished electric toothbrush*. For questions about *Parts requiring repair* and *Repair attempted*, participants that answered no to *Repair considered* were excluded. For the questions about *Repair success* participants that answered no to *Repair attempted* were excluded.

Elaborations given for why participants would not buy refurbished were paraphrased and grouped. While related, a difference was made between *Unhygienic* (Hygiene is a problem) and *Contaminated* (The idea of another person having used the toothbrush before), as well as between *A new electric toothbrush is cheap* (General low price of electric toothbrushes) and refurbished is *Too expensive compared to new* (Too little price difference between new and refurbished electric toothbrushes). All elaborations occurring more than once were presented separately, and elaborations occurring only once were grouped as *Other*.

To assess the relationship between *Reduced battery performance* as a reason for replacement and the maintenance practice of *Not charging continuously* a chi-square test of independence was performed. This was done to evaluate the effectiveness of this maintenance practice for extending the lifecycle of the battery.

To analyse the relationship between *Lifetime extension efforts* and *Rated importance of sustainability when choosing an electric toothbrush*, the *Rated importance of sustainability when choosing an electric toothbrush* was compared based on *Repair consideration* and *Willingness to purchase refurbished electric toothbrushes*. For *Repair consideration*, the dataset was split into participants that did consider repair and participants with a broken toothbrush that did not consider repair. For *Willingness to purchase refurbished electric toothbrushes* the dataset was split into participants that would, maybe would and would not buy refurbished toothbrushes. Means for each split group were compared.

## Results

### Purchase

#### Importance of purchase factors

Mean importance of factors when choosing an electric toothbrush (n = 120)

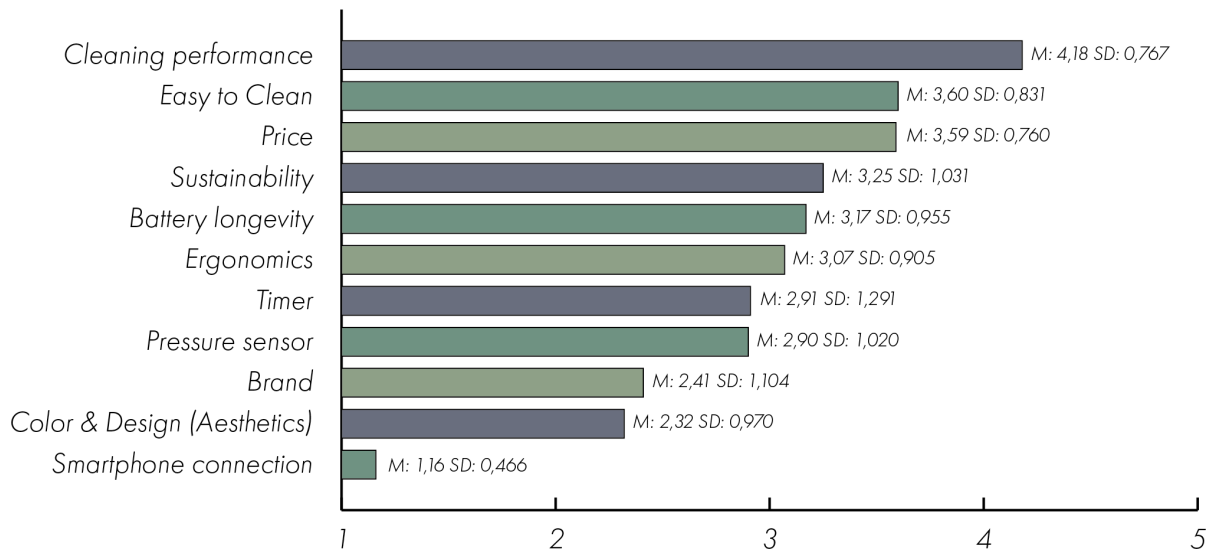


Figure 1: Mean importance of factors when choosing an electric toothbrush. Rated on a 1 (Not at all important) to 5 (Extremely important) scale.

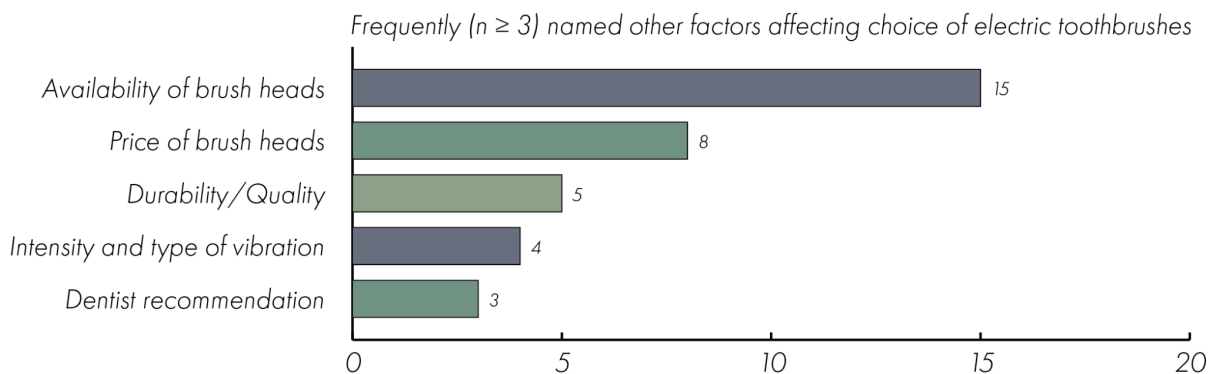
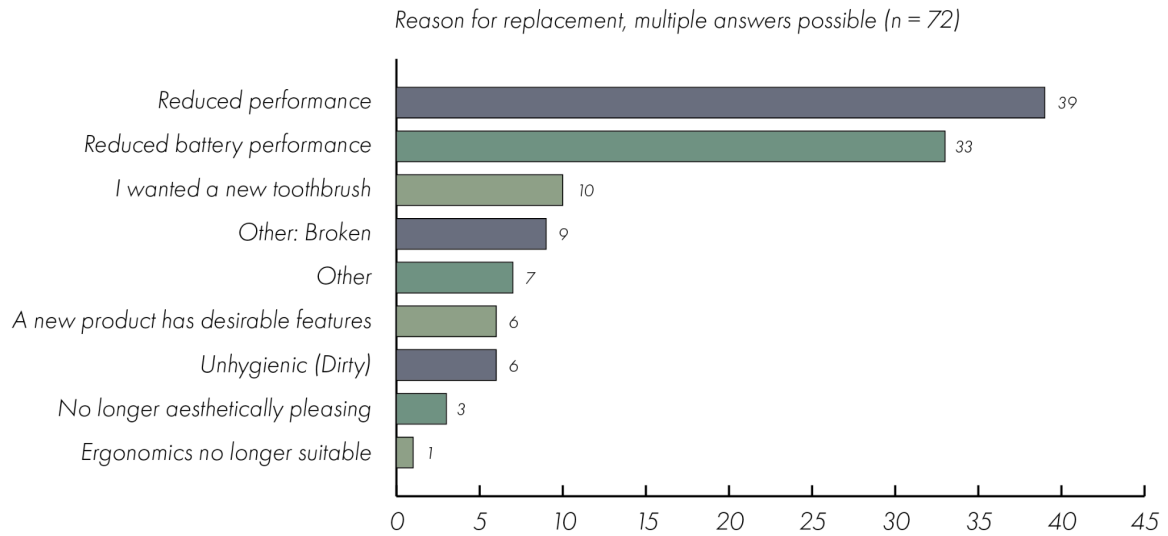


Figure 2: Frequently named other factors that are important when choosing an electric toothbrush.

### Replacement

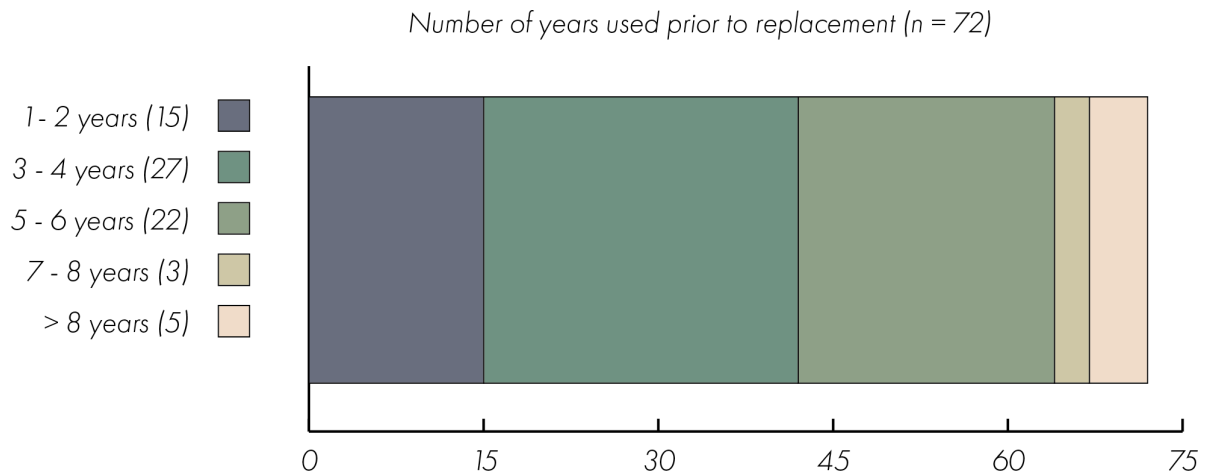
72 out of 121 respondents stated to have replaced their electric toothbrush with a new model. Figure 3 shows the reasons stated for replacement, sorted by frequency. Each participant could state multiple reasons for replacement.

### Reason for replacement



**Figure 3: Reasons for replacement of electric toothbrushes with a new model.**

### Number of years used prior to replacement



**Figure 4: Number of years participant's last electric toothbrush was used prior to replacement.**

### What happened to the old electric toothbrush after replacement

What happened to old electric toothbrush after replacement (n = 72)

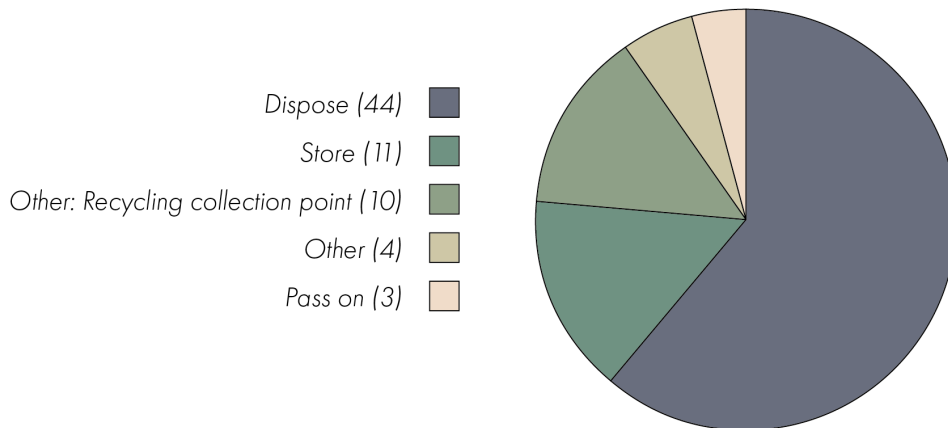


Figure 5: What happened to the old electric toothbrush after replacement.

### Relationship between Importance of factors for purchase and Reason for replacement

Mean importance of factors when choosing an electric toothbrush, split by respondent's (not) indicating the paired reason for replacement (n = 72)

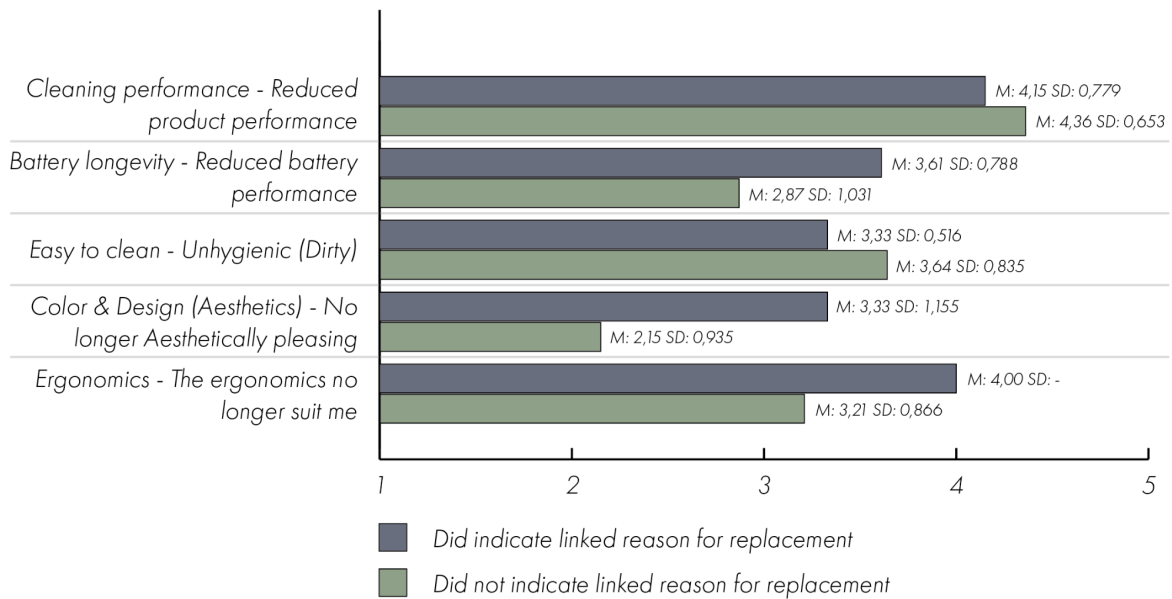
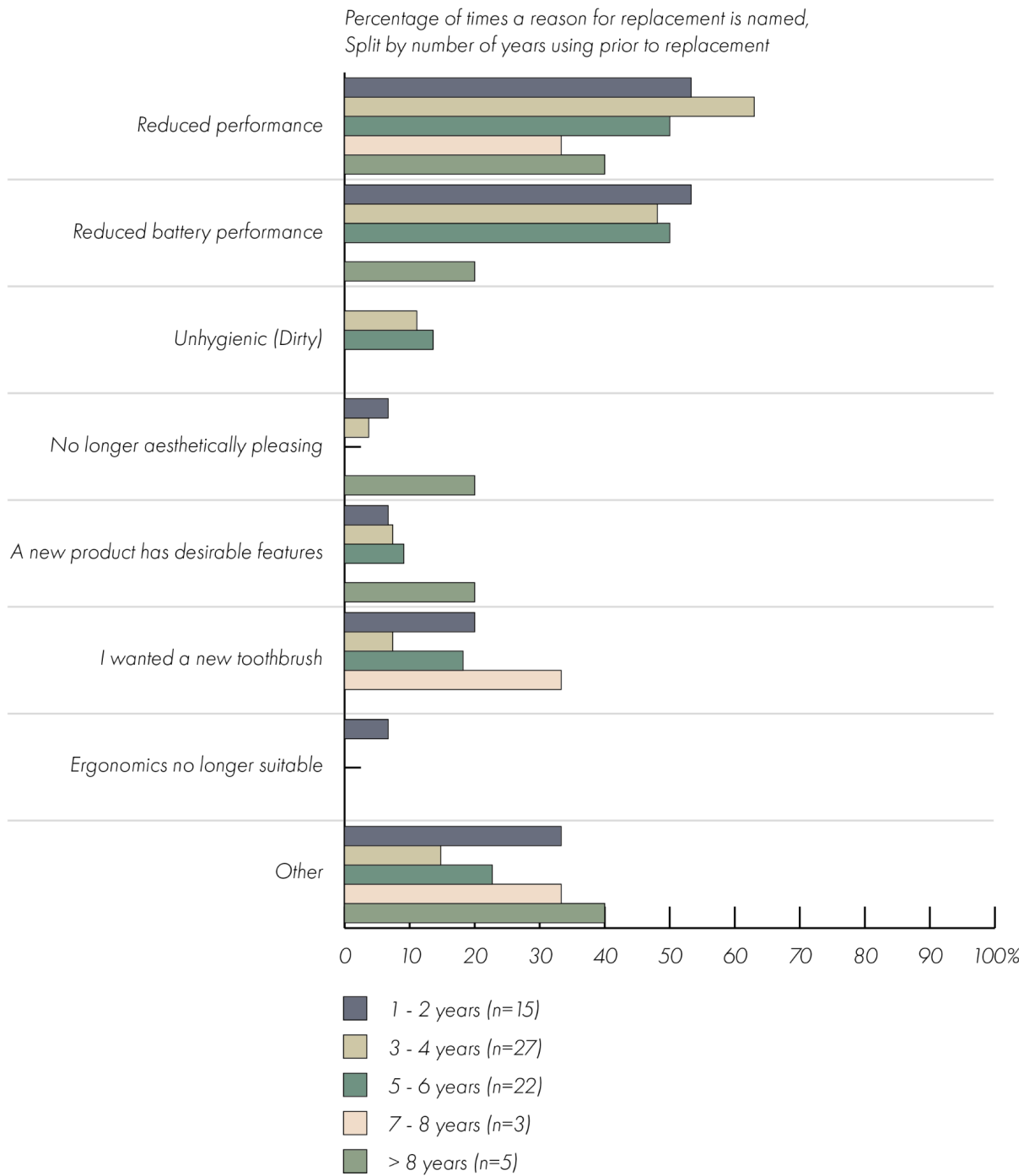


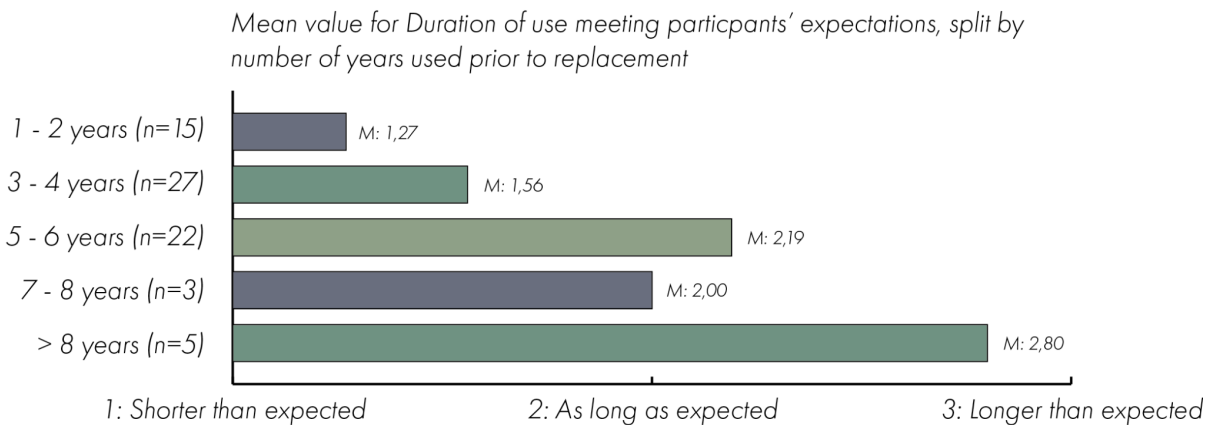
Figure 6: Mean importance of factors when choosing an electric toothbrush, rated on a 1 (Not at all important) to 5 (Extremely important) scale, split by whether respondents indicated the paired reason for replacement or not.

**Relationship between the Reason for replacement and Number of years used prior to replacement**



**Figure 7: Reasons for replacement of electric toothbrushes with a new model, split by the number of years the electric toothbrush was used prior to replacement.**

**Relationship between the Number of years used prior to replacement and Duration of use meeting participants' expectations**

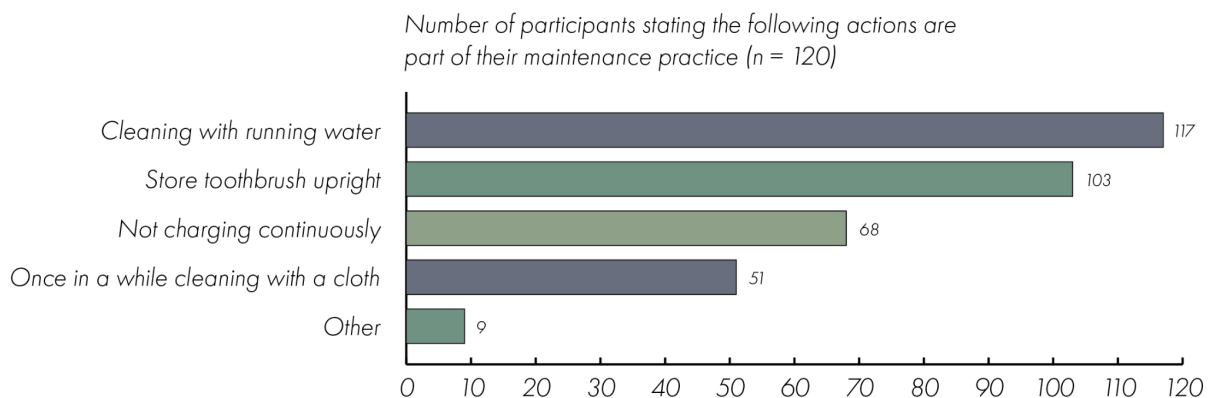


**Figure 8: Mean values for duration of use meeting participants' expectations, split by the number of years the electric toothbrush was used prior to replacement.**

A Spearman's rank-order correlation was computed to further assess the relationship between the *Number of years used prior to replacement* and *Duration of use meeting participants' expectations*. There was a strong, positive monotonic correlation between the duration of use and the duration meeting participant's expectations, which was statistically significant ( $r_s(69) = .610, p = < .001$ ).

**Lifetime extension efforts**

**Maintenance practice**



**Figure 9: Number of participants stating specified actions are part of their maintenance practice.**

## Repair considered

Division of participants considering repair of their electric toothbrush (n = 121)

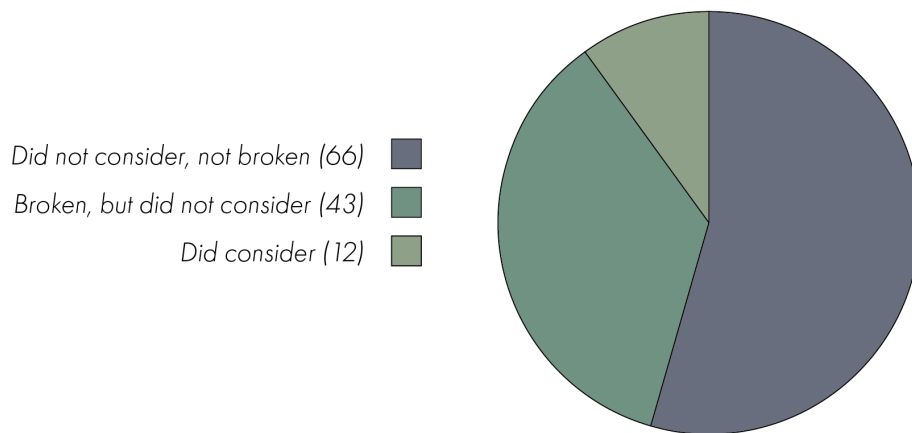


Figure 10: Overview of participants (not) considering repair.

## Parts requiring repair

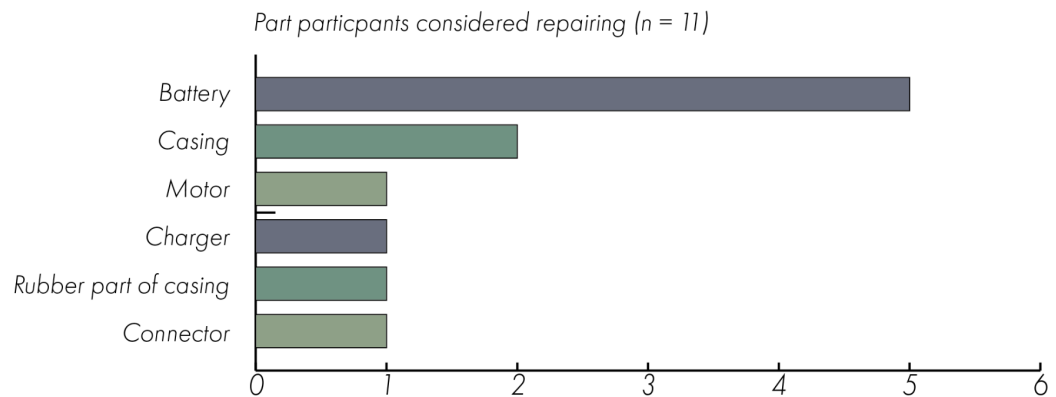


Figure 11: Overview of parts that are being considered for repair.

## Repair attempted & Repair success

Out of the 12 participants considering repair, only 3 attempted repair. Reasons stated for not attempting repair were *Too much effort (2x)*, *Too time consuming*, *Too expensive*, *Battery not replaceable*, *Risk of failure* and *Not repairable*.

Out of the 3 participants attempting repair, only 1 repair was successful. The successful repair was completed for the casing. Reasons stated for unsuccessful repairs were *Battery is soldered* and *Unavailability of parts for the casing*.

## Willingness to purchase a refurbished electric toothbrush

Would buy a refurbished electric toothbrush? (n = 120)

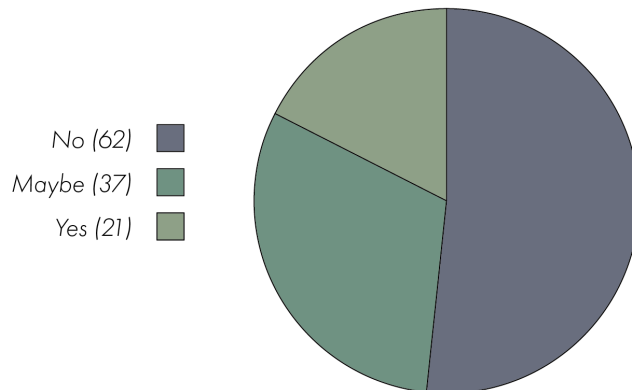


Figure 12: Overview of participants (not) willing to buy refurbished electric toothbrushes.

Reason for not wanting to buy a refurbished electric toothbrush (n = 62)

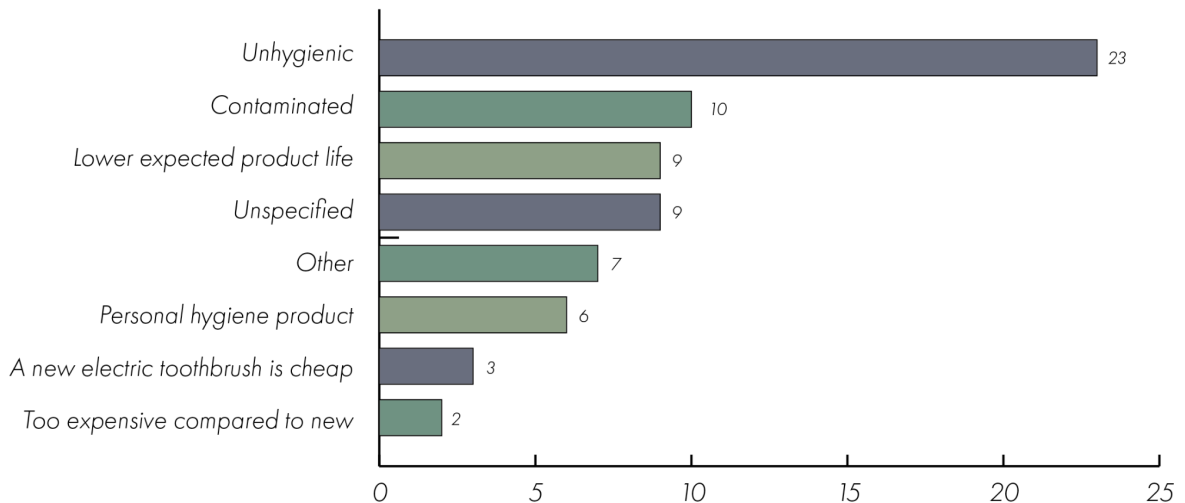


Figure 13: Stated reasons for not wanting to buy refurbished electric toothbrushes.

## Relationship between Reduced battery performance as a reason for replacement and the maintenance practice of Not charging continuously

A chi-square test of independence was performed to examine the relation between *Not charging continuously* and *Reduced battery performance* as a reason for replacement. The relation between these variables was insignificant,  $X^2(1, N = 120) = 0,288, p = .592$ .

## Relationship between Lifetime extension efforts and Rated importance of sustainability when choosing an electric toothbrush

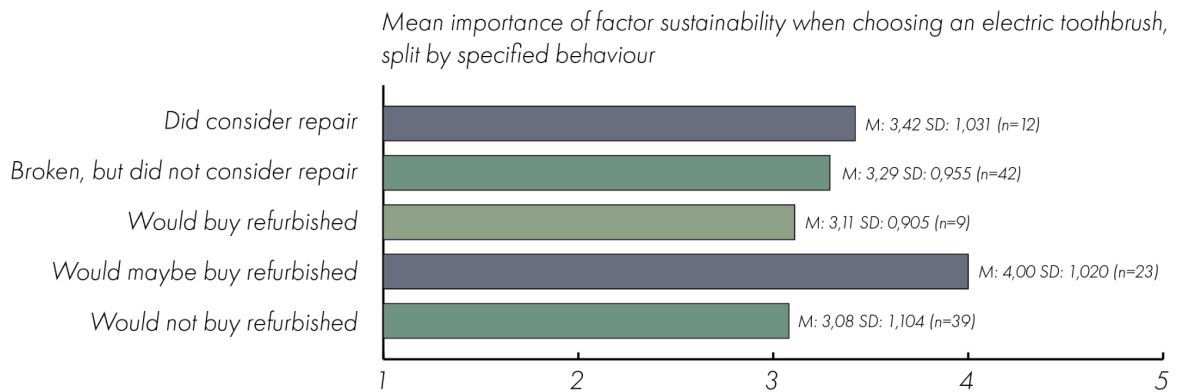


Figure 14: Mean importance of factors when choosing an electric toothbrush, rated on a 1 (Not at all important) to 5 (Extremely important) scale, split by whether respondents indicated specified lifetime extension efforts or not.

## Discussion

### **Purchase**

Cleaning performance is by far the most important factor when choosing an electric toothbrush ( $M = 4,18$ ;  $SD = 0,767$ ), followed by Ease of cleaning ( $M = 3,60$ ;  $SD = 0,831$ ) and Price ( $M = 3,59$ ;  $SD = 0,760$ ). From this, it appears that functional aspects and value for money dominate purchase motivations. Ensuring proper function and good value for money are thus important aspects to focus on for extended product life.

Smartphone connection is by far the least important factor when choosing an electric toothbrush ( $M = 1,16$ ;  $SD = 0,466$ ), followed by Color & Design (Aesthetics) ( $M = 2,32$ ;  $SD = 0,970$ ) and Brand ( $M = 2,41$ ;  $SD = 1,104$ ). While participant's stated brand is not important when choosing an electric toothbrush, the availability of brush heads was the most frequently named other factor that is important when choosing an electric toothbrush ( $n=15$ ), which is partly related to brand and thus brand is still likely to affect the purchase decision.

Participants rate sustainability as the fourth most important factor for choosing an electric toothbrush. When analysed there appears to be no relationship between participants that do make *efforts for lifetime extensions* and those that do not and the *importance of sustainability as a factor when buying an electric toothbrush*.

### **Replacement**

Reduced performance ( $n=39$ ) and Reduced battery performance ( $n=33$ ) are by far the two most frequently occurring reasons for the replacement of electric toothbrushes. While separated as answer options for this survey, it is highly likely that the reduced performance of the product overall is strongly related to reduced battery performance, as a degrading battery will experience both capacity fade and power fade (Edge et al., 2021).

Only 12,5% of the participants state *Broken* as the reason for replacement, making relative obsolescence the dominant type of obsolescence of electric toothbrushes. Even so, improving ease of repair is still an effective way of reducing relative obsolescence as it can alleviate reduced performance and reduced battery performance.

When evaluating the reason for replacement split by the duration of use prior to replacement, some interesting observations can be made.

Even for disposal after only 1-2 years of use, reduced performance and reduced battery performance are by far the most occurring reason for replacement, meaning they are the dominant factors leading to an early end of life. Improving the reparability of parts related to these factors is not only important for extending the product's life beyond the expected life, but also for preventing premature disposal.

Unhygienic (Dirty) was only reported as a reason for replacement when replacements were done after 3-6 years. Prior to this duration, toothbrushes have likely not yet reached a level of Unhygienic that is unacceptable to users. Participants that have used the toothbrush for 7 years or longer might have a higher tolerance for an unhygienic appearance.

While the average number of years used prior to replacement appears to be in line with the 3 - 5 years expected (Ordo, 2020), about 20% of electric toothbrushes were replaced after just 1-2 years of use. Looking into the mean values of the duration of use meeting participants' expectations, it can be observed that a lifetime of 5-6 years or more is meeting participants' expectations. These expectations are in line with earlier research by Cooper (2004). As basic logic would suggest, the longer the use the more likely the duration of use is to meet or even exceed expectations.

Once replaced, most participants dispose of the old toothbrush. A bit under 15% of participants specified taking their old electric toothbrushes to a dedicated e-waste collection point. This is quite a bit below the Dutch national average e-waste collection rate for small appliances of 44% (Baldé et al., 2020). A possible reason for this big difference is that respondents consider this regular 'Disposal'.

What stands out is that only 1 respondent states returning their electric toothbrush to the manufacturer (for warranty). All other toothbrushes (> 98%) enter general waste streams, meaning collection rates are near zero.

Contrary to what was expected based on the work of Harmer et al. (2019), no strong evidence for a correlation between motivations for purchase and reasons for replacement was found. While the mean ratings for the importance of Battery longevity, Color & Design and Ergonomics are clearly higher for participants that indicate replacement due to the related reason for replacement, there is no significant difference in Cleaning performance and Easy to clean.

### ***Lifetime extension efforts***

Maintenance actions of *cleaning with running water* and *storing upright* are widely accepted. More thorough cleaning is done by less than half of the users (42,5%), however, only 6 participants named *unhygienic (dirty)* as a reason for replacement, so this is unlikely to have a big effect.

Charging behaviour was mixed, with 57% not continuously charging. No significant relation could be found between *not continuously charging* and *reduced battery performance as a reason for replacement*. This empirical evidence is not in line with the commonly accepted principle of overcharging causing battery degradation (Sweda et al., 2017).

Only just under 2% of broken products is successfully repaired. In 66% of cases, the reason for not attempting the repair is related to ease of repair (*Too much effort (2x)*, *Too time consuming*, *Battery not replaceable*, *Risk of failure*, *Not repairable*). The parts requiring repair most often are the battery (n=5) and casing (n=2). Making these parts easier to repair could increase repair success from 8% to 58%. Further research has to be conducted on how to increase the number of people considering repair.

Acceptance of refurbished toothbrushes is low, with only 17,5% of participants saying they would buy a refurbished electric toothbrush. Including the participants that indicated maybe, the number goes up to 48%, very similar to the 44% found by Mugge et al. (2017).

The most named reasons for not wanting to buy a refurbished electric toothbrush were *unhygienic (23x)*, *contaminated (10x)*, *lower expected longevity (9x)* and *it's a personal hygiene product (6x)*. If refurbishment is selected as a strategy to increase circularity for electric toothbrushes, alleviating concerns about hygiene and contamination is key. Achieving this will be tricky, as several respondents stated being aware that there is probably no reason to actually be concerned about hygiene, but still getting an uncomfortable feeling about it.

## Conclusion

The goal of this quantitative research was to gain insight into the state of the circular economy of current electric toothbrushes from a user perspective. The state of the circular economy was defined as the user's decisions for purchase, use and replacement, as well as their view on maintenance, repair and refurbishment.

The study provided an insight into purchase motivations and showed that electric toothbrush buyers care about the sustainability of their purchases. However, this care for sustainability does not yet reflect users' behaviour regarding lifetime extension efforts. While most advised maintenance practice is well accepted and performed by the participants in this research, repair and refurbishment are only considered by a small number of participants. In this regard, there are two big improvements to be made;

Firstly, the ease of repair and/or maintenance of components related to product performance and battery performance has to be improved. This will allow more users to successfully alleviate concerns for reduced performance and reduced battery performance and allow for lifetime extension as well as preventing premature obsolescence.

Secondly, concerns about hygiene and contamination for refurbished toothbrushes have to be alleviated. Earlier suggestions for this are improving design for ease of cleaning or further promoting the cleaning efforts done (Harmer et al., 2019). Another option for this is to switch focus to the strategy of remanufacturing instead of refurbishment, as it allows the toothbrushes to be sold as new. However, remanufacturing allows for less value to be captured and is thus less likely to be economically viable.

While the two improvements mentioned above could promote an increase in circularity for electric toothbrushes, another major limiting factor is the near-zero collection rate of electric toothbrushes at end of life. Increasing collection rates is required for leveraging circular design strategies like refurbishment, remanufacturing and high-value recycling. As such, the cost associated with increasing collection rates should be considered in the design phase of this thesis.

The state of the circular economy of current electric toothbrushes leaves a lot of room for improvement. Collection rates are low and lifetime extension efforts by users are minimal. However, with targeted interventions, there is great potential for improvement.

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## Appendix

### Appendix A: Full survey

#### Start of Block: Introduction

Survey information Thank you for taking the time to fill out this survey. This survey is part of a thesis project on the circular design of electrical toothbrushes at Delft university of technology. The goal of this survey is to investigate the factors leading to the end of life of electric toothbrushes. The survey starts by asking you some general information.

Note: This survey is exclusively meant for people that own an electric toothbrush.

All responses to this survey are processed anonymously.

Page Break

Age What is your age?

---

Gender What is your gender?

- Male
- Female
- Nonbinary
- Prefer not to say

Ownership Do you own an electric toothbrush?

- No
- Yes

End of Block: Introduction

Start of Block: Purchase

Choosing The following questions are about the factors important to you when choosing a new electric toothbrush.

Page Break

Choosing1 Please indicate the importance of the following factors when choosing an electric toothbrush

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Cleaning performance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Battery longevity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Easy to clean	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Color & Design (aesthetics)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Smartphone connection	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Brand	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sustainability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Price	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Ergonomics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Timer	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Pressure sensor (Checks if too much force is applied during brushing)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Choosing2 Are there other factors that are important to you when choosing an electric toothbrush?

---

End of Block: Purchase

Start of Block: Obsolescence

Replacing The following questions are about replacing your electric toothbrush.

Replace1 Have you ever replaced your electric toothbrush with a new model?

No

Yes

Page Break

Replace information If you have replaced your electric toothbrush multiple times already, please refer to the last time you replaced your electric toothbrush for answering the following questions.

Replace2 What was the reason for replacing your electric toothbrush? (Select all that apply)

- Reduced product performance
  - Reduced battery performance (Less brush time on one charge)
  - Unhygienic (Dirty)
  - No longer aesthetically pleasing
  - A new product had desirable features (Please specify which features)
- 

- I wanted a new toothbrush
  - The ergonomics no longer suit me
  - Other (Please specify)
- 

Replace3 For how many years did you use your electric toothbrush before replacing it with a new model?

- 1 - 2 years
- 3 - 4 years
- 5 - 6 years
- 6 - 8 years
- Over 8 years

Replace 4 Did the amount of years using your electric toothbrush meet your expectations?

- It lasted shorter than I expected
- It lasted as long as I expected
- It lasted longer than I expected

Replace 5 What did you do with your old electric toothbrush after replacing it with a new model?

- Resell
- Pass on
- Store
- Dispose
- Other (Please specify) \_\_\_\_\_

End of Block: Obsolescence

Start of Block: Efforts made

Efforts made The following questions are about the maintenance, repair and refurbishment of electric toothbrushes.

Page Break

Maintenance Which of the following actions are part of your electric toothbrush maintenance practice?

- Cleaning with running water
  - Once in a while cleaning with a cloth
  - Storing the electric toothbrush upright
  - Not charging continuously (Only charging once empty)
  - Other (Please specify)
- 
- None of these actions

Page Break

Repair 1 Have you ever considered repairing your electric toothbrush?

- No, my electric toothbrush has never broken down
- No, my electric toothbrush broke but I did not consider repairing my electric toothbrush
- Yes, I did consider repairing my electric toothbrush

Page Break

Repair 2 Which part of the electric toothbrush did you consider repairing?

- Battery
- Motor

Casing

Button

Charger

Other (Please specify) \_\_\_\_\_

Repair 3 Was a repair of the part attempted?

No (Please specify why not)

\_\_\_\_\_

Yes, I attempted to repair the part myself

Yes, I send the toothbrush to a repair service

Repair 4 Was the repair successful?

No (Please specify why not)

\_\_\_\_\_

Yes

Page Break

Refurbishment Would you buy a refurbished electric toothbrush? Refurbished products are products that have had a previous owner, but have been refinished and sanitized. Refurbished products often are cheaper than new products and come with warranty.

No (Please specify why not)

\_\_\_\_\_

Maybe

Yes

End of Block: Efforts made

End of survey

## **Appendix C. Oral-B IO quick analysis**

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*Appendix on the following pages*

# Insights quick analysis Oral-B IO

## Why a quick analysis?

The Oral-B IO toothbrushes was provided for this project by IFixit. Unfortunately the toothbrush arrived too late for inclusion in the analysis phase.

## Key findings:

### Bottom cap

The bottom cap uses a bayonet style closing mechanism that can be operated using the included wireless charger. The bayonet closing is easy to reuse and does not require a lot of force for opening. One thing that is lacking is an indication for when the bayonet is closed or open.



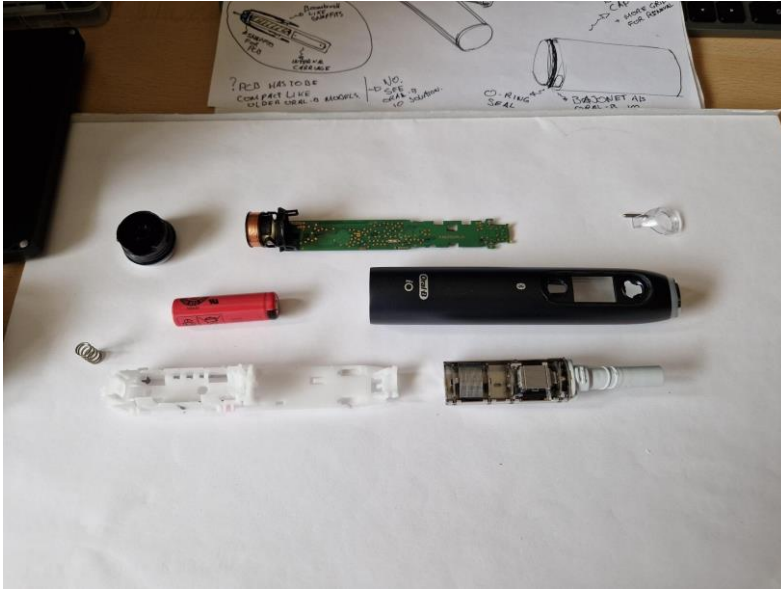
### Battery

The battery is not soldered in the toothbrush, but is fixed in place with snap fits. This makes the battery easy to remove. It is however an unprotected li-ion battery with the same size as regular AA batteries, which could lead to issues for battery safety when the battery is used in different applications.



## Number of components

While not all components are shown in the picture below, the amount of components in the Oral-B IO is more similar to that in the Boombush. The motor no longer features a complex gearbox for the rotating mechanism. The pressure sensor now uses a hall sensor through the inner carriage, making for a much simpler design.



## 2K moulding

2K moulding is still used in the main body to ensure waterproofing. It is no longer used for improving grip on the brush.

## ***Appendix D. BOMs current electric toothbrushes***

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*Appendix on the following pages*

Model	Boombrush
Number of parts	21
Number of unique parts	15
Total weight (added up)	134
Total weight (measured)	135
Total CO2	1689,13
Total economic value	18,5538145

#	Part	Number of parts	Material	Mass			Footprint			Material value			Notes
				per part (g)	total (g)	total (%)	CO2 per part (g)	CO2 total (g)	CO2 total (%)	per part (euro)	total (euro)	total (%)	
1	Brush head	1	Mixed, mainly ABS	5	5	3,7	17,2	17,2	1,0	0,0095	0,0095	0,1	Sinks
2	Main body	1	ABS	34	34	25,4	116,96	116,96	6,9	0,0646	0,0646	0,3	Sinks
3	Bottom cap + Charging port	1	HDPE + other electronics	5	5	3,7	29,65	29,65	1,8	0,373075	0,373075	2,0	assume hdpe door 2
4	Bottom cap ring	1	ABS	1	1	0,7	3,44	3,44	0,2	0,0019	0,0019	0,0	Sinks
5	Seal ring	1	Elastomer	1	1	0,7	3	3	0,2	0,0012	0,0012	0,0	Sinks
6	Top seal	1	Elastomer	1	1	0,7	2,325	2,325	0,1	0,0006845	0,0006845	0,0	Sinks
7	Tape	4	PP	0	0	0,0	0	0	0,0	0	0	0,0	
8	Motor cap screws	4	Steel	0	0	0,0	0	0	0,0	0	0	0,0	
9	Motor cap	1	PC + ABS	3	3	2,2	14,61	14,61	0,9	0,01059	0,01059	0,1	
10	Motor	1	E-motor	26	26	19,4	306,8	306,8	18,2	1,6653	1,6653	9,0	
11	Motor top damper	1	Elastomer	1	1	0,7	3,2	3,2	0,2	0,001495	0,001495	0,0	Sinks
12	Motor bottom damper	1	Elastomer	1	1	0,7	2,915	2,915	0,2	0,0012	0,0012	0,0	Sinks
13	PCB	1	PCB	3	3	2,2	483	483	28,6	1,7625	1,7625	9,5	
14	Battery	1	Rechargeable	44	44	32,8	662,2	662,2	39,2	14,63	14,63	78,9	
15	Internal carriage	1	PC + ABS	9	9	6,7	43,83	43,83	2,6	0,03177	0,03177	0,2	
16				0	0	0,0	0	0	0,0	0	0	0,0	
17				0	0	0,0	0	0	0,0	0	0	0,0	
18				0	0	0,0	0	0	0,0	0	0	0,0	
19				0	0	0,0	0	0	0,0	0	0	0,0	
20				0	0	0,0	0	0	0,0	0	0	0,0	
21				0	0	0,0	0	0	0,0	0	0	0,0	
22				0	0	0,0	0	0	0,0	0	0	0,0	
23				0	0	0,0	0	0	0,0	0	0	0,0	
24				0	0	0,0	0	0	0,0	0	0	0,0	
25				0	0	0,0	0	0	0,0	0	0	0,0	
26				0	0	0,0	0	0	0,0	0	0	0,0	
27				0	0	0,0	0	0	0,0	0	0	0,0	
28				0	0	0,0	0	0	0,0	0	0	0,0	
29				0	0	0,0	0	0	0,0	0	0	0,0	
30				0	0	0,0	0	0	0,0	0	0	0,0	

Materials	CO2 per kg	Value per kg (euro)	
PP	2,915	1,2	Sourced from Granta Edupack 2020, used middle of given range
Low carbon steel	2,325	0,6845	Sourced from Granta Edupack 2020, used middle of given range
Battery	3,15	9,845	Sourced from HS mapping sheet
PCB	161	587,5	Sourced from HS mapping sheet
E-motor	11,8	64,05	Sourced from HS mapping sheet
Other electronics	10	148,2	Sourced from HS mapping sheet
ASA	4,865	2,335	Sourced from Granta Edupack 2020, used middle of given range
ABS	3,44	1,9	Sourced from Granta Edupack 2020, used middle of given range
Thermoset	3	3,4	Sourced from HS mapping sheet -> Thermoset
POM	3,2	1,495	Sourced from Granta Edupack 2020, used middle of given range
HDPE	1,86	1,03	Sourced from Granta Edupack 2020, used middle of given range
ABS + PC	4,87	3,53	Sourced from Granta Edupack 2020, used middle of given range
Rechargeable	15,05	332,5	Sourced from HS mapping sheet
Thermoplastic	3,027	2,76	Sourced from HS mapping sheet

Parts ordering & grouping					
Group	Part - general	Part - specific	% mass	% footprint	% value
High impact, occurring in all brushes	Battery	Battery	32,8	39,2	78,9
	PCB	PCB	2,2	28,6	9,5
	Motor	Motor	19,4	18,2	9,0
Waterproofing	Main body	Main body	25,4	6,9	0,3
	Bottom seal	Seal ring	0,7	0,2	0,0
Other - electronics	Top seal	Top seal	0,7	0,1	0,0
	Bottom cap + Charging port		3,7	1,8	2,0
	Motor cap screws		0,0	0,0	0,0
Other - metals	Brush head		3,7	1,0	0,1
	Bottom cap ring		0,7	0,2	0,0
	Tape		0,0	0,0	0,0
Other - plastics	Motor cap		2,2	0,9	0,1
	Motor top damper		0,7	0,2	0,0
	Motor bottom damper		0,7	0,2	0,0
	Internal carriage		6,7	2,6	0,2

Material	# of different types
Polymers	4 (ABS, HDPE, PP, PC + ABS)
Polymers - unidentified but assumed unique	0
Polymers - unidentified but assumed same as identified	0
Polymers - total	4
Elastomer	0
Elastomers - unidentified but assumed unique	3 (Seal ring, motor damper, top seal)
Polymers - unidentified but assumed same as identified	0
Elastomers - total	3
Metals	1 (steel)
Metals - unidentified but assumed unique	0
Metals - unidentified but assumed same as identified	0
Metals - total	1

Model	Oral-B advance power
Number of parts	21
Number of unique parts	20
Total weight (added up)	136
Total weight (measured)	137
Total CO2	889,747
Total economic value	3,2688115

#	Part	Number of parts	Material	Mass			Footprint			Material value			Notes
				per part (g)	total (g)	total (%)	CO2 per part (g)	CO2 total (g)	CO2 total (%)	per part (euro)	total (euro)	total (%)	
1	Brush head	1	Mixed, mainly ?	5	5	3,68	15,135	15,135	1,7	0,0138	0,0138	0,4	Sinks
2	Bottom cap	1	ASA	4	4	2,94	19,46	19,46	2,2	0,00934	0,00934	0,3	
3	Bottom cap spring	1	Steel	1	1	0,74	2,325	2,325	0,3	0,0006845	0,0006845	0,0	
4	AA battery	2	Battery	23	46	33,82	72,45	144,9	16,3	0,226435	0,45287	13,9	
5	Seal ring	1	Elastomer -> Thermoplastic	1	1	0,74	3,027	3,027	0,3	0,00276	0,00276	0,1	Sinks
6	Seal spring	1	Steel	1	1	0,74	2,325	2,325	0,3	0,0006845	0,0006845	0,0	
7	Main body	1	ABS/ TPE	28	28	20,59	105,35	105,35	11,8	0,0588	0,0588	1,8	TPE: Floats, Polyisoprene rubber chosen based on its frequent use for toothbrushes
8	PCB	1	PCB	1	1	0,74	161	161	18,1	0,5875	0,5875	18,0	
9	Battery contact short	1	Steel	0	0	0,00	0	0	0,0	0	0	0,0	
10	Battery contact long	1	Steel	0	0	0,00	0	0	0,0	0	0	0,0	
11	Gearbox cover	1	POM	3	3	2,21	9,6	9,6	1,1	0,004485	0,004485	0,1	
12	Motor Axis connector	1	Thermoplastic	0	0	0,00	0	0	0,0	0	0	0,0	
13	Power button	1	Other electronics	0	0	0,00	0	0	0,0	0	0	0,0	
14	Top seal	1	Metal + Elastomer -> Thermoplastic	0	0	0,00	0	0	0,0	0	0	0,0	Non magnetic metal, elastomer
15	Axis / Powerbutton holder	1	POM	1	1	0,74	3,2	3,2	0,4	0,001495	0,001495	0,0	
16	Axis	1	Steel	4	4	2,94	9,3	9,3	1,0	0,002738	0,002738	0,1	
17	Motor off centre axis	1	Thermoplastic	0	0	0,00	0	0	0,0	0	0	0,0	Sinks
18	Motor bracket	1	POM	7	7	5,15	22,4	22,4	2,5	0,01932	0,01932	0,6	
19	Motor spring	1	Steel	1	1	0,74	2,325	2,325	0,3	0,0006845	0,0006845	0,0	
20	Motor	1	E-motor	33	33	24,26	389,4	389,4	43,8	2,11365	2,11365	64,7	
21							0	0	0,0	0	0	0,0	
22							0	0	0,0	0	0	0,0	
23							0	0	0,0	0	0	0,0	
24							0	0,0	0,0	0	0,0	0,0	
25							0	0,0	0,0	0	0,0	0,0	
26							0	0,0	0,0	0	0,0	0,0	
27							0	0,0	0,0	0	0,0	0,0	
28							0	0,0	0,0	0	0,0	0,0	
29							0	0,0	0,0	0	0,0	0,0	
30							0	0,0	0,0	0	0,0	0,0	

Materials	CO2 per kg	Value per kg (euro)
PP	2,915	1,2 Sourced from Granta Edupack 2020, used middle of given range
Low carbon steel	2,325	0,6845 Sourced from Granta Edupack 2020, used middle of given range
Battery	3,15	9,845 Sourced from HS mapping sheet
PCB	161	587,5 Sourced from HS mapping sheet
E-motor	11,8	64,05 Sourced from HS mapping sheet
Other electronics	10	148,2 Sourced from HS mapping sheet
ASA	4,865	2,335 Sourced from Granta Edupack 2020, used middle of given range
ABS	3,44	1,9 Sourced from Granta Edupack 2020, used middle of given range
Polyisoprene rubber	4,085	2,3 Sourced from Granta Edupack 2020, used middle of given range
POM	3,2	1,495 Sourced from Granta Edupack 2020, used middle of given range
Thermoplastic	3,027	2,76 Sourced from HS mapping sheet

Parts ordering & grouping					
Group	Part - general	Part - specific	% mass	% footprint	%value
High impact, occurring in all brushes	Battery	AA battery	33,8	16,3	13,9
	Motor	PCB	0,7	18,1	18,0
		Motor	24,3	43,8	64,7
Waterproofing	Main body	Main body	20,6	11,8	1,8
	Bottom seal	Seal ring	0,7	0,3	0,1
	Top seal	Top seal	0,0	0,0	0,0
Other - electronics	-	Power button	0,0	0,0	0,0
	-	Bottom cap spring	0,7	0,3	0,0
	-	Seal spring	0,7	0,3	0,0
Other - metals	-	Battery contact short	0,0	0,0	0,0
	-	Battery contact long	0,0	0,0	0,0
	-	Axis	2,9	1,0	0,1
Other - plastics	-	Motor spring	0,7	0,3	0,0
	-	Brush head	3,7	1,7	0,4
	-	Bottom cap	2,9	2,2	0,3
	-	Gearbox cover	2,2	1,1	0,1
	-	Motor Axis connector	0,0	0,0	0,0
	-	Axis / Powerbutton holder	0,7	0,4	0,0
	-	Motor off centre axis	0,0	0,0	0,0
	-	Motor bracket	5,1	2,5	0,6
	-				
	-				

Material type count	# of different types
Material	
Polymers	3 (ASA, ABS, POM)
Polymers - unidentified but assumed unique	4 (Brush head, Main body, motor axis connector, motor off centre axis)
Polymers - unidentified but assumed same as identified	0
Polymers - total	7
Elastomer	0
Elastomers - unidentified but assumed unique	3 (seal ring, main body, top seal)
Polymers - unidentified but assumed same as identified	0
Elastomers - total	3
Metals	1 (Steel)
Metals - unidentified but assumed unique	1 (top seal)
Metals - unidentified but assumed same as identified	0
Metals - total	2

Model	Oral-B professional care
Number of parts	31
Number of unique parts	28
Total weight (added up)	130
Total weight (measured)	129
Total CO2	1481,7575
Total economic value	11,725843

#	Part	Number of parts	Material	Mass			Footprint			Material value			Notes
				per part (g)	total (g)	total (%)	CO2 per part (g)	CO2 total (g)	CO2 total (%)	per part (euro)	total (euro)	total (%)	
1	Brush head	1	Mixed, mainly ?	5	5	3,8	15,135	15,135	1,0	0,0138	0,0138	0,1	Sinks
2	Bottom cap	1	ASA / Elastomer	5	5	3,8	24,325	24,325	1,6	0,011675	0,011675	0,1	
3	Spring	1	Steel	1	1	0,8	2,325	2,325	0,2	0,0006845	0,0006845	0,0	
4	Main body	1	ABS/TPE (Polyisoprene rubber)	27	27	20,8	101,5875	101,5875	6,9	0,0567	0,0567	0,5	Assumed based on oral b advance power
5	Power button pressure plate	1	Stainless steel	4	4	3,1	21,78	21,78	1,5	0,01124	0,01124	0,1	
6	Battery	1	Rechargeable	23	23	17,7	346,15	346,15	23,4	7,6475	7,6475	65,2	
7	Pressure sensor PCB connector	1	ABS/Steel (mainly ABS)	1	1	0,8	3,44	3,44	0,2	0,0019	0,0019	0,0	
8	PCB	1	PCB	3	3	2,3	483	483	32,6	1,7625	1,7625	15,0	
9	Battery holder	1	POM	3	3	2,3	9,6	9,6	0,6	0,00485	0,00485	0,0	
10	Pressure sensor axis	1	Stainless steel	1	1	0,8	5,445	5,445	0,4	0,00281	0,00281	0,0	
11	LED bracket lock ring	1	Thermoplastic	0	0	0,0	0	0	0,0	0	0	0,0	Sinks
12	LED bracket	1	POM	2	2	1,5	6,4	6,4	0,4	0,00299	0,00299	0,0	Sinks
13	LED wire	2	-	0	0	0,0	0	0	0,0	0	0	0,0	x
14	LED	1	Other electronics	0	0	0,0	0	0	0,0	0	0	0,0	
15	Motor / Gearbox bracket	1	Steel	8	8	6,2	18,6	18,6	1,3	0,005476	0,005476	0,0	
16	Rotating oscillating converter gear	1	Thermoplastic	0	0	0,0	0	0	0,0	0	0	0,0	Sinks
17	Brush axis spring	1	Steel	0	0	0,0	0	0	0,0	0	0	0,0	
18	Brush axis housing	1	POM	4	4	3,1	12,8	12,8	0,9	0,00598	0,00598	0,1	
19	Motor / Gearbox connector	1	POM	1	1	0,8	2,325	2,325	0,2	0,0006845	0,0006845	0,0	Sinks
20	Pressure sensor springs	2	Steel	0	0	0,0	0	0	0,0	0	0	0,0	
21	Pressure sensor contact	1	Steel	0	0	0,0	0	0	0,0	0	0	0,0	
22	Motor	1	E-motor	34	34	26,2	401,2	401,2	27,1	2,1777	2,1777	18,6	
23	Top seal	1	Metal/Elastomer -> Thermoplastic	0	0	0,0	0	0	0,0	0	0	0,0	Non magnetic metal, elastomer
24	Brush axis	1	Steel	4	4	3,1	9,3	9,3	0,6	0,002738	0,002738	0,0	
25	Axis spacers	2	Steel	0	0	0,0	0	0	0,0	0	0	0,0	
26	Axis holder	1	POM	1	1	0,8	3,2	3,2	0,2	0,001495	0,001495	0,0	
27	Charging coil	1	Copper	2	2	1,5	8,1	8,1	0,5	0,01175	0,01175	0,1	
28	Charging coil bracket	1	PA	1	1	0,8	7,045	7,045	0,5	0,003735	0,003735	0,0	
29							0	0	0,0	0	0	0,0	
30							0	0	0,0	0	0	0,0	

Materials	CO2 per kg	Value per kg (euro)	
PP	2,915	1,2	Sourced from Granta Edupack 2020, used middle of given range
Low carbon steel	2,325	0,6845	Sourced from Granta Edupack 2020, used middle of given range
Battery	3,15	9,845	Sourced from HS mapping sheet
PCB	161	587,5	Sourced from HS mapping sheet
E-motor	11,8	64,05	Sourced from HS mapping sheet
Other electronics	10	148,2	Sourced from HS mapping sheet
ASA	4,865	2,335	Sourced from Granta Edupack 2020, used middle of given range
ABS	3,44	1,9	Sourced from Granta Edupack 2020, used middle of given range
Polyisoprene rubber	4,085	2,3	Sourced from Granta Edupack 2020, used middle of given range
POM	3,2	1,495	Sourced from Granta Edupack 2020, used middle of given range
HDPE	1,86	1,03	Sourced from Granta Edupack 2020, used middle of given range
ABS + PC	4,87	3,53	Sourced from Granta Edupack 2020, used middle of given range
Rechargeable	15,05	332,5	Sourced from HS mapping sheet
Stainless steel	5,445	2,81	Sourced from Granta Edupack 2020, used middle of given range
Copper	4,05	5,875	Sourced from Granta Edupack 2020, used middle of given range
PA	7,045	3,735	Sourced from Granta Edupack 2020, used middle of given range
Thermoplastic	3,027	2,76	Sourced from HS mapping sheet

Parts ordering & grouping					
Group	Part - general	Part - specific	% mass	%footprint	%value
High impact, occurring in all brushes	Battery	Battery	17,7	23,4	65,2
	PCB	PCB	2,3	32,6	15,0
Waterproofing	Motor	Motor	26,2	27,1	18,6
	Main body	Main body	20,8	6,9	0,5
	Bottom seal	Bottom cap	3,8	1,6	0,1
Other - electronics	Top seal	Top seal	0,0	0,0	0,0
	LED	LED	0,0	0,0	0,0
Other - metals	Spring	Spring	0,8	0,2	0,0
	Power button pressure plate	Power button pressure plate	3,1	1,5	0,1
	Pressure sensor axis	Pressure sensor axis	0,8	0,4	0,0
	LED wire	LED wire	0,0	0,0	0,0
	Motor / Gearbox bracket	Motor / Gearbox bracket	6,2	1,3	0,0
	Brush axis spring	Brush axis spring	0,0	0,0	0,0
	Pressure sensor springs	Pressure sensor springs	0,0	0,0	0,0
	Pressure sensor	Pressure sensor	0,0	0,0	0,0
	contact	contact	0,0	0,0	0,0
	Brush axis	Brush axis	3,1	0,6	0,0
	Axis spacers	Axis spacers	0,0	0,0	0,0
	Charging coil wire	Charging coil wire	1,5	0,5	0,1
	Brush head	Brush head	3,8	1,0	0,1
	Pressure sensor PCB connector	Pressure sensor PCB connector	0,8	0,2	0,0
	Battery holder	Battery holder	2,3	0,6	0,0
LED bracket lock ring	LED bracket lock ring	0,0	0,0	0,0	
LED bracket	LED bracket	1,5	0,4	0,0	
Rotating oscillating converter gear	Rotating oscillating converter gear	0,0	0,0	0,0	
Brush axis housing	Brush axis housing	3,1	0,9	0,1	
Motor / Gearbox connector	Motor / Gearbox connector	0,8	0,2	0,0	
Axis holder	Axis holder	0,8	0,2	0,0	
Charging coil bracket	Charging coil bracket	0,8	0,5	0,0	

Material	# of different types
Material	
Polymers	4 ASA,ABS,POM,PA
Polymers - unidentified but assumed unique	2 Brush head, LED bracket lock ring
Polymers - unidentified but assumed same as identified	1 Rotating oscillating converter gear (POM)
Polymers - total	6
Elastomer	0
Elastomers - unidentified but assumed unique	2 (Main body + bottom cap, Top Seal)
Polymers - unidentified but assumed same as identified	0
Elastomers - total	2
Metals	3 Steel, Stainless steel, copper)
Metals - unidentified but assumed unique	1 (top seal)
Metals - unidentified but assumed same as identified	0
Metals - total	4

Model	Philips Sonicare EasyClean
Number of parts	30
Number of unique parts	28
Total weight (added up)	129
Total weight (measured)	131
Total CO2	1565,9925
Total economic value	10,640546

#	Part	Number of parts	Material	Mass			Footprint			Material value			Notes
				per part (g)	total (g)	total (%)	CO2 per part (g)	CO2 total (g)	CO2 total (%)	per part (euro)	total (euro)	total (%)	
1	Brush head	1	?	5	5	3,9	15,135	15,135	1,0	0,0138	0,0138	0,1	Tip floats, bottom sinks
2	Main body	1	PA + ABS Thermoplastic, polymer	31	31	24,0	177,94	177,94	11,4	0,100285	0,100285	0,9	Sinks
3	Power button	1	1 + elastomer	1	1	0,8	3,027	3,027	0,2	0,00276	0,00276	0,0	Floats
4	PCB cover	2	1 Thermoplastic	2	2	1,6	6,054	6,054	0,4	0,00552	0,00552	0,1	Floats
5	Seal ring	0	0	0	0,0	0	0	0,0	0	0	0,0	0,0	Sinks
6	Bottom cap	2	1 Thermoplastic	2	2	1,6	6,054	6,054	0,4	0,00552	0,00552	0,1	Sinks
7	Battery cover	3	1 Thermoplastic	3	3	2,3	9,081	9,081	0,6	0,00828	0,00828	0,1	Floats
8	Front axis lock	1	1 Steel	0	0	0,0	0	0	0,0	0	0	0,0	0,0
9	Spring holder	1	1 Thermoplastic	1	1	0,8	3,027	3,027	0,2	0,00276	0,00276	0,0	Floats
10	Spring	1	1 Steel	1	1	0,8	2,325	2,325	0,1	0,006845	0,006845	0,0	
11	Motor	1	1 E-motor	22	22	17,1	259,6	259,6	16,6	1,4091	1,4091	13,2	
12	Battery	1	1 Rechargeable	20	20	15,5	301	301	19,2	6,65	6,65	62,5	
13	Charging coil	2	1 Copper	2	2	1,6	8,1	8,1	0,5	0,01175	0,01175	0,1	
14	PCB	4	1 PCB	4	4	3,1	644	644	41,1	2,35	2,35	22,1	
15	PCB / Battery carriage	1	?	6	6	4,7	18,162	18,162	1,2	0,01656	0,01656	0,2	Sinks
16	Charging coil pins	2	2 Metal	0	0	0,0	0	0	0,0	0	0	0,0	non magnetic
17	Top bracket	1	1 Stainless steel	5	5	3,9	27,225	27,225	1,7	0,01405	0,01405	0,1	
18	Top axis holder	1	1 Thermoplastic	1	1	0,8	3,027	3,027	0,2	0,00276	0,00276	0,0	
19	Bottom bracket	1	1 Stainless steel	5	5	3,9	27,225	27,225	1,7	0,01405	0,01405	0,1	
20	Bottom axis holder	2	1 Thermoplastic	1	2	1,6	3,027	6,054	0,4	0,00276	0,00552	0,1	Sinks
21	Magnet lock	1	1 Steel	0	0	0,0	0	0	0,0	0	0	0,0	
22	Magnet	1	1 Ferrite	7	7	5,4	6,1915	6,1915	0,4	0,0061075	0,0061075	0,1	<a href="#">Ferrite Magnets/Ceramic Magnets   Eclipse Magnetics</a>
23	Axis bracket	1	1 Steel	1	1	0,8	2,325	2,325	0,1	0,006845	0,006845	0,0	
24	Axis	1	1 Steel	1	1	0,8	2,325	2,325	0,1	0,006845	0,006845	0,0	
25	Top seal lock	0	1 Thermoplastic	0	0	0,0	0	0	0,0	0	0	0,0	
26	Top seal	0	1 Elastomer	0	0	0,0	0	0	0,0	0	0	0,0	Sinks
27	Front axis	7	1 Stainless steel	7	7	5,4	38,115	38,115	2,4	0,01967	0,01967	0,2	
28	Top seal rear positioner	1	1 Thermoplastic	0	0	0,0	0	0	0,0	0	0	0,0	Sinks
29													
30													

Materials	CO2 per kg	Value per kg (euro)	
PP		2,915	1,2 Sourced from Granta Edupack 2020, used middle of given range
Low carbon steel	2,325	0,6845	Sourced from Granta Edupack 2020, used middle of given range
Battery	3,15	9,845	Sourced from HS mapping sheet
PCB	161	587,5	Sourced from HS mapping sheet
E-motor	11,8	64,05	Sourced from HS mapping sheet
Other electronics	10	148,2	Sourced from HS mapping sheet
ASA	4,865	2,335	Sourced from Granta Edupack 2020, used middle of given range
ABS	3,44	1,9	Sourced from Granta Edupack 2020, used middle of given range
Thermoset	3	3,4	Sourced from HS mapping sheet -> Thermoset
POM	3,2	1,495	Sourced from Granta Edupack 2020, used middle of given range
HDPE	1,86	1,03	Sourced from Granta Edupack 2020, used middle of given range
ABS + PC	4,87	3,53	Sourced from Granta Edupack 2020, used middle of given range
Rechargeable	15,05	332,5	Sourced from HS mapping sheet
Stainless steel	5,445	2,81	Sourced from Granta Edupack 2020, used middle of given range
Copper	4,05	5,875	Sourced from Granta Edupack 2020, used middle of given range
PA	7,045	3,735	Sourced from Granta Edupack 2020, used middle of given range
Ferrite	0,8845	0,8725	Sourced from Granta Edupack 2020, used middle of given range
Thermoplastic	3,027	2,76	Sourced from HS mapping sheet
PA + ABS	5,74	3,235	Sourced from Granta Edupack 2020, used middle of given range

Parts ordering & grouping	Part - general	Part - specific	% mass	%footprint	%value
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High impact, occurring in all brushes	Battery	Battery	15,5	19,2	62,5
	PCB	PCB non magnetic	3,1	41,1	22,1
	Motor	Motor	17,1	16,6	13,2
	Main body	Main body	24,0	11,4	0,9
Waterproofing	Bottom seal	Seal ring	0,0	0,0	0,0
	Top seal	Top seal	0,0	0,0	0,0
Other - electronics	-	Power button	0,8	0,2	0,0
	-	Front axis lock	0,0	0,0	0,0
	-	Spring	0,8	0,1	0,0
	-	Charging coil	1,6	0,5	0,1
	-	Charging coil pins	0,0	0,0	0,0
	-	Top bracket	3,9	1,7	0,1
	-	Bottom bracket	3,9	1,7	0,1
	-	Magnet lock	0,0	0,0	0,0
	-	Magnet	5,4	0,4	0,1
	-	Axis bracket	0,8	0,1	0,0
Other - metals	-	Axis	0,8	0,1	0,0
	-	Front axis	5,4	2,4	0,2
	-	Brush head	3,9	1,0	0,1
	-	PCB cover	1,6	0,4	0,1
	-	Bottom cap	1,6	0,4	0,1
	-	Battery cover	2,3	0,6	0,1
	-	Spring holder	0,8	0,2	0,0
	-	PCB / Battery carriage	4,7	1,2	0,2
	-	Top axis holder	0,8	0,2	0,0
	-	Bottom axis holder	1,6	0,4	0,1
Other - plastics	-	Top seal lock	0,0	0,0	0,0
	-	Top seal rear positioner	0,0	0,0	0,0

Material type count	# of different types
Material	
Polymers	1 (PA + ABS)
Polymers - unidentified but assumed unique	(Brush head, PCB/Battery carriage, Top axis holder+Bottom axis holder+Top seal rear positioner, Top seal lock, Power button
Polymers - unidentified but assumed same as identified	5
Polymers - total	1 (bottom cap (PA + ABS))
Elastomer	0
Elastomers - unidentified but assumed unique	(Power button, PCB cover+Battery cover+Spring holder, Seal ring, top seal)
Polymers - unidentified but assumed same as identified	4
Metals	3 (steel, stainless steel, copper)
Metals - unidentified but assumed unique	1 (Charging coils pins)
Metals - unidentified but assumed same as identified	0
Metals - total	4

## ***Appendix E. Hotspot mapping sheets***

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*Appendix on the following pages*



# HotSpot Mapping Datasheet

## General project information

Brand name	Oral-B advance power
Product category	Electric Toothbrush
Authors	Mart Drummen
Date	1-4-2022
Location	Delft

You can enter data in the light blue cells

To:	Steps:	Time (s):
Motor	19	950
Battery	2	10
PCB	14	925
Main body	6	590

## Overall HotSpot Results

Total:	Average:
- time to disassemble 1040 sec	- force 2
- number of tasks 32	- accessibility 1
- number of steps 25	- positioning 3
- number of tools 11	

[1=low .. 5=high .. 10=extreme]  
 [1=clear .. 5=moderate .. 10=difficult]  
 [1=easy .. 5=moderate .. 10=difficult]

Step number	Name	General properties		Activity properties			Difficulty of Access			Functional sensitivity			Material properties		HotSpot Indicators			Notes				
		Subassembly	Part of ...	Activity	Required tool	Tool size	Task frequency	Time to disconnect (sec)	Force	Accessibility	Positioning	Maintenance	Functionality	Extra requirement	Material group	Weight (g)	Time		Activity	Priority part	Environmental	Economic
1	Brush head	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 1 - Part wears during u	level 2 - Main functionality	level 0 - Not important	Mixed materials mainly plast	5						
2	Bottom cap	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	4						
3	Bottom cap spring	no	main assembly	Disconnect snapjoi	Screwdriver	1.8 mm flat	2	15	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Steel	1	▶					
4	AA batteries	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 2 - High chance of brea	level 2 - Main functionality	level 0 - Not important	Battery	46			▶	▶	▶	
5	Seal ring	no	main assembly	Remove	Screwdriver	1.8 mm flat	1	10	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
6	Seal spring	no	main assembly	Remove	Screwdriver	1.8 mm flat	1	15	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Steel	1	▶					
7	Main body	no	main assembly	Other	Uncommon tool	Saw, destroy part	1	530	level 2 - Heavy resistance	level 0 - Clear	level 2 - High precision	level 1 - Part wears during u	level 1 - Sub functionality	level 0 - Not important	Mixed materials mainly plast	28	▶	▶		▶	▶	This step is required to reach any of the following parts. Removing the body without destroying it appears impossible due to the use of irreversible snap fits.
8	PCB	no	main assembly	Remove	Soldering iron	-	7	330	level 1 - Moderate resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	PCB	1	▶	▶		▶	▶	4x powerbutton, 1x battery, 1x motor, 1x battery & motor. Is made more difficult due to having to pull up the pcb and desolder simultaneously
9	Battery contact short	no	main assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	Aluminium	0						
10	Battery contact long	no	main assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Aluminium	0						Same move
11	Brush axis assembly	yes	main assembly	Disconnect snapjoi	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important								
12	Motor assembly	yes	main assembly	Disconnect snapjoi	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important								
13	Gearbox cover	no	Brush axis assembly	Remove	Screwdriver	1.8 mm flat	1	20	level 1 - Moderate resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	3	▶					
14	Motor Axis connector	no	Brush axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	0						
15	Power button	no	Brush axis assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Other Electronics	0						
16	Top seal	no	Brush axis assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 2 - Heavy resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Mixed materials mainly met	0						
17	Axis / Powerbutton holder	no	Brush axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
18	Axis	no	Brush axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 2 - Main functionality	level 0 - Not important	Mixed materials mainly met	4						
19	Motor off centre axis	no	Motor assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	0						
20	Motor bracket	no	Motor assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	7						
21	Motor spring	no	Motor assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintena	level 1 - Sub functionality	level 0 - Not important	Steel	1						Same move
22	Motor	no	Motor assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 1 - Part wears during u	level 2 - Main functionality	level 0 - Not important	E-motor	33			▶	▶	▶	



# HotSpot Mapping Datasheet

## General project information

Brand name	Philips Sonicare EasyClean
Product category	Electric Toothbrush
Authors	Mart Drummen
Date	1-4-2022
Location	Delft

You can enter data in the light blue cells

## Priority part accessibility

To:	Steps:	Time (s):
Motor	39	1095
Battery	8	320
PCB	17	710
Main body	3	125

## Overall HotSpot Results

Total:	Average:
- time to disassemble	1720 sec
- number of tasks	65
- number of steps	46
- number of tools	19
- force	2
- accessibility	1
- positioning	4

[1=low .. 5=high .. 10=extreme]  
 [1=clear .. 5=moderate .. 10=difficult]  
 [1=easy .. 5=moderate .. 10=difficult]

Step number	Name	General properties		Activity properties		Difficulty of Access			Functional sensitivity			Material properties		HotSpot Indicators		Notes						
		Subassembly	Part of ...	Activity	Required tool	Tool size	Task frequency	Time to disconnect (sec)	Force	Accessibility	Positioning	Maintenance	Functionality	Extra requirement	Material group		Weight (g)	Time	Activity	Priority part	Environmental	Economic
1	Brushhead	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 1 - Part wears during use	level 2 - Main functionality	level 0 - Not important	Mixed materials mainly plastic	5						
2	Main body	no	main assembly	Remove	Lever / Prybar	Ifixit Jimmy	1	110	level 2 - Heavy resistance	level 0 - Clear	level 1 - Moderate precision	level 1 - Part wears during use	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	31						
3	Main body	no	main assembly	Remove	Hands	-	1	10	level 2 - Heavy resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
4	Power button	no	main assembly	Disconnect snap joint	Screwdriver	1.8 mm flat	1	40	level 0 - Light resistance	level 1 - Recessed	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
5	PCB cover	no	main assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 0 - No-to-low functionality	level 0 - Not important	Thermoplastic	2						
6	Seal ring	no	main assembly	Remove	Screwdriver	1.8 mm flat	1	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	0						
7	Bottom cap	no	main assembly	Disconnect snap joint	Hands	-	1	5	level 1 - Moderate resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	2						
8	Bottom cap	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 0 - No-to-low functionality	level 0 - Not important	Thermoplastic	3						
9	Battery cover	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 0 - No-to-low functionality	level 0 - Not important	Thermoplastic	3						
10	Front axis lock	no	main assembly	Unscrew	Screwdriver	Philips #1	1	15	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Steel	0						
11	Front axis lock	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Steel	0						
12	Front axis assembly	yes	main assembly	Disconnect snap joint	Screwdriver	1.8 mm flat	1	15	level 1 - Moderate resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
13	Spring holder	no	main assembly	Remove	Hands	-	1	5	level 1 - Moderate resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
14	Spring	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Steel	1						
15	Motor	no	main assembly	De-solder	Soldering iron	-	2	120	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 1 - Part wears during use	level 2 - Main functionality	level 0 - Not important	E-motor	22						The motor cannot be removed after this step
16	Battery	no	main assembly	De-solder	Soldering iron	-	2	180	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 2 - High chance of breakage	level 2 - Main functionality	level 0 - Not important	Rechargeable	20						
17	Battery	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	High-end metals	2						
18	Charging coil	no	main assembly	De-solder	Soldering iron	-	2	240	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	High-end metals	2						
19	Charging coil	no	main assembly	Remove	Hands	-	1	50	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	PCB	4						
20	PCB	no	main assembly	De-solder	Soldering iron	-	2	15	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	PCB	4						
21	PCB	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	PCB	4						
22	PCB / Battery carriage	no	main assembly	Disconnect snap joint	Screwdriver	1.8 mm flat	2	10	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	6						
23	PCB / Battery carriage	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	6						
24	Charging coil pins	no	main assembly	Remove	Pliers	1 hand use	2	100	level 2 - Heavy resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Aluminium	0						
25	Top bracket	no	main assembly	Other	Uncommon tool	Small angle grinder (Dremel)	10	330	level 2 - Heavy resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Stainless Steel	5						10 spot welds, cannot be pried open so a small angle grinder was used
26	Top bracket	no	main assembly	Unscrew	Screwdriver	Philips #0	1	10	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Stainless Steel	5						
27	Top bracket	no	main assembly	Disconnect snap joint	Screwdriver	1.8 mm flat	4	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Stainless Steel	5						
28	Top axis holder	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Mixed materials mainly plastic	1						
29	Bottom bracket	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Mixed materials mainly plastic	1						
30	Bottom bracket	no	main assembly	Unscrew	Screwdriver	Philips #0	1	10	level 0 - Light resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Stainless Steel	5						
31	Motor	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Mixed materials mainly plastic	1						
32	Bottom axis holder	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
33	Bottom axis holder	no	main assembly	Disconnect snap joint	Hands	-	2	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
34	Magnet lock	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	1						
35	Magnet lock	no	main assembly	Unscrew	Screwdriver	Philips #1 (Actually used: 3.0 mm flat, after using angle grinder)	1	300	level 2 - Heavy resistance	level 0 - Clear	level 2 - High precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Aluminium	0						Due to loctite on screw, it could not be unscrewed directly. The original screw head (philips 0) got destroyed. A new flathead screwhead was created using the angle grinder. The screw is not reusable. The loctite is likely applied due to the high frequency vibrations in this part.
36	Magnet	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 2 - Main functionality	level 0 - Not important	Mixed materials mainly metal	7						
37	Axis bracket	no	main assembly	Unscrew	Screwdriver	Philips #0	1	5	level 0 - Light resistance	level 0 - Clear	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Steel	1						
38	Axis bracket	no	main assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Steel	1						
39	Axis	no	main assembly	Remove	Hands	-	1	0	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 2 - Main functionality	level 0 - Not important	Steel	1						
40	Top seal lock	no	Front axis assembly	Disconnect snap joint	Lever / Prybar	Ifixit Jimmy	1	25	level 1 - Moderate resistance	level 1 - Recessed	level 1 - Moderate precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	0						
41	Top seal lock	no	Front axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	0						
42	Top seal	no	Front axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 1 - Sub functionality	level 0 - Not important	Thermoplastic	0						
43	Front axis	no	Front axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 2 - Main functionality	level 0 - Not important	Stainless Steel	7						
44	Top seal rear positioner	no	Front axis assembly	Remove	Hands	-	1	5	level 0 - Light resistance	level 0 - Clear	level 0 - No-to-low precision	level 0 - No-to-low maintenance	level 0 - No-to-low functionality	level 0 - Not important	Thermoplastic	0						

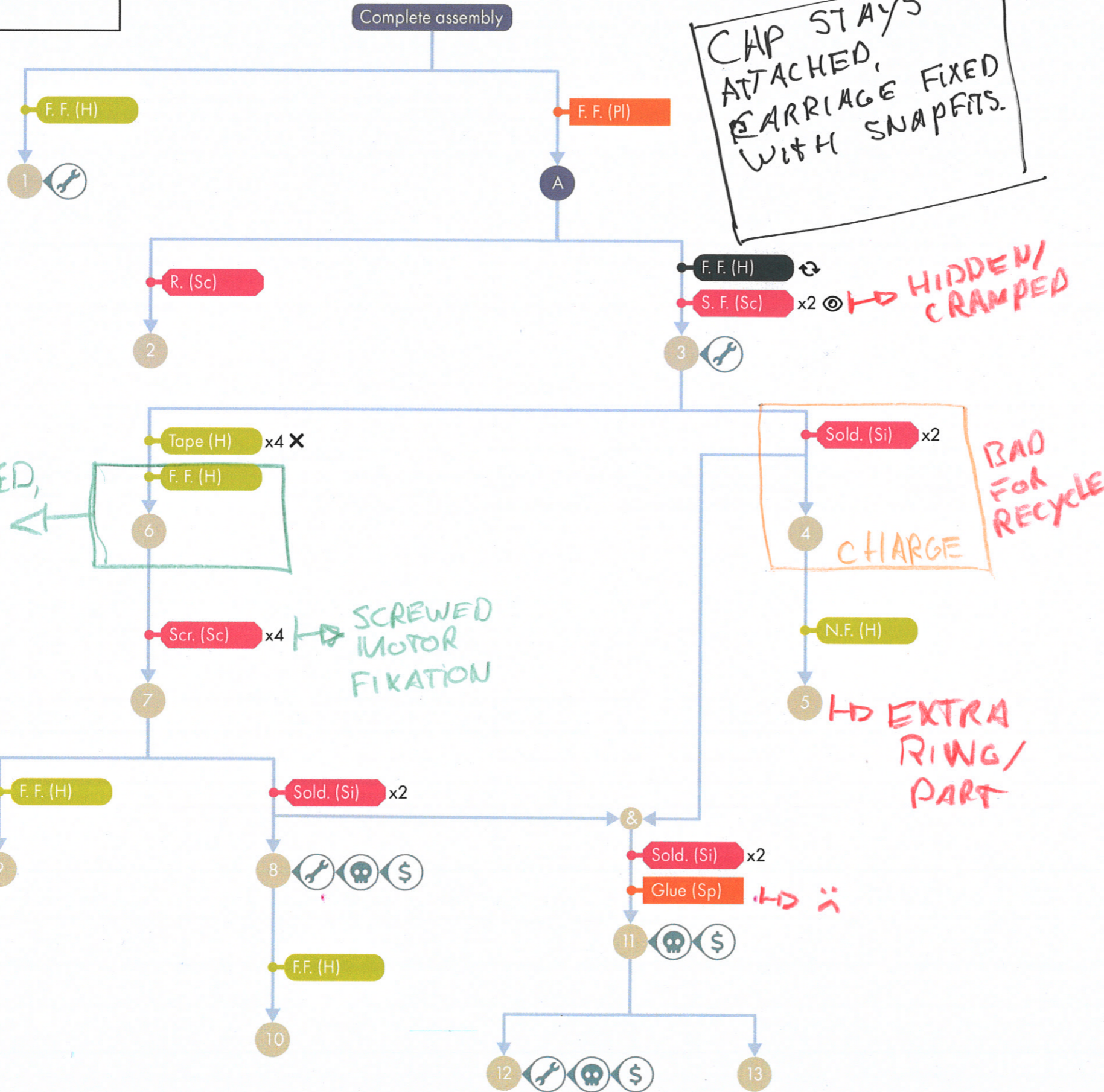
## ***Appendix F. Annotated disassembly maps***

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*Appendix on the following pages*

# Disassembly Map

Electric Toothbrush  
BoomBrush  
Mart Drummen



- Components**
- A. Bottom cap assembly
  - 1. Brush head
  - 2. Seal ring (A)
  - 3. Main body
  - 4. Bottom cap / Charging port (A)
  - 5. Bottom cap ring (A)
  - 6. Top seal
  - 7. Motor cap
  - 8. Motor
  - 9. Motor top damper
  - 10. Motor bottom damper
  - 11. PCB
  - 12. Battery
  - 13. Internal carriage

**Legend**

**Motion type**

- = Hand motion
- = Single motion tool
- = Multiple motion tool

**Force intensity**

Low	Mid	High
<span style="background-color: #FFEB3B; border-radius: 50%; padding: 2px;"> </span>	<span style="background-color: #FFC107; border-radius: 50%; padding: 2px;"> </span>	<span style="background-color: #FF5722; border-radius: 50%; padding: 2px;"> </span>

**Type of tool**

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Penalties**

- ↻ = Product manipulation
- 👁 = Low visibility/identifiability
- ⚠ = Uncommon tool
- ✗ = Non-reusable connector

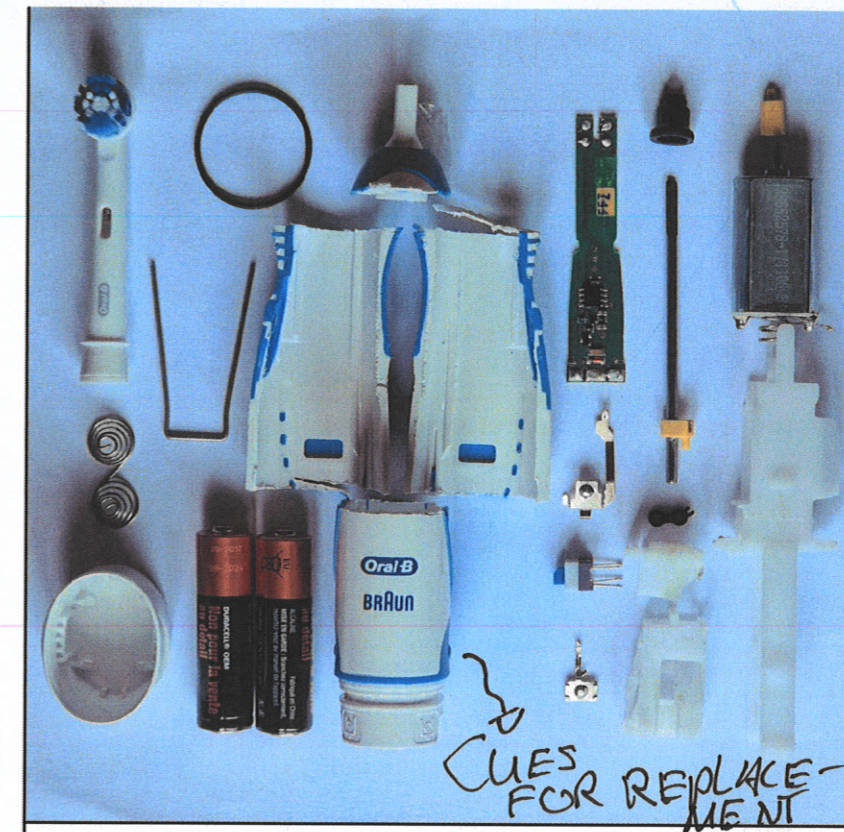
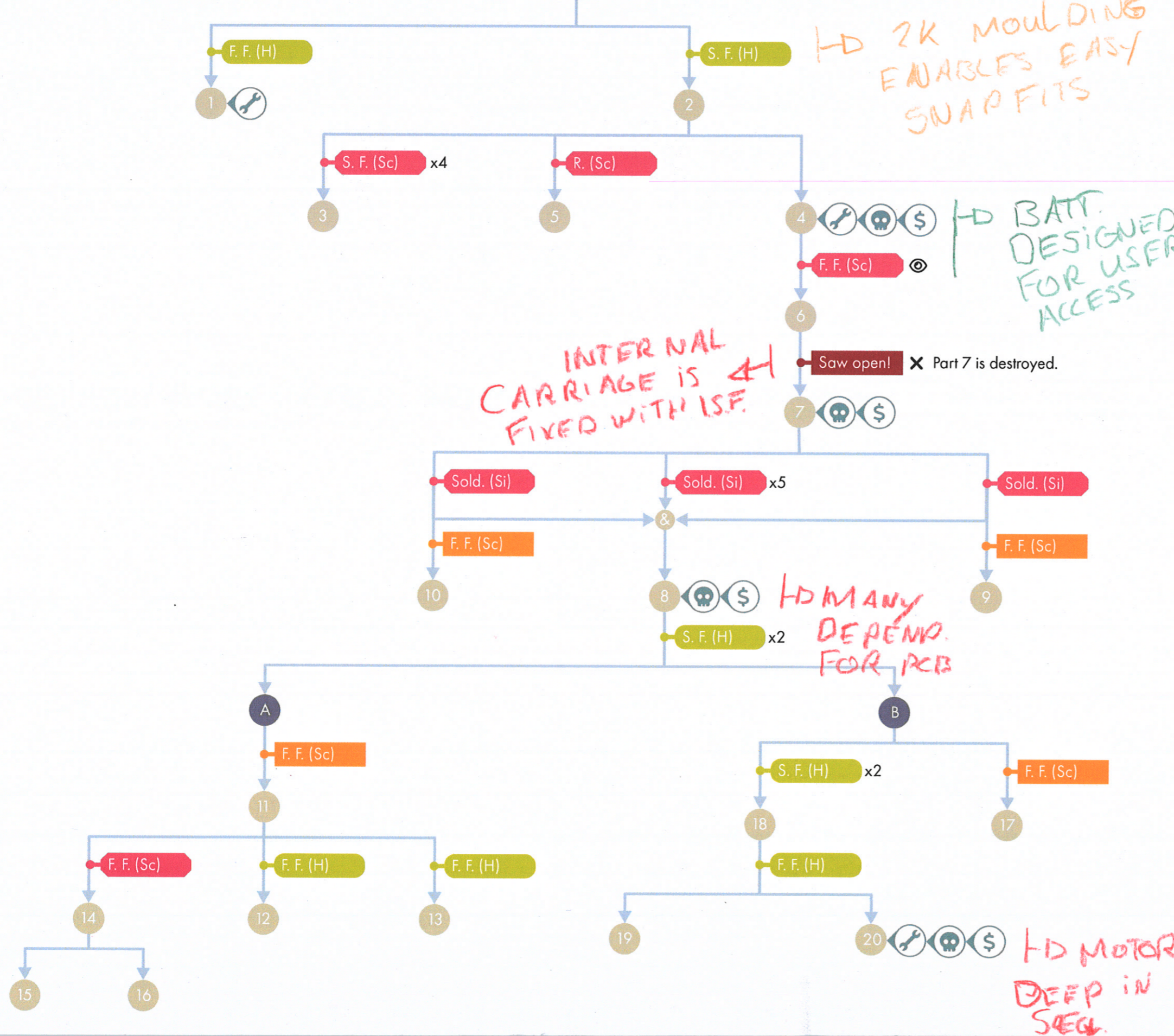
**Target components**

- 🔧 Failure Indicator
- 💀 Environmental Indicator
- 💰 Economic Indicator

# Disassembly Map

Electric Toothbrush  
Oral-B advance power battery  
Mart Drummen

Complete assembly



- Components**
- |                        |                                    |               |
|------------------------|------------------------------------|---------------|
| A. Brush axis assembly | 9. Battery contact short           | 20. Motor (B) |
| B. Motor assembly      | 10. Battery contact long           |               |
| 1. Brush head          | 11. Gearbox cover (A)              |               |
| 2. Bottom cap          | 12. Motor axis connector (A)       |               |
| 3. Bottom cap spring   | 13. Power button (A)               |               |
| 4. AA batteries        | 14. Top seal (A)                   |               |
| 5. Seal ring           | 15. Axis / Power button holder (A) |               |
| 6. Seal spring         | 16. Axis (A)                       |               |
| 7. Main body           | 17. Motor off centre axis (B)      |               |
| 8. PCB                 | 18. Motor bracket (B)              |               |
|                        | 19. Motor spring (B)               |               |

**Legend**

**Motion type**

- Green circle = Hand motion
- Orange square = Single motion tool
- Red square = Multiple motion tool

**Force intensity**

Low	Mid	High
Light green	Light red	Dark red

**Type of tool**

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Penalties**

- Recycling symbol = Product manipulation
- Eye symbol = Low visibility/identifiability
- Warning triangle = Uncommon tool
- X symbol = Non-reusable connector

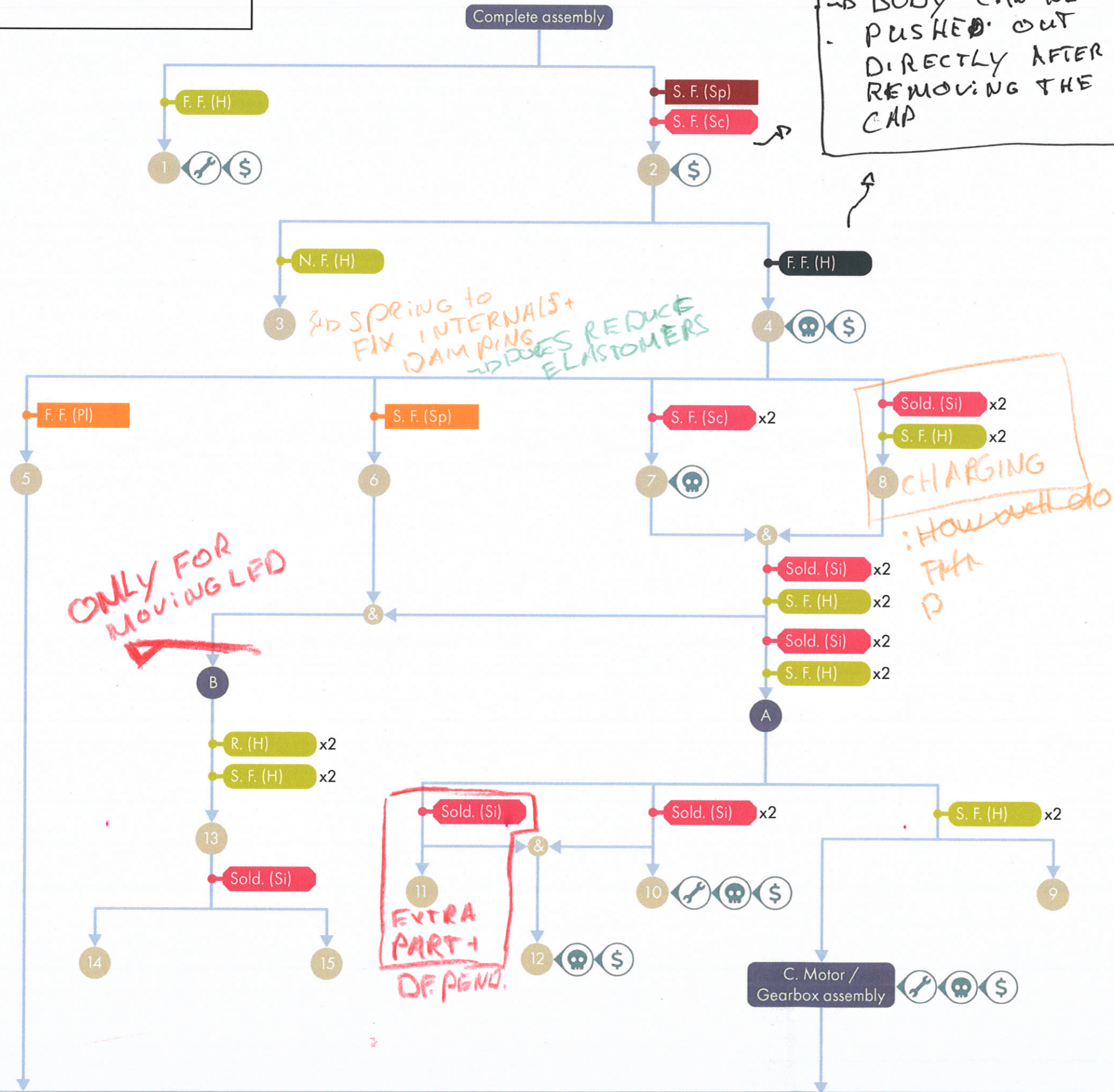
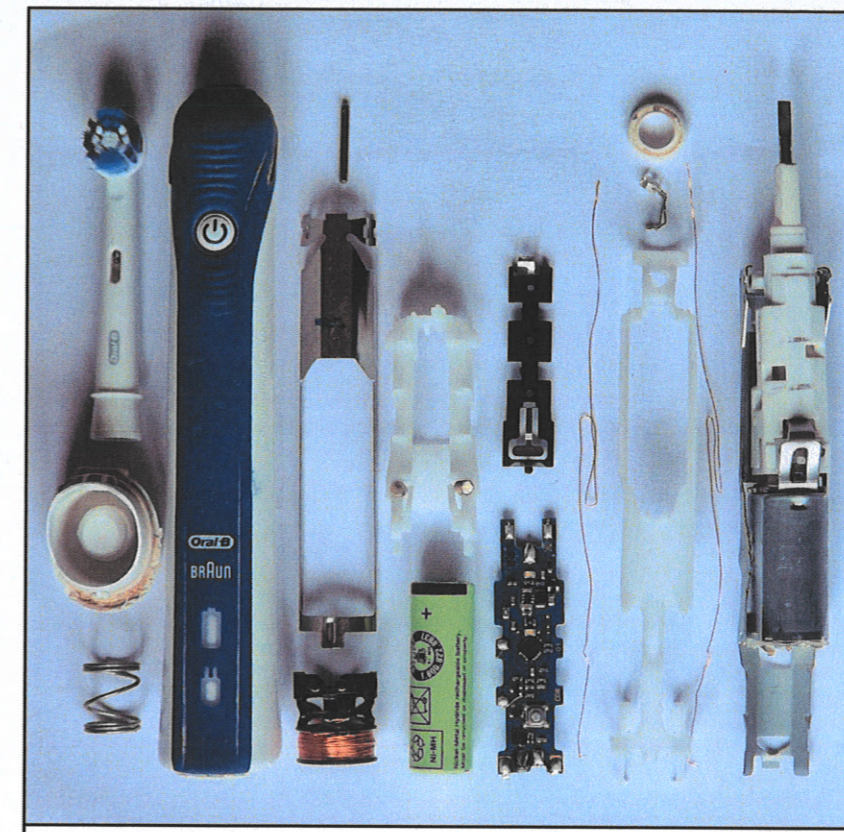
**Target components**

- Wrench icon = Failure Indicator
- Skull icon = Environmental Indicator
- Dollar sign icon = Economic Indicator

# Disassembly Map

Electric Toothbrush  
Oral-B Professional Care 3000  
Marl Drummen

CAP CAN BE REMOVED  
WO. STAYING ATTACHED  
→ BODY CAN BE  
PUSHED OUT  
DIRECTLY AFTER  
REMOVING THE  
CAP



- Components**
- A. Battery / PCB assembly
  - B. LED assembly
  - C. Motor / Gearbox assembly
  - 1. Brush head
  - 2. Bottom cap
  - 3. Spring
  - 4. Main body
  - 5. Pressure sensor axis
  - 6. LED bracket lock ring
  - 7. Power button pressure plate
  - 8. Charging coil
  - 9. Battery holder
  - 10. Battery (A)
  - 11. Pressure sensor PCB connector (A)
  - 12. PCB (A)
  - 13. LED bracket (B)
  - 14. LED wires (B)
  - 15. LED (B)

**Legend**

**Motion type**

- = Hand motion
- = Single motion tool
- = Multiple motion tool

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Target components**

- Failure Indicator
- Environmental Indicator
- Economic Indicator

**Force intensity**

- Low ■
- Mid ■
- High ■

**Type of tool**

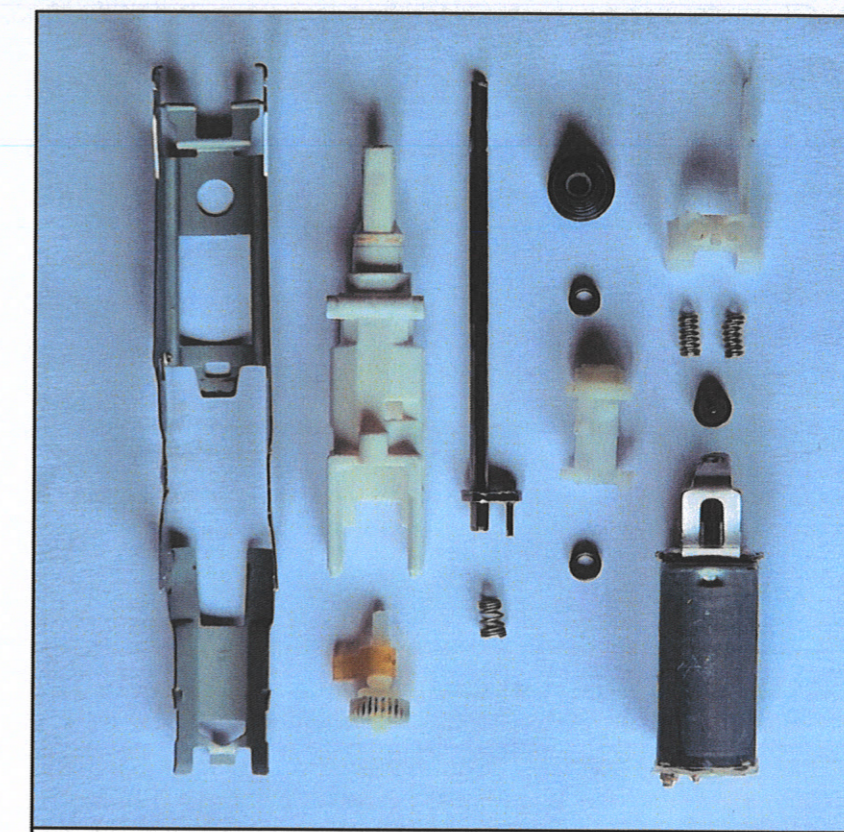
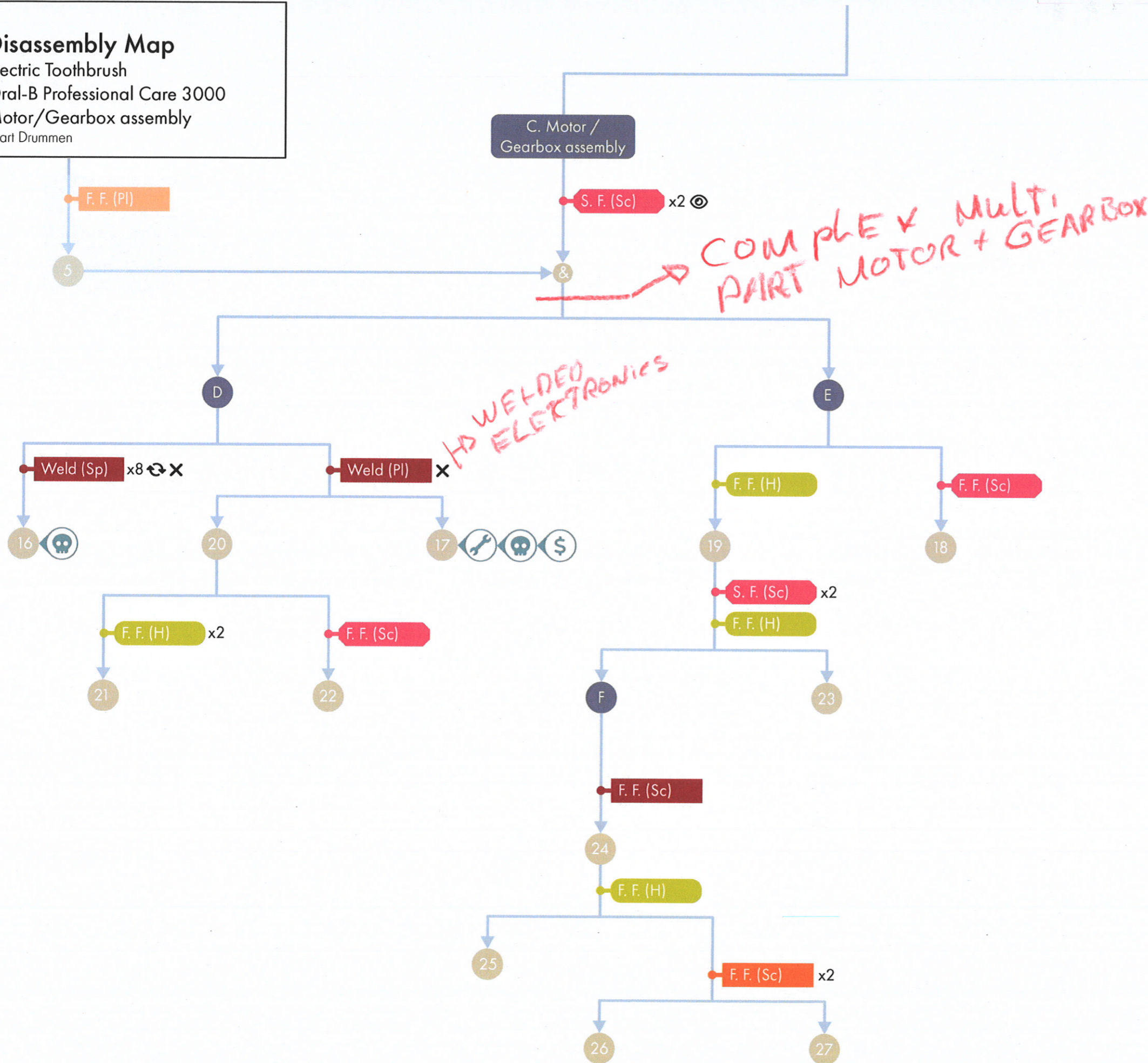
- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Penalties**

- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

# Disassembly Map

Electric Toothbrush  
Oral-B Professional Care 3000  
Motor/Gearbox assembly  
Mart Drummen



## Components

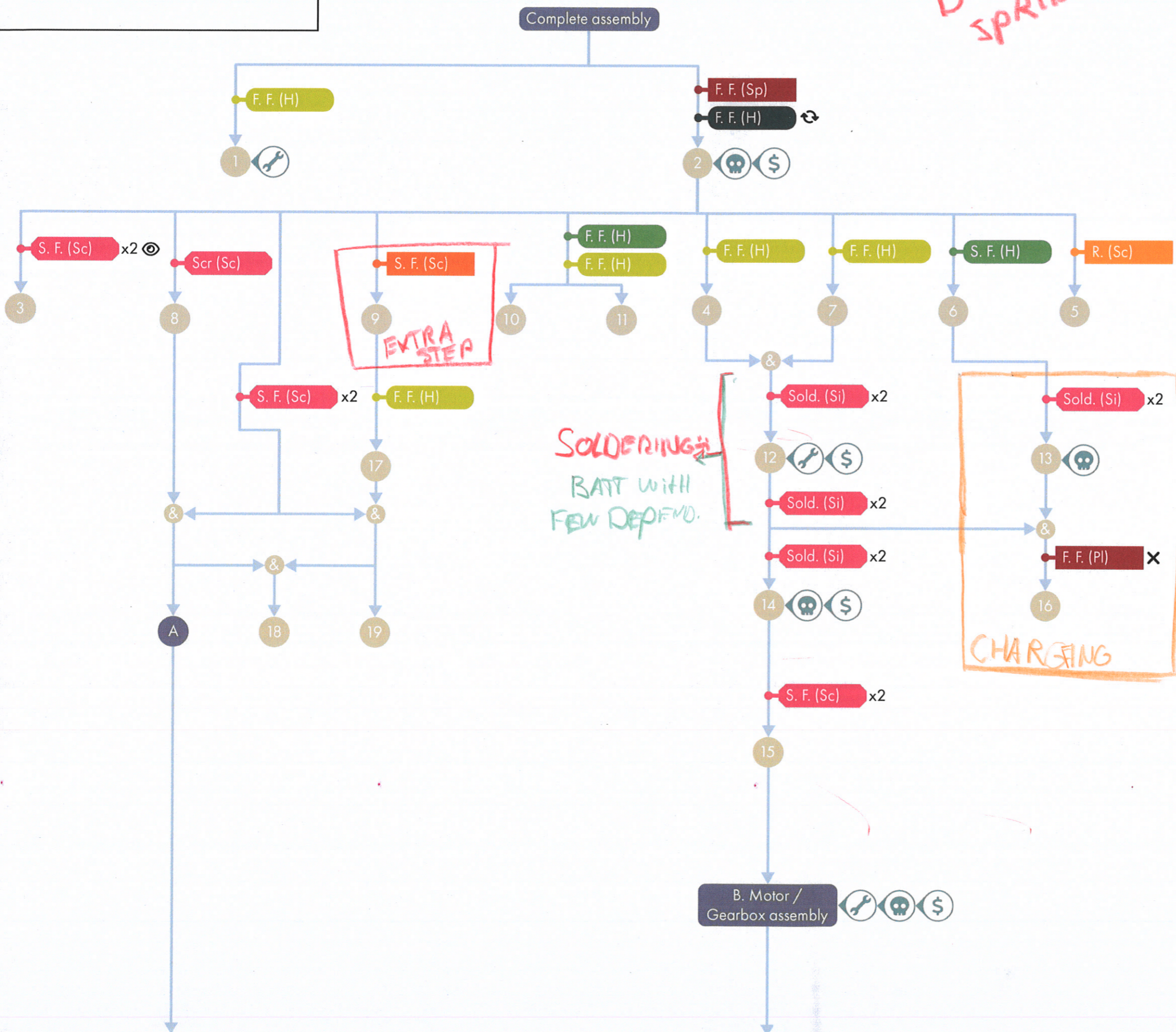
- C. Motor / Gearbox assembly
- D. Motor assembly (C)
- E. Gearbox assembly (C)
- F. Brush axis assembly (E)
- 5. Pressure sensor axis
- 16. Motor/Gearbox bracket (D)
- 17. Motor (D)
- 18. Brush axis spring (E)
- 19. Rotating oscillating converter gear (E)
- 20. Motor/Gearbox connector (D)
- 21. Pressure sensor springs (D)
- 22. Pressure sensor contact (D)
- 23. Brush axis housing (E)
- 24. Top seal (F)
- 25. Brush axis (F)
- 26. Axis spacers (F)
- 27. Axis holder (F)

## Legend

- Motion type**
- = Hand motion
  - = Single motion tool
  - = Multiple motion tool
- Force intensity**
- | Low | Mid | High |
|-----|-----|------|
| ■   | ■   | ■    |
- Type of tool**
- (H) = Hand
  - (Sc) = Screwdriver
  - (Sp) = Spudger
  - (Pl) = Pliers
  - (Si) = Soldering iron
  - (Ag) = Angle grinder
- Type of connector**
- S. F. = Snap Fit
  - F. F. = Friction Fit
  - N.F. = Not Fixed
  - Sold. = Soldered
  - R. = Recessed
  - Weld = Welded
  - Glue = Glued
  - Scr. = Screwed
  - Tape = Taped
- Penalties**
- = Product manipulation
  - = Low visibility/identifiability
  - = Uncommon tool
  - = Non-reusable connector
- Target components**
- Failure Indicator
  - Environmental Indicator
  - Economic Indicator

**Disassembly Map**  
 Electric Toothbrush  
 Philips Sonicare Easyclean  
 Mart Drummen

*MULTIPLE  
 LARGE ELASTOMER  
 DAMPERS +  
 SPRING*



- Components**
- |                             |                                  |
|-----------------------------|----------------------------------|
| A. Front axis assembly      | 9. Top seal lock (A)             |
| B. Motor / Gearbox assembly | 10. Spring holder                |
| 1. Brush head               | 11. Spring                       |
| 2. Main body                | 12. Battery                      |
| 3. Power button             | 13. Charging coil                |
| 4. PCB cover                | 14. PCB                          |
| 5. Seal ring                | 15. PCB / Battery carriage       |
| 6. Bottom cap               | 16. Charging coil pins           |
| 7. Battery cover            | 17. Top seal (A)                 |
| 8. Front axis lock          | 18. Top axis (A)                 |
|                             | 19. Top seal rear positioner (A) |

**Legend**

**Motion type**

- = Hand motion
- = Single motion tool
- = Multiple motion tool

**Force intensity**

Low	Mid	High
<span style="color: lightgreen;">■</span>	<span style="color: green;">■</span>	<span style="color: darkgreen;">■</span>

**Type of tool**

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N.F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Penalties**

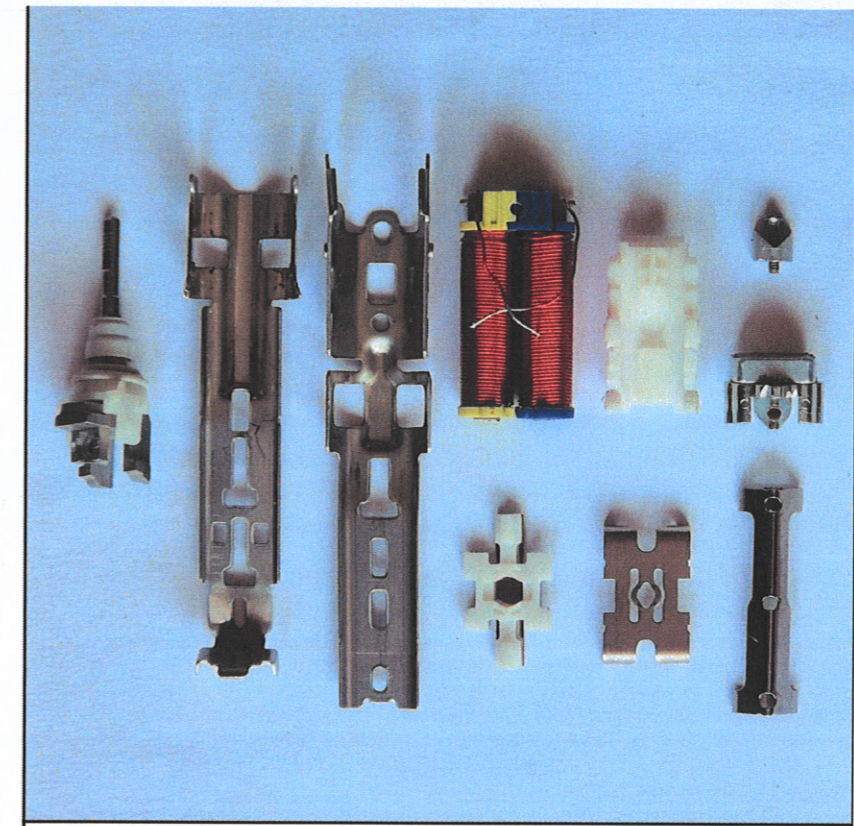
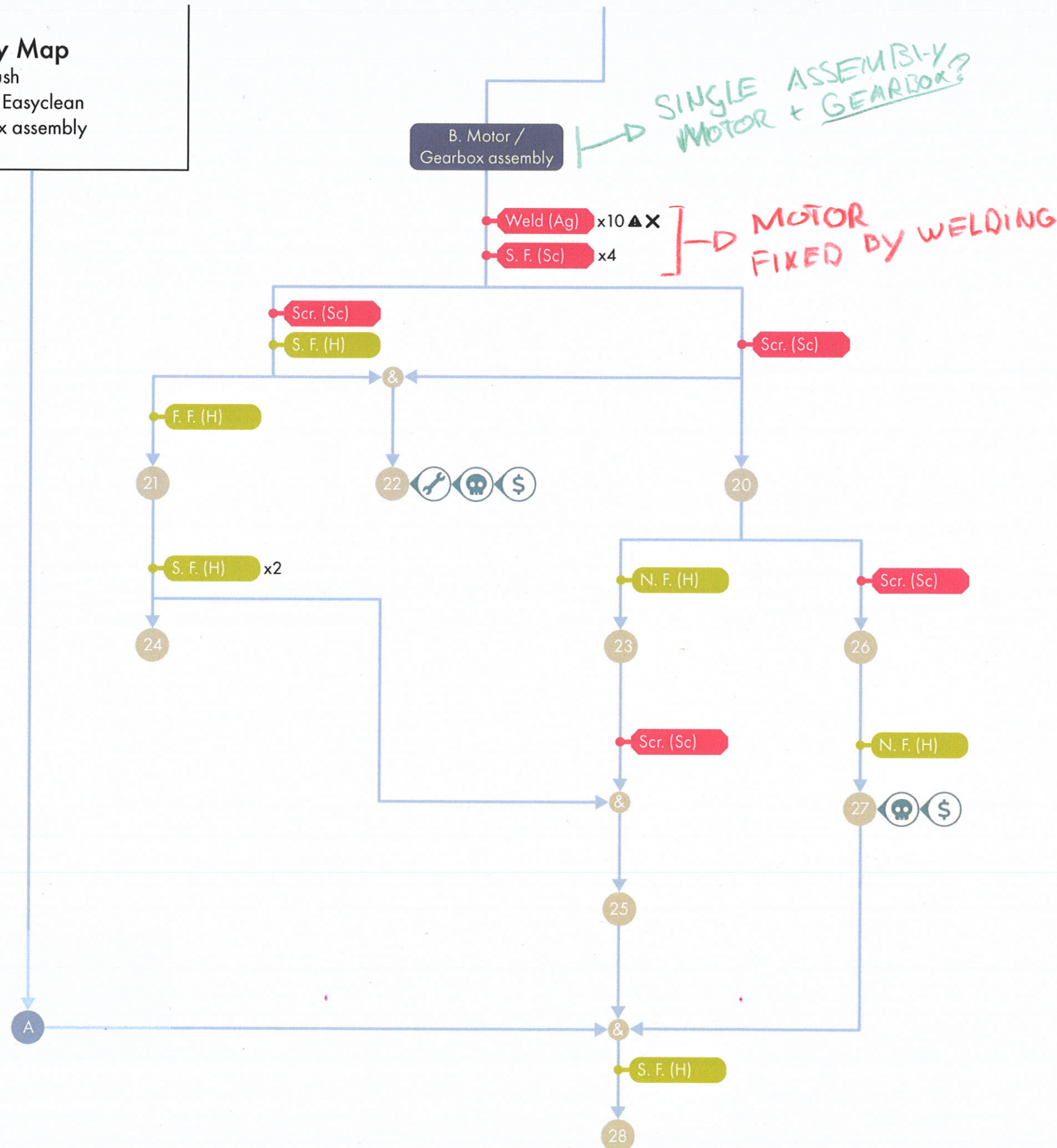
- = Product manipulation
- = Low visibility/identifiability
- = Uncommon tool
- = Non-reusable connector

**Target components**

- Failure Indicator
- Environmental Indicator
- Economic Indicator

# Disassembly Map

Electric Toothbrush  
 Philips Sonicare Easyclean  
 Motor/Gearbox assembly  
 Mart Drummen



## Components

- A. Front axis assembly
- B. Motor / Gearbox assembly
- 20. Top bracket (B)
- 21. Bottom bracket (B)
- 22. Motor (B)
- 23. Top axis holder (B)
- 24. Bottom axis holder (B)
- 25. Axis bracket (B)
- 26. Magnet lock (B)
- 27. Magnet (B)
- 28. Axis (B)

**Legend**

**Motion type**

- Hand motion
- Single motion tool
- Multiple motion tool

**Type of connector**

- S. F. = Snap Fit
- F. F. = Friction Fit
- N. F. = Not Fixed
- Sold. = Soldered
- R. = Recessed
- Weld = Welded
- Glue = Glued
- Scr. = Screwed
- Tape = Taped

**Force intensity**

- Low
- Mid
- High

**Type of tool**

- (H) = Hand
- (Sc) = Screwdriver
- (Sp) = Spudger
- (Pl) = Pliers
- (Si) = Soldering iron
- (Ag) = Angle grinder

**Penalties**

- Product manipulation
- Low visibility/identifiability
- Uncommon tool
- Non-reusable connector

**Target components**

- Failure Indicator
- Environmental Indicator
- Economic Indicator

## **Appendix G. Brainwriting sheets**

---

*Appendix on the following pages*

# Brainstorm session – Design of an electric toothbrush for the circular economy

## Goal

The goal of this brainstorm session is to generate a bunch of ideas. There is no need for qualitative analysis of the ideas.

## Method

The brainstorm will start with an introduction of the topics and themes to be brainstormed about.

After the introduction, a brain drawing exercise will be performed in three rounds. Each round tackles a different brainstorm topic (BsT). Each round has a duration of 12 minutes.

The session ends with a 10 minute discussion of the ideas in which they can be further elaborated of developed.

## Themes

Three main themes have been identified for designing an electric toothbrush for the circular economy: *long-life products*, *loops for priority parts* and *high value recycling*. For this brainstorm session we focus on two of the themes: *long-life products* and *loops for priority parts*.

These themes are primary drivers for reduction of environmental impact, as the impact is mainly generated by transport (from China) and materials. By extending product life and looping priority parts (high material impact) locally, the total material impact and transport movements can be reduced.

## Long life products

Two strategies to enable long life products have been identified for the brainstorm.

- User replaceable battery

The battery is the primary reason for end of life and currently mostly non user replaceable. In some cases it is user replaceable, but there is a lack of intent: the user is not made to feel like he/she is meant to replace the battery. Another concern is that users perceive the replacement procedure as high effort: They will have to replace the battery at some point, another *tedious* thing added to their daily routine...

To tackle these concerns the design of the battery replacement needs to feel integrated and intentional, inviting the user to perform the procedure. Think of the Apple EarPods, with their satisfying case which you just cannot stop opening. At the same time, the battery procedure needs to be as quick and easy as possible.

This leads to the brainstorm topic:

*BsT1: How can battery maintenance be made an inviting/intentional experience?*

- Increase repair considerations

A big issue for the product life of electric toothbrushes is that currently only 20% of users with a broken toothbrush consider repairing their toothbrush. Most users feel that after 4 years, their trusty toothbrush has served its purpose and it's time for something new. To make consumers think differently about replacing their toothbrush, consumer attachment to their electric toothbrushes should be improved.

Product attachment is a tricky topic however, as it is not easy to influence by design. However, there are several strategies for trying to achieve this.

By adding product personalisation users can grow attached to their own toothbrush. Important to know for personalisation is that the degree of effort required for personalisation by the user positively influences the amount of attachment.

By allowing product to age with dignity (think of how leather ages), the product can wear and still look good. This allows the wear that is on the product to capture memories or experiences the user had in the product. This also strengthens product attachment.

Lastly, by making the product unique in the first place, it can feel irreplaceable. Think of the Freitag backpacks made from truck tarps, making each back pack unique. This feeling of being irreplaceable increases product attachment.

For this round, the brainstorm topic is made general, but three more specific topics have been added to inspire you.

*BsT2: How can consumers attachment to electric toothbrushes be increased?*

*How can product personalisation be implemented for electric toothbrushes?*

*How can ageing with dignity be implemented for electric toothbrushes?*

*How can design for unique products be implemented for electric toothbrushes?*

## **Loops for priority parts**

There are several challenges to address to enable looping priority parts. For this brainstorm, the focus is on only one of those challenges: acceptance of refurbished toothbrushes is low due to hygiene and contamination concerns under users.

The idea of the toothbrush having been used by other users previously is uncomfortable for users, as they feel some disgust. How can this negative emotion be alleviated? Or how can it be prevented in the first place?

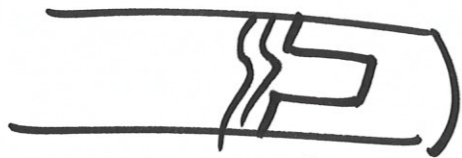
As such the brainstorm topic for this theme will be:

*BsT3: How can consumer concerns about hygiene of refurbished electric toothbrushes be alleviated?*

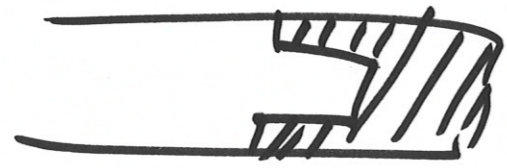
Tip: Suggestions on how to tackle this issue have often been to *stress cleaning efforts* to consumers, so maybe there are creative ways to achieve this?

# Battery Replacment

intentional  
-markings



design follows (highlights) relevant join lines.

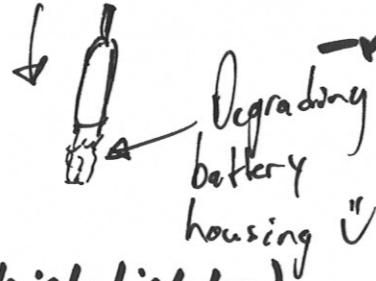


different patterns highlight difference of components.

GRIPPED SHAPE SHOWS INTENTION



Battery housing made from inferior material (degrading over time)



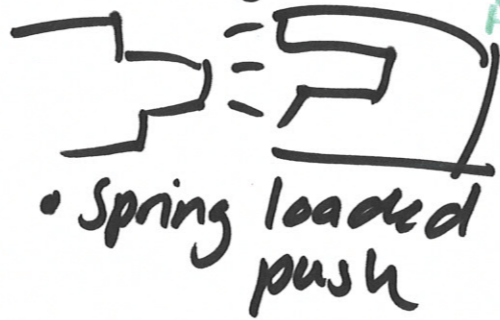
MAGNETS pull BACK ON



Electromagnets only allow to remove the battery when needed.

Effect on battery life?

-mechanic

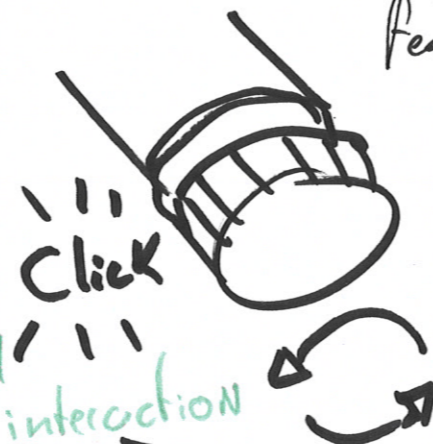


• Spring loaded push

+ ID1 + tactile interaction → could aid product Attachment

Replacing the battery

unlocks something → decrease barrier / hesitation.



Twist & click Bottom cap.

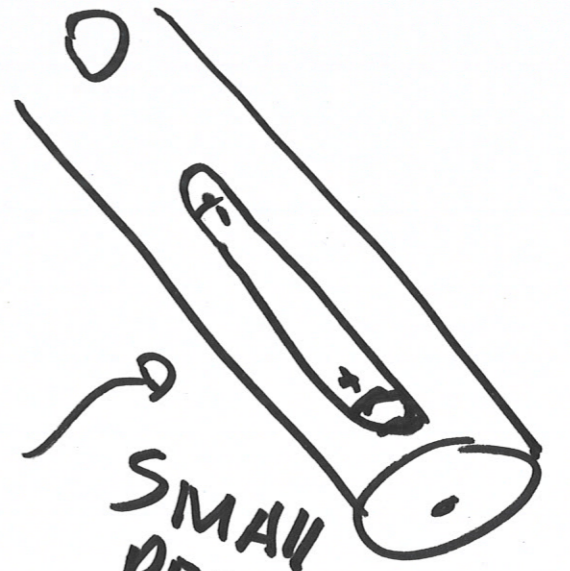
Automatic unscrewing / release once the battery is dead / dying?

explosion!

initiating



transparency makes it accessible (you know what is inside)



SMALL PEAK WINDOW

ID3 + TRANSPARENT ELEMENT  
- ADDS WATERPROOF ISSUE + HOUSING MATERIAL

Features?

Many Gifts?

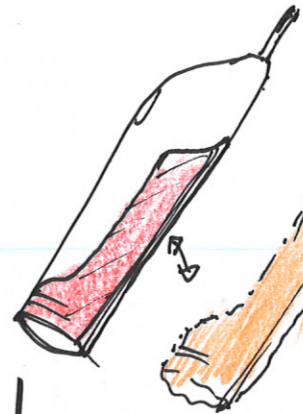
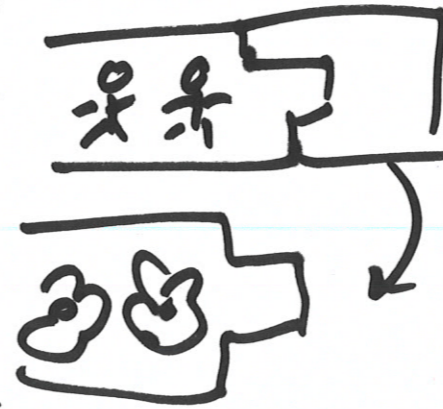
(+) feature.

Power?

discount for replacement part, etc.

(battery charging can be secondary)

design charging is the goal.



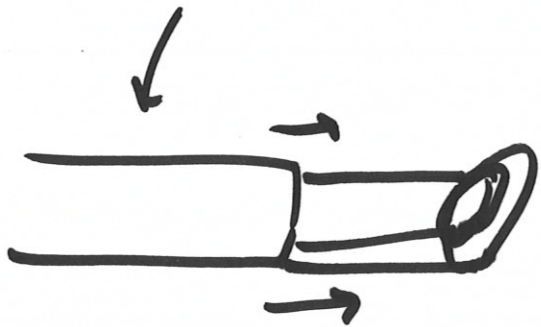
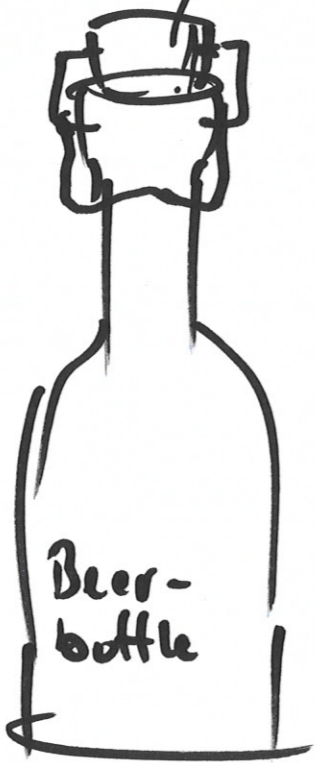
- intentional  
- initiating  
- ~ year

Battery "component" can be replaced and changes the overall look of the toothbrush

ID4 + CUSTOM BATTERY  
+ MARKET CONTROL FOR OEM

Create an emotional bond between the user and the toothbrush ♡

"pop"-ing mechanism



battery carriage / drawer. slides out → use conventional home battery? AA

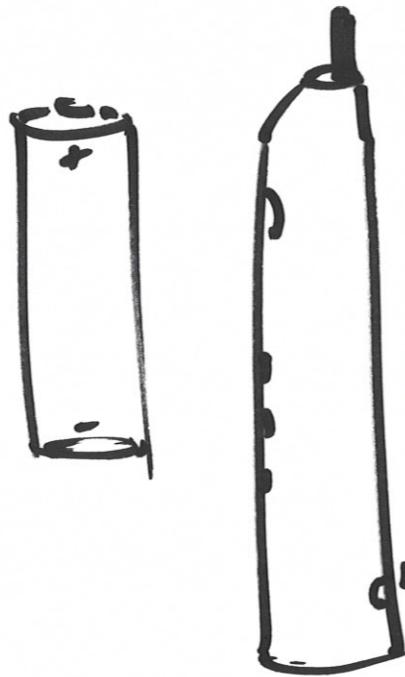
ID7: BATTERY CARRIAGE SLIDING

fiddling

inviting & intentional

incentive: Battery upgrade → stronger, longer duration

Host pop-up events where people get coffee, cookies and a new battery



reload



release  
ID6: ONE CLICK BATTERY RELEASE



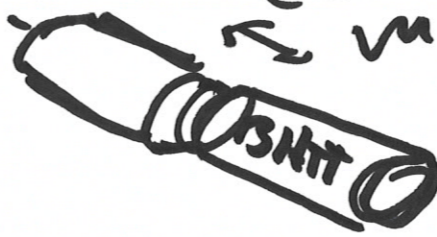
Finger Print Button to make INVITING.

Make it look cool

Loading a gun  
Magazine  
Shotgun

Starting a chainsaw

Battery as a module  
Connect with magnets.



wireless charge

like FLASH light

Rotate to connect Batteries.

no on only on

button, put battery in / out. → get used to dealing w/ battery.

operation of built onto brush battery.



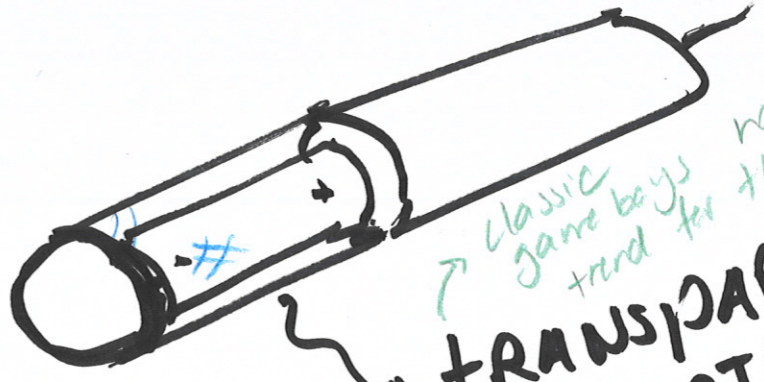
ID5: COMBINE POWER Button AND BATTERY RELEASE

**- Inviting**

Make everything look very nice

Chemical salt-based battery that "crystallises" over time

↳ beautiful & clear indication of replacement

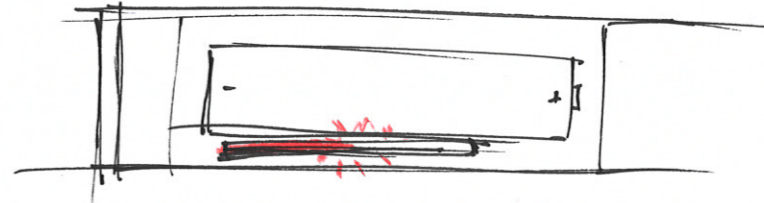


↳ classic game boys trend for this  
**TRANSPARENT COMPARTMENT**

↳ Fancy LED to show battery status? or sound

No PCB / ugly internals visible

transparent shell, battery has the design



fancy casing

pack battery in nicely designed casing

↳ subscription system home delivery periodically



ID8: MAGNET CLOSURE

Battery → power crystal or energy gem

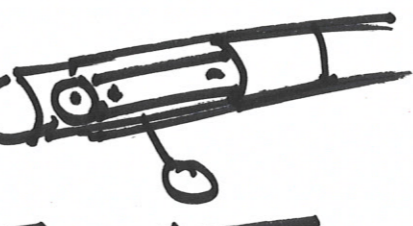
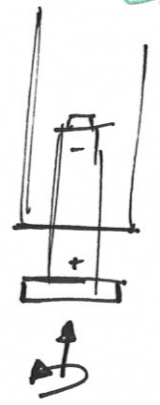
↳ combine

Magnets

magnetic attach fancy compartment

Are they strong enough? ↳ use tensile/shear strength difference

Bayonet

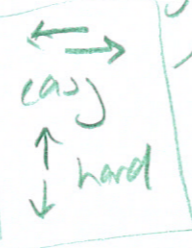


use AA-style rechargeable batteries, that you can load your teeth shotgun with

**Shotgun style**

combine battery change with toothbrush head replacement

↳ colour indication of the bristles



**intentional**

- inviting  
- intentional

- battery replacement  
- 2x per year or once every 4 years



Separate tool comes with the unit

Battery that can be "replaced" by replacing the battery-fluid (which is water)

put battery inside the brushhead

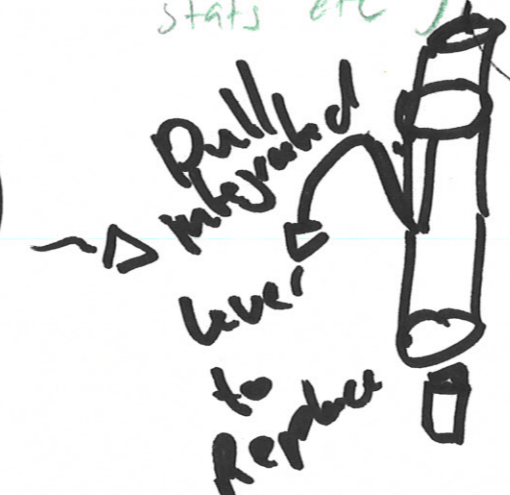
replacing the brushhead replaces the battery



"Smooth feeling"

phone app battery health? (can also show charge state, toothbrush stats etc)

Water-tightness



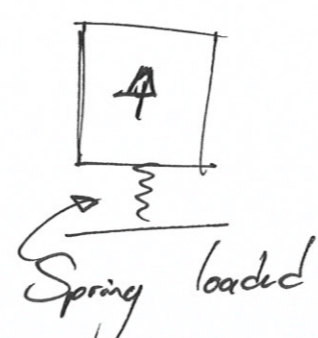
You don't want to see the PCB, I guess?

fidget toys texture difference

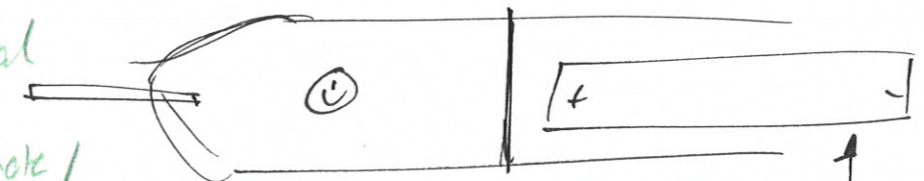
Airpods

Click in place

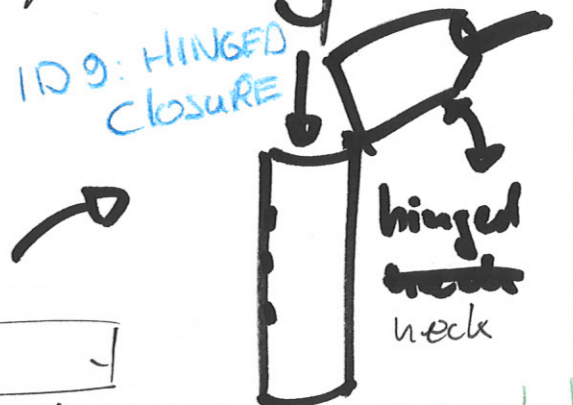
Camera Battery Replacement



- same usual language as the remote / camera batteries to indicate behavior.



First compartment with PCB etc.



Dedicated battery compartment. usually indicate 'worn out' (Rimona suitcases) scratches reveal pattern

product categorization.

- expects 'clean' from medical  
↳ position toothbrush as something else.

↳ eg. we have no problem w/ secondhand clothes. or hotel bed's.

communicate clean (ed)

design (transparent parts, light colors, shiny)

delivery.

↳ comes in vacuum-sealed box

"pop" when open

Make new toothbrushes

dirty before being sold

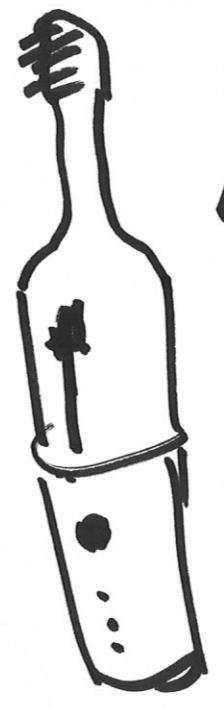
↳ no difference between new and old

ID7

agency

- user can clean at home / get it cleaned themselves.

comes in parts put together



Brush Head is "Big" Replaceable Part

ID1: INCREASE SIZE OF USER REPLACEABLE PART

- MORE WASTE

Cleaned in store, in front of user.

ID3: IN STORE CLEANING

UV-curing machine like nail artists use but for disinfection

Replace a few parts with "higher-end" parts to compensate for old parts

- Communicate Clean categorization

Use materials that never get a dirty look / feeling

ID2: MATERIALS

↳ Stainless Steel

↳ Gold

↳ Copper → no patina → clean



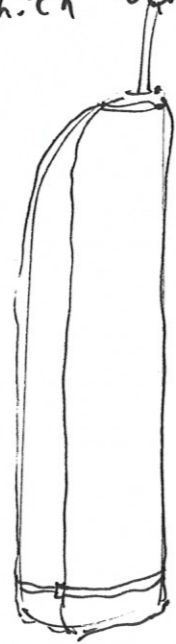
Make refurbished toothbrushes

better than new ones, in some way

↳ Features which were unlocked already stay on/with it

change casing

↳ Personalised Casing.



re-wrap in clear plastic foil with satisfactory peel-off "unboxing" interaction

ID4: RE-PACKAGE

- IF PURCHASED WITH SUSTAINABLE INTENTION, THIS MIGHT RUIN THE EXPERIENCE  
- AFFECTS EXP. AFTER PURCHASE

cleaning certificate

video of how this particular toothbrush has been cleaned

↳ trace the cleaning like origin-trace of coffee

ID6: SETTING A NEW STANDARD

Media campaign to change ~~the~~ general attitude to toothbrushes  
cleaned/refurbished brushes

Smell of factory-wear

↳ plastic, chemical  
↳ like a new car

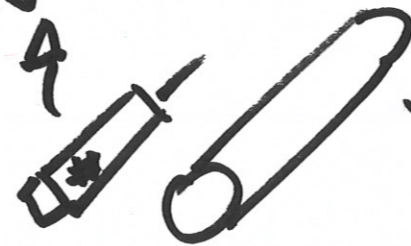
↳ How does/should A 'new' toothbrush smell?

ID5: NEW SMELL / LOOK  
- AFFECTS EXPERIENCE AFTER PURCHASE



↳ pick which parts you want new.

Used water



↳ New body



↳ new battery

ID7: WHAT IS NEW?

Charge money for clean +  
 ↳ when selected they ARE SURE IT MUST BE GOOD  
 ID8: TRICK CUSTOMERS

Give people a way to inspect "cleanness" themselves  
 ↳ UV-light?  
 ↳ self test at home like for dioxides

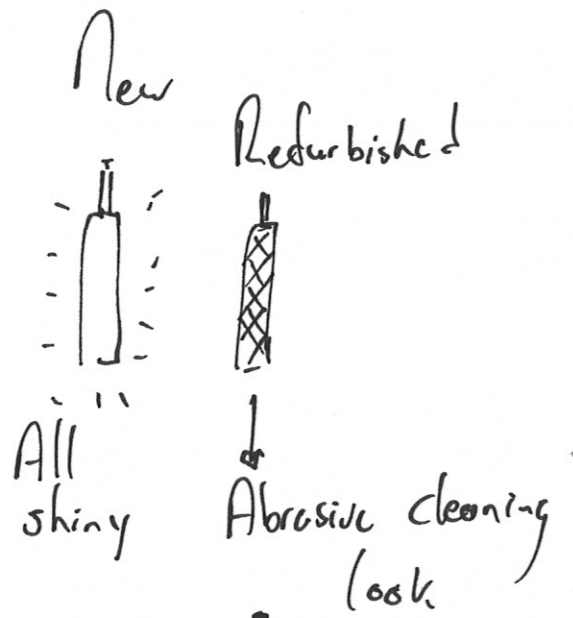
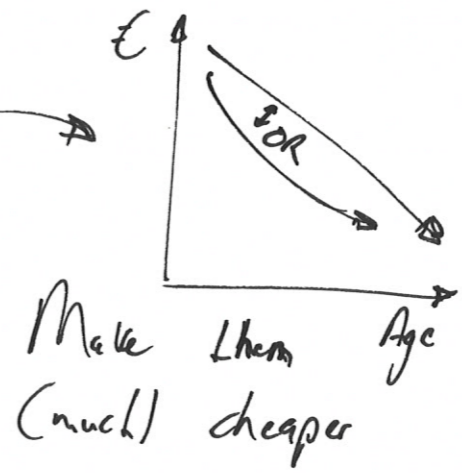
exploit legislation loopholes for the sake of the environment

Just don't tell they're refurbished  
 ↳ Mix new and refurbished ones  
 ↳ or make all products refurbished. make this the norm

↳ spots people / attach celebrity figures

Acceptance of refurbished toothbrushes

How does something LOOK / SMELL CLEANED?  
 ID5: NEW SMELL / LOOK



new spray-paint coating  
 ↳ metal-coating  
 ↳ exclusiveness  
 ↳ visual upgrade

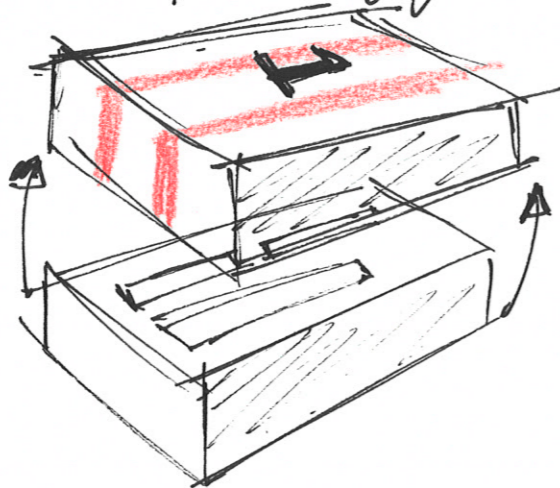
Only refurbish the internals → Recycle the housing

modularize whole toothbrush.  
 (1/10 parts refurbished)

indicate level of "refurbishedness"  
 ID6: NEW COAT or 10% or parts  
 ●●●●● 60%  
 ○●●●● new  
 ●●●●● 100% reused

ALWAYS SOME PARTS CAN BE SELECTED  
 ID7

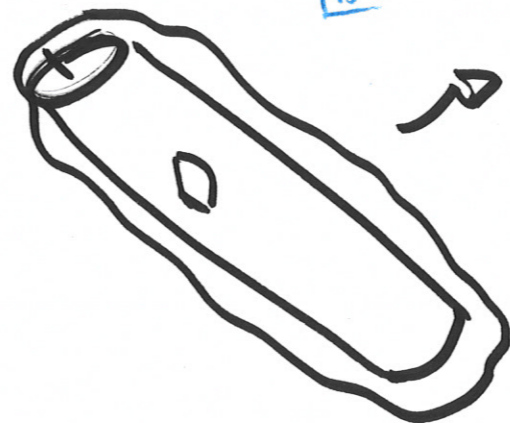
Ship it in super fancy packaging



104

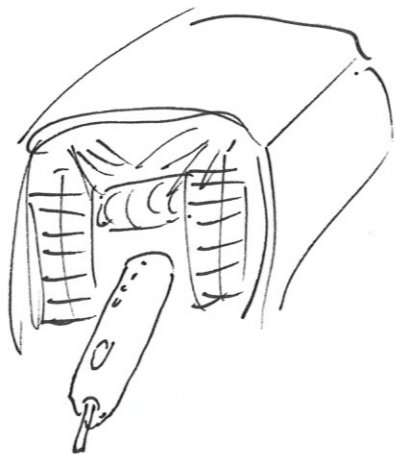


Like peeling plastic off new phone.



104

Reseal in plastic wrap.



make it hard for tooth brush to be accepted into refurbishment "vigorous" testing / inspection for old one

Sell it where new stuff is sold

# Acceptance of Refurbished.

Cleaning Check List.



(or let them check there at home)

1010: CERTIFICATE



food grade Certificate from Known BRAND

"We also clean xyz"

"oh, they must be alright then"



Top Ring Changes Color on first water contact.

109: UNBROKEN SEAL AFTER PURCHASE

(does that mean it has never seen water? Even for cleaning?)

tooth brush cleaning facilities

like carwash's



let people do a final cleaning themselves

1011: DIY

or at the grocery store. moms sterilize baby stuff at home

when you listen to music in the bathroom, toothbrush adapts cleaning cycle & phases to match songs

It learns your music taste and becomes your personal DJ

aging slowly bones see-through and reveals inner workings

track your cleaning behaviour pitch control for vibration to "sing"

product personalization

ID2: AI LEARNING Features OUT OF SCOPE

AI + Haptics For Personalised Haptics

sync with menstrual cycle and behave differently dep. on phase (handle idea with care!)

Automatically makes a selfie every-day to create a personal timelapse

haptic feedback (convey personality)

expose shiny inner paint over time

happy chirp, battery dead

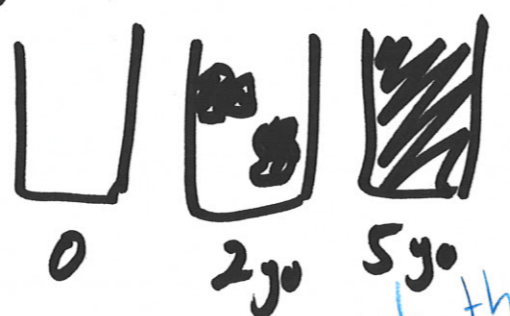
has good days, has bad days

show it as a being with emotion

match user's emotions?

Slow vibration = SAD.

ID1: Paint that changes over time EXPOSES



Aging with dignity.

milestone badges / stickers (sent from company)



# years # uses - birthdays - collectibles for events (eurovision, world cup etc)

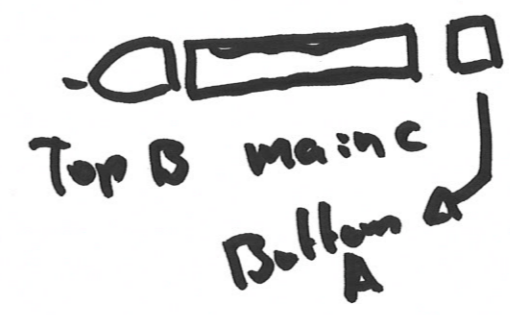
For repair/maintenance

19/04

all unique (from mfg)

fully ergonomic for u (dentist takes hand measurements)

Pick components.



ID5: USER CONFIGURABLE TOOTH BRUSH

grip is a 1 time cure plastic (you shape it at home when you set)

- cost vs lifetime - product attachment

manually remind  
toothbrush like  
old watch

Age with  
dignity

Wear  
Color  
changes  
multi  
Color  
CASING



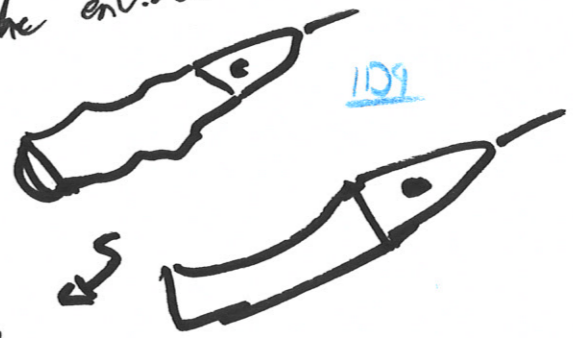
etching  
some parts "disappear"  
over time

Offer them as kit:  
ID5 - DIY - Cheaper - Include options/choices  
- User gets attached

Personalisation

personalization inside?  
put name on PCB  
(can't see, but)  
know

Color changes over  
time to match  
the environment



Adapts to user's  
hand over time

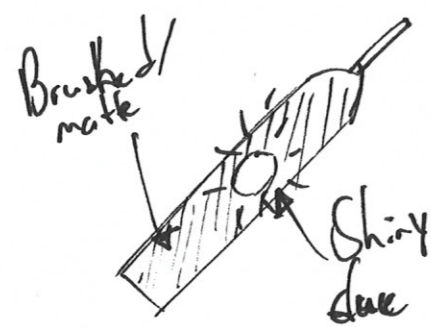
Personalised  
Grip  
Shape

Can be re-done  
when heated

changing over time  
Like Sneakers



ID1+4  
C/DID6: GRIP  
THAT WEARS TO  
USERS HANDS



Shiny/polished  
due to frequent use

ID1+ :  
PRE-PLANNED  
PATTERN EXPOSURE

reveal a pattern  
over time. (eg. world map)  
or country  
(if only some places  
get shiny with time)

Product  
Attachment

Unique

x-ray scan of your mouth  
to pattern for case



# product attachment

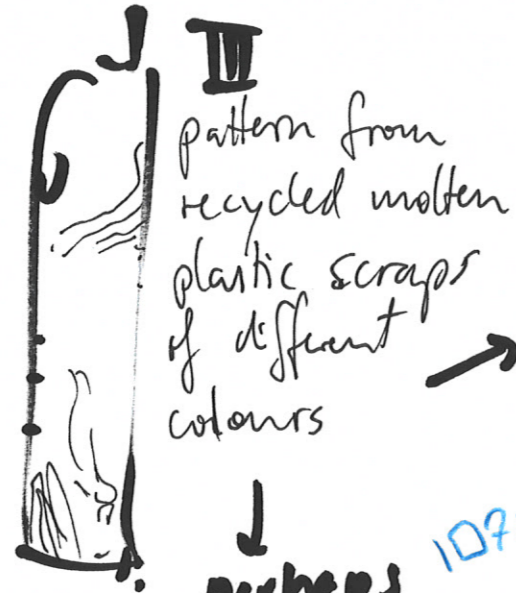
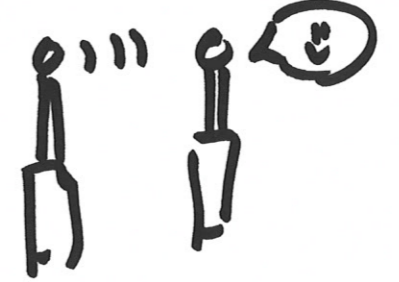
- I personalisation effort → chance
- II aging w/ dignity
- III uniqueness
- IV extra functionalities

I certain time of brushing  
 „unlocks“ custom vibration  
 melodies

↳ 10.000 hrs → play Dua Lipa  
 when done with  
 brushing

Dentist made  
 Brush pattern  
 Custom  
 Prog.

inspired  
 → ability to transfer  
 them  
 (send a song to  
 your brother's  
 tooth brush)



III pattern from  
 recycled molten  
 plastic scraps  
 of different  
 colours

→ shedding with  
 time /  
 vibration.

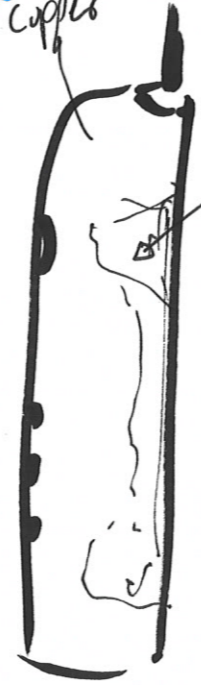
ID7: UNIQUE PATTERN  
 CASING - RECYCLED PLASTIC  
 - WOOD  
 - COPPER

perhaps  
 from your  
 old  
 toothbrush

Or random plastic  
 stuff/products you sent in

IV II toothbrush can  
 function as  
 vibrating alarm clock

II



patina



I

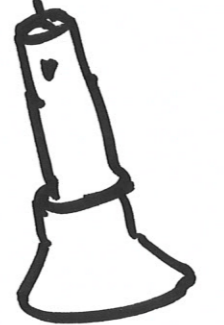


custom  
 jewelry-kind  
 click-ons



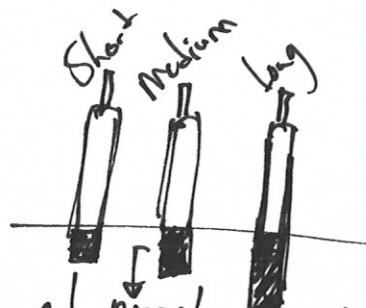
bands  
 (like  
 rings)

Or Functional  
 mods?



Stabiliser

Custom battery sizes



2/26

2-day business trip  
 Normal use  
 long jungle trips

Wood  
 Leather  
 Element



Angled  
 grip

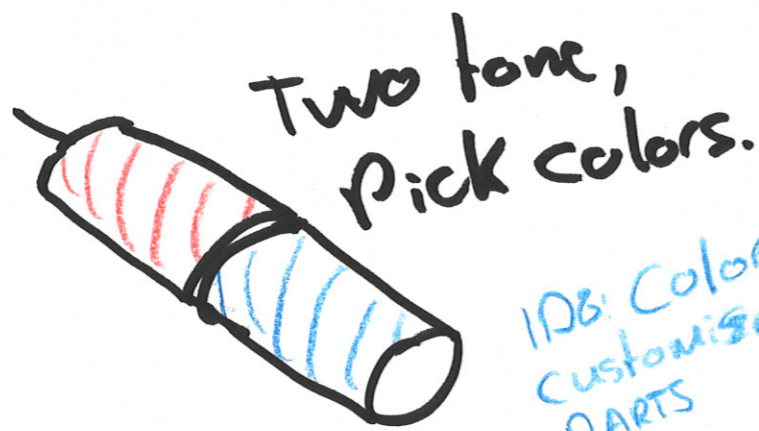
"20% of users consider repair"

avg. lifespan: ±4 yrs  
↑ expected

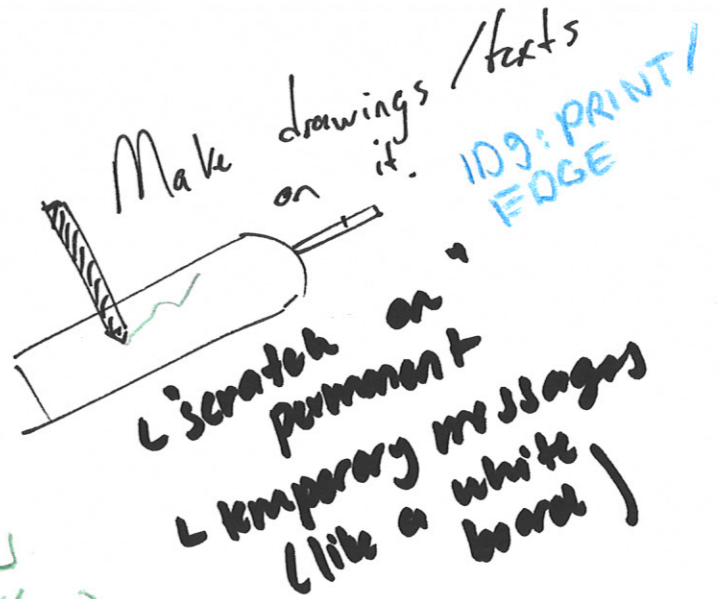
increasing product attachment increases  
likelihood to repair.

- 1) Adding product personalization
- 2) Aging with dignity
- 3) Make it unique in the first place

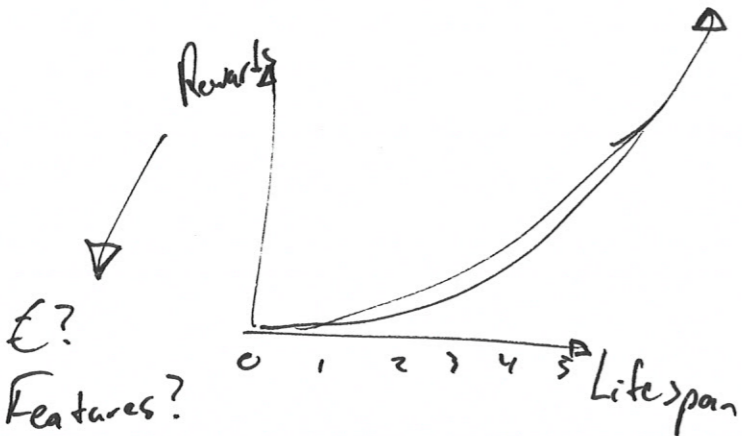
→ Too hard: won't work.  
→ More effort = more attachment



IDB: Color  
CUSTOMISABLE  
PARTS



Non-linear rewards:



£?  
Features?  
Gift-cards?  
Varna?  
Discounts  
on brush  
heads

Challenge:  
Who can keep their  
toothbrush for longest?  
↳ Oldtimer qualities

Personalization

based on  
3D-scan  
of hand  
↳ moldable by  
user before  
first use

custom  
grip  
shape



Different textures  
on "soft touch" parts

↳ Make them limited editions → by other  
Brands!

→ trend: journey where your  
toothbrush has accompanied you  
to. IDB: (LOCATION) BADGES

Use random plastic  
blends for the housing  
↳ Or parts of it  
or metal → perhaps a collaboration  
with high-end car brand?  
or glass

↳ what are some interesting  
product scraps? - watches  
keys  
beer bottle glass

↳ Manual  
Brushes

- WILL NOT  
WORK FOR  
MOST USERS

## ***Appendix H. Concept elaboratoin***

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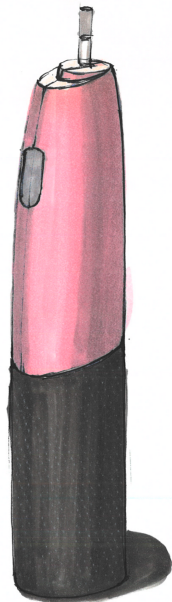
*Appendix on the following pages*

# Concept elaboration

## Concept 1: Half split

### Concept introduction

When analysing existing toothbrush architectures, it stood out that all of them open up via a small removable cap at the bottom of the brush. This means that in order to access the priority parts, the assembly of internal components needs to be separated from the body fully. By moving the split line higher up on the body of the toothbrush and making the bottom half of the main body removable, the battery is accessible directly after opening the brush.



*Figure 1 - Concept 1 - Half split*

### Long product life

The philosophy of this concept is based around improving the accessibility of the battery, and this shows with just two steps for battery replacement (see figure 2). The steps are made easy as well. The brush is slightly oval-shaped (see figure 3), aiding the user's grip on the brush when screwing the two halves lose. An additional benefit is how the screw thread is used to push the o-ring beyond its seal (see figure 4).

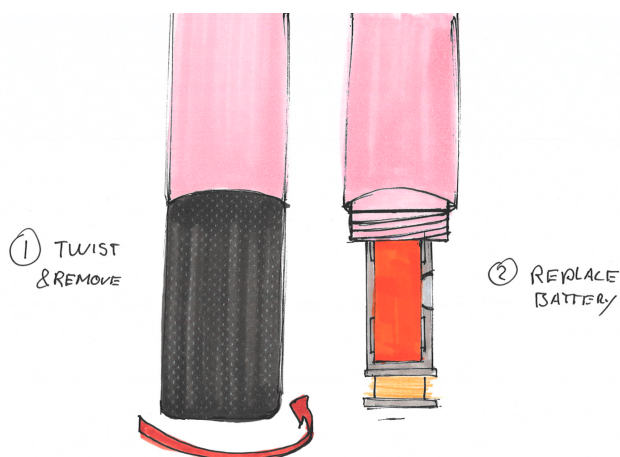


Figure 2 - Just two steps are required for the battery replacement.

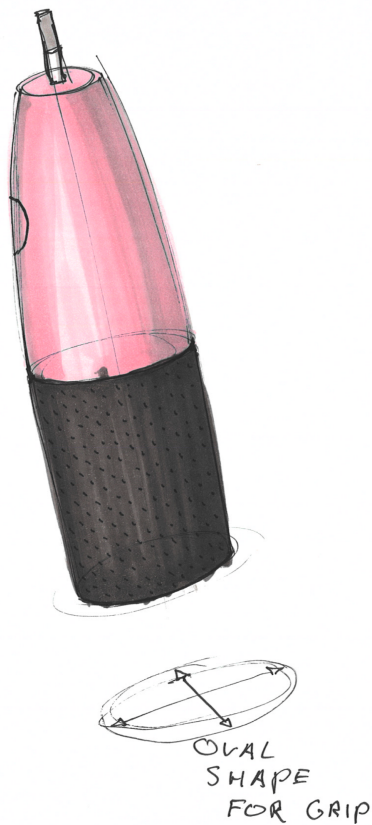


Figure 3 - The brush is oval-shaped to improve the grip for opening the brush.

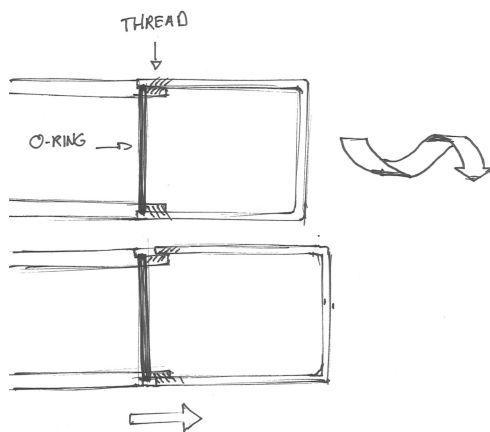


Figure 4 - By rotating the bottom half over the thread, the o-ring seal is broken.

Besides significantly improving the battery replacement procedure, the half split allows for a playful integration of a two-tone colour scheme (see figure 5). By allowing users to pick different colours for one of the halves, product attachment is increased slightly. This could be further increased by doing limited production runs of unique colours or patterns for the top half of the brush. By increasing consumer attachment, repair considerations are also increased. A further increase in repair considerations is achieved by reducing repair costs, as further elaborated in the next section.

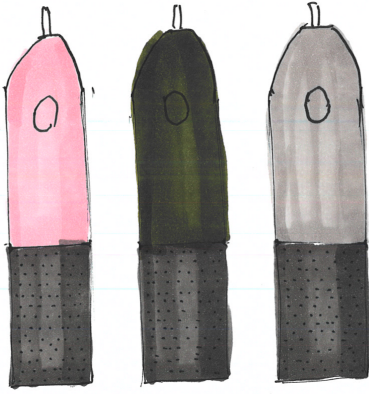


Figure 5 - Two-tone colour design on the half split concept.

### Local loops for priority parts

For this concept, no special design features have been added in order to improve refurbishment considerations. However, an option could be to leverage the half split design and offer users the option to select a new top half. A big disadvantage to such a system is that the material value of the top half is lost, and materials are one of the biggest contributors to the toothbrushes' environmental impact (Lyne et al., 2020).

The ease of disassembly for priority parts has been optimized by minimizing the number of steps required and making most of the procedure toolless. The motor can be replaced in just 7 steps, with only one step requiring a screwdriver (unscrewing the motor cap). The PCB removal is fully toolless and requires just 4 steps.

A major improvement over current electric toothbrushes for the ease of disassembly is the implementation of snap-fits to fix the inner carriage to the main body. While using snap fits for this purpose is not unique, the way the snap fits are implemented allows for easy removal of the inner carriage (see figure 6).

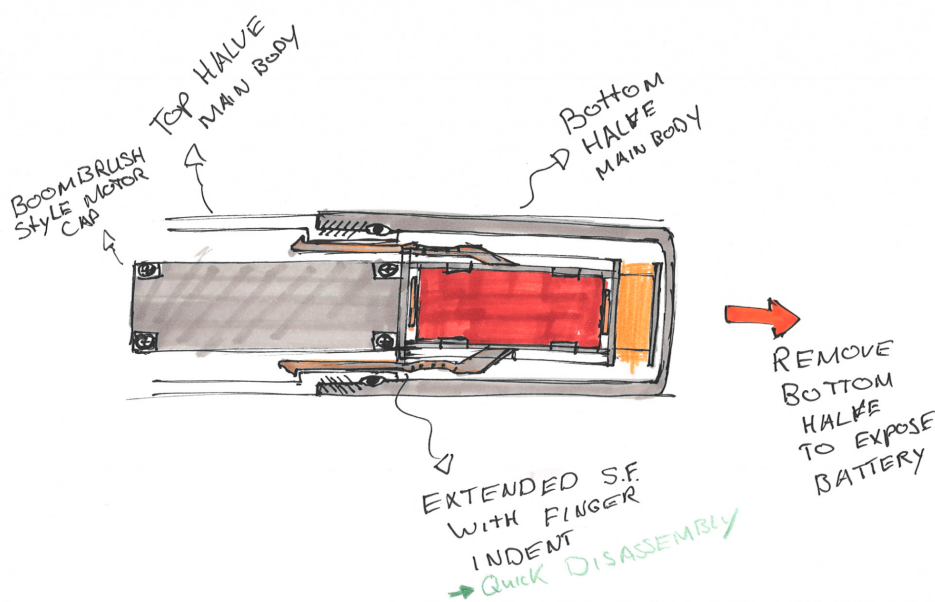
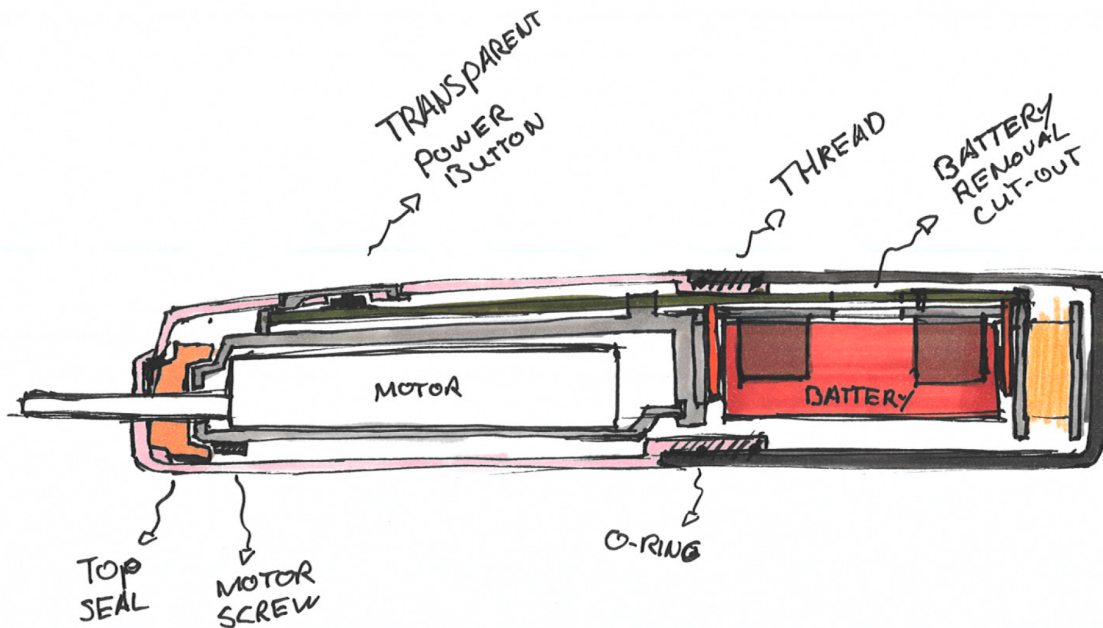


Figure 6 - The snap fits in the half-split concept extend beside the battery. This allows for easy removal of the inner carriage.

### High-value recycling

The use of elastomers is minimized using a power button inspired by the Philips Sonicare toothbrush. By making the power button of a transparent elastomer, no additional seals or material 2k moulding is required to add a battery/power LED.

While the half-split concept has many upsides, there is one major downside to the concept. As the bottom half rotates and is removed in its entirety, options for implementing charging methods are limited. Induction charging was deemed the most sensible method (see figure 7). While the copper coil added in the brush itself is not a major issue, the design of the wireless charger will have to be changed significantly from the wireless chargers that currently come with electric toothbrushes.



*Figure 7 - The internal configuration of the half split concept shows the induction charging coil in the bottom. Implementing other charging methods would have required adding electronics to the bottom half of the main body and wiring these to the PCB.*

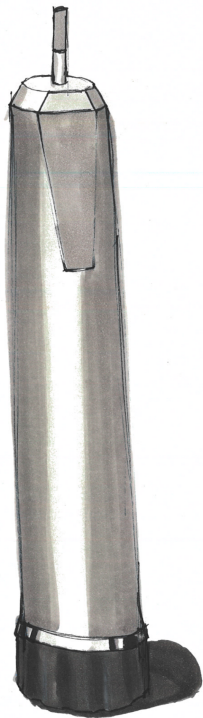
## Concept 2: High capacity

### Concept introduction

During the analysis of existing toothbrush architectures, it stood out that the disassembly procedure of the newest Oral-B model, the Oral-B IO, was improved significantly compared to older Oral-B models. While still requiring the included wireless charger to open, the bottom cap had a bayonet closing mechanism implemented that can be opened using less force and is easy to reuse.

Another interesting feature observed during the analysis was the large battery cell of the Boombbrush, which was combined with a wired charger. This larger cell requires charging less often, meaning the life of the battery is theoretically longer as the cycles are used up less quickly. The removal of wireless charging means that chargers no longer have to be waterproofed.

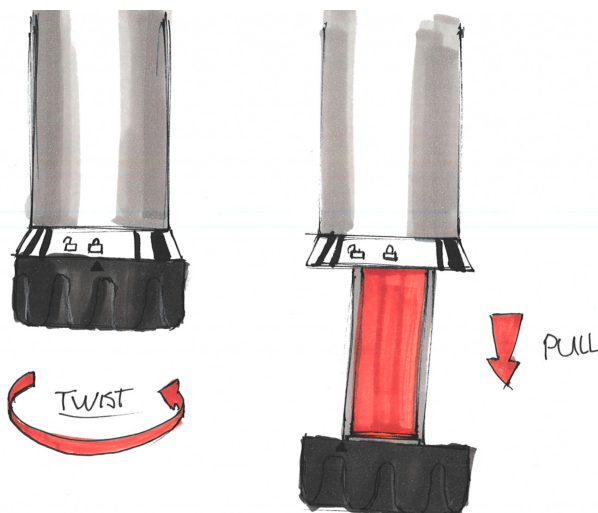
The high capacity concept aims to leverage the advantages of using a Boombbrush-style large battery cell and combining them with the improved mechanisms of the Oral-B IO toothbrush.



*Figure 8 - Concept 2 - High capacity*

### Long product life

Replacing the battery on the high capacity concept takes 4 steps. None of the steps requires tools, making the procedure easy to perform for any user. The end cap has been textured to ensure users have a good grip on it and it is fixed to the inner carriage, making it easy to slide out (see figure 9).



*Figure 9 - The bayonet-style endcap that is fixed to the internal carriage makes the battery easy to replace.*

The metal ring above the bayonet-style endcap can be interchanged by the user for rings with different colours (see figure 10). By allowing users to customize their electric toothbrush product attachment is increased slightly. An advantage of the metal material used for the customization ring is that this material can age with dignity, further increasing product attachment. By increasing consumer attachment, repair considerations are also increased. A further increase in repair considerations is achieved by reducing repair costs, as further elaborated in the next section.

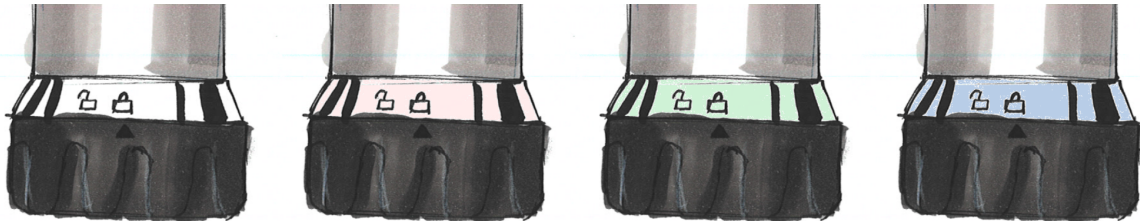


Figure 10 - The ring above the end cap can be exchanged for rings in different colours.

#### Local loops for priority parts

The customizable metal ring does not only serve as a personalisation option but is also used to relieve users' concerns for hygiene or contamination when purchasing refurbished. As the metal ring clearly shows traces of wear over time, a new ring is easy to distinguish. By replacing the small metal ring for refurbishment, users are made to feel the toothbrush is not contaminated.

The ease of disassembly for priority parts has been optimized by minimizing the number of steps required and making the procedure fully toolless. The motor can be replaced in just 7 steps. The PCB removal requires just 6 steps.

To make the disassembly as easy as possible, a feature from the Oral-B Advance Power toothbrush was implemented; a single part that is connected to the inner carriage using snap fits holds the motor in place. The same part is also used to fixate the PCB and functions as the top seal positioner (see figure 11).

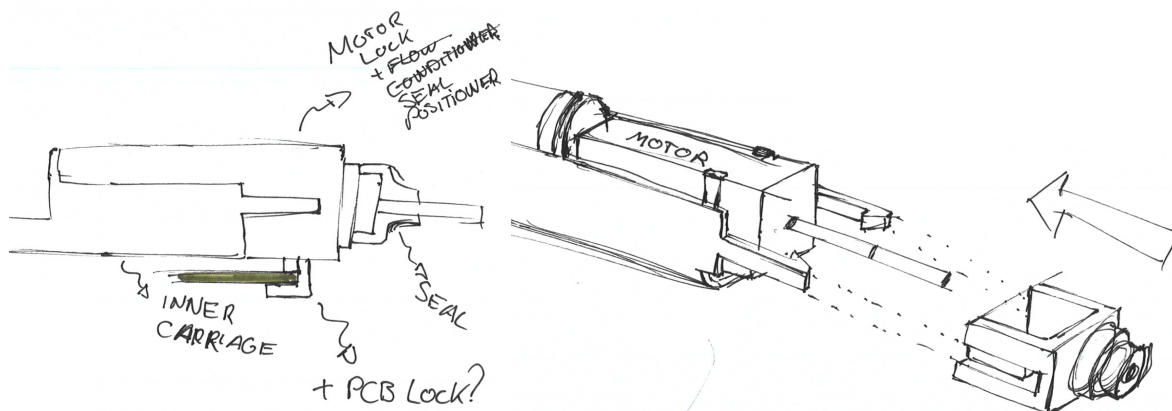


Figure 11 - A single part is used to fix both the motor and PCB in place and functions as the top seal positioner.

### High-value recycling

In total, three elastomer parts are used for the high capacity concept. The amount of elastomers is limited by applying a capacitive button that works through the casing. This is possible to implement in products that make contact with water but are not submerged (Embedded, 2011). LEDs are implemented by moulding transparent parts into the casing, similar to the Boombrush (see Figure 12). As long as the transparent and opaque parts are made of the same materials, this should be okay for recycling (PolyCE, 2021).



Figure 12 - Moulded in transparent parts in the Boombrush.

In the Oral-B IO implementation of the bayonet mechanism, the entire bottom cap is made rotating. However, for the high capacity concept, a wired charging solution was implemented. In order to enable this, the inner part of the bottom cap is fixed to the inner carriage (see Figure 13), while the bayonet is formed by two identical parts that are attached to each other using snap fits (see Figure 14). This allows a fixed charging port to be added.

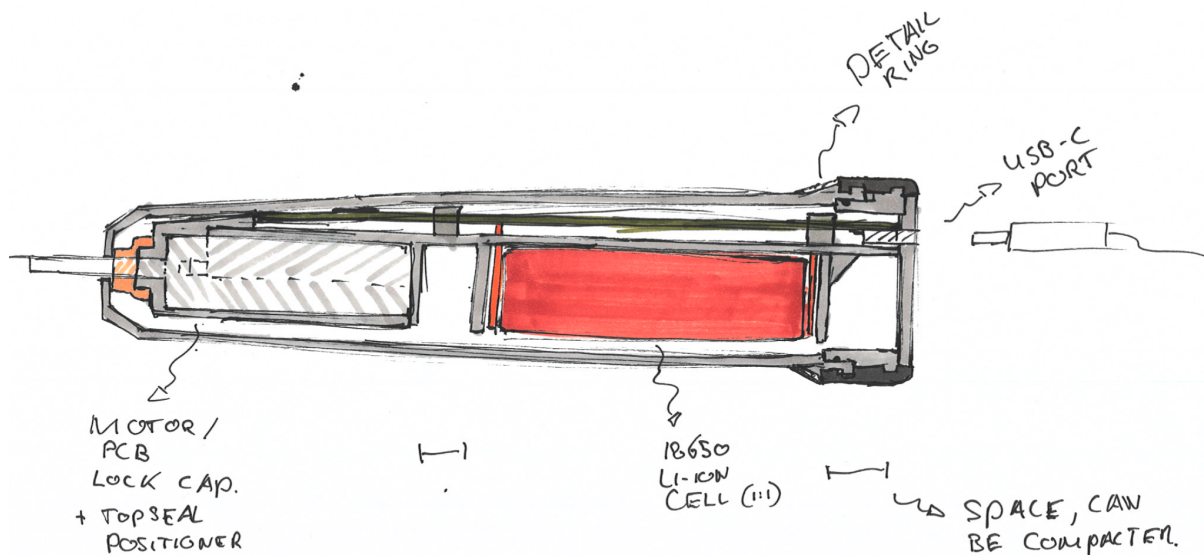


Figure 13 - The bayonet ring (dark grey) at the bottom is a separate part that is able to rotate. The inner components do not rotate and are fixed to the inner carriage.

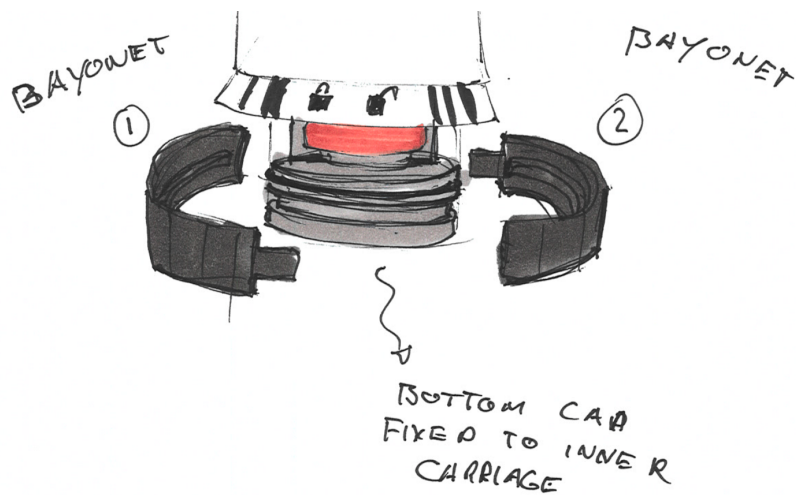
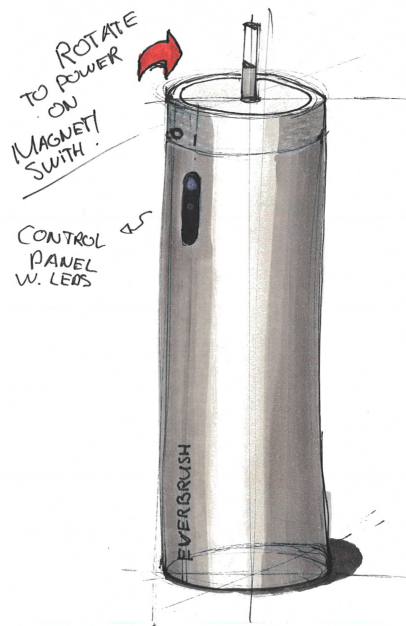


Figure 14 - The bayonet ring consists of two identical parts that rotate around a fixed bottom cap.

The charging port implemented is a USB-C port, meaning the brush can be charged with chargers that users already have. No extra e-waste has to be generated. This is in line with EU goals of unifying chargers for small and medium-sized electronic devices to reduce e-waste (Deal on Common Charger: Reducing Hassle for Consumers and Curbing e-Waste | News | European Parliament, 2022).

### Concept 3: Full metal - Everbrush



#### Concept introduction

The Everbrush concept is meant to truly be a toothbrush that can last a lifetime. The goal is to let durability and long product life be the character of the product.

A major issue for the product life of electric toothbrushes and other similar equipment is that users expect them to only last for 5 to 6 years (Survey phase 1; Cooper, 2004). This expectation is problematic, as it means that when a toothbrush breaks after several years of use, users believe the device has had its time.

In order to change this perception a more radical approach is taken: A metal housing.

Apple's implementation of machined aluminium frames for their Macbook computers served as an inspiration for this change. These devices are renowned for their durability and are often bought by people expecting to hold onto them for long a time.

Figure 15 - Concept 3 - Full metal

#### Long product life

The battery replacement procedure of the Everbrush concept is a little less easy than that of the other two concepts. While it still takes only 4 steps, a screwdriver is required in order to access the battery or any of the other internals. After removing the screw, the inner carriage pops out partly, and there are grips on it that allow the user to slide out the inner carriage (see Figure 16). This pop-out mechanism is part of the reason why a sealing screw was selected: In order to move the o-ring all the way to the bottom, minimizing the strength of the spring required, the 'button' is used to actuate the mechanism had to seal itself.

As the screw might seem like a barrier to battery replacement for some users, texts are added that encourage the user to open the toothbrush in a playful way.

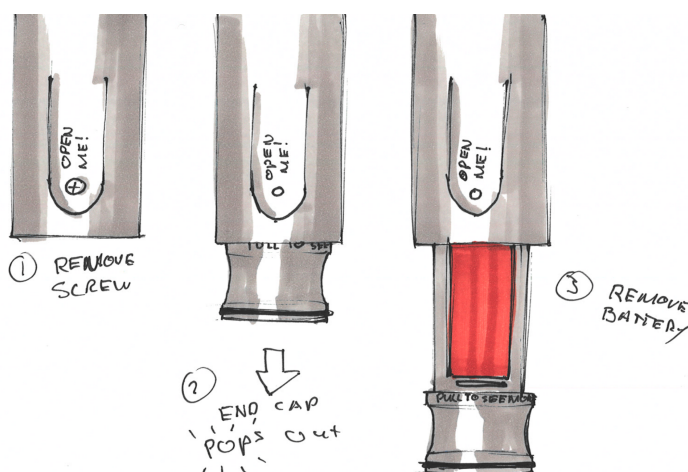


Figure 16 - The battery replacement procedure for the Everbrush concept.

Like the MacBook pro's with the machined aluminium housings, one of the primary advantages of the metal toothbrush housing is that it is able to age with dignity. This increases product attachment significantly. While there are no customization options currently implemented, it would be possible to sell different colours.

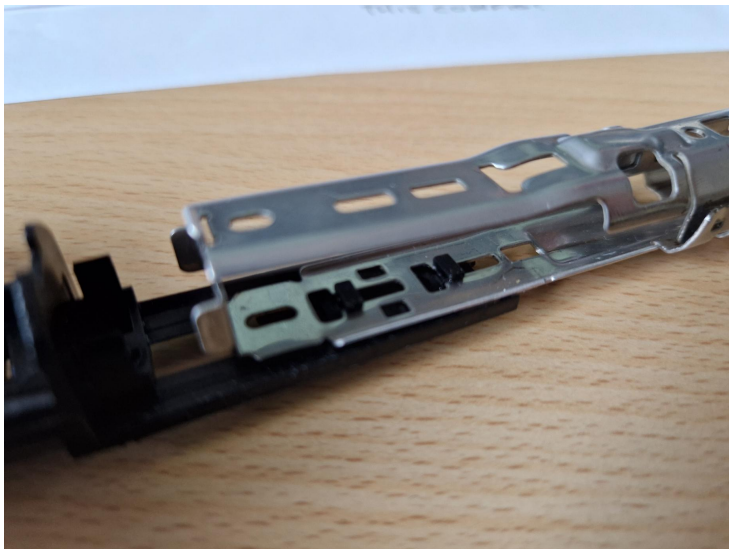
By increasing consumer attachment, repair considerations are also increased. Another potential benefit of the metal housing is that the perceived value for users is higher, which is also linked to increased repair consideration (Lilley et al., 2016). A further increase in repair considerations is achieved by reducing repair costs, as further elaborated in the next section.

#### Local loops for priority parts

It is expected the metal casing will also help alleviate users' concerns about refurbishment, as they are more likely to perceive the material as clean. The material is also less likely to show undesirable wear. Another idea that could potentially be implemented, if the housing has a brushed finish, is to re-brush the housing for refurbishment, restoring the housing to a like-new condition.

The ease of disassembly for priority parts has been optimized by minimizing the number of steps required and making most of the procedure toolless. The motor can be replaced in just 7 steps. The PCB removal requires just 5 steps. The only step that requires a tool is the initial removal of the screw to open the brush which is also required for battery replacement.

The inclusion of the pop-out mechanism means a spring had to be included somewhere in the product. To implement this spring, a mechanism similar to that in the Philips Sonicare Easyclean was implemented (see figure 17). The motor cap is fixed to the inner carriage using fits that allow it to slide (see figure 18). When the brush is closed, the spring is in its compressed position.



*Figure 17 - The Philips Sonicare uses a similar sliding fit mechanism.*

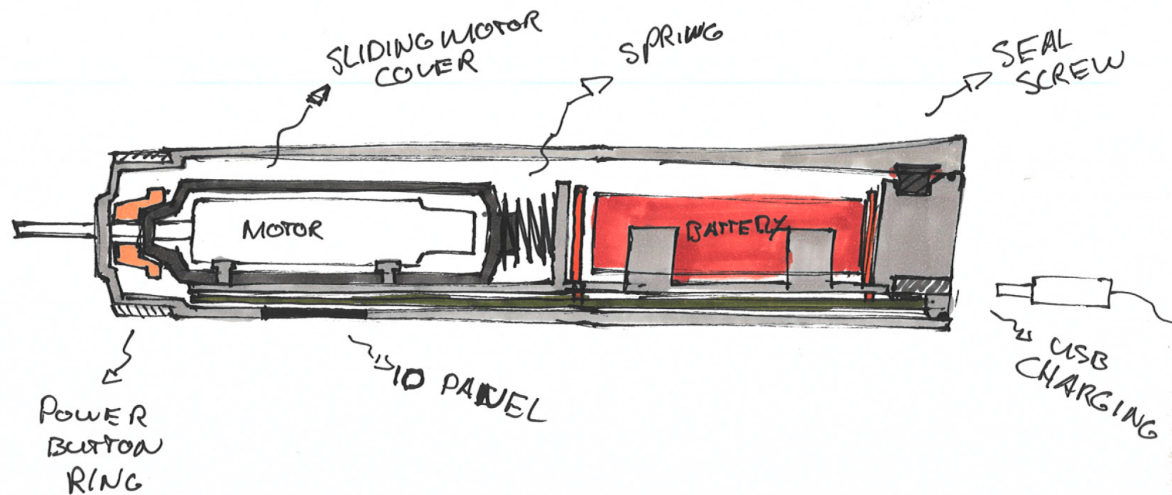


Figure 18 - View of the internal configuration of the full metal concept. The motor housing is fixed in a way that allows it to slide. The spring pushes out part of the internal carriage when the seal screw is loosened.

### High-value recycling

A disadvantage of the Everbrush concept is that five elastomer parts are used. There are additional elastomers used for the seal screw, the small interface panel that hides two LEDs on the front and the USB port. No elastomers are used in the power button, as it is replaced by a rotating knob at the top of the brush that uses a magnetic switch (see figure 19).

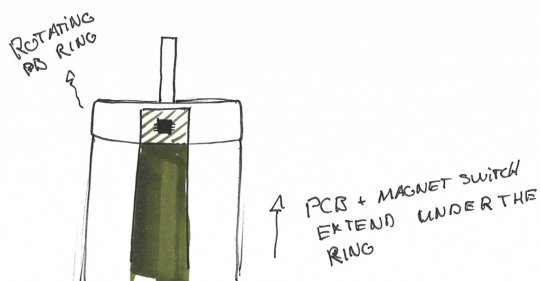


Figure 19 - The top part of the Everbrush is a rotating ring containing a magnet. A magnet switch is located behind the ring on the PCB inside the brush.

A USB-C charging port is implemented in the bottom cap of the brush, meaning the brush can be charged with chargers that users already have. No extra e-waste has to be generated. This is in line with EU goals of unifying chargers for small and medium-sized electronic devices to reduce e-waste (Deal on Common Charger: Reducing Hassle for Consumers and Curbing e-Waste | News | European Parliament, 2022).

### Other

While it is assumed the main body of the first two concepts will not vary significantly in brushing experience and cost compared to current electric toothbrushes, the metal housing of the Everbrush potentially makes a difference.

While the brushing experience will be influenced on multiple fronts, weight appears the most direct concern at this stage. Assuming the volume of the housing and weight of the other components remains the same, the weight of the Boombrush would increase from 135 to 188 grams when making the housing out of aluminium. After testing this difference with a mobile phone, this increase did not appear to be a reason for concern. More thorough research on the topic of brushing comfort with a metal brush housing should be performed if this concept is selected.

To get a feel for the cost of making the housing from metal, the [custompartnet.com](http://custompartnet.com) cost estimator was used to estimate the cost of a Boombrushed size housing made either by ABS injection moulding or aluminium die casting. Assuming 10.000 parts are made, the aluminium part would cost around 4 euros, while the ABS part would cost a little over 2 euros. While this is twice as expensive, this increase seems reasonable.

## ***Appendix I. KPI scoring justification***

---

*Appendix on the following pages*

Concept	Concept 1: Half split		Concept 2: High capacity, standard charging		Concept 3: Full metal		Notes
	Score	Justification	Score	Justification	Score	Justification	
K1	5	Easiest to replace battery of all concepts, two actions required, no tools.	4	Battery replacement is easy and the textured button makes it intentional. However, sliding out the inner carriage is not ideal.	3	Battery replacement requires a screwdriver. Besides requiring a common tool, the procedure is similar in complexity and intent to concept 2.	Concept 3 loses points due to the use of a common tool, but the impact of this requirement for a procedure that needs to happen once every 4-5 years is minimal. Important to consider, but not specified as a KPI is the simplicity of the mechanism --> Design for durability. In this metric, the mechanism used for Concept 1 & 3 are better.
K2	3	Repairs are easy to perform, but product attachment is barely increased via picking a product colour.	3	Repairs are easy to perform, but product attachment is only slightly increased via the customizable ring.	5	The higher product value and significant increase in product attachment due to the whole body ageing with dignity makes this the concept with by far the highest expected increase in repair consideration.	
K3	2	Product attachment is barely increased via picking a product colour.	2	Product attachment is only slightly increased via the customizable ring.	4	Significant increase in product attachment due to the main body ageing with dignity	All concepts are cheaper to repair than current brushes, but it is expected that users will consider repair concept 3 more often.
K4	2	No design implementation that aid the acceptance of refurbishment. Some flexibility for optional implementations due to split design.	2	The customizable ring could improve acceptance of refurbishment, but the effect of the ring works only after the purchase. As such, the effects on purchase intentions are likely negligible.	4	The metal housing is easier to clean than the plastic housings of the other brushes and less likely to show undesirable wear. Optionally the metal housing allows for a rebrushing action to happen, making the entire appearance like new.	
K5	5	Fewest steps for PCB (4) and matching the other concepts for motor (7). Implementing the motor fixations of the other concepts here can further improve this.	4	Most steps for PCB (6) and matching other concepts for the motor (7). The bayonet closure is a bit more complex to open and that shows, but the entire disassembly can be done without tools.	4	Average steps for PCB (5) and matching other concepts for the motor (7). Only one screw has to be removed (seal screw), the rest of the procedure is toolless.	
K6	5	Three elastomer parts, can be reduced to two by replacing the button with a capacitive button (see concept 2).	4	Three elastomer parts.	1	5 elastomer parts are used. Possibly the seal screw can be replaced by a regular screw by smartly redesigning the internals.	
K7	3	Current induction chargers use permanent connections for waterproofing. This has to be solved or it will be a disadvantage.	4	LED transparent parts are moulded in the body, intention is to make these out of the same material as the body.	5	No permanent connections are used.	
Concept	Concept 1: Half split	Concept 2: High capacity, standard charging	Concept 3: Full metal				
K1	5	4	3				
K2	3	3	5				
K3	2	2	4				
K4	2	2	4				
K5	5	4	4				
K6	5	4	1				
K7	3	4	5				
Total	25	23	26				

## **Appendix J. Test O-ring force Boombrush**

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*Appendix on the following pages*

# Boombrush O-ring force measurement

## Setup

The Boombrush electric toothbrush was disassembled. The o-ring was fitted to the bottom cap. A steel rod was placed through the main body and connected to the bottom cap using a zip tie (see figure 1). A kitchen scale was used for the force measurement. A phone camera was placed to film the scale reading during the measurement.



Figure 1: Boombrush modified for force testing.

## Procedure

The bottom cap with O-ring was pushed into the main body. The other end of the steel rod was placed on the scale. With everything in position, the researcher held on to the main body part and started applying a slowly increasing force. Once the bottom cap released from the main body, the researcher stopped applying force.

After performing the procedure, the camera was checked and the maximum reading was noted. The procedure was repeated five times.

## Results

Reading number	Reading in grams	Force in N (assuming $g = 9,81$ )
----------------	------------------	-----------------------------------

1	1207	11,84
2	1214	11,90
3	1247	12,23
4	1216	11,92
5	958	9,39

*Table 1: Results*

Table 1 shows the results of the test. While the 5<sup>th</sup> try yielded a lower outlier results, the general reading was around 1200 grams, or about 12 N of force.

## ***Appendix K. Spring selection***

---

*Appendix on the following pages*

## Spring selection for the pop-out mechanism

### Setup

A suitable spring for the pop-out mechanism was selected. There are two states to consider in order to determine what makes a suitable spring (see figure 1).

The first state is the compressed state. This is the state when the inner carriage is fixed in the toothbrush. The spring force in this state should be as low as possible, as this makes re-inserting the inner carriage after a battery replacement easier.

The second state is the extended state. This is the state after pressing the release button. The inner carriage should extend 15 millimetres from the main body to allow the user to grab the grip. In this state the spring force should be 12N.

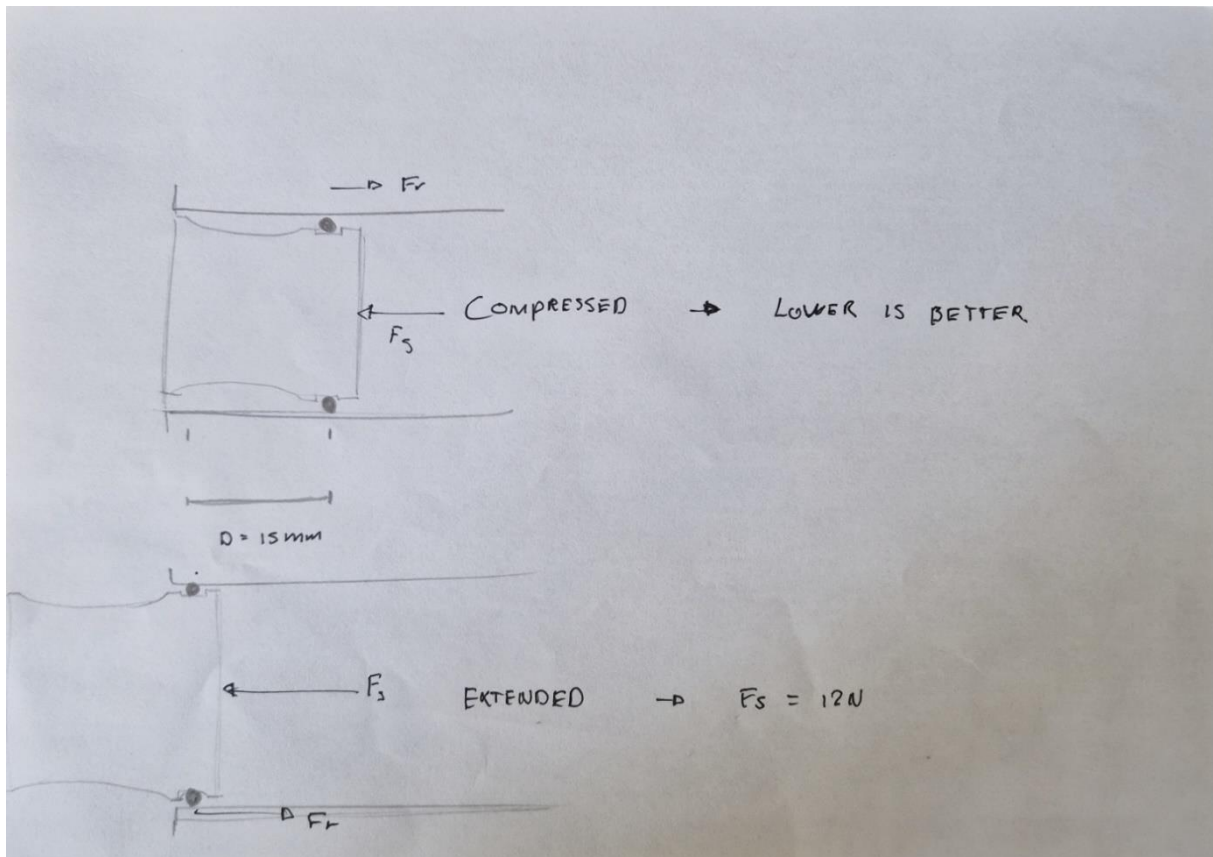


Figure 1: Schematic drawing of the two spring states.

Other important limitations for the spring selections are the inner and outer diameter. Space in the top part of the brush is limited. The inner diameter has to be at least 14 mm to prevent interference with the top seal. The outer diameter can be a maximum of 18 mm.

## Selection

While there are probably many more suitable springs out there, the selection of springs was made from the Alcomex Springs webshop (Alcomex Springs, n.d.). Two potential springs were identified: the D2300 and DR2300 (see table 1).

	D (mm)	Dm (mm)	L0 (mm)	Ln (mm)	As (mm)	Bus (mm)	Fn (N)	C (N/mm)	Materiaal
D2300	1.25	16.00	40.5	9.10	14.10	18.20	54.23	1.73	Verenstaal
DR2300	1.25	16.00	10.5	9.10	14.10	18.20	45.17	1.44	RVS 302

Table 1: Specifications of the D2300 and DR2300 springs.

## Sources

Alcomex Springs. (n.d.). *Drukveren kopen? | Binnen 48 uur geleverd | Alcomex*. Alcomex

Webshop. Retrieved 23 June 2022, from <https://webshop.alcomex.nl/drukveren>


## **Appendix L. Cost calculation [custompartnet.com](http://custompartnet.com)**

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*Appendix on the following pages*


# Cost estimates – Main body part

Estimate aluminium die casting:

 **Cost Estimator**

New Estimate ▾ Save Share Units ▾

Die Casting Reports Additional Processes ▾

 **Part Information**

[Quantity:](#)

[Material:](#) Aluminum A360.0, Die Cast [Browse...](#)

[Envelope X-Y-Z \(in\):](#)  x  x

[Max. wall thickness \(in\):](#)

[Projected area \(in<sup>2</sup>\):](#)  or  % of envelope

[Projected holes?:](#)  Yes  No


[Surface area \(in<sup>2</sup>\):](#)  (optional)


[Volume \(in<sup>3</sup>\):](#)  or  % of envelope

[Tolerance \(in\):](#)  ▾

[Surface roughness:](#)  ▾

[Complexity:](#)  ▾ [Show advanced complexity options](#)

 **Process Parameters**

 **Cost**


[Update Estimate](#)

Material: \$3,410 (\$0.341 per part)  
Production: \$8,284 (\$0.828 per part)  
Tooling: \$50,061 (\$5.006 per part)  
Total: **\$61,756 (\$6.176 per part)**

[Feedback/Report a bug](#)


Save As Next...

Estimate ABS injection moulding:

 **Cost Estimator**

New Estimate ▾ Save Share Units ▾

Injection Molding Reports Additional Processes ▾

 **Part Information**

[Rapid tooling?:](#)  Yes  No

[Quantity:](#)

[Material:](#) Acrylonitrile Butadiene Styrene (ABS), Molded [Browse...](#)

[Envelope X-Y-Z \(in\):](#)  x  x

[Max. wall thickness \(in\):](#)

[Projected area \(in<sup>2</sup>\):](#)  or  % of envelope


[Projected holes?:](#)  Yes  No


[Volume \(in<sup>3</sup>\):](#)  or  % of envelope

[Tolerance \(in\):](#)  ▾

[Surface roughness \(µin\):](#)  ▾

[Complexity:](#)  ▾ [Show advanced complexity options](#)

 **Process Parameters**

 **Cost**

[Update Estimate](#)

Material: \$858 (\$0.086 per part)  
Production: \$1,682 (\$0.168 per part)  
Tooling: \$34,147 (\$3.415 per part)  
Total: **\$36,687 (\$3.669 per part)**

[Feedback/Report a bug](#)

Save As Next...

## **Appendix M. BOM Everbrush**

---

*Appendix on the following pages*

Model	Everbrush
Number of parts	18
Number of unique parts	17
Total weight (added up)	122,7
Total weight (measured)	
Total CO2	1889,1148
Total economic value	9,5775115

Materials	CO2 per kg	Value per kg (euro)
PP	2,915	1,2 Sourced from Granta Edupack 2020,
Low carbon steel	2,325	0,6845 Sourced from Granta Edupack 2020,
Battery	3,15	9,845 Sourced from HS mapping sheet
PCB	161	587,5 Sourced from HS mapping sheet
E-motor	11,8	64,05 Sourced from HS mapping sheet
Other electronics	10	148,2 Sourced from HS mapping sheet
ASA	4,865	2,335 Sourced from Granta Edupack 2020,
ABS	3,44	1,9 Sourced from Granta Edupack 2020,
Thermoset	3	3,4 Sourced from HS mapping sheet -> T
POM	3,2	1,495 Sourced from Granta Edupack 2020,
HDPE	1,86	1,03 Sourced from Granta Edupack 2020,
ABS + PC	4,87	3,53 Sourced from Granta Edupack 2020,
Rechargeable	15,05	332,5 Sourced from HS mapping sheet
Stainless steel	5,445	2,81 Sourced from Granta Edupack 2020,
Copper	4,05	5,875 Sourced from Granta Edupack 2020,
PA	7,045	3,735 Sourced from Granta Edupack 2020,
Ferrite	0,8845	0,8725 Sourced from Granta Edupack 2020,
Thermoplastic	3,027	2,76 Sourced from HS mapping sheet
PA + ABS	5,74	3,235 Sourced from Granta Edupack 2020,
Thermoplastic	3,027	2,76 Sourced from HS mapping sheet
SEBS-TPE	4,595	2,18 Sourced from Granta Edupack 2020,
Aluminium	13,05	2,245 Sourced from Granta Edupack 2020,

#	Part	Number of par	Material	Manufacturing	Mass			Footprint			Material value			Notes
					per part (g)	total (g)	total (%)	CO2 per part (g)	CO2 total (g)	CO2 total (%)	per part (euro)	total (euro)	total (%)	
1	Brush head	1	Mixed, mainly ABS	Injection moulding	5	5	4,1	17,2	17,2	0,9	0,0095	0,0095	0,1	
2	Power switch	1	Aluminium	CNC	4	4	3,3	52,2	52,2	2,8	0,00898	0,00898	0,1	
3	Led panel	1	SEBS-TPE	Injection moulding	0,1	0,1	0,1	0,4595	0,4595	0,0	0,000218	0,000218	0,0	
4	Main body	1	Aluminium	Die casting	54	54	44,0	704,7	704,7	37,3	0,12123	0,12123	1,3	
5	Power switch lock	1	Aluminium	CNC	1	1	0,8	13,05	13,05	0,7	0,002245	0,002245	0,0	
6	Power switch postion lock	1	ABS	Punching	0,2	0,2	0,2	0,688	0,688	0,0	0,00038	0,00038	0,0	
7	Magnet	1	Ferrite	Standard part	0,2	0,2	0,2	0,1769	0,1769	0,0	0,0001745	0,0001745	0,0	
8	Motor	1	E-motor	Standard part	26	26	21,2	306,8	306,8	16,2	1,6653	1,6653	17,4	
9	Battery	1	Rechargeable	Standard part	18	18	14,7	270,9	270,9	14,3	5,985	5,985	62,5	
10	Top seal	1	SEBS-TPE	Injection moulding	0,6	0,6	0,5	2,757	2,757	0,1	0,001308	0,001308	0,0	
11	O-ring (bottom seal)	1	Elastomer	Standard part	0,2	0,2	0,2	0,6054	0,6054	0,0	0,000552	0,000552	0,0	
12	Bottom cap	1	ABS	Injection moulding	3	3	2,4	10,32	10,32	0,5	0,0057	0,0057	0,1	
13	Internal carriage	1	ABS	Injection moulding	5	5	4,1	17,2	17,2	0,9	0,0095	0,0095	0,1	
14	Motor cap	1	ABS	Injection moulding	2	2	1,6	6,88	6,88	0,4	0,0038	0,0038	0,0	
15	PCB	1	PCB	-	3	3	2,4	483	483	25,6	1,7625	1,7625	18,4	
16	Spring	1	Stainless steel	Standard part	0,4	0,4	0,3	2,178	2,178	0,1	0,001124	0,001124	0,0	
17	Battery contact	2	Brass	Punching	0	0	0,0	0	0	0,0	0	0	0,0	
18						0	0,0	0	0	0,0	0	0	0,0	
19						0	0,0	0	0	0,0	0	0	0,0	
20						0	0,0	0	0	0,0	0	0	0,0	
21						0	0,0	0	0	0,0	0	0	0,0	
22						0	0,0	0	0	0,0	0	0	0,0	
23						0	0,0	0	0	0,0	0	0	0,0	
24						0	0,0	0	0	0,0	0	0	0,0	
25						0	0,0	0	0	0,0	0	0	0,0	
26						0	0,0	0	0	0,0	0	0	0,0	
27						0	0,0	0	0	0,0	0	0	0,0	
28						0	0,0	0	0	0,0	0	0	0,0	
29						0	0,0	0	0	0,0	0	0	0,0	
30						0	0,0	0	0	0,0	0	0	0,0	

Parts ordering & grouping				
Group	Part - general	% mass	%footprint	%value
High impact, occuring in all brushes	Battery	14,7	14,3	62,5
	PCB	2,4	25,6	18,4
	Motor	21,2	16,2	17,4
Waterproofing	Main body	44,0	37,3	1,3
	Bottom seal	0,2	0,0	0,0
	Top seal	0,5	0,1	0,0
Other - metals	LED panel	0,1	0,0	0,0
	Battery contact	0,0	0,0	0,0
	Spring	0,3	0,1	0,0
	Power switch lock	0,8	0,7	0,0
	Power switch	3,3	2,8	0,1
Other - plastics	Magnet	0,2	0,0	0,0
	Brush head	4,1	0,9	0,1
	Power switch position lock	0,2	0,0	0,0
	Bottom cap	2,4	0,5	0,1
	Internal carriage	4,1	0,9	0,1
	Motor cap	1,6	0,4	0,0

## ***Appendix N. Everbrush concept validation study***

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*Appendix on the following pages*

# Everbrush - Concept validation study

Author: Drummen, Mart | Date: June 2022

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## Introduction

The Everbrush electric toothbrush concept was developed as a design solution to challenges found in transitioning electric toothbrushes to the circular economy. During the design of the concept, several assumptions were made that require validation through user testing. This study evaluates four of those assumptions, split into three categories.

### **Battery replacement**

A core aspect of the Everbrush electric toothbrush concept is the addition of a user-replaceable battery. It is expected this procedure needs to be performed once every five years. The user will receive a new battery and needs to place this battery in the brush autonomously. The first assumption to be tested in this study is that *the battery replacement procedure enables users to replace the battery in the product*. In this study, insight is gained into how the design affects the participants' ability to perform the battery replacement procedure.

### **Refurbishment**

The willingness to buy refurbished electric toothbrushes was found to be low in the user study performed at the start of the thesis, with only 17,5% of respondents stating they would buy refurbished toothbrushes. The main reasons for not wanting to buy refurbished were concerns about hygiene and contamination, with concerns about product quality a distant second.

Several ideas were conceived to improve how consumers think about refurbished electric toothbrushes, of which two ideas will be tested in this study. The first idea is introducing an aluminium main body part, which is assumed to *relieve users' concerns about contamination and hygiene when buying refurbished*. The second idea is the introduction of the 'everything is refurbished' strategy, which aims to challenge what it means for a product to be refurbished. For this idea, it is also assumed that it *relieves users' concerns about contamination and hygiene when buying refurbished*.

In this study, insights are gained into how the implementation of these ideas affects participants' perception of refurbished toothbrushes. The goal is not to determine consumers' willingness to purchase.

### **Brushing experience**

The introduction of the aluminium main body part is expected to have several positive effects on the circularity of the brush, but it should be ensured it does not negatively affect the brushing experience. In this study, insight is gained into how the aluminium main body affects the participants' brushing experience.

## Methods

### **Participants**

The participants in this study were 5 adults ranging from 21 to 25 years old. 3 were male, 2 female. All participants were volunteers recruited via personal contact.

### **Procedure**

Participants were informed about the study procedure and allowed to ask questions before the study. When everything was clear, participants were asked to fill out an informed consent form (see appendix A). The study was split into three sections.

### ***Battery replacement***

Section one evaluated the battery replacement. Participants were given a battery replacement prototype with a brush head attached to the brush and asked to perform a battery replacement. The procedure was finished once the brush head was re-attached again. Participants were filmed while performing the procedure and asked to think aloud (Clayton, 1982) during the procedure.

This method was chosen as replaceable batteries for electric toothbrushes are uncommon. When someone is unfamiliar with an object, his/her ability to use a product depends significantly on past experience with similar features (Blackler et al., 2010, p.87). Dan Norman calls this conventions (Norman, 2013). The thinking aloud method can help determine which conventions are present and how they affect the procedure.

### ***Refurbishment***

Section two evaluated both hypotheses about refurbishment. Participants were first shown a mock-up webshop interface with a new toothbrush. An interface with a new brush was tested first as this served as a reference for the refurbished brushes. A semi-structured interview was conducted in which questions about the participant's perception of product quality and hygiene were asked (see appendix B). These two areas of interest were identified based on the user study in phase 1. Semi-structured interviews were chosen given the exploratory objective of the research (Patton, 2002). The procedure was then repeated with the other two mock-up webshop interfaces. The interviews were recorded for later analysis.

### ***Brushing experience***

Section three evaluated the brushing experience. Participants were given a prototype simulating an electric toothbrush with an aluminium housing. Each participant was provided with a new brush head and toothpaste. Participants were asked to perform a two-minute brushing routine. After completing the brushing performance, participants were asked about the (dis)comfort of the aluminium brush (see appendix C) in a semi-structured interview. A semi-structured interview was chosen given the exploratory objective of the research (Patton, 2002). The interview was recorded for later analysis.

## **Stimuli**

For each section of the study, different stimuli were used.

### ***Battery replacement***

To evaluate the battery replacement procedure, a prototype simulating the battery replacement procedure was built (see figure 1). To ensure a realistic experience, several parts from a Boombush electric toothbrush were reused. Other parts were 3d printed. The spring required for the pop-out mechanism was ordered online and modified to suit the prototype. The prototype aims to simulate the intended experience for the battery replacement procedure and does not use identical parts to the final design.



*Figure 1 - Battery replacement prototype.*

### ***Refurbishment***

Three mock-up webshop interfaces were made to evaluate participants' perception of the toothbrush in a refurbished condition. The first interface shows the toothbrush in a new condition (see figure 2). The second interface indicates the toothbrush is refurbished (see figure 3). An additional text box in this interface highlights the cleaning efforts that are made. The third interface indicates all toothbrushes can contain refurbished parts (see figure 4). In an additional text box, the concept is explained and the high quality of the parts is stressed.

Webshop

Search



## Everbrush Electric Toothbrush

Keeping your teeth in shape is easy with this electric toothbrush.

Figure 2 - Mock-up webshop interface - New toothbrush

Webshop

Search



## Everbrush Electric Toothbrush

Refurbished

Keeping your teeth in shape is easy with this electric toothbrush.

### Carefully refurbished

Everbrush treats refurbishment with extreme care to ensure you receive the highest quality product. The toothbrush has been checked and performs like any of our new brushes. The toothbrush has been sterilized with the medical grade vaporized hydrogen peroxide technique, removing any contaminants.

Figure 3 - Mock-up webshop interface - Refurbished toothbrush with cleaning efforts highlighted



## Everbrush Electric Toothbrush

Keeping your teeth in shape is easy with this electric toothbrush.

### Can contain refurbished parts

Every part in the Everbrush is designed to last a lifetime. As such, we don't believe the quality of refurbished parts is inferior.

Every Everbrush can contain refurbished parts. If you are unsatisfied with the quality of your toothbrush, you can return it free of charge.

*Figure 4 - Mock-up webshop interface - Everything is refurbished*

### **Brushing experience**

To evaluate the effect of an aluminium product housing on the brushing experience, a prototype simulating the brushing experience was used (see figure 5). The prototype was built using an existing electric toothbrush, around which an aluminium profile with a 35mm diameter was placed. A hole was drilled to make the power button accessible and all edges were sanded to remove sharp edges. The total weight of the prototype was 197 grams. Participants were provided with a new brush head for each test.



*Figure 5 - Prototype for evaluating the brushing experience*

### **Analysis**

The researcher reviewed the video/audio footage and entered aspects noted by the participants in a spreadsheet file. Aspects were grouped into positive and negative aspects and coded. Similar aspects were grouped under the same code. The number of participants noting a code was counted.

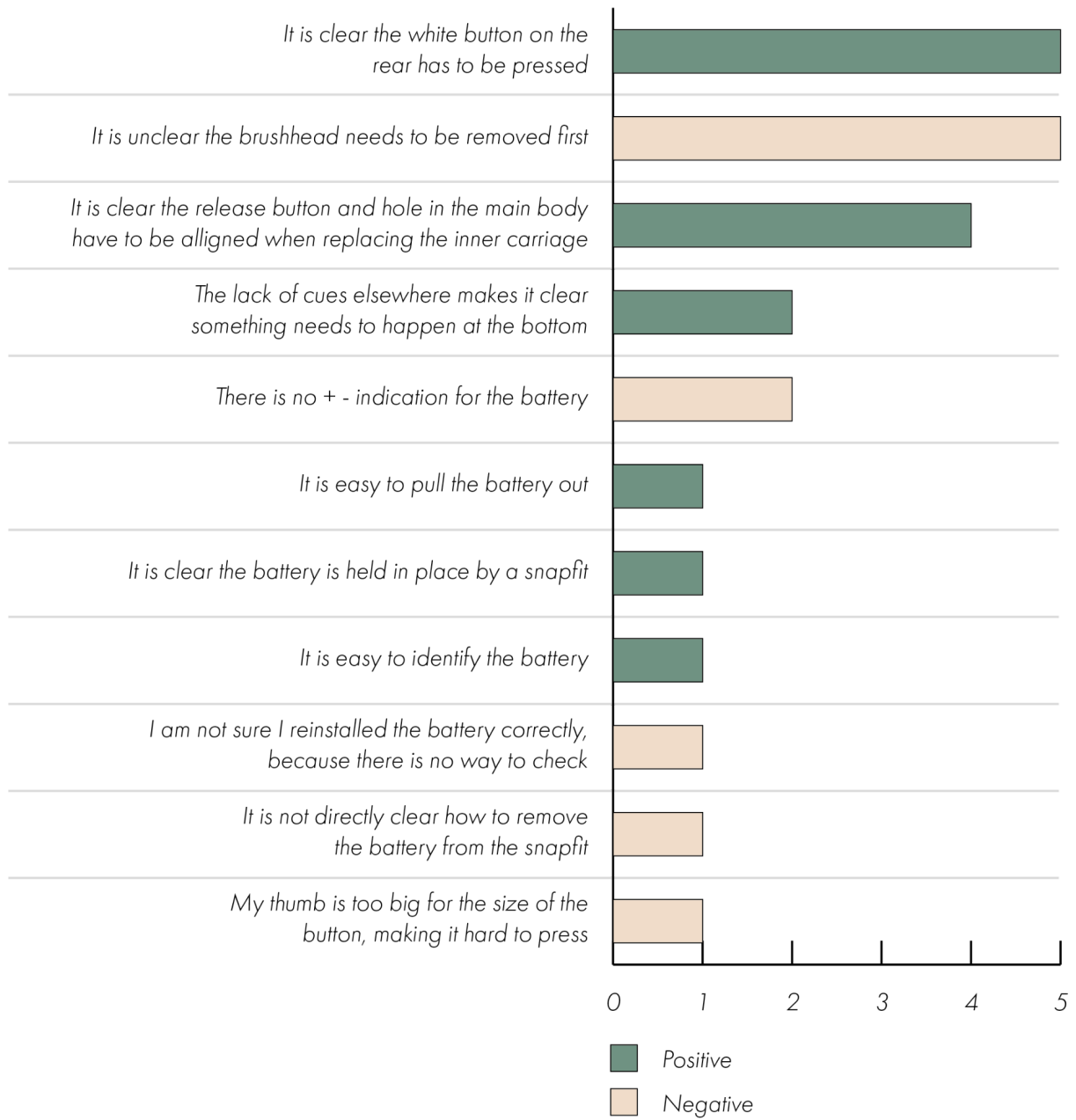
Aspects that were noted during the interviews about refurbishment which were not related to refurbishment, perception of product quality and/or perception of product hygiene were excluded from the results.

A full overview of the data and analysis can be found in Appendix D.

# Results

## Battery replacement

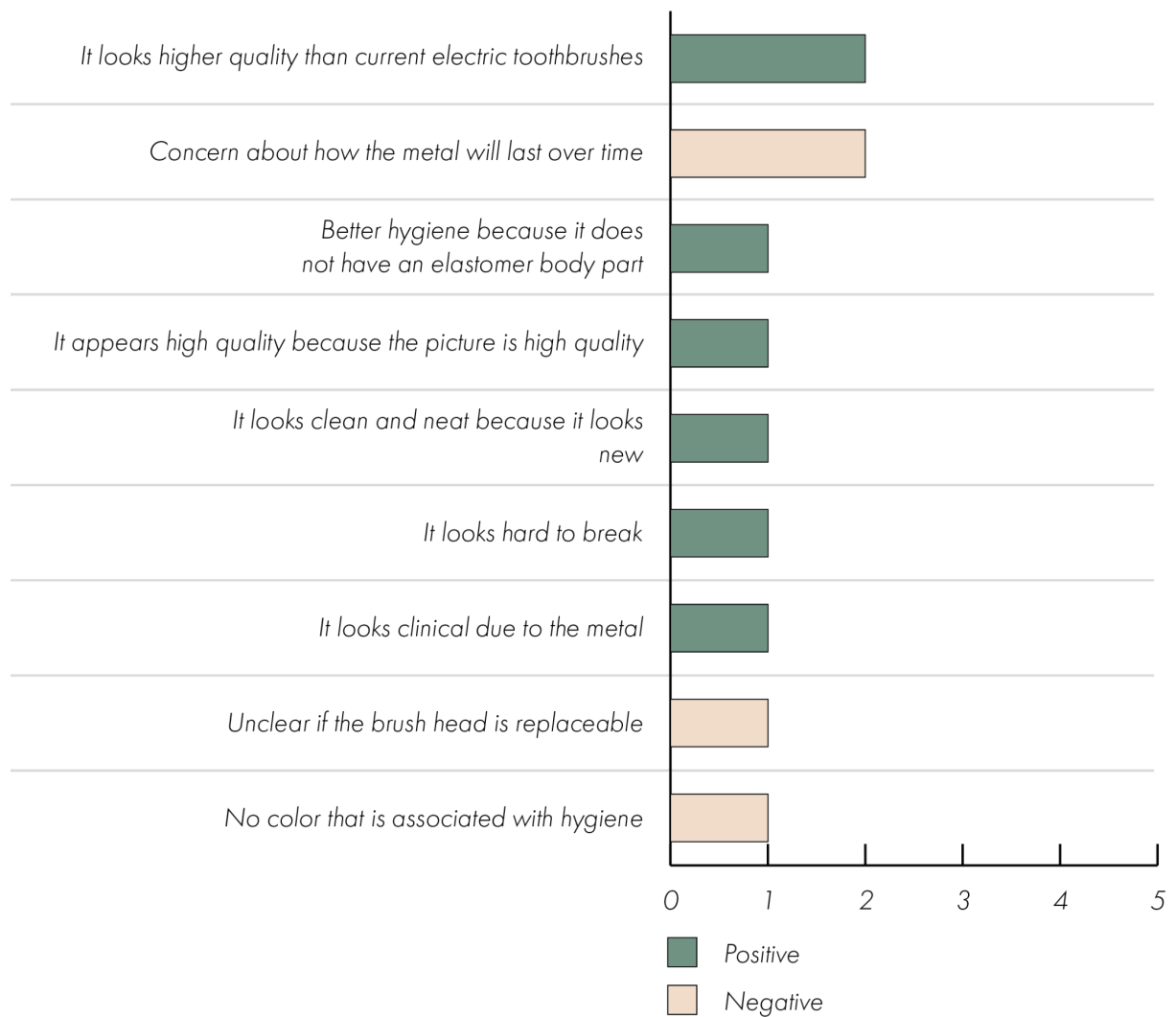
Aspects named for battery replacement (n = 5)



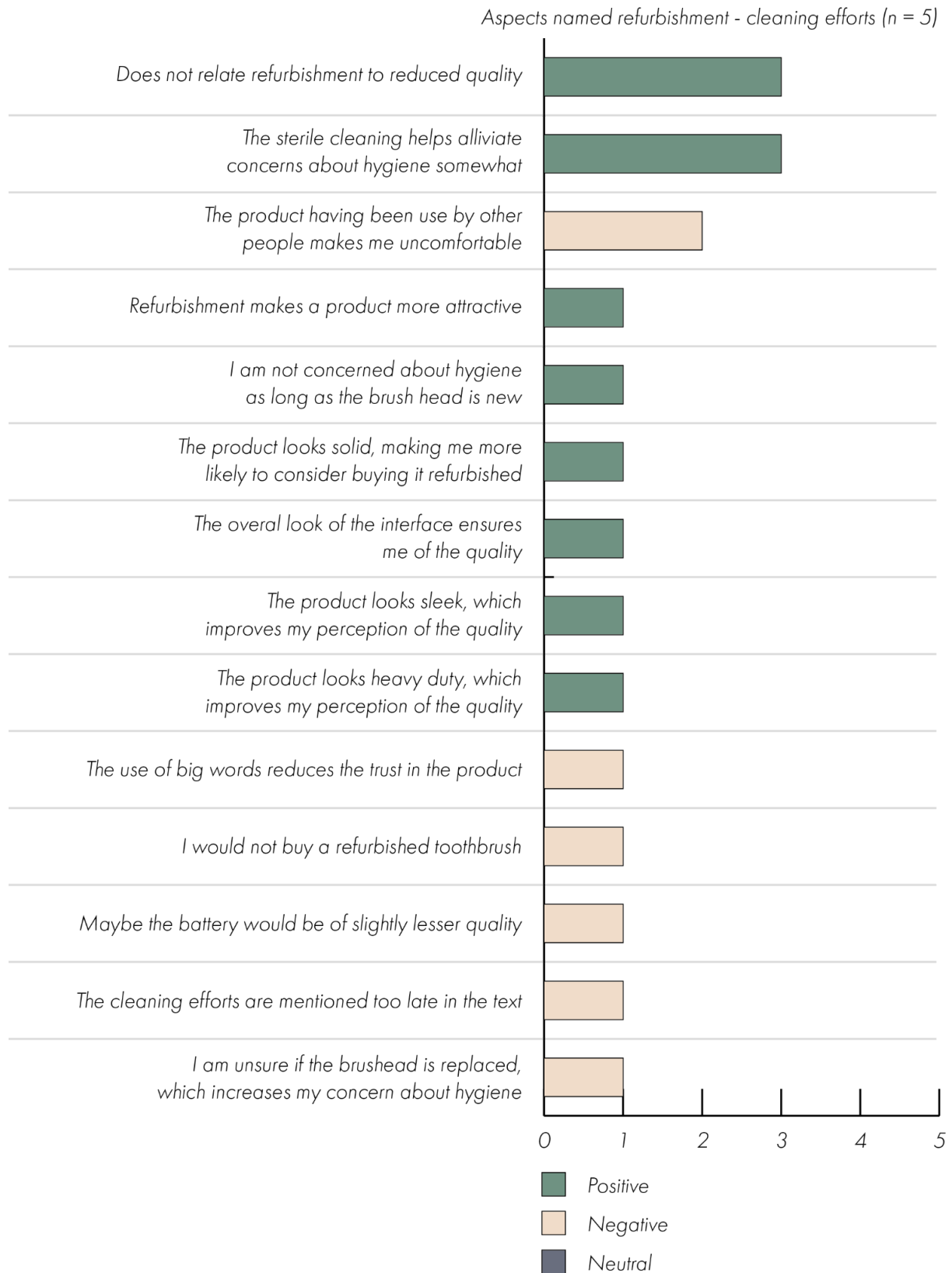
## Refurbishment

### New

Aspects named refurbishment - new (n = 5)

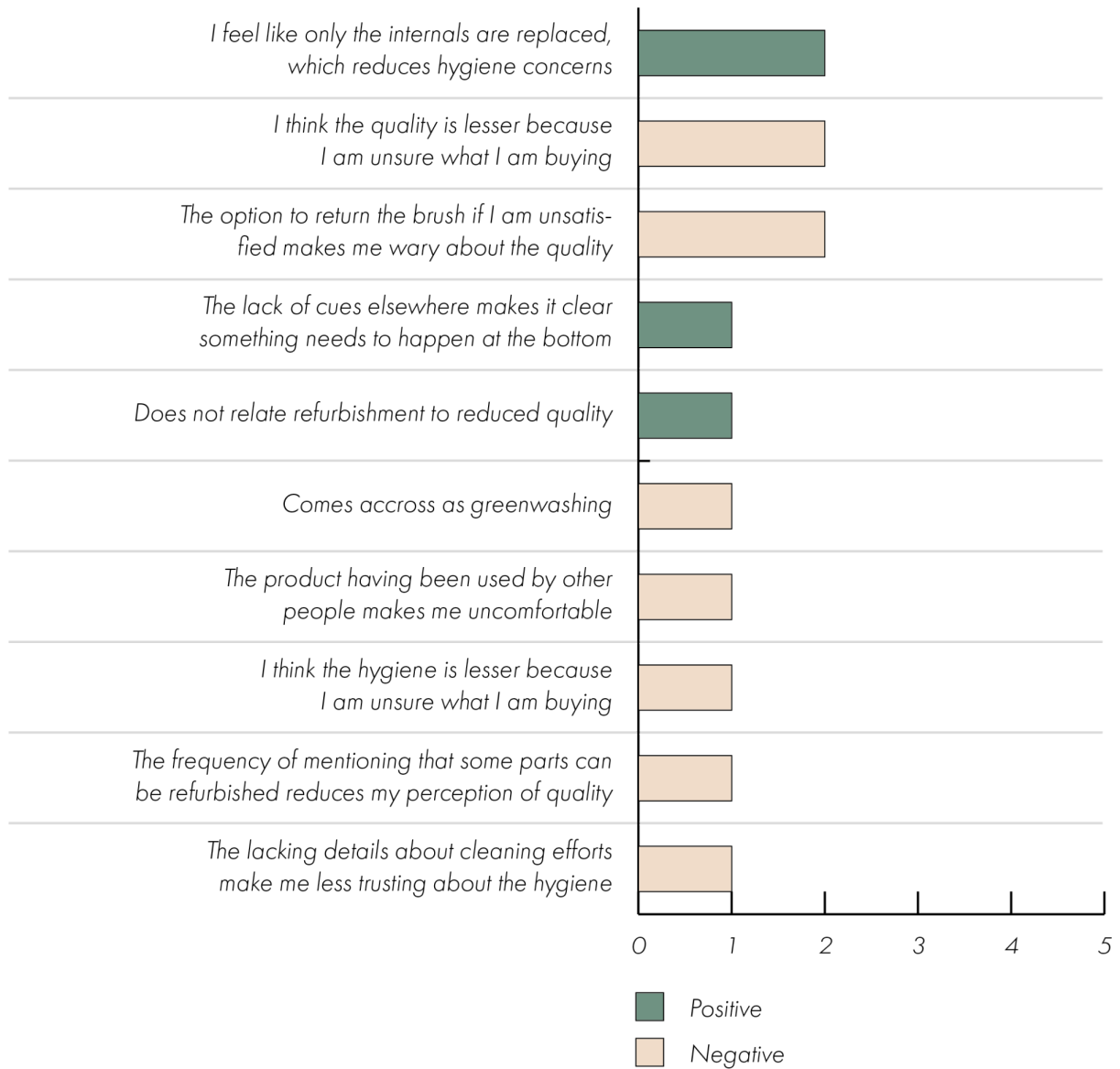


## Refurbished - Cleaning efforts



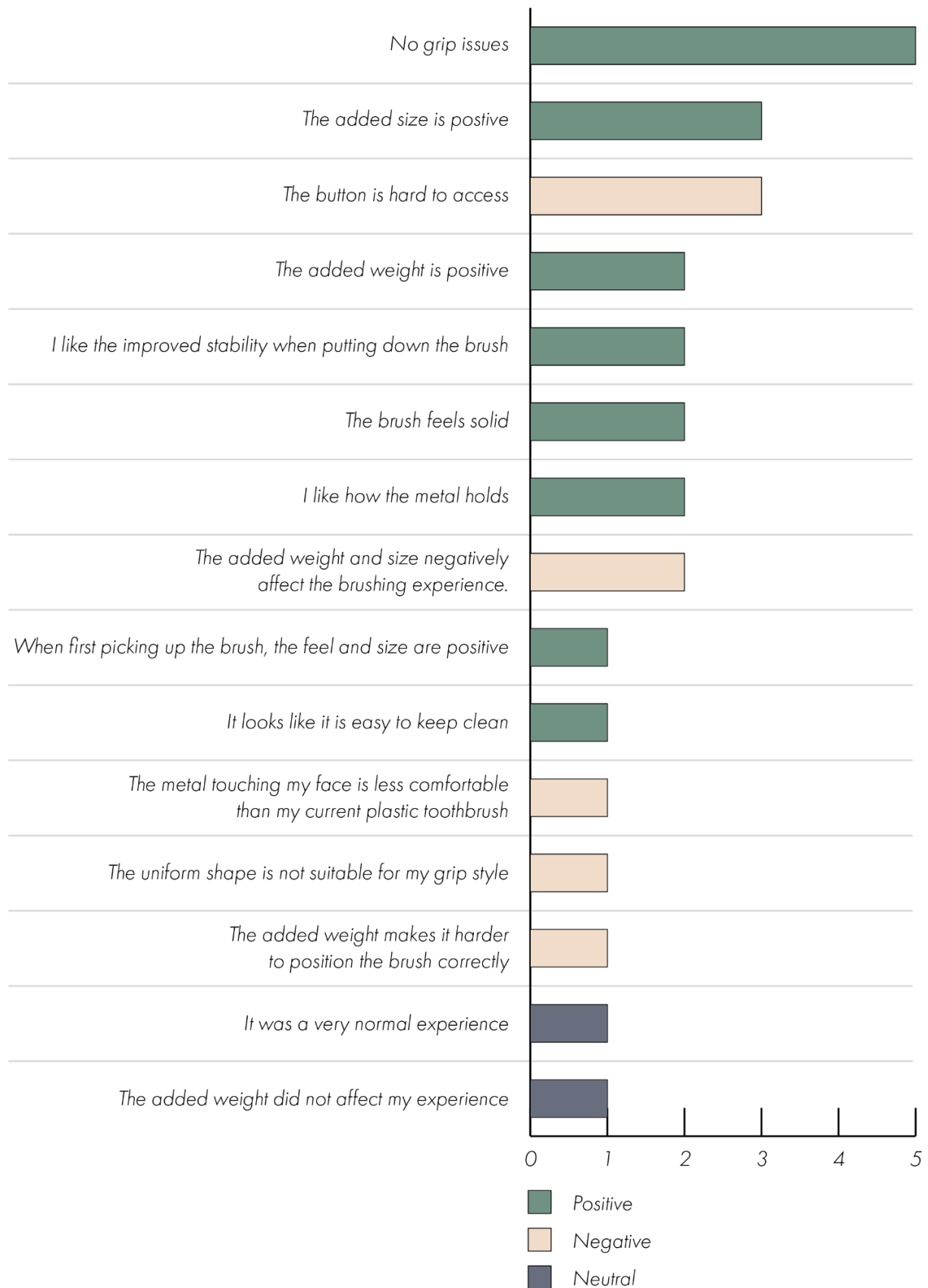
## Refurbished - Everything is refurbished

Aspects named refurbishment - everything is refurbished (n = 5)



## Brushing experience

Aspects named for brushing experience (n = 5)



## Discussion

### **Battery replacement**

No major complications were found in the battery replacement procedure as all of the participants were able to complete the procedure without receiving instructions. However, one hurdle that all participants encountered was that they did not remove the brush head before pressing the release button. A solution to this issue could be to instruct users to remove the brush head first in the packaging used for the batteries.

Another issue that was noted by two participants, but that all participants encountered, was the lack of an indication of how the battery terminals should be oriented. A clear indication for this should be added and verified in future research. Most participants were able to circumvent the issue in the test as they remembered how the battery was previously oriented.

Some issues only noted once, but potentially interesting for further research were the size of the release button being too small and the lack of a way to check whether the installation of the battery was successful.

Some participants were even impressed by the ease of the procedure, with participant 1 stating the procedure was “very clear” and participant 4 stating “it was almost too easy”.

### **Refurbishment**

#### *New*

Responses on the interface showing a new toothbrush were mixed. While most participants made positive remarks about their perception of the quality of the product, two of the participants also expressed their concerns about how the aluminium will hold up over time. Participant 5 made an interesting remark on this, as she was worried about scale building up on the textured rotating power button. The ease of cleaning of the power button texture should receive additional attention in the further development of the brush.

The product's design appeared to have a somewhat positive effect on the participant's perception of hygiene, with participant 5 highlighting the clinical look due to the metal body and participant 2 specifically mentioning the benefit of not having any elastomer grips that get dirty over time. However, as the product is shown as a new product, it would be unlikely for participants to express concerns about hygiene at this stage.

#### *Cleaning efforts*

Responses on the interface showing a refurbished brush with the cleaning efforts highlighted were also mixed. Two participants expressed concerns about contamination when purchasing a refurbished electric toothbrush. At 40% of the participants, this number is similar to the findings of the research in phase 1 and as such it appears the metal housing has little effect on concerns about contamination. Testing with more participants is necessary to draw more informed conclusions about this effect.

Several participants noted the medical-grade sterile cleaning mentioned in the text did help their perception of the product's hygiene somewhat (n=3), indicating that communicating cleaning efforts indeed could help sell refurbished electric toothbrushes as suggested by Mugge et al. (2017).

None of the participants appeared to doubt the refurbished product's quality, with multiple participants stating the looks of the product positively affected the perception of quality. As such, it does appear that the metal housing has a positive effect on the perception of product quality. However, as three of the participants expressed not relating refurbishment to reduced product quality anyways, the effect of the metal body could be minor.

### *Everything is refurbished*

The interface showing a refurbished toothbrush with the 'everything is refurbished' strategy highlighted consistently got a more negative response than the interface with cleaning efforts highlighted. In general, the lack of information about which specific parts were refurbished appeared to be causing some distrust, which led to a lower perception of the product quality in two participants. For one of these participants, it also caused a knock-on effect on the perception of product hygiene. Another participant noted the absence of an explanation on the cleaning efforts as a reason for perceiving the product hygiene as worse than the other interface.

The specific wording used in the text possibly had a negative effect on the perception of quality among participants, with two participants expressing that the option to return the brush when unsatisfied with the quality lowered their perception of the quality and one of those participants also mentioned that the number of times it was mentioned some of the parts could be refurbished reduced the perception of quality.

One positive effect of the everything is refurbished strategy is that two participants somehow felt the refurbishment now only related to internal parts, removing their concern about hygiene altogether. Whether this advantage can be kept while providing consumers with the additional information they desire to be ensured of the quality of the product should be further researched.

### **Brushing experience**

No major complications related to the aluminium main body were found during the brushing experience test. None of the participants reported grip issues related to the material and in general participants appreciated the feel in the hand of the brush.

There were two minor concerns expressed by participants. Participant 2 reported minor discomfort related to his specific brushing style. In this style, he tries to reach all the way behind his molars while brushing, causing the main body of the brush to touch his face which he experienced as less comfortable with the aluminium housing. This could partly be caused by the increase in the diameter of the prototype. Participant 3 reported that the uniform shape of the grip did not suit his brushing style in which he sometimes likes to hold the brush with just his fingertips. Both concerns should be considered in the further development of the brush, in which the ergonomics should receive additional attention.

Besides the observations related to the shape and material of the brush, there were some prototype-related observations. The prototype used was both heavier and larger than the actual brush is expected to be, at 197 grams and a diameter of 35 millimetres. The increase in size and weight over current electric toothbrushes received a mixed response, with some participants stating they liked the increase in size (n=3) and weight (n=2), but others stating it negatively affected their brushing experience (n=2). The button on the prototype was tricky to press and this attribute was noted by participants (n=3) but is not relevant to the actual concept.

An interesting finding was that some participants noted improved stability when putting down the brush (n=2). One of the two participants stated that two toothbrushes had previously broken due to a lack of stability when putting them down. The increase in stability was not intentional in the design and is likely caused by the increase in diameter and weight of the prototype. How to increase the stability intentionally should be a point of attention in the further development of the brush.

## Conclusion

### ***Battery replacement***

While some areas of improvement were found, the battery replacement procedure enables all participants to replace the battery in the product. Some improvements that should be made are adding indications for the correct battery orientation and instructions to remove the brush head prior to performing the battery replacement. An area that could receive further attention is the size of the release button.

### ***Refurbishment***

No strong evidence was found for the aluminium product housing relieving user concerns about contamination and hygiene when buying refurbished. While some participants made statements indicating that aluminium improved their perception of product hygiene, the number of participants expressing concerns about contamination appears to not have changed significantly from the study in phase 1.

The aluminium product housing did however positively affect participants' perception of the product's quality, with none of the participants expressing concerns about product quality when buying refurbished.

The everything is refurbished strategy appeared to relieve concerns about contamination and hygiene for some users, as they were led to believe refurbishment now only applied to internal parts. This is however untrue (the externals could also be refurbished), so whether this is an acceptable way of alleviating the concerns is debatable.

While alleviating concerns about hygiene and contamination for some participants, the everything is refurbished strategy in its current form negatively affected participants' perception of the quality of the product.

What stood out for both refurbishment tests is that the specific wording, interface and images used strongly affects the participants' perception. As such, further research should be performed to ensure this is optimized.

### ***Brushing experience***

All participants were able to perform a regular brushing routine without experiencing significant discomfort. However, two participants experienced some minor discomfort related to their specific brushing styles. For one participant, this minor discomfort did originate from the aluminium housing, but the effects were possibly strengthened by the prototype. Further research into brushing styles and the resulting ergonomic requirements should be performed to ensure a satisfying brushing experience for most users.

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## Appendix

### A. Informed consent form

#### Consent Form for Everbrush concept evaluation study

<i>Please tick the appropriate boxes</i>	Yes	No
<b>Taking part in the study</b>		
I have read and understood the study information dated 22/06/2022, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="radio"/>	<input type="radio"/>
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="radio"/>	<input type="radio"/>
I understand that taking part in the study involves performing light physical tasks which are recorded on video for later analysis and answering interview questions regarding to the activities. Video recordings are deleted after 90 days.	<input type="radio"/>	<input type="radio"/>
I give the researchers permission to use the video recordings of the study in the documentation describing the design process of the project.	<input type="radio"/>	<input type="radio"/>
I understand that taking part in the study involves answering interview questions which are record on audio for later analysis. Audio recordings are deleted after 90 days.	<input type="radio"/>	<input type="radio"/>
I understand that personal information collected about me that can identify me, such as video, will not be shared beyond the study team.	<input type="radio"/>	<input type="radio"/>

#### Signatures

\_\_\_\_\_  
Participant                      Signature                      Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Mart Drummen                      \_\_\_\_\_  
Researcher                      Signature                      Date

Study contact details for further information:

Name: Mart Drummen

Phone: 0612027385

Email: [m.drummen@student.tudelft.nl](mailto:m.drummen@student.tudelft.nl) | [mart.drummen@outlook.com](mailto:mart.drummen@outlook.com)

### B. Questions refurbishment

#### Interface 1 - new

- What are your first thoughts about the product?
- What do you think about the quality of the product? How long do you think it will last? Why do you think this?

- Are you concerned about the hygiene of the product? Why are you (not) concerned about it?

### **Interface 2 - refurbished, cleaning effort highlighted**

- What are your first thoughts about the product?
- What do you think about the quality of the product? How long do you think it will last? Why do you think this?
- Are you concerned about the hygiene of the product? Why are you (not) concerned about it?

### **Interface 3 - everything is refurbished**

- What are your first thoughts about the product?
- What do you think about the quality of the product? How long do you think it will last? Why do you think this?
- Are you concerned about the hygiene of the product? Why are you (not) concerned about it?

### **C. Questions brushing experience**

- What is your usual method of brushing? (Manual or electric?)
- What are your first thoughts about the brushing experience?
- How was the feeling in the hand of the toothbrush?
- Did you experience any grip issues?
- Did you experience any other forms of discomfort?

### **D. Data and analysis**

See the following pages for spreadsheets containing the data and analysis.

Participant	1	2	3	4	5	Combined	Count
Battery replacement						Code	Count
Positive aspects	It is clear the white button on the rear has to be pressed	It is clear the white button on the rear has to be pressed	It is clear the white button on the rear has to be pressed	It is clear the white button on the rear has to be pressed	It is clear the white button on the rear has to be pressed	It is clear the white button on the rear has to be pressed	5
	It is clear the release button and hole in the main body have to be aligned when replacing the inner carriage	It is clear the release button and hole in the main body have to be aligned when replacing the inner carriage	It is clear the release button and hole in the main body have to be aligned when replacing the inner carriage	It is clear the release button and hole in the main body have to be aligned when replacing the inner carriage		It is clear the release button and hole in the main body have to be aligned when replacing the inner carriage	4
			I don't see an opening anywhere but at the bottom, so I think something needs to happen at the bottom		I don't see an opening anywhere but at the bottom, so I think something needs to happen at the bottom	The lack of cues elsewhere makes it clear something needs to happen at the bottom	2
					It is easy to pull the battery out, you don't have to press a spring	It is easy to pull the battery out	1
	It is clear the battery is held in place by a snapfit					It is clear the battery is held in place by a snapfit	1
	It is easy to identify the battery					It is easy to identify the battery	1
Negative aspects	It is unclear the brushhead needs to be removed first	It is unclear the brushhead needs to be removed first	It is unclear the brushhead needs to be removed first	It is unclear the brushhead needs to be removed first	It is unclear the brushhead needs to be removed first	It is unclear the brushhead needs to be removed first	5
	There is no + - indication for the battery			There is no + - indication for the battery		There is no + - indication for the battery	2
				I am not sure I reinstalled the battery correctly, because there is no way to check		I am not sure I reinstalled the battery correctly, because there is no way to check	1
		It is not directly clear how to remove the battery from the snapfit				It is not directly clear how to remove the battery from the snapfit	1
		My thumb is too big for the size of the button, making it hard to press				My thumb is too big for the size of the button, making it hard to press	1

Participant	1	2	3	4	5	Code	Combined	Count	Purchasing refurbished	Perception of quality	Perception of hygiene
New											
Positive aspects		It looks sleek and sturdy, better looking than most toothbrushes.	It looks sleek.	It looks premium, but I would like to see more angles of the product.		Elegant/sleek Design.		3			
	I think it looks better quality wise than a regular Oral-B brush.	It looks like a long lasting product, the aluminium makes it look of higher quality than most toothbrushes.				It looks higher quality than current electric toothbrushes.		2		y	
		I have an Oral-B myself, and I think the elastomer part is very dirty. This looks easier to clean, so I think the hygiene is better.				Better hygiene because it does not have an elastomer body part.		1			y
			You are not sure, but the way it is presented it appears high quality because the picture is good.			It appears high quality because the picture is high quality.		1		y	
			It looks clean and neat (hygiene), but it would be strange if it did not because it is new.			It looks clean and neat because it looks new.		1			y
					It looks expensive.	It looks expensive.		1			
					It looks like it is hard to break.	It looks hard to break.		1		y	
					It looks more clinical/fresh, due to the metal.	It looks clinical due to the metal.		1			y
Negative aspects				I am not sure how well the brushed aluminium will last over time.	I would be concerned that scale would build up on the metal, especially around the top.	Concern about how the metal will last over time.		2		y	y
				I wonder if the brush head is replaceable, it is not clear from the images.		Unclear if the brush head is replaceable.		1			y
				It looks a bit cold, which makes me concerned about the comfort.		It looks cold, which could compromise comfort.		1			
	I associate the green and blue colors of other brushes more with hygiene, that association is lacking here.					No color that is associated with hygiene.		1			y
Refurbished - Cleaning efforts											
Positive aspects	I like that there is more information now.					It is positive that there is more information (compared to interface - new).		1			
	A toothbrush does not interest me that much, the fact that it is refurbished makes it more interesting to me.					Refurbishment makes a product more attractive.		1	y		
	I like that it is refurbished, I do not like buying new devices.										
	The quality is not affected by the fact that it is refurbished.	I believe the quality is the same to a new product, I trust refurbished products in general.		I have good experiences with previous refurbished products, so I have no concerns about the quality.		Does not relate refurbishment to reduced quality.		3		y	
	As long as the brush head is new, hygiene is not an issue for me.					I am not concerned about hygiene as long as the brush head is new.		1			y
		I would be more likely to buy this toothbrush refurbished than other Oral-B brushes, because it looks more solid.				The product looks solid, making me more likely to consider buying it refurbished		1	y		
		The sterile cleaning could help convince me.	I think the hygiene is okay because the method of cleaning is mentioned, it seems it is well thought about.	That the cleaning method is highlighted and explained makes me trust the hygiene of the product.		The sterile cleaning helps alleviate concerns about hygiene somewhat.		3			y
			It seems well thought out, it is not just refurbished. This is due to mentioning the specific method of cleaning.								
			No concerns about the quality, due to the overall look of the interface (not specifically the text).			The overall look of the interface ensures me of the quality.		1		y	
			The product looks sleek, which helps the quality appeal (it has the apple vibe).			The product looks sleek, which improves my perception of the quality.		1		y	
					The product looks heavy duty, so it is easy to believe the quality is still good when refurbished.	The product looks heavy duty, which improves my perception of the quality.		1		y	
Negative aspects		A refurbished product that went in other peoples' mouths feels a bit unnatural.			I still have this image in my head of someone else using the toothbrush, which needs to be gone before I would consider purchasing this.	The product having been use by other people makes me uncomfortable.		2			y
		I wouldn't buy a refurbished toothbrush.				I would not buy a refurbished toothbrush.		1	y		
		Maybe the battery would be of a slightly worse quality.				Maybe the battery would be of slightly lesser quality.		1		y	
					It takes a lot of time before it is mentioned that the product is cleaned well, I would have stopped reading already and thought it was dirty.	The cleaning efforts are mentioned too late in the text.		1			y
					The language is too complicated.	The language is too complicated.		1			
					It is not mentioned that the brush head is replaced, which does not help my perception of the hygiene.	I am unsure if the brushhead is replaced, which increases my concern about hygiene.		1			y
					The use of 'expensive' words makes me less trusting about the product.	The use of big words reduces the trust in the product.		1		y	
Refurbished - Everything is refurbished											
Positive aspects		I believe the quality is the same to a new product, I trust refurbished products in general.				Does not relate refurbishment to reduced quality.		1		y	
					My first thought was positive: Everything that can be re-used is re-used.	Everything that can be re-used is re-used.		1	y		
	The hygiene is not that affected for me, it feels like the refurbishment relates to the internals only.				My feeling about the hygiene is good, because I think the refurbishment is purely about the internals.	I feel like only the internals are replaced, which reduces hygiene concerns.		2			y
Negative aspects	This comes across as greenwashing for me.					Comes across as greenwashing.		1	y		
	I want to know which parts are refurbished.			It makes me unsure what I am purchasing.		I think the quality is lesser because I am unsure what I am buying.		2		y	
	I think the quality is less, because I lack trust from the lack of information.			I perceive the quality as lesser, because I am unsure what I am buying. I don't fully understand what I am buying.							
		A refurbished product that goes in other peoples' mouths feels a bit unnatural.				The product having been use by other people makes me uncomfortable.		1			y
		It is clean, but it does not feel that way.									
				Hygiene feels a bit lesser than the other two, due to the general unclarity of what I am buying.		I think the hygiene is lesser because I am unsure what I am buying.		1			y
			The sentence indicating you can return the toothbrush if it is not okay gives me less trust.		It is repeated three times in the text that it can contain used parts and than it is said you can return the product, which makes me wary about the quality.	The option to return the brush if I am unsatisfied makes me wary about the quality.		2		y	
					Often when commercials say you can return the product I think the product is not of high quality, but they assume I won't return it.						
					It is mentioned multiple times that there can be old parts in it, which strenghtens the feeling that the product is of lesser quality.	The frequency of mentioning that some parts can be refurbished reduces my perception of quality.		1		y	
			In the previous text (cleaning efforts) the trust is built well, here the trust is lacking.								y
			Hygiene is not mentioned, so it comes across worse than the previous interface.			The lacking details about cleaning efforts make me less trusting about the hygiene (compared to interface refurbished - cleaning efforts)		1			

Participant	1	2	3	4	5	Combined	Count
Brushing experience						Code	
Positive aspects	The grip was good.	No grip issues.	No grip issues from the material.	No grip issues. (also when wet)	No grip issues.	No grip issues.	5
	The added weight makes it feel like the quality is higher.		I like the added weight.			The added weight is positive.	2
	The added weight makes it feel like I have more control.						
	I like that the brush is a bit larger.	The added size of the brush is nice, it feels more like a tool and improves the grip.	I like that the brush is a bit larger.			The added size is positive.	3
	I like that the brush is more stable when putting it down, I have broken two toothbrushes this way.		I like that the added weight makes the brush is more stable when putting it down.			I like the improved stability when putting down the brush	2
		Metal directly feels more solid.		It felt solid.		The brush feels solid.	2
		It feels more solid than my regular toothbrush.					
				When first picking it up I like the feel and size.		When first picking up the brush, the feel and size are positive.	1
			It looks clean, I think it is easy to keep it clean.			It looks like it is easy to keep clean.	1
			I like how it holds.		The metal was comfortable to hold.	I like how the metal holds.	2
Negative aspects	The button is a bit deep in the brush, which is annoying.			The button is a bit deep in the brush, which is annoying.	The button is a bit deep in the brush, which is annoying.	The button is hard to access.	3
		I brush quite deep, the metal touches my face. With the plastic this is less bothersome.				The metal touching my face is less comfortable than my current plastic toothbrush	1
			I like to grip the brush a bit more between more fingers, so I miss some grips to accommodate that. (shape of the grip, not the material. Mentions indents for fingers).			The uniform shape is not suitable for my grip style.	1
				During brushing I found the brush a bit too large and too heavy.	It was very heavy. I thought about how I often brush my teeth when tired and my current brush already feels heavy.	The added weight and size negatively affect the brushing experience.	2
					The brush was too large to hold it comfortably.		
					The weight of the brush made it harder to position the brush correctly.	The added weight makes it harder to position the brush correctly.	1
Neutral	Very normal experience.					It was a very normal experience.	1
		Added weight not an issue, but not a benefit.				The added weight did not affect my experience.	1