

Creating an easy-to-use tool for (re)designing repairable products.

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Abstract

This project aims to develop an easy-to-use method to (re)design products for ease of disassembly and subsequently for circular strategies, such as repair, refurbish, remanufacture, etc. Improving repairability is one of the first steps in decreasing the environmental impact of products by prolonging their technical lifespan. This thesis focuses on two separate tools that have the potential to be integrated: the Hotspot Mapping tool and the Disassembly Map. Both tools assess a product by disassembling it into its core parts and recording the properties of the parts and the disassembly steps (Fazio & et al., 2021; Flipsen et al., 2020).

The Hotspot Mapping tool highlights parts and disassembly activities that are important due to their failure rate, functionality, disassembly effort, and environmental and economic impact. On the other hand, the Disassembly Map uses these highlighted features to create a visual representation of the product architecture. Since the inputs for both tools are similar, it raises the question of whether it is possible to link them together.

The tools are analysed by literature review and usability questionnaires, resulting in a usability score of the original tool and strengths and weaknesses in terms of features and usability. Through an iterative approach, a new tool is developed, that uses a node/edge lists data structure to describe the product architecture of a product. This data-structure allows for the automatic generation of a dynamic Disassembly Map (Figure 1) in the visualisation software program yEd Graph Editor. The dynamic Disassembly Map allows designers to select which properties to display and which to hide, enabling focused attention and a better overview.

Through user testing the new method has been proven to offer increased usability, requiring less time to fill in, and an overall preference by all usability test participants over the original Hotspot Mapping and Disassembly Map tools.

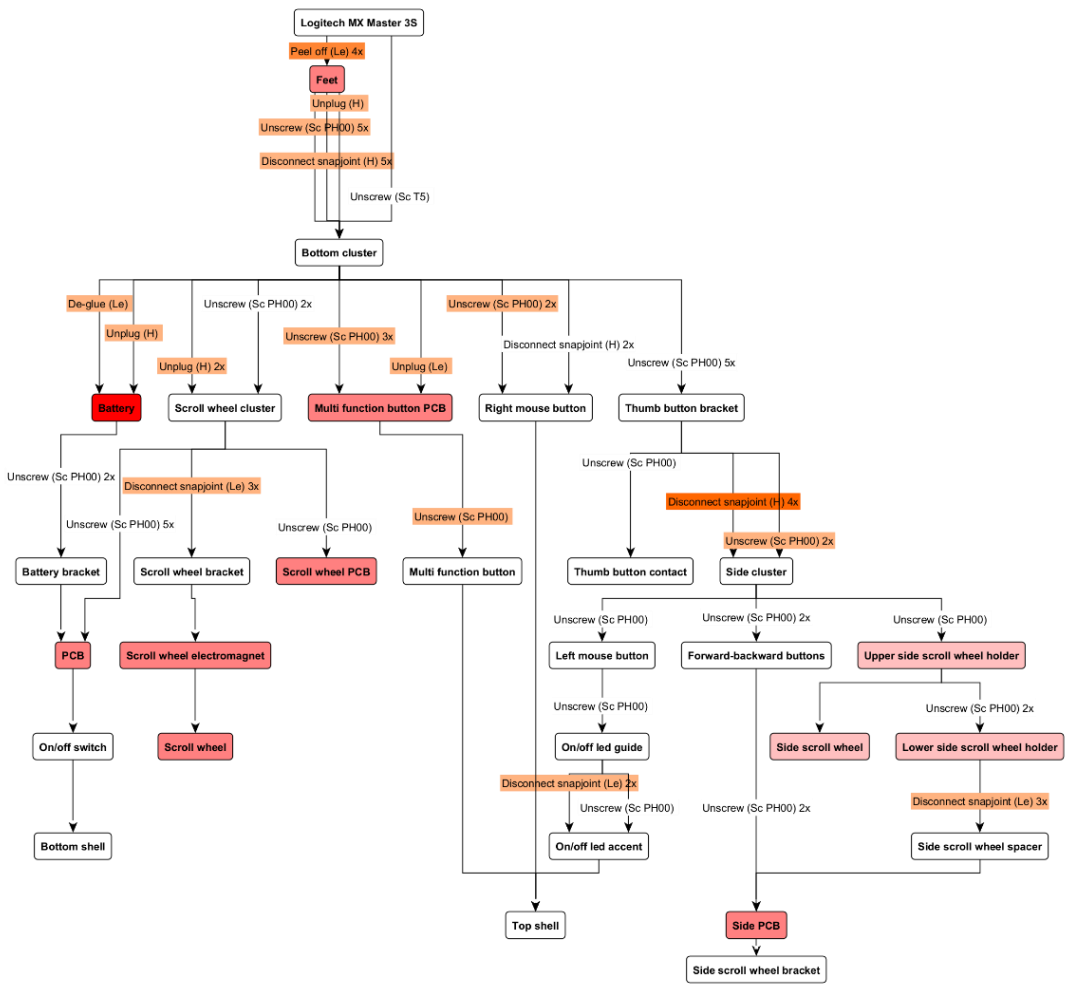


Figure 1 Dynamic disassembly tree highlighting disassembly activity penalties and priority parts.

Glossary

Terminology

Circular economy

The circular economy is a pragmatic and business-focused approach that prioritizes the reuse, remanufacturing, refurbishment, repair, cascading, and upgrading of products, components, and materials. Additionally, it promotes the use of renewable energy sources such as solar, wind, biomass, and waste-derived energy throughout the product value chain and cradle-to-cradle life cycle. (Korhonen et al., 2018)

Re-use

"The use of a product again for the same purpose in its original form or with little enhancement or change." (MacArthur, 2013)

Repair

"To put something that is damaged, broken, or not working correctly, back into good condition or make it work again." (*Cambridge Dictionary*, n.d.)

Refurbish

"A process of returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making 'cosmetic' changes to update the appearance of a product, such as cleaning, changing fabric, painting, or refinishing. Any subsequent warranty is generally less than issued for a new or a remanufactured product, but the warranty is likely to cover the whole product (unlike repair). Accordingly, the performance may be less than as-new." (MacArthur, 2013)

Remanufacture

"A process of disassembly and recovery at the subassembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a new one. This process includes quality assurance and potential enhancements or changes to the components." (MacArthur, 2013)

Recycling

"Functional recycling; A process of recovering materials for the original purpose or for other purposes, excluding energy recovery. Downcycling; A process of converting materials into new materials of lesser quality and reduced functionality. Upcycling; A process of converting materials into new materials of higher quality and increased functionality. " (MacArthur, 2013)

Upgrade

"To improve the quality or usefulness of something, or change it for something newer or of a better standard." (*Cambridge Dictionary*, n.d.)

Energy recovery

"The conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of so-called waste-to-energy processes, including combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery." (MacArthur, 2013)

Life Cycle Assessment

"Life cycle assessment is a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use." (Muralikrishna Iyyanki, 2017)

Product architecture

Product architecture refers to the arrangement of a product's functional elements and their corresponding physical components, as well as the interactions between those components. This architecture can be examined at varying levels of granularity, from overarching systems to individual components. The interactions between these elements may take numerous forms, including mechanical, electrical, information interaction, functional interactions that involve the transfer of energy or materials, and spatial interactions that involve physical proximity or contact between parts. (Tilstra et al., 2012; Ulrich, 1995).

Priority Part

"Parts that are most likely to be repaired or replaced during normal service life of the product and/or parts that are characterized by a high assumed failure rate and/or are critical for the product to deliver the main desired function. " (Bracquené et al., 2018)

Abbreviations

HSM	Hotspot Mapping Tool
DM	Disassembly Map
DSM	Design/Dependency Structure Matrix
BOM	Bill of Materials
SUS	System Usability Scale
RtD	Research through Design

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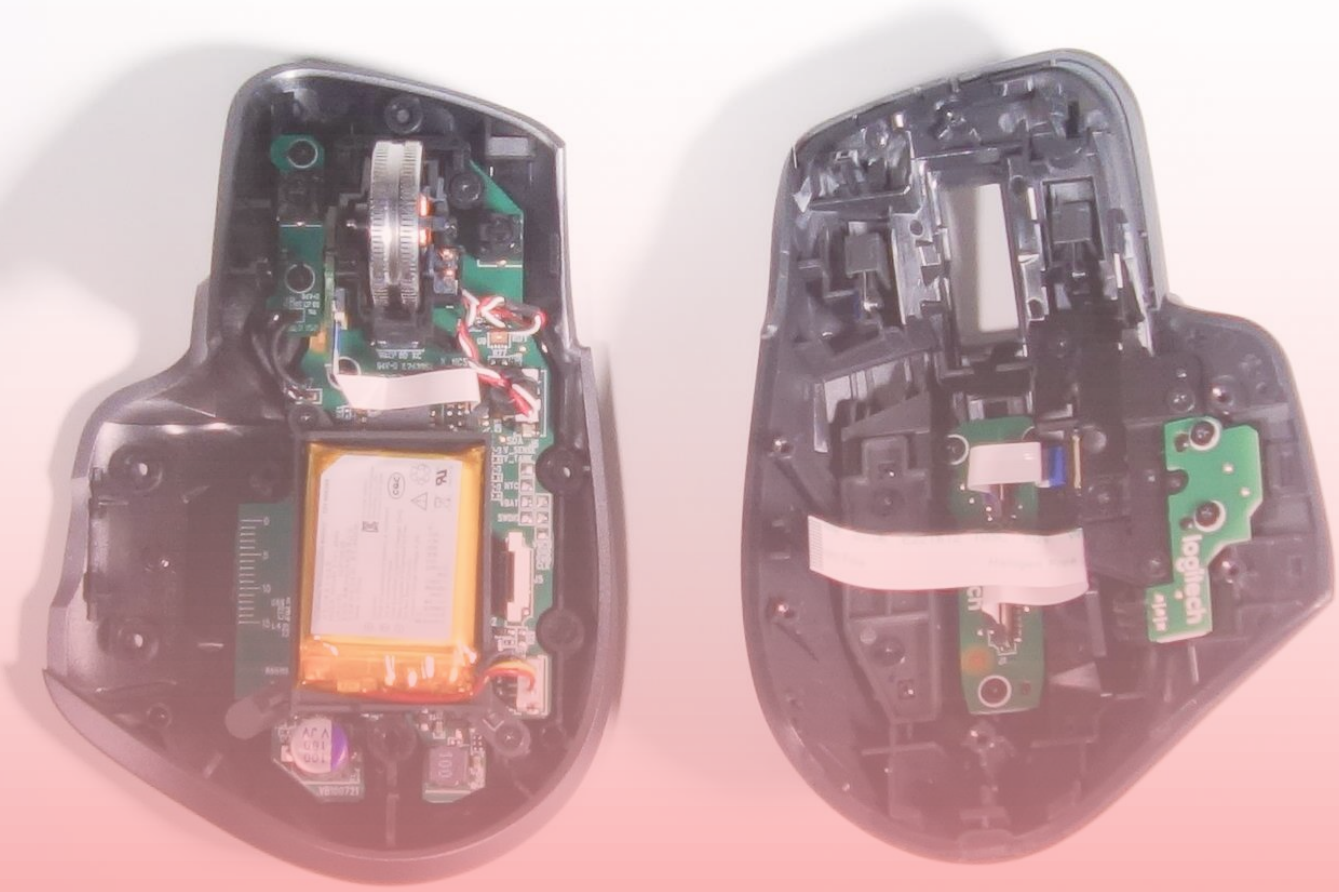
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Introduction

1 Introduction

1.1 Background

In 2015 the Paris Climate Agreement was adopted by 196 countries with the objective of keeping the rise in global temperatures limited to 2 degrees Celsius while aiming for not more than 1.5 degrees increase (UNFCCC, 2021). Furthermore, the European Commission created an action plan with specific goals for reducing impact (European Commission, 2020). One of these goals is to design sustainable products with the goal of transitioning from a linear to a circular economy.

The difference between a linear and circular economy is illustrated in the value hill (Achterberg et al., 2016). This hill-shaped diagram represents the added value created during the pre-use stage, including manufacturing, distribution, and retail, as well as the lost value after the product is used (Figure 2). In a circular economy, the goal is to maintain the value of the product or its material resources after use for as long as possible. This can be achieved through multiple circular strategies such as repairing, reusing, refurbishing, remanufacturing, and recycling. Similar to the butterfly diagram (MacArthur, 2013) the general rule applies that strategies with a smaller loop result in less value lost and a lower environmental impact.

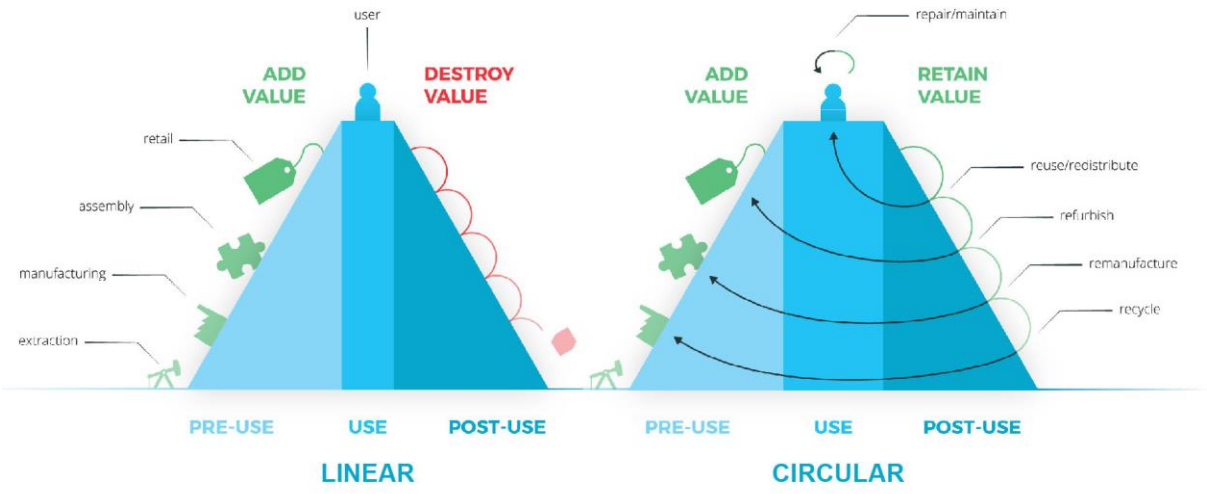


Figure 2 The value hill in a linear economy (Left) and a circular economy (Right) (Achterberg et al., 2016)

Most of these strategies require a product to be taken apart. However, many products are not designed taking ease of disassembly into account (Bakker, C., opening lecture course ID5422 Repair!, 01/03/2023). In the transition towards a more sustainable world, products need to be redesigned with disassembly and reassembly in mind, facilitating multiple circular strategies(Laitala et al., 2021).

1.2 Problem definition

Designers can use various tools and methods to evaluate and understand how easily a product can be disassembled and reassembled. This thesis focuses on two such tools: the Hotspot Mapping tool (HSM tool) and the Disassembly Map (DM). Used together, these tools provide insight into the product's architecture and critical components by highlighting key parts based on factors like environmental impact, cost, and maintenance needs. While the Hotspot Mapping tool identifies critical parts and disassembly activities, it does not show the disassembly depth of components(Ligtelijn, 2021). On the other hand, the Disassembly Map displays the product's architecture, visualising how difficult it is to access a critical part. However, it relies on information from the Hotspot Mapping tool to identify hotspots or penalties (De Fazio, 2019). Despite their complementary nature, the Hotspot Mapping tool and Disassembly Map are not connected, even though they require similar input properties. Consequently, designers must do extra work to benefit from both tools.

1.3 Objective

The goal of this thesis is to develop a data-driven connection between the Hotspot Mapping tool and the Disassembly Map. This requires a data structure that captures both the product architecture and the Hotspot Mapping tool properties. This data structure can then be used to generate a Disassembly Map. Resulting in a connection between the data in the HSM tool and the DM, solving the problem of having to enter the same data twice to obtain the result of both tools.

To reach this goal, it is important to understand the current state of the tools and their strengths and weaknesses regarding their scope, features, and usability. Furthermore, it is necessary to explore what data structures exist that can describe the product architecture. A new tool must be developed that integrates the product architecture and mitigates the found weaknesses. Once the tool is developed, its results must be validated against those of the original tools and its usability must be evaluated. This results in the following research objectives:

RO1: Explore the usability of the Hotspot Mapping tool and Disassembly Map.
The usability of the tools is assessed by a usability questionnaire, literature review, user observations and complemented by my own experience. Through these methods, a usability score will be extracted and complemented by the strengths and weaknesses of the tools based on usability aspects and features that are provided by the tools.

RO2: Investigate data structures that describe the product architecture.
Data structures from the mathematical field of graph theory are assessed for their applicability to be used to describe the data structure and be integrated into the new Hotspot Mapping tool.

RO3: Identify the requirements for the new tool.
Based on the usability of the tools, a list of requirements is established for the design of the new tool.

RO4: Develop a new tool using the selected data structure that guides designers in increasing the ease of disassembly and reassembly.
In an iterative approach, the selected data structure is integrated into the HSM tool in addition to adding missing features that were determined based on the usability of the two tools.

RO5: Verify and validate the effectiveness and usability of the new tool.
Through user testing the usability of the new tool is evaluated, compared to the original HSM en DM. The findings are used to assess the progress of the new tool and suggest further improvements for the next version. Furthermore, a case study demonstrates the value of the tool.

The five research objectives are discussed in the upcoming chapters as displayed in Table 1.

	RO1	RO2	RO3	RO4	RO5
1 INTRODUCTION					
2 DESIGN FOR DIS- AND REASSEMBLY					
3 HSM & DM IN LITERATURE	■				
4 HSM & DM IN PRACTICE	■				
5 PRODUCT ARCHITECTURE DATA STRUCTURES		■			
6 REQUIREMENTS			■		
7 DEVELOPMENT OF THE NEW TOOL				■	
8 USER TESTING					■
9 REFLECTION ON SUBJECTIVITY					■
10 CASE STUDY					■

Table 1 Research objective discussed per chapter.

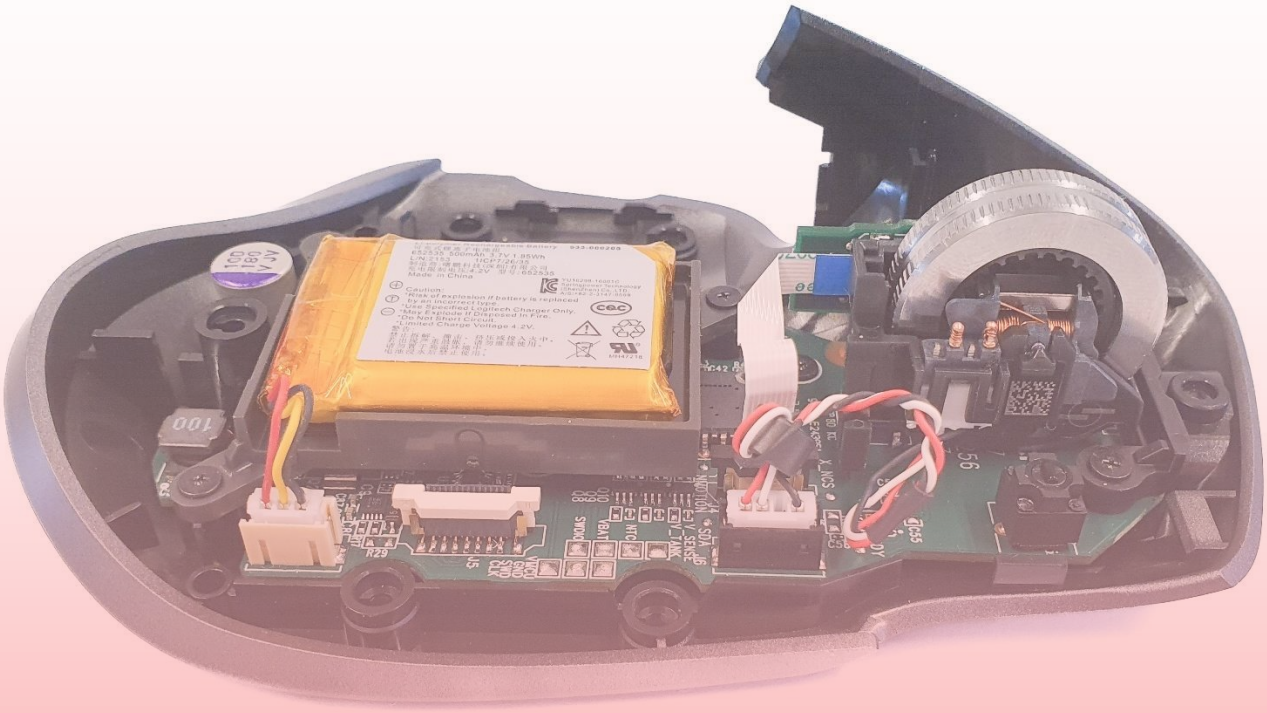
1.4 Scope & Limitations

This project aims to design a new tool that will increase the ease of disassembly of products, with the ultimate goal of facilitating repairability. This includes repair by both consumers and professional repairers. However, it is important to note that the scope of this project is limited by several factors.

While the focus of this project is on improving the ease of disassembly, it is important to recognize that repairability involves more than just being able to take a product apart. Other factors, such as the availability and affordability of replacement parts and the availability of documentation and repair instructions, also play a crucial role in determining whether a product can be repaired. These aspects are beyond the scope of this project.

Another limitation of the project is that although the new tool is intended to apply to a wide product range, it is developed by using only Logitech computer peripherals as case studies. This means that while the tools may be useful for other products as well, their effectiveness may vary depending on the specific product in question.

Lastly, to prototype the tool Microsoft Excel (Microsoft, 2023a) was chosen as the basis for the tool. This could result in Microsoft Excel-specific limitations. For further development of the tool, dedicated software should be developed, which includes both the HSM and DM results into one software package.



Analysis

In the Analysis part three research objectives are discussed.

RO1: **Explore the usability of the Hotspot Mapping tool and Disassembly Map.**
RO2: **Investigate data structures that describe the product architecture are addressed.**
RO3: **Identify the requirements for the new tool**.

Chapter 2 explores the design guidelines for designing products for dis- and reassembly. The design guidelines will be used in Chapter 3 and 4 to assess the Hotspot Mapping and Disassembly Mapping tools. Chapter 3 introduces the Hotspot Mapping and Disassembly Mapping tool and presents weaknesses and strengths based on literature findings. Chapter 4 expands on the strengths and weaknesses through a usability questionnaire, observations and my own experience using the tools. Chapter 5 addresses research objective two and presents four different data structures, analyses them, and select he most suitable one to use in the development of an improved tool. Chapter 6 combines the findings from Chapter 2 till 5 in a list of requirements for the new tool.

2 Design for dis- and reassembly.

Designing for disassembly and reassembly entails various aspects, going beyond just product features. Which of these aspects are important for tools that help designers redesign for disassembly? By exploring these design guidelines, the tools can be analysed and improved to adhere to design guidelines for disassembly.

Unless mentioned otherwise the following summary of design guidelines for disassembly and reassembly is based on the work of Lützen and Lissalde (2020) and Dangal (2022).

When designing a product with priority parts, it is important to consider the ease of disassembly. To achieve this, priority parts should not be bundled with other parts and should be individually removable. This helps to reduce the price of the priority part and decrease disassembly time. An exception to this rule is when a priority component is part of a cluster to make it more accessible (Flipsen, 2020). The product structure should also be designed for damage-free disassembly. Modular design can help to ease disassembly and reduce the number of components needed.

To further decrease disassembly time, the number of components that need to be removed before reaching priority parts or parts with higher material, economic or environmental value should be minimized. Hierarchically dependent connections between components should be minimized and geometric locking should be incorporated. Geometric locking refers to the strategic use of shapes and physical features that enable easy disassembly of the components without tools. Additionally, the diversity of fasteners along the disassembly pathway should also be minimized. Using a low variation of fasteners can help to minimize tool changes and keep track of fasteners for reassembly.

If different types of fasteners are ordered consecutively to be removed, the disassembly pathway should be designed such that fasteners that require the same tools are clustered together. This minimizes tool changes and reduces disassembly time. Ideally, fasteners that require no tools or basic (standardized) tools should be used to facilitate disassembly by common users. Fixed joints and connectors, such as welding or rivets, should be avoided.

Providing disassembly instructions, such as a guide in the manual or indicating which fasteners need to be removed on the product itself, can also help to promote ease of disassembly. Additionally, providing correct assembly indication, such as keying or marking connections, can promote ease of reassembly.

Non-reusable fasteners or fasteners prone to breaking, such as glued components or one-way snap fits, should be avoided. If glueing is required, features facilitating its removal, such as pull tabs, stretch tabs, reversible glue or non-toxic soluble, should be provided.

In summary, a tool that aims to guide designers towards products that are easier to disassembly and reassemble should assess a product on the following features:

- Determine priority parts and parts with high economic or environmental value (REQ 9).
- Determine the disassembly depth of these parts (REQ 13).
- Determine the diversity of tools and how common they are (REQ 14).
- Determine non-reusable fasteners (REQ 15).

Scope limitations:

- Although important, disassembly and reassembly instructions are not deemed interesting for the tool since they do not assess the product itself.
- Rivets and connections that cannot easily be disconnected are outside of the scope of the tool since the tools are based on the gentle dismantling of a product.

3 HSM & DM in literature

In this chapter, the Hotspot Mapping tool and Disassembly Map are shortly described after which the strengths and weaknesses of the two tools are explored based on literature. This chapter thereby aims to partly answer the first research objective: **Explore the usability of the Hotspot Mapping tool and Disassembly Map.**

3.1 Hotspot Mapping tool

The Hotspot Mapping tool is the basis of this project; therefore, it is important to understand what the tool is designed for and how it is set up. The Hotspot Mapping tool assesses the ease of disassembly of a product by flagging five hotspot indicators. These include the time required to disconnect parts, the level of difficulty in accessing components, priority parts, environmental impact, and economically valuable components (REQ 11 & 12). The purpose of these highlights is to provide designers with direction in the process of redesigning a product to make dis- and reassembly more effortless (W 7). This can lead to a product that maintains a higher value for an extended period by increasing its lifespan through maintenance and repair, facilitating refurbishment, and allowing for the materials to be cleanly recycled after end-of-life.

Hotspot Mapping is a spreadsheet-based tool (as illustrated in Figure 3) that records every disassembly step taken during the disassembly of a product. With each disassembly step part properties and disassembly activity properties are recorded. Part properties include material, weight, failure likelihood and functional relevance. Disassembly activity properties include the required tools, task frequency, required time, force, accessibility and positioning of the tool (REQ 10). For further explanation of how the hotspots are determined and calculated see Appendix B.

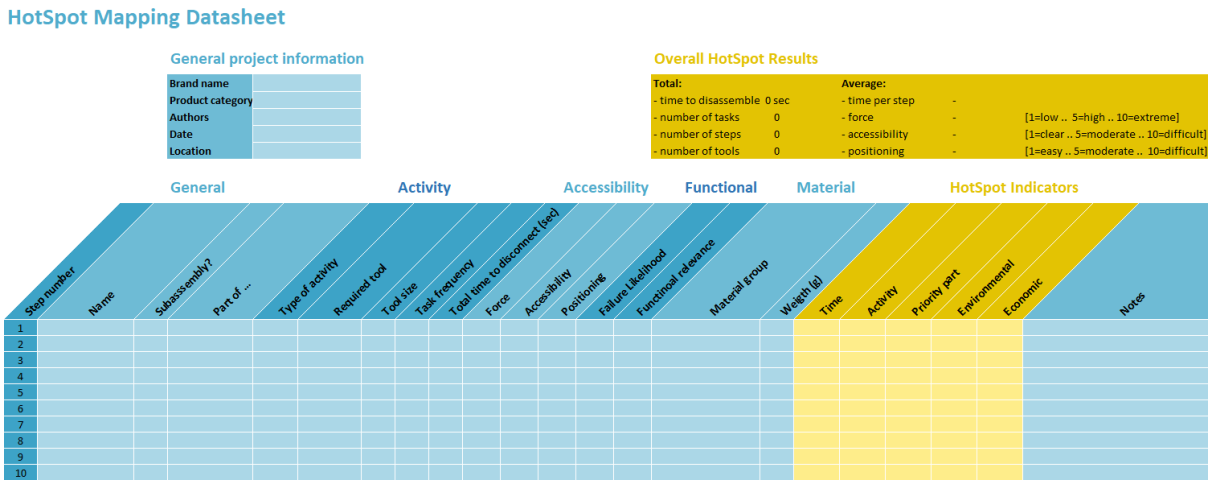


Figure 3 Original Hotspot Mapping tool

Strengths and weaknesses of HSM

As a starting point for analysing the Hotspot Mapping tool, I used the findings of Sharina Ligtelijn (2021). I complemented this with other papers, mostly master theses from the TU Delft, which used the Hotspot Mapping tool. To get a better overview of the findings I divided them into three categories: scope, features, and usability. Findings relating to the scope can help understand what the tools are designed for and what they are not designed to do. Feature-related findings will help understand which features are valued and used, which are missing, and which still need improvements. Finally, usability findings will help to understand how the tools can be adjusted to increase the ease of use for the user.

Scope

Indicative tool: The HSM tool is an indicative tool (not a full Life Cycle Analysis) and therefore not exact. Especially the calculated values for the environmental and economic values should be seen as such since they are only based on embodied material impact (Ligtelijn, 2021). In general, the environmental impact of materials is greater than that of the production process (Flipsen et al., 2020). As a result, focusing on the impact of materials can be a straightforward and effective approach if its limitations are taken into account when using the tool.

Features

Time: The recorded disassembly time is different for each disassembler. This is a weakness because it is dependent on the operators' skill and learning curves which might not represent the skill of the intended disassembler. There is a lot of research being done towards using proxy times(Sodhi et al., 2004; Vanegas et al., 2018). This would make disassembly times more consistent. However, self-recorded disassembly times have the advantage that it takes into account the most interesting time frame since it also takes into account the inspection and positioning of the product (Ligtelijn, 2021). Furthermore, Flipsen et al. (2020) concludes that proxy times are still too unreliable.

Reuse of components: An expert interviewed by Ligtelijn (2021) suggested including whether a component stays intact during disassembly. This is of importance for multiple circular strategies that require the reusing of components and is currently missing from the HSM tool. If components break during disassembly is also dependent on the skills of the disassembler.

Hotspots: The Hotspot Mapping tool highlights components based on different aspects. A part that is highlighted however does not automatically mean that it is necessary to be redesigned (Ligtelijn, 2021). For example, a part that is highlighted as a priority component but is already high up in the product architecture does not have the same priority to be redesigned as a priority part that is buried deep in the structure.

Disassembly depth: To be able to assess if a highlighted part should be redesigned it is important to know how deep it is buried in the product architecture (Ligtelijn, 2021). This feature is currently missing from the Hotspot Mapping tool, therefore it is required to also use the Disassembly Map, to see the depth of the parts of interest.

Required tools: The Hotspot Mapping tool records the tools that are required for the disassembly. This is relevant for the disassembly process since the disassembly process becomes easier when only using standardized tools and fewer tool changes are required (as was explained in the design guidelines for product disassembly and reassembly).

Materials: The materials available in the Hotspot Mapping tool are limited, for example, ceramics and flexible materials such as fabrics are missing (Kumar, 2022; Vermaat, 2020). In the latest HSM version (2023.03) fabrics are present, however, ceramics are still missing.

Usability (ease of use, ease of learning)

Failure rates: Flipsen et al. (2020) describes that it is necessary for a user of the tool to have adequate knowledge of the failure rates of parts to gain valuable insight. Consequently, this can limit the value of the output of the tool if a user does not have adequate knowledge.

Takeaways:

- Scope
  - HSM is an indicative tool, there are no exact numbers.
- Features
  - Use self-recorded disassembly times in further development (REQ 17).
  - Record if components stay intact during disassembly (W 10).
  - Allow users to differentiate between hotspots (REQ 18).
  - Integrate disassembly depth into the Hotspot Mapping tool (REQ 13).
  - Include an overview of the required tools (REQ 14).
  - Make the material database adjustable by the user (W 6).
- Usability
  - Failure rates are something a user needs to get a feel for or do research to determine.

3.2 Disassembly Map

The Disassembly Map (See Figure 5) is a method that visually represents the architecture of a product, showing different routes towards target components (Fazio & et al., 2021). It was created to facilitate design for disassembly, which is essential when designing for serviceability and repairability (Fazio & et al., 2021). By illustrating the relationships among parts, disassembly actions, tools used, and priority components (based on factors like failure rate, financial and environmental importance/impact), designers can effectively determine which parts ask for attention in a redesign. As a rule, components positioned lower in the product's architecture tend to be situated deeper within the disassembly sequence, requiring more time and effort to access. For example, in Figure 5, parts 24 (the motor) and 29 (the main PCB) are high-failure rate components which are crucial to the functionality of the product. However, they are buried deep in the disassembly sequence making it a high barrier for consumers to replace/repair.

Logic of the Disassembly Map

The Disassembly Map is represented by components visualized as numbered circles that are connected to communicate the disassembly direction. The Disassembly Map is based on three logic operations described below, plus the inclusion of clusters, which combines multiple components when they can be removed at once (REQ 5 & W 4). The three logic operations are as follows:

Sequential dependence: In this logic operation each part must be removed before it is possible to reach the next part (see Figure 4). This dependency typically results in a longer disassembly time, making the procedure more challenging. Sequence-dependent steps are always represented vertically to convey a sense of depth (Fazio & et al., 2021).

Sequential independence (parallel): This is the preferred configuration since a repairer can select and remove a component without affecting the disassembly time of other components (Fazio & et al., 2021). Figure 4 shows how a parallel operation is represented by a graph that branches out and places the components on the same depth level.

Multiple dependencies: When the disassembly of a component requires the prior disassembly of two or more independent components, this is indicated as visualized in Figure 4.

Besides these three operations, the Disassembly Map also includes cluster blocks, where it is possible to remove multiple parts at once to reach the part below it (Figure 4). If a cluster block is used in the visualisation depends on the disassembler's priority. Figure 4 on the lower right side shows two alternative disassembly paths, and which part is the focus for each version.

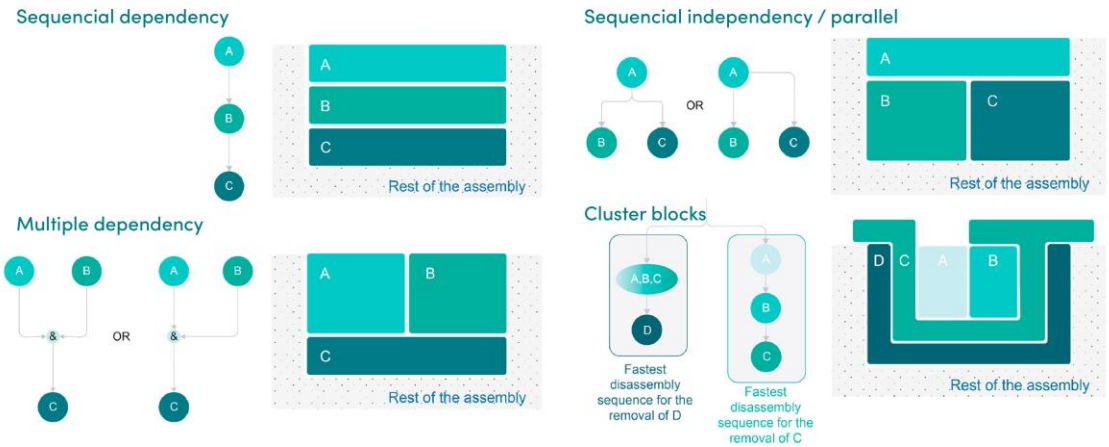


Figure 4 Logic principles of the Disassembly Map by Fazio and et al. (2021)

Figure 5 (Next page) DM made by (Fazio & et al., 2021) including explanatory remarks.

Disassembly Map

Vacuum cleaner 1.

Low-end Bagless, Brand A.

Francesco De Fazio et al.



Complete assembly

1 S. F., (Sp) Push B. (H)
2,3,4
5 S. F., (Sp) Push B. (H)
6
5,6 3x S. F., (Sp)
7 S. F., (H)
8 Push B. (H)
9 S. F., (Sp) x3
10 Push B. (H)
11 S. F., (H)
4 Push B. (H)
3
12 S. F., (Sp) x2 Push B. (H)

& COT¹
Ph. #2 (Sc) x6
S. F., (Sp) x2

Alternation of different types of tools, which determines higher disassembly time

13
14 S. F., (H) x2
15 S. F., (H)
16 Ph. #2 (Sc) x2
F. F., (H)
17
30 F. F., (H)

Too many hidden connectors requiring the use of a disassembly tool and the application of high force

& COT¹
18 S. F., (Sp) x2
Ph. #2 (Sc) x4
S. F., (Sp) x2
C. Plug, (H)
19
20 Ph. #2 (Sc) x2
Ph. #2 (Sc)
21
S. F., (H) x2
C. Plug (H) x2
22
Ph. #2 (Sc) x6
F. F., (H)

Use of an uncommon tool

Connectors breakage and product manipulation

23,24,25
26 S. F., (Sp) x5
27 S. F., (Sp) x5
COT¹ Ph. #2 (Sc) x3
S. F., (Sp) x4
23
F. F., (H)
C. Plug (H) x2
24
Ph. #2 (Sc) x2
28
Ph. #2 (Sc) x2
S. F., (H)
29
25
&
31

¹COT= Change Of Tool

1 Cluster = 1 Step

Top buttons (8 & 9) 2 steps

1 Changes Of Tool

Top cover (13) 4 steps

Lower handle (16) 5 steps

Middle housing (17) 6 steps

1 Change Of Tool

Rear housing (20) 8 steps

Most of the target components

Components

1. Caster wheel
2. Hose
3. Hose tube
4. Nozzle
5. Dust bucket lid
6. Dust bucket
7. Dust bucket filter
8. On/off button
9. Cord-winder button
10. Exhaust grill
11. Exhaust filter
12. Hose assy
13. Top cover
14, 15. Rubber covers
16. Lower handle cover
17. Middle housing
18. Power slider assembly
19. Power slider
20. Rear housing cover
21. Cord outlet
22. Cordwinder
23. Motor housing lid
24. Motor
25. Rear motor housing
26. Rearwheel assy left
27. Rearwheel assy right
28. Motor brushes
29. Main PCBA
30. Hose inlet
31. Bottom housing

Legend

Motion Type

= Hand motion

= Single motion tool

= Multiple motion tool

Penalties

= Product manipulation

= Low visibilty/ identifiability

= Uncommon tool

Connectors

S. F.= Snap Fit

F. F. = Friction Fit

C. Plug = Cable plug

Push B.= Push button

Ph. #2 = Phillips 2 screw

Force Intensity

Low Mid High

Type of tool

(Pl) = Pliers

(Sc) = Screwdriver

Target components

= Failure indicator

= Environmental indicator

= Economic indicator

the product architecture

Strengths and weaknesses of DM

I started analysing the Disassembly Map by collecting the limitation of the method described by de Fazio himself. These were complemented by findings from other literature.

Scope

Suitability in the design process: While the Disassembly Map is not suitable for use during the initial stages of product design, it can serve as a source of inspiration by analysing and mapping a similar or previous product (Fazio & et al., 2021).

Interpretation of the disassembly sequence: The Disassembly Map can be created by applying the provided rules for using the tool. However, a product architecture is a complex system and there is not one correct Disassembly Map for every product. Since the Disassembly Map is not an automated tool, it is subject to the personal interpretation of the disassembler (Fazio & et al., 2021).

Reassembly: The Disassembly Map does not consider reassembly. For example, sometimes a reassembly process is not the reverse of the disassembly process. Furthermore, the loss of parts during the disassembly, such as springs or keys, can influence the reassembly and should be taken into account. (Kumar, 2022)

Features

Disassembly depth: The disassembly depth of parts is not representative of the effort it takes to reach a part, since it only takes into account the number of disassembly steps/activities and not the time or effort it takes to carry them out (Fazio & et al., 2021; Kumar, 2022).

Usability

Overview/Readability: Kumar (2022) describes that the Disassembly Map allows for great insights into the product architecture, critical parts and their disassembly depth. However, Vermaat (2020) mentions that to make the Disassembly Map more coherent the number of different shapes should be reduced.

Takeaways

- Scope
  - The disassembly sequence in the Disassembly Map is subject to the personal interpretation of the disassembler (W3).
  - Reassembly aspects are lacking in the Disassembly Map (W9).
- Features
  - The disassembly depth is imperfectly represented in the Disassembly Map.
- Usability
  - The visual representation of the product architecture allows for easy understanding and a great overview.

3.3 Conclusion

This chapter provided an overview of the Hotspot Mapping tool and the Disassembly Map in literature. The HSM tool assesses the ease of disassembly by flagging five hotspot indicators, while the DM visually represents the architecture of a product and shows different disassembly routes. Multiple strengths and weaknesses concerning the scope or features of the tools were found and presented based on the literature. Usability strengths and weaknesses are mostly missing from literature and will therefore be explored in Chapter 4. By considering the findings and suggestions from literature, these tools can be further enhanced to improve their accuracy, usability, and scope, ultimately facilitating more efficient and sustainable product disassembly and reassembly processes.

4 HSM & DM in practice

To gain more insight into the strength and weaknesses of the two tools a questionnaire was conducted. Since the literature describes very little regarding the usability of the two tools this was the main focus point of the questionnaire. The questionnaire aims to answer the following three research questions:

- RQ1: How usable are the HSM and DM as a method?
- RQ2: What are the strong and weak usability features of HSM and DM?
- RQ3: What are the strong and weak features of HSM and DM?

4.1 Approach

To determine the usability and weaknesses of the HSM and DM (RQ1) a questionnaire was sent to students that followed the course ID5422 Repair! in 2022/2023 (Flipsen, 2023). These students have used both tools and are familiar with them. To test the usability I chose to use a standardized questionnaire since standardized usability questionnaires have been proven to be more reliable than self-made ones (Hornbæk, 2006). A usability score also allowed me to determine if the redesigned version had improved usability over the original tools.

There are a lot of different standardized usability questionnaires available. Sauro (2016) has analysed the most popular standardized questionnaires and recommends the use of the System usability scale (SUS) questionnaire, developed by Brooke (1996), for post-study use. The SUS questionnaire outputs valid results even for small sample sizes (Sauro, 2016).

After selecting the SUS questionnaire, I adjusted it based on the recommendations described by Sauro (2016). I included “awkward” instead of “cumbersome” (as recommended by (Bangor et al., 2008; Finstad, 2006)) and replaced “system” with the name of the tools (the Hotspot Mapping and Disassembly Mapping tools). As this should not affect the results(Lewis & Sauro, 2009).

I decided to treat the Hotspot Mapping tool and Disassembly Map as one system/method because they are interdependent and have less value on their own. This also simplifies the comparison of results later with the usability test of the improved tool/method, which combines the results of both tools. The SUS questions are presented below. These questions are answered on a scale from 1 to 5.

1. I think that I would like to use the Hotspot Mapping tool and Disassembly Map frequently.
2. I found the Hotspot Mapping tool and Disassembly Map unnecessarily complex.
3. I thought the Hotspot Mapping tool and Disassembly Map were easy to use.
4. I think that I would need the support of a technical person to be able to use the Hotspot Mapping tool and Disassembly Map.
5. I found that the various functions in the Hotspot Mapping tool and Disassembly Map were well integrated.
6. I thought there was too much inconsistency in the Hotspot Mapping tool and Disassembly Map.
7. I would imagine that most people would learn to use the Hotspot Mapping tool and Disassembly Map very quickly.
8. I found the Hotspot Mapping tool and Disassembly Map very awkward to use.
9. I felt very confident using the Hotspot Mapping tool and Disassembly Map.
10. I needed to learn a lot of things before I could get going with the Hotspot Mapping tool and Disassembly Map.

To answer research questions two and three, two approaches were used. Open questions were added to the questionnaire and through a process of research through design (RtD) my own experiences using the tool were added. The open questions are shown below:

- Name one thing you liked about Hotspot Mapping and why.
- Name one thing you disliked about Hotspot Mapping and why.
- Name one thing you liked about Disassembly Mapping and why.
- Name one thing you disliked about Disassembly Mapping and why.
- Using the two tools in conjunction with each other, what worked well?
- Using the two tools in conjunction with each other, what did not work?
- Remarks?

Research through design is an approach to conducting research that incorporates design practices and methodologies as a means of analysis. RtD focuses on generating new knowledge and insights by actively creating and experimenting with designs, prototypes, and interventions. In the case of the HSM and DM, I used the two tools and tried to integrate several features to gain knowledge of the logic of the tools and their strengths and weaknesses. The experimenting and developing of the tools are described in Chapter 7. Throughout the design process, I found strengths and weaknesses regarding the usability and features of the two tools, which are described at the end of this chapter. On top, multiple requirements concerning the data structure, and software were found, these were added to the requirement list in Chapter 6.

4.2 Results

Nine students answered the questionnaire. The SUS score is presented as a single value representing the overall usability of the Hotspot Mapping tool and the Disassembly Mapping tool as a method. The results of the open questions are divided into three sections; the Hotspot Map, the Disassembly Map, and results that refer to the combination of the two. For each of these sections, the results are divided into the same categories as before: scope, features, and usability. The results of the open questions will be complemented by user observations and informal conversations during the repair course. Lastly, my own experiences with the tools are discussed. The individual answers to both the SUS questions and open questions can be found in Appendix E.

Results system usability scale

The SUS Score for the original system is 50 with a standard deviation of 16,2 (n = 9). The SUS Score is a nonlinear scale, this means that 50 is not equal to a 5 (on the Dutch grading scale). A score of 50 means that the system is deemed not acceptable as can be seen in Figure 6. The score should be at least improved to the average score of 68 for usability of systems (REQ 4).

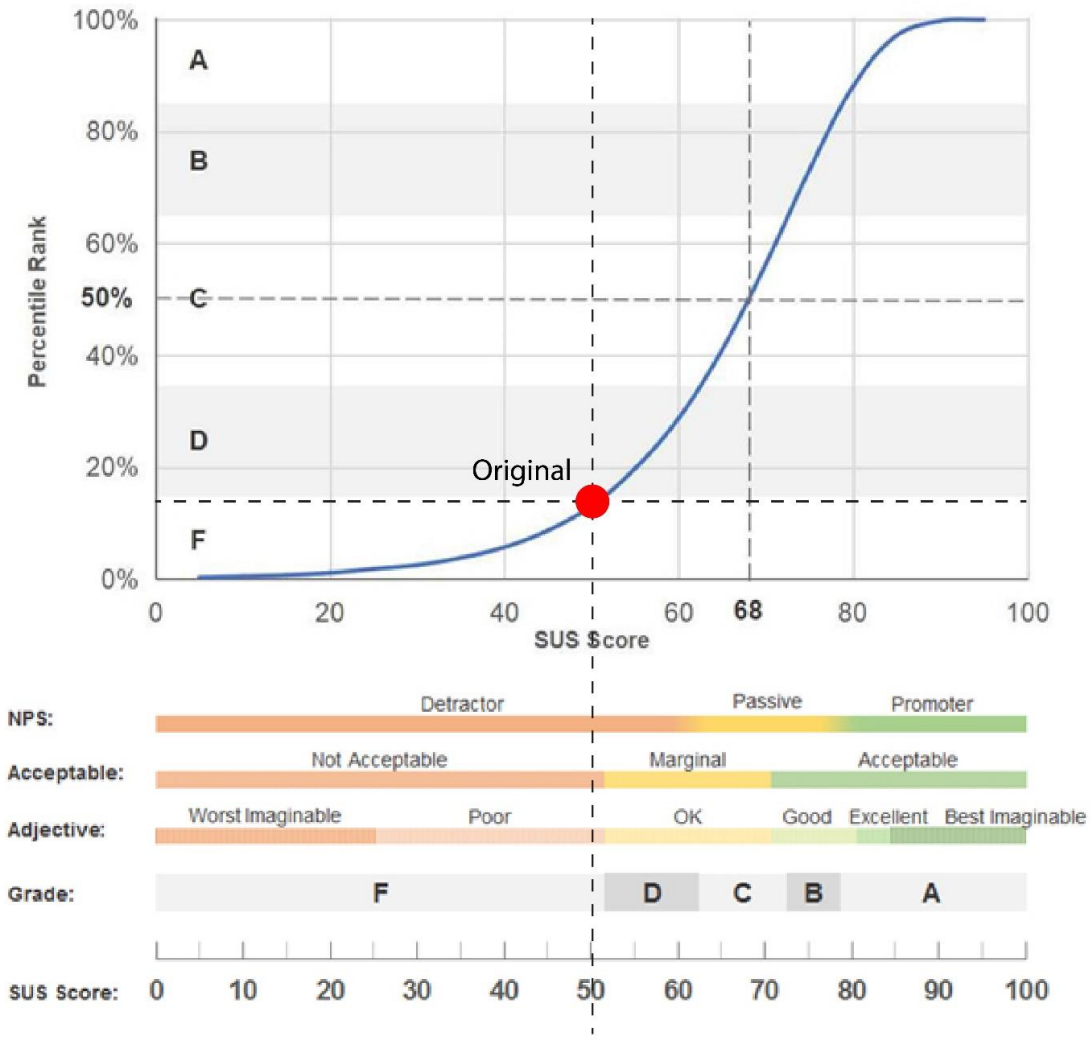


Figure 6 SUS Score interpretation

Results HSM

Scope

The questionnaire did not highlight any specific problems or strengths concerning the scope of the Hotspot Mapping tool.

Features

Materials: In conversation with Bas Flipsen**,** he mentioned that the current material database uses normalized data since the correct data is proprietary. As a result, the tool's calculated output might be less accurate than if it had access to more precise material data, potentially leading to distorted results.

Hotspots: The values underneath the hotspots are hidden, making it difficult to differentiate between highlighted parts (mouse and keyboard expert with in-depth disassembly experience, personal communication, 02/03/2023). For example, a main-PCB and sub-PCB both get a red flag based on their environmental impact, however, the main-PCB has a 3 times higher impact than the sub-PCB.

Usability (ease of use, ease of learning)

The order of disassembly: The Hotspot Mapping tool is supposed to be filled in in the order of disassembly. However, the HSM only allows for sequential entry, while a disassembly sequence has more possibilities, such as parallel disassembly, multiple dependencies, and removal of a cluster of parts at once (as described in paragraph 3.2)**.** Furthermore, multiple students mentioned that they struggled with filling in the HSM tool because it was not possible to reorder the sequence. This meant that when finding out they forgot a component or disassembly action they needed to redo a lot of work.

Input guidance: Students struggled with knowing when to skip certain input rows. For example, if a part required multiple disassembly activities, they filled in the part properties again. Even though it is described in the HSM manual (Flipsen, 2020) that you only need to enter this once. This indicates that it is necessary to guide users on which cells they need to fill in and which they can skip. In conversations with students, this confusion is created by the combination of both components and disassembly actions in one list.

Using the levels: Both when observing students and in their questionnaire responses, students mention that interpreting and staying consistent in selecting the correct level is difficult. They mention needing to consult the manual multiple times when filling in the HSM tool.

Time-consuming: Students mention that filling in the tool can be very tedious and time-consuming. However, this is not necessarily a problem if it is offset by the value the tool provides.

Takeaways

- Features
    - Make the material database adjustable by the user (W 6).
    - Show the values of the hotspots allowing designers to better understand the differences between components (REQ 18).
- Usability
    - Include the possibility to easily reorder components and activities (W 5).
    - Guide users in which cells need to be populated (W 1 & 2).
    - Separate disassembly activities from the components (W 11).
    - Include explanations of the different levels within the tool itself (W 1 & 2).
    - Time-consuming tools are acceptable if the value it provides is in proportion (W 8)

Results DM

Scope

Interpretation of the disassembly sequence: Since the disassembly sequence can be understood differently by different people, several students expressed uncertainty about whether they created an accurate DM and selected the right steps. This uncertainty arises because there are cases where multiple disassembly sequences could be considered valid.

Features

Overview/Readability: According to students, the Disassembly Map provides valuable insights into product architecture, critical parts, and their disassembly depth. Its visual nature enables a comprehensive overview and facilitates an understanding of interdependencies. From a conversation with a student, the Disassembly Map can also be quite overwhelming. There are a lot of colours, shapes and icons present which can distract and make it hard to understand where to focus.

Usability

Complexity: The Disassembly Map can be complicated to create. Multiple students had difficulty with correctly visualising interdependencies which reside on different levels in the Disassembly Map. Students describe it can become chaotic quickly, especially since there is no dedicated template or tool. Furthermore, multiple students had difficulty determining how to place the last two parts of a disassembly tree (observation of students and student conversations). Since the last disassembly activity results in two parts.

Tool/template: All icons, action blocks and visuals must be created and arranged manually. When there are many steps/parts, it can also become difficult and time-consuming to adjust the map. Another student mentioned that due to the lack of a template, the results can look different or cluttered.

Takeaways

- Scope
    - The Disassembly Map is subject to the personal interpretation of the disassembler (W3).
- Features
    - The visual aspect of the tool makes it easy to understand the product architecture.
    - The different colours and icons can both be helpful and overwhelming.
- Usability
    - Creating the Disassembly Map is a complex and time-consuming process.
    - The Disassembly Map is hard to get consistent and organised.

Results from HSM and DM as a method

Scope

Hotspots: The HSM and DM use the same hotspots making it easy to see details in the HSM and the placement of the component in the product architecture in the DM. Students mention that the two tools are dependent on each other, only using one would be far less insightful.

Features

Same parts: The two tools should have the same number of parts, and naming convention making it easier to determine if parts are forgotten. However, in the HSM parts are named, while in the DM they are numbered.

Usability

Same info twice: Students mention that the integration between the HSM and DM is lacking. They need to fill in similar data in both tools, essentially doing the same work twice to be able to fully understand the product architecture.

> *"Often it seems like you are filling in the same data, especially when specifying the tools used, force, type of fasteners." (Quote from usability questionnaire)*

Visual/Cognitive link: Students describe that the visual and the cognitive link between the Hotspot Mapping tool and Disassembly Map is not very strong. For example, action blocks use different naming conventions than the Hotspot Mapping tool while they are similar in information.

> *"Also, the fact that you make the Disassembly Map completely stand-alone from the Hotspot Mapping tool, you basically have to fill in similar information two times. It would be really nice if somehow you can produce a Disassembly Map from the Hotspot Map tool or visa versa." (Quote from usability questionnaire)*

Not linked: Students describe that when you need to change data in the HSM you now must also manually change that data in the DM. This makes it cumbersome and more work than feels necessary.

Takeaways

- Scope
  - No coherence between the disassembly depth of the two tools (REQ 13).
  - Without either tool, you miss a lot of insights.
- Features
  - Parts should have the same naming conventions between the two tools (REQ 19).
  - Disassembly activities should have the same naming conventions (REQ 19).
- Usability
  - The same information needs to be filled in twice (REQ 16).
  - The visual/cognitive link between HSM and DM can be improved by using the same naming conventions (REQ 19).
  - Linking the data from the tools would allow for easier adjustments of the tools (REQ 16).

Results Research through Design

Scope

Disassembly depth: There is a mismatch between the disassembly depth in the HSM and DM. While the DM does show a positional disassembly depth it does not perfectly represent the disassembly depth, since the depth is dependent on the number of disassembly activities and not how much effort or time it takes. On the other hand, the HSM represents the disassembly depth by how far down in the list the component is mentioned. However, this can be influenced more by when the disassembler entered that specific disassembly step rather than the actual disassembly depth in terms of steps, time, or effort.

Features

Required tools: The Hotspot Mapping tool does record the required tools. However, an overview of which tools are required and at what frequency is lacking. This would allow designers to determine which connection methods to avoid in the next redesign.

Overview/Readability: The Disassembly Map has a large amount of information, making it difficult to read and understand. In my experience, it can be challenging to focus on important details due to the complexity of the map. There are various indicators, colours, shapes, and numbers, each with different meanings. To understand them, you often need to refer back to the legend. Additionally, while representing all parts with numbers improves organization, it hinders readability as you constantly need to cross-reference with the parts list.

Usability

Input guidance: When using the HSM tool it was sometimes confusing which cells needed to be skipped. From my own experience, this confusion arises due to having both components and disassembly actions in a single list. As a result, components end up being entered multiple times without requiring that their corresponding property data be entered again.

Takeaways

- Scope
    - The disassembly depth in both the HSM and DM is imperfectly represented (REQ 13).
- Features
    - Include an overview of required tools and the number of times they are used (REQ 14).
    - Using numbers to represent parts makes the DM hard to read (REQ 19).
- Usability
    - Separate disassembly activities from the components (W 11).

4.3 Conclusion

To answer the three research questions about the usability, strengths, and weaknesses of the HSM and DM, I used a combination of methods. These included conducting questionnaires, having conversations with students from the repair course, and making observations. Additionally, I employed research through design to include my own experiences with the tools.

- RQ1: How usable are the HSM and DM as a method?
- RQ2: What are the strong and weak usability features of HSM and DM?
- RQ3: What are the strong and weak features of HSM and DM?

The System usability scale (SUS) revealed that with a score of 50 the current tools are considered unacceptable and require usability improvements. Via the open questions, multiple improvements regarding scope, features and usability were found. Feedback on the HSM tool highlighted the need for improvements in features such as required tools, materials database, and displaying values of hotspots. Usability issues included the inability to easily reorder components, confusion in input guidance, difficulties in interpreting different levels, and time-consuming data entry.

When considering the use of HSM and DM together, students emphasized the interdependence of the tools, with using only one tool deemed less insightful. Usability issues included redundant data entry, weak visual and cognitive links between HSM and DM, and the lack of automatic data synchronization.

The findings in this chapter will be used in combination with the findings from the literature to set up a complete list of requirements in Chapter 6.

4.4 Limitations

The research has several limitations that need to be considered:

Small Sample Size: Only nine students from the ID5422 Repair! course participated in the questionnaire. This limited sample size might not fully represent the opinions and experiences of all potential users of the HSM and DM. A larger and more diverse sample would yield more reliable results.

Subjective Interpretation: The questionnaire and open-ended questions rely on the participants' subjective opinions and interpretations. Different individuals may interpret the questions differently, leading to potential biases in the responses.

Limitation of Research through Design: RtD has inherent biases since it is based on the experiences and perspectives of the researcher. The researcher's/My biases and preferences may influence the outcomes and findings.

Lack of User Diversity: The research focused on students from a specific course, which might limit the diversity of perspectives. Including users from different backgrounds, experiences, and expertise could lead to more comprehensive insights.

5 Product architecture data structures

The HSM and DM are used together to get an overview of the priority parts and their location in the product architecture. To integrate these tools, I explored possibilities to describe a disassembly sequence in a data structure. This resulted in studying the mathematical field of graph theory.

Graph theory is a branch of mathematics that studies the relationships between objects using graphs. These graphs consist of vertices (or nodes/points) connected by edges (or links/lines) as shown in Figure 7. A product architecture can be represented by a directed graph, where the nodes represent the components and the edges represent the disassembly actions. There are two types of graphs: undirected, where edges connect two vertices symmetrically and directed, where edges connect two vertices asymmetrically (Bang-Jensen & Gutin, 2008).

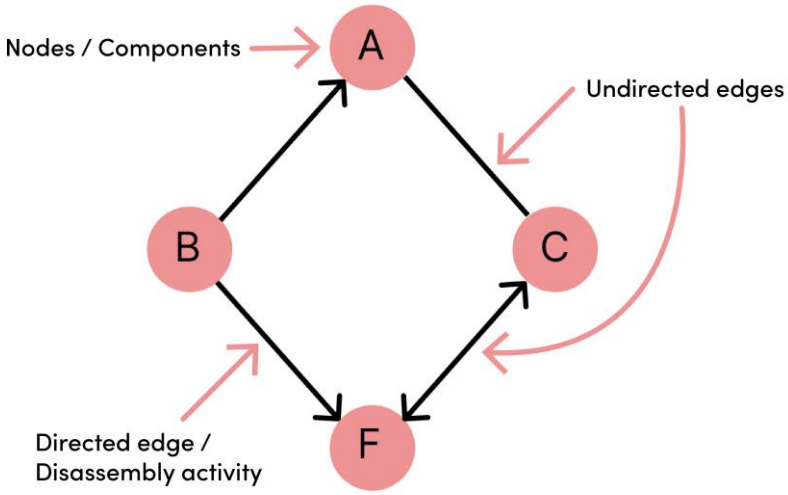


Figure 7 Example of undirected and directed graph elements.

Several data structures can represent a graph. These include an adjacency matrix, incidence matrix, adjacency list and edge/node list (Bang-Jensen & Gutin, 2008; Singh & Sharma, 2012). In the next sections, these data structures will be explored for their suitability to represent connections between parts while allowing users to add other disassembly and component properties. The data structure must also allow multiple edges between nodes and multiple edge properties to make adding multiple disassembly activities between components possible. Furthermore, to be able to use the data structure in this project it must be compatible with MS Excel. When the tool will be built into a dedicated program, this requirement is not mandatory, however, this is currently out of the scope of the project. In summary, to be suitable the data structure must adhere to the following requirements:

- The data structure should allow for the visualisation of the graph/disassembly sequence (REQ 3).
- The data structure must include both part (nodes) properties and disassembly activity (edge) properties (REQ 2).
- The data structure needs to allow for multiple disassembly activities between components (REQ 6).
- The data structure needs to be compatible with MS Excel (REQ 7).

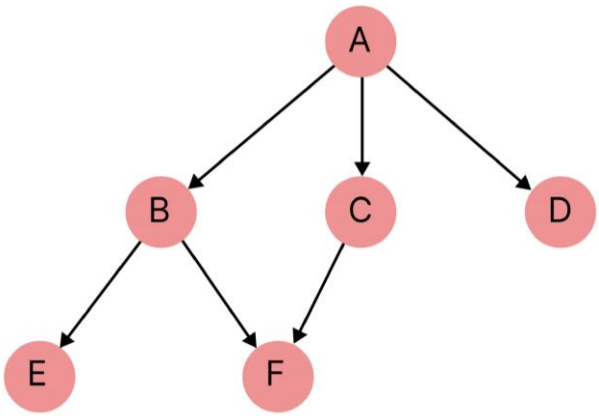
5.1 Adjacency matrix

An adjacency matrix (also known as a dependency structure matrix or design structure matrix (DSM)) is a way of representing a system, project, or product in a matrix form. This data structure allows the modelling of complex systems straightforwardly while also including interdependencies (*Introduction to DSM*, 2019). Table 2 presents an assortment of DSMs, their use cases, and the respective analysis methods applicable to each type. For this project, only the component-based DSM holds relevance. The table illustrates that the component-based DSM facilitates clustering analysis, which could be beneficial for enhancing repairability. This would help in identifying which parts could be grouped for simultaneous disassembly.

DSM TYPES	REPRESENTATION	APPLICATION	ANALYSIS METHOD
TASK BASED	Task/Activity Input/Output Relationships	Project scheduling, Activity sequencing Cycle time reduction	Partitioning, Tearing, Banding simulation and Eigenvalue Analysis
PARAMETER BASED	Parameter decision points and necessary precedents	Low-level activity sequencing and process construction	Partitioning, Tearing, Banding, Simulation and Eigenvalue Analysis
TEAM BASED	Multi-team interface characteristics	Organization design, interface management, team integration	Clustering
COMPONENT BASED	Multi-component relationships	System architecting, engineering and design	Clustering

Table 2 Types of design structure matrices (Gomes, 2018)

An adjacency matrix is composed of a square graph with both the x and y axis containing the product components in the same order (see Figure 8). If there is a connection between two components, the overlapping square is marked.



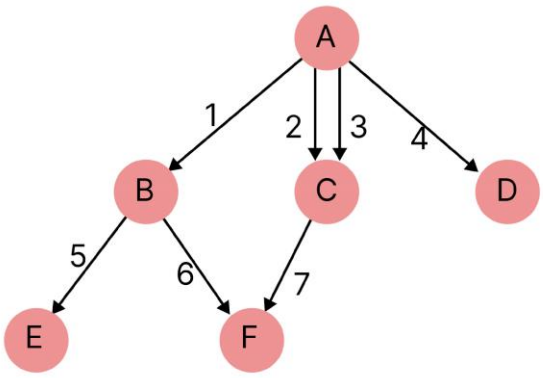
	A	B	C	D	E	F
A	0	1	1	1	0	0
B	0	0	0	0	1	1
C	0	0	0	0	0	1
D	0	0	0	0	0	0
E	0	0	0	0	0	0
F	0	0	0	0	0	0

Figure 8 Adjacency matrix and the graph it represents.

The adjacency matrix only accounts for the presence of a disassembly step between two parts. The matrix does not provide the capability to incorporate additional attributes such as tools required, accessibility, force, and so forth. While component and activity properties can be accommodated in a multi-dimensional design structure matrix, this increases the complexity of the methodology and was deemed impossible to implement using Excel. Furthermore, the matrix only allows for one connection between two components, making it impossible to add multiple disassembly actions.

5.2 Incidence matrix

The incidence matrix is similar to the adjacency matrix in the sense that it describes the relations between vertices/nodes and edges (Kepner & Gadepally, 2014). However, the matrix is now created with the vertices on one axis and the edges on the other axis (see Figure 9). The direction of the arrows can be given by using positive and negative values. Unlike the adjacency matrix, multiple connections between components are possible. However, the incidence matrix does not allow attaching multiple properties to the edges and nodes.

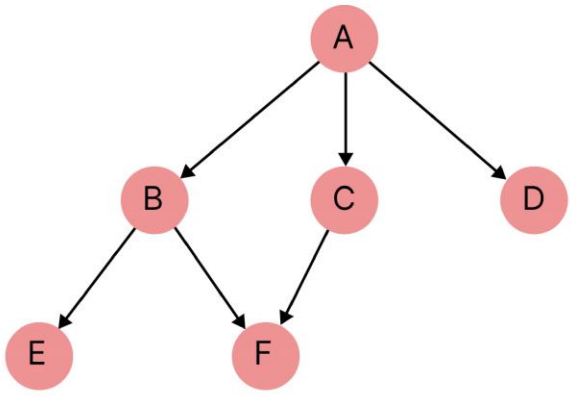


	1	2	3	4	5	6	7
A	1	1	1	1	0	0	0
B	-1	0	0	0	1	1	0
C	0	-1	-1	0	0	0	1
D	0	0	0	-1	0	0	0
E	0	0	0	0	-1	0	0
F	0	0	0	0	0	-1	-1

Figure 9 Incidence matrix and the graph it represents.

5.3 Adjacency list

An adjacency list is the representation of a graph in a list instead of a matrix (Singh & Sharma, 2012). Usually, it is chosen over the adjacency matrix in the case of a sparse graph (Cormen et al., 2022; Singh & Sharma, 2012).
The adjacency list (see Figure 10) consists of a list of all nodes, with in the next column all the nodes it is connected to (Cormen et al., 2022). This data structure does allow for adding node/component properties but does not allow for edge/activity properties. Furthermore, it does not allow for multiple connections between two components.

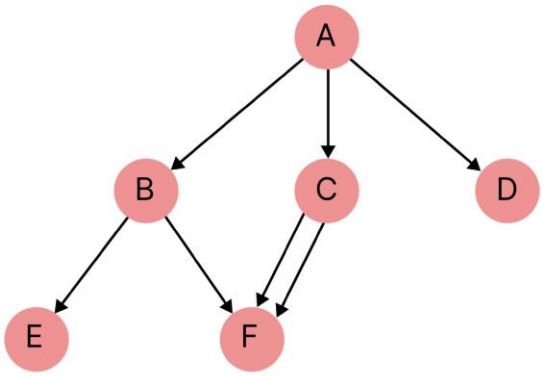


Source	Target		
A	B	C	D
B	E	F	
C	F		
D			
E			
F			

Figure 10 Example of adjacency list and the graph it represents.

5.4 Edge List

An edge list is a variation of an adjacency list, it is a data structure where each row represents a connection between two vertices. If edges have weights or more properties, more columns can be added to include this data (*Representing graphs*, 2014). An example of the edge list can be seen in Figure 11. Furthermore, properties of the vertices/nodes themselves can be added by including a node list with the edge list. Lastly, the edge list allows for multiple connections between the same component, by adding another row with the same source and target nodes.



Source	Target
A	B
A	C
A	D
B	E
B	F
C	F
C	F

Figure 11 Example of edge list and graph representation

5.5 Conclusion

This chapter explored different data structures for representing product architecture and disassembly sequences. The data structures are taken from the mathematical field of graph theory, which studies relationships between objects using graphs consisting of nodes connected by edges. A product architecture can be represented as a directed graph, with nodes representing components and edges representing disassembly actions.

The goal was to find a suitable data structure that fulfils the following requirements.

- The data structure should allow for the visualisation of the graph/disassembly sequence.
- The data structure must include both part (nodes) properties and disassembly activity (edge) properties.
- The data structure needs to allow for multiple disassembly activities between components.
- The data structure needs to be compatible with MS Excel.

The edge/node list was the only data structure that complies with all four requirements as can be seen from Table 3 summarizing the findings. The edge/node list allows for visualisation of the disassembly sequence, properties for both components and disassembly activities can be added, multiple disassembly activities between two components are possible and it can be built in Excel. Therefore, this is the data structure that will be implemented in the improved tool to make a connection between the Hotspot Mapping tool and the Disassembly Map.

	ADJACENCY MATRIX	INCIDENCE MATRIX	ADJACENCY LIST	EDGE/NODE LIST
VISUALISATION	yes	yes	yes	yes
PROPERTIES	no	no	semi	yes
MULTIPLE ACTIVITIES	no	yes	no	yes
EXCEL	yes	yes	yes	yes

Table 3 Summary of data structure requirements compliance.

6 Requirements

This chapter presents a comprehensive list of requirements for the development of a tool/method and product architecture visualization software. These requirements are based on the findings from previous chapters and aim to ensure the functionality, usability, and effectiveness of the tools in guiding users towards redesigning products for dis- and reassembly. The requirements are divided into two parts: one for the tool/method's functionality and usability (Table 4 & Table 5), and the other for the product visualization software (Table 6 & Table 7), which generates the Disassembly Map using the redesigned Hotspot Mapping tool's output.

6.1 Tool/method

	REQUIREMENTS	REFERENCE
1	The tool needs a data structure that describes the product architecture.	1.3
2	The data structure needs to allow multiple properties to be attached to the components and disassembly activities.	5
3	The data structure needs to allow for visualization of the product architecture.	5
4	The tool needs to reach a minimum SUS score of 68, which is the average for all systems.	4.2
5	The tool needs to be capable of describing the three logic operations: sequential dependence, sequential independence (parallel) and multiple dependencies.	3.2
6	The data structure needs to allow for multiple disassembly activities between components.	5
7	The data structure needs to be compatible with MS Excel.	5
8	The tool needs to have at least the same features as the HSM tool.	
9	The tool needs to record component properties, such as weight, material, failure likelihood, and functional relevance.	2
10	The tool needs to record disassembly activity properties, such as the activity, tool, task frequency, disassembly time, required force, accessibility, and tool positioning.	3.1
11	The tool needs to calculate the three component hotspots: Priority, Environmental impact, and Economic value.	3.1
12	The tool needs to calculate the two disassembly activity hotspots: Disassembly duration and disassembly activity effort.	3.1
13	The tool needs to calculate the disassembly depth in seconds and the total disassembly effort for each part.	2, 3.1 & 4.2
14	The tool needs to keep track of the number of different types of fasteners and tools (Dangal, 2022; Lützen & Lissalde, 2020).	2, 3.1 & 4.2
15	The tool needs to penalise non-reusable fasteners.	2
16	The tool needs to allow the generation of a DM based on the input in the HSM tool.	4.2
17	The tool needs to use self-recorded disassembly time.	3.1
18	The tool needs to display the calculated data instead of hotspot flags.	3.1 & 4.2
19	The tool needs to have coherent naming conventions between the HSM and DM.	4.2 & 7.3

Table 4 List of requirements for the HSM tool.

	WISHES	REFERENCE
1	The tool should be as user-friendly as possible considering the complexity of the tool.	4.2
2	The tool should give internal guidance to the user as to how the tool should be used and the data should be entered.	4.2
3	The tool should reduce the subjectivity of the Disassembly Map as much as possible.	3.2 & 4.2
4	The tool should allow clusters to be added, to represent the disassembly sequence more accurately.	3.2
5	The tool should allow for the reordering of components and disassembly activities.	4.2
6	The tool should allow users to add and adjust materials. This would allow for specific materials and sharing of the tool without proprietary data.	3.1 & 4.2
7	The tool should guide users in which components need focus in a redesign for different circular strategies.	3.1
8	The required time to use the tool should be in proportion to the value it provides.	4.2
9	The tool should include reassembly properties.	3.2
10	The tool should record if a component stays intact during disassembly.	3.1
11	The tool should separate the disassembly activities from the components.	4.2

Table 5 List of wishes for the HSM tool.

6.2 Product architecture visualisation software

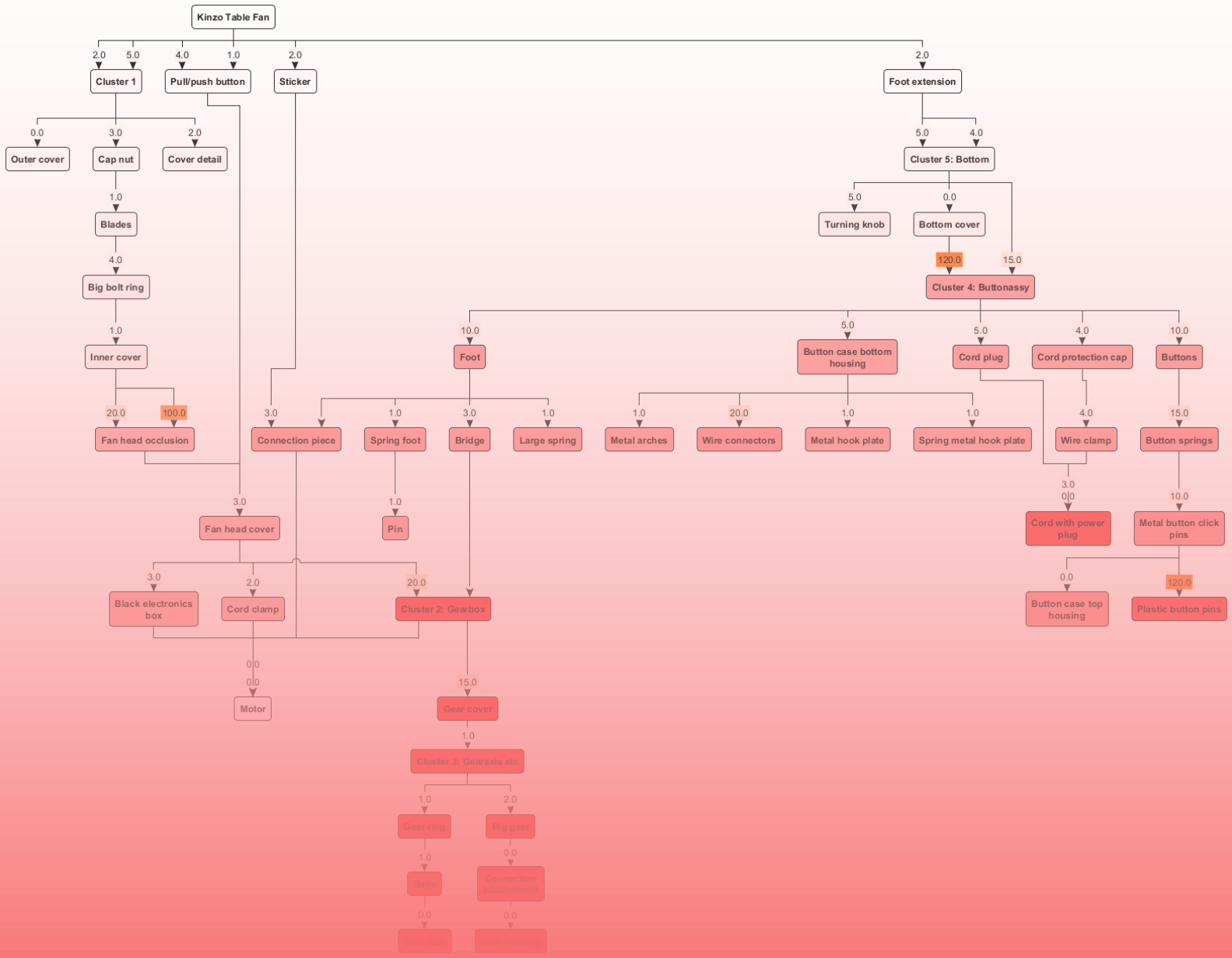
Because the original Disassembly Map does not use dedicated software, this aspect was not analysed during the analyses part. The requirements for the product visualization software were established through experimentation in the Research through Design process outlined in Chapter 7.

	REQUIREMENTS
1	The software needs to be able to use the data (including formulas) in the HSM tool.
2	The software needs to be able to generate a visual product architecture based on the imported data.
3	The software needs to be able to display multiple edges (disassembly activities) between two nodes (components).
4	The software needs to allow for different configurations, highlighting different aspects of the DM. Such as highlights based on disassembly depth, priority, and other hotspots.
5	The software needs to have an automatic layout option resembling the original Disassembly Map structure (hierarchical/vertical tree).
	The software needs to be accessible. Everyone should be able to download it.

Table 6 List of requirements for the product architecture visualisation software.

	WISHES
1	The software should be open source.
2	The software should be free.
3	The software preferably is compatible with the most popular operating systems: Windows, Mac OS, and Linux.
4	Importing the data for generating the DM should be as easy as possible. In other words, as few modifications, and actions as possible should be required.
5	The software should allow for the dynamic displaying of different properties in the product architecture to focus attention.

Table 7 List of wishes for the product architecture visualisation software.



Development

This part addresses research objective four:

Develop a new tool using the selected data structure that guides designers in increasing the ease of disassembly and reassembly.

This part only contains one chapter. Chapter 7 describes the method and process of improving the Hotspot Mapping and Disassembly Mapping tools through 6 iterations. The final version is assessed based on the requirements set in Chapter 6.

7 Development of the new tool

7.1 Approach

An iterative approach was used of first disassembling products to evaluate the state of the tools, followed by ideating and exploring new improvements. A selection of products was made available by Logitech to conduct this project.

The approach to developing an updated version of the tool was as follows. A Logitech product was chosen at random to be disassembled. After disassembling the product, the Hotspot Mapping tool was filled in and the Disassembly Map was made. In the beginning, the Disassembly Map was made manually, but in later stages, this was done automatically.

When the data was all entered one aspect was chosen to focus on and improve. This could be a usability issue or feature that was determined based on literature findings, user input, or my findings when filling in the tool. Furthermore, throughout the process, a lot of iterations were required to try out different ways of calculating multiple outputs and to experiment with applying specific MS Excel functions. Throughout the different iterations the Logitech K780 keyboard, Zone Vibe 100 headphones, Brio 500 webcam and MX Vertical mouse, shown in Figure 12, were disassembled and used as input for the HSM tool.



Figure 12 Disassembled Logitech products. From left top to right bottom, K780 keyboard, Zone Vibe 100 headphones, Brio 500 webcam and MX vertical mouse.

7.2 Iteration 1: Exploring the design structure matrix.

The most important goal of the project is to connect the Hotspot Mapping tool and the Disassembly Map. This was the first feature I tried to implement in the tool. I already started working on this before and during the analysis phase of the project. Therefore, I did not know yet about the field of graph theory and the different data structures that are available to describe it. My knowledge at that time was limited to the Design Structure Matrix (DSM) as a potential bridge between the HSM and DM.

Consequently, my initial approach involved implementing a DSM within the tool. An example DSM (from *Introduction to DSM* (2019)) was used to fill in the disassembly sequence for the Logitech K780 depicted in

Figure 13. However, I learned quickly that this would not be an effective translation layer between the HSM and DM. The process of populating the matrix proved challenging, requiring continuous going back and forth between the input in the matrix and the resulting output DM. Furthermore, the DSM did not allow for adding multiple properties to either the components or the disassembly activities. These limitations led me to conclude that the DSM was not a suitable option.

With the DSM dismissed, I explored alternative methods for connecting the HSM and DM. As described in Chapter 5, I analysed various data structures associated with graph theory. Based on this analysis, the Edge/Node list was selected as a suitable approach for establishing the connection between the HSM and DM.

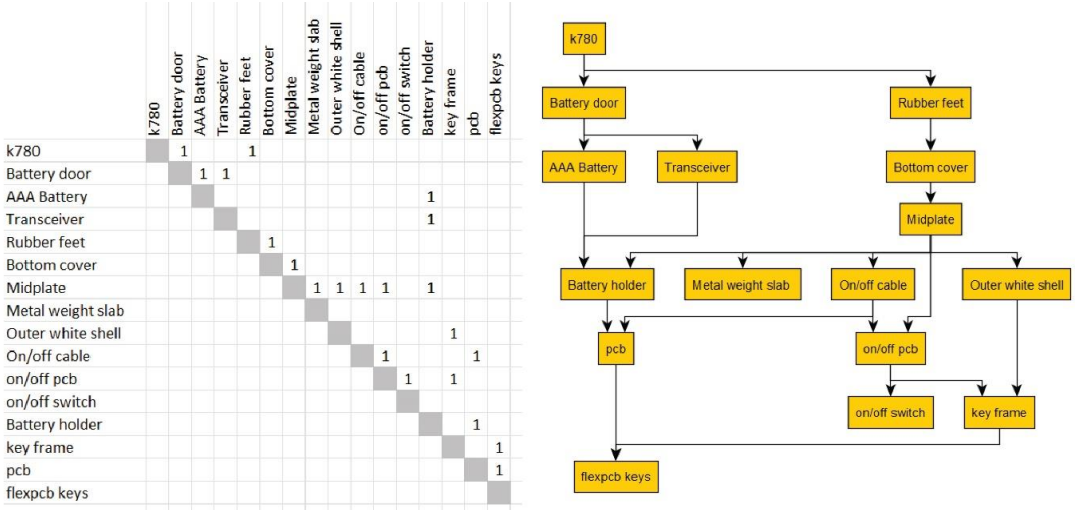


Figure 13 Reverse-engineered DSM table with generated Disassembly Map

7.3 Iteration 2: Integrating the Edge/Node list.

In the second iteration, the Edge/Node list was integrated into the HSM tool. The edge/node list is explained in Chapter 5.4. Initially, small experiments were performed with a simple edge list without additional properties to see if yEd Graph Editor (yWorks, 2023) could generate a product architecture from this dataset. This edge/node list consisted of two tables in MS Excel, one for the components and one for the activities. As a consequence, data that was previously entered in one table in the original HSM tool is now divided into two tables. Potentially, this will also reduce the confusion mentioned by users that was caused by components and activities being part of one list.

After confirming that the simple version of the edge/node list could successfully generate a product architecture in yEd, all component properties and disassembly activity properties from the original HSM tool were added. To make the two lists work together, they must use the same naming conventions. To help the user, Excel is set up in a way where you first need to enter all the parts in the node list (component/part table) and then only these parts can be selected in the edge list (disassembly activities table).

Populating the integrated edge/node list with the disassembly information for the Logitech Zone Vibe 100 (see Table 8) was significantly easier than populating the DSM in the initial iteration, resulting in the creation of the DM shown in Figure 14. However, during the integration of the edge/node list, a few limitations were identified that could be improved. The source and target node columns are currently named "previous step" and "next step," which can be confusing and requires better wording or good instructions to guide the user. Another limitation is the current inability to add clusters to the disassembly sequence. While not essential for the Disassembly Map, clusters would provide a more accurate representation of the disassembly sequence.

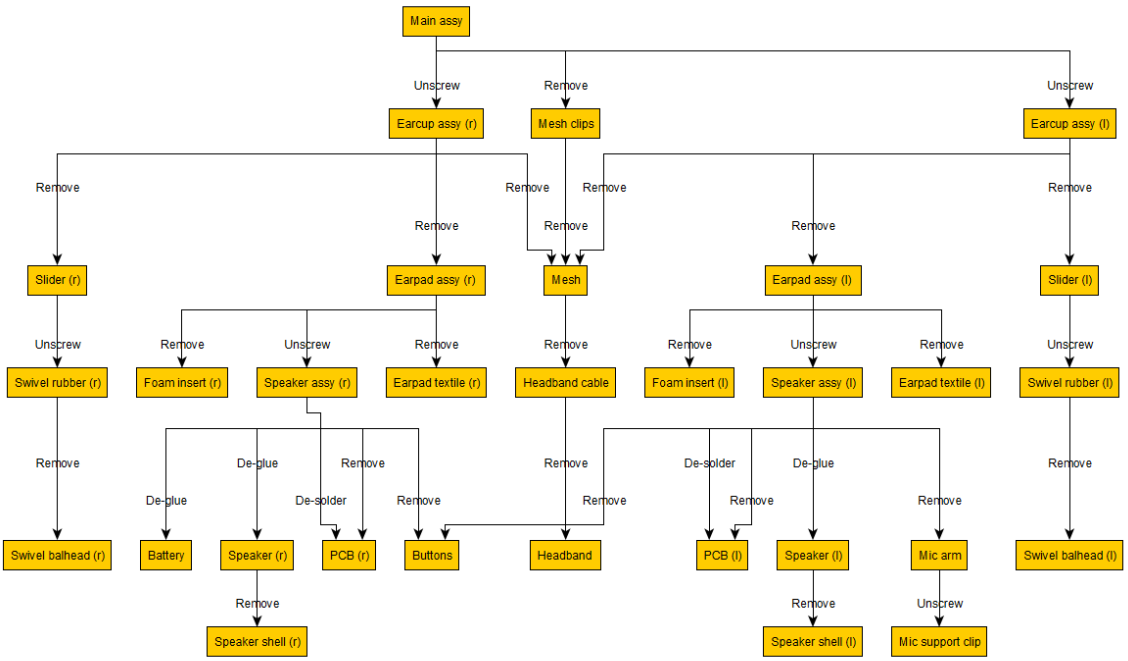


Figure 14 DM of Logitech Zone Vibe 100 headphone (see Figure 12)

	Previously r	Next part	Removal act	Tool	
1	Main assy	Earcup assy (r)	Unscrew	Screwdriver	
2	Earcup assy (r)	Earpad assy (r)	Remove		
3	Earpad assy (r)	Foam insert (r)	Remove		
4	Earpad assy (r)	Earpad textile (r	Remove		
5	Earpad assy (r)	Speaker assy (r)	Unscrew		
6	Speaker assy (r)	Speaker (r)	De-glue		
7	Main assy	Earcup assy (l)	Unscrew		
8	Earcup assy (l)	Earpad assy (l)	Remove		
9	Earpad assy (l)	Foam insert (l)	Remove		
10	Earpad assy (l)	Earpad textile (l	Remove		
11	Earpad assy (l)	Speaker assy (l)	Unscrew		
12	Speaker assy (l)	Speaker (l)	De-glue		
13	Speaker (l)	Speaker shell (l	Remove		
14	Speaker (r)	Speaker shell (r	Remove		
15	Earcup assy (r)	Mesh	Remove		
16	Earcup assy (l)	Mesh	Remove		
17	Main assy	Mesh clips	Remove		
18	Mesh clips	Mesh	Remove		
19	Mesh	Headband cable	Remove		
20	Headband cable	Headband	Remove		
21	Speaker assy (r)	PCB (r)	De-solder		
22	Speaker assy (r)	PCB (r)	Remove		
23	Earcup assy (l)	Slider (l)	Remove		
24	Earcup assy (r)	Slider (r)	Remove		
25	Slider (l)	Swivel rubber (l	Unscrew		
26	Swivel rubber (l)	Swivel balhead	Remove		
27	Slider (r)	Swivel rubber (r	Unscrew		
28	Swivel rubber (r)	Swivel balhead	Remove		
29	Speaker assy (l)	PCB (l)	De-solder		
30	Speaker assy (l)	PCB (l)	Remove		
31	Speaker assy (r)	Buttons	Remove		
32	Speaker assy (l)	Buttons	Remove		
33	Speaker assy (l)	Mic arm	Remove		
34	Mic arm	Mic support clip	Unscrew		
35	Speaker assy (r)	Battery	De-glue		

Table 8 Edge list of Logitech Zone Vibe 100

7.4 Iteration 3: Translation to Disassembly Map.

In the analysis, the edge/node list was selected as a possible translation layer between HSM and DM. After integrating and testing the edge/node list with the Logitech Zone Vibe 100, the edge node list was found capable to generate a representative product architecture and allowed entering all required data. The next step is integrating and visualising the part properties, disassembly activity properties and hotspots into the Disassembly Map.

Visualisation software

To visualise the product architecture and its properties I used yEd Graph Editor, which was recommended by Bas Flipsen (verbal communication) because of its open-source nature. To make sure this was the best option, I also explored alternative software programs designed for either flowchart or graph visualisation. As a starting point, I collected programs that were free and open source to increase the accessibility of the method.

List of programs:

- yEd Graph Editor
- Microsoft Visio (not open source, but there is a free plugin for Excel)(Microsoft, 2023b)
- Cytoscape (Cytoscape, 2023)
- Diagrams.net (JGraph Ltd, 2023)
- Gephi (Bastian et al., 2009)
- Graphviz (AT&T Labs Research, 2023)

In the following subsection, each of the programs will be described, followed by my experiences and a judgement on their capability to serve as visualisation software for the disassembly map. To determine the suitability of the program it has to comply with the requirements described in section 6.2:

- The software needs to be able to use the data (including formulas) in the HSM tool.
- The software needs to be able to generate a visual product architecture based on the imported data.
- The software needs to be able to display multiple edges (disassembly activities) between two nodes (components).
- The software needs to allow for different configurations, highlighting various aspects of the DM. Such as highlights based on disassembly depth, priority, and other hotspots.
- The software needs to have an automatic layout option resembling the original Disassembly Map structure (hierarchical/vertical tree).
- The software needs to be accessible. Everyone should be able to download it.

yEd Graph editor

yEd graph editor is a free and open-source software tool designed for creating and editing diagrams, flowcharts, and network representations. It offers a range of automatic layout algorithms (including hierarchical) and allows for visual customization options.

One notable feature of yEd is its ability to import an edge/node list, guiding users through an import window for generating graphs. The program includes a function called "Properties Mapper" that enables users to map data to different visual and textual aspects of the graph, facilitating displaying distinct types of information. For instance, components can be colourized based on factors like priority parts or economic and environmental values. However, accessing these features may require importing specific configurations and navigating buried menus, emphasizing the importance of clear instructions for ease of use.

Additionally, yEd allows multiple disassembly activities between two components, as can be seen in Figure 15, where the Battery, Main PCB and Hand Grip all need multiple actions to be disassembled. Lastly, yEd provides a useful feature where selecting a target component reveals all dependent components and activities, visually illustrating the specific disassembly steps required to reach the target. For example, in Figure 15, the disassembly steps for reaching the hand grip are displayed when the grip is selected in the DM.

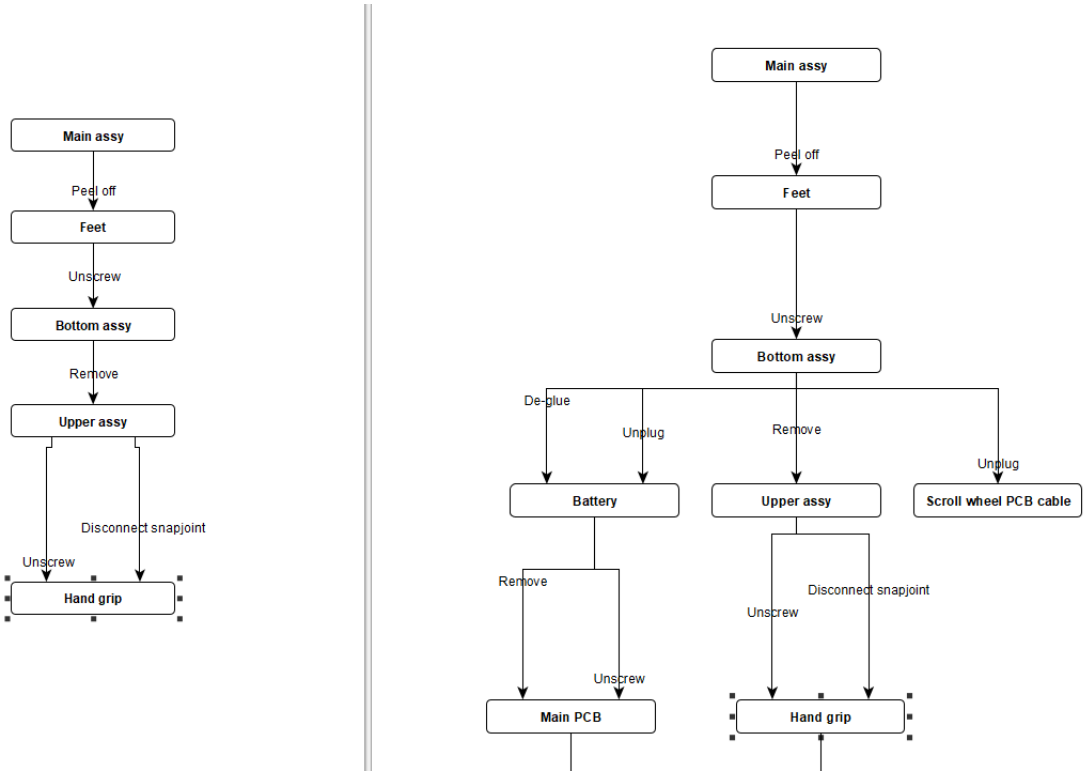
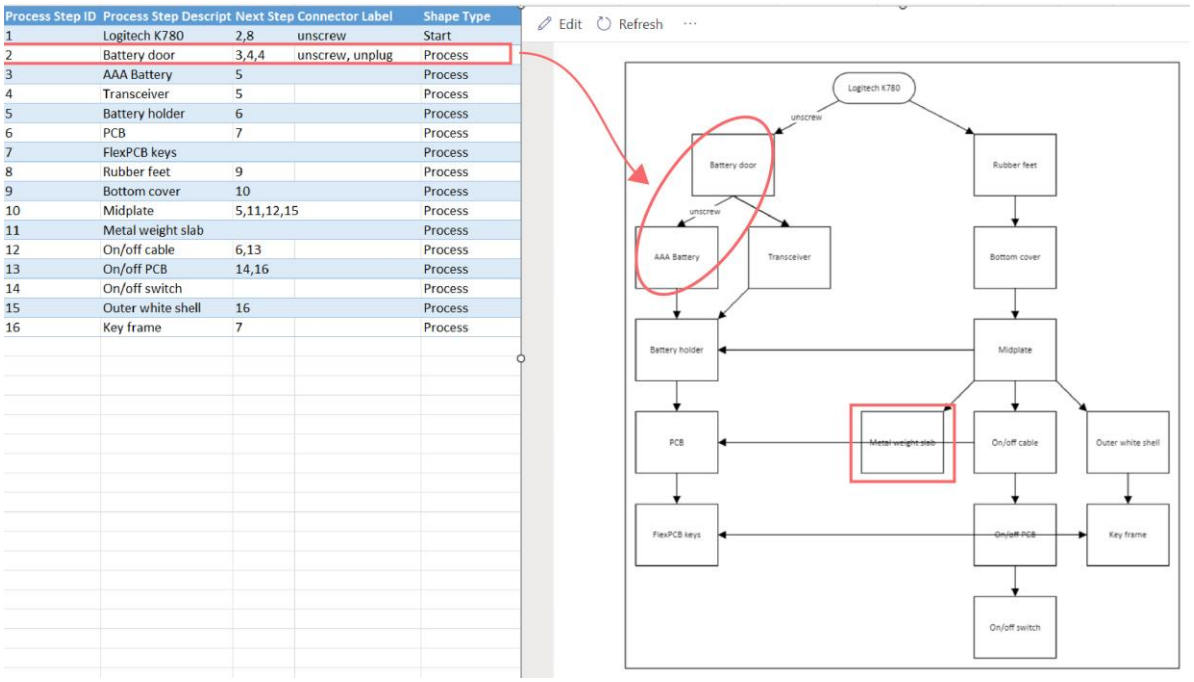


Figure 15 Screenshot of "predecessors" function in yEd Graph Editor

MS Visio Excel plugin

MS Visio is neither open source nor free to use. However, it does offer a free Excel plugin that facilitates the direct connection of data from Excel to a graph visualization program. This allows for automatic updates to the graph whenever there are changes in the data, making it convenient for data entry.

When evaluating the plugin with one of the populated HSM spreadsheets, a graph could only be generated with a data table that did not contain formulas (Figure 16). Consequently, a plain text version of the data must be used as input, which eliminates the advantage of dynamic data linking. Furthermore, the plugin lacks customization options. For example, it is not possible to correct the arrows running through components in Figure 16. These limitations make the MS Visio plugin unsuitable for further use in the development of the tool. Lastly, the plugin only works with an adjacency list data structure, consequently, it can not contain multiple disassembly steps between the same two components.



Process Step ID	Process Step Descript	Next Step	Connector Label	Shape Type
1	Logitech K780	2,8	unscrew	Start
2	Battery door	3,4,4	unscrew, unplug	Process
3	AAA Battery	5		Process
4	Transceiver	5		Process
5	Battery holder	6		Process
6	PCB	7		Process
7	FlexPCB keys			Process
8	Rubber feet	9		Process
9	Bottom cover	10		Process
10	Midplate	5,11,12,15		Process
11	Metal weight slab			Process
12	On/off cable	6,13		Process
13	On/off PCB	14,16		Process
14	On/off switch			Process
15	Outer white shell	16		Process
16	Key frame	7		Process

Figure 16 Simple example of graph generated using the MS Visio Excel plugin.

Cytoscape

Cytoscape is a software tool designed to visualize complex networks and their attributes. While it supports importing Excel databases, it does not work with included Excel formulas. This means that in practice it only accepts plain text data, necessitating manual copying for successful import. As an advantage, the program offers the capability to colourize and arrange data based on different properties (as depicted in Figure 17). However, its layout algorithm relies on a plugin from yFiles, the creator of yEd. Thus, employing the same algorithm as yEd but with a more challenging import process.

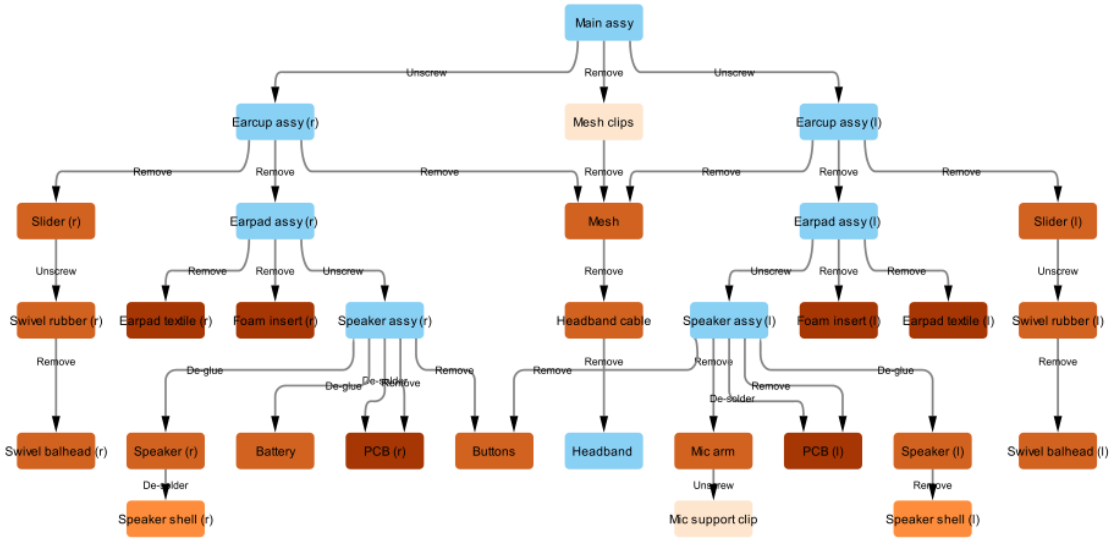


Figure 17 DM generated in Cytoscape, highlighting parts with a high embodied environmental impact.

Diagrams.net

Diagrams.net, previously known as draw.io, is an online graph drawing tool ideal for creating flowcharts, wireframes, organizational charts, and network diagrams. It provides a user-friendly interface for easily creating graphs from scratch. With the ability to import CSV files, Diagrams.net facilitates the effortless transformation of spreadsheet information into visual graphs. Various configuration files can be used to achieve multiple visual styles and highlights. In Figure 18, an example of a CSV file is shown that has been transformed into a diagram. A limitation, however, is that the importing function does not permit multiple connections between two components. This issue is illustrated in Figure 18, where Diagrams.net generates multiple instances of the same component (see highlighted pairs), rendering the software inappropriate for constructing a Disassembly Map.

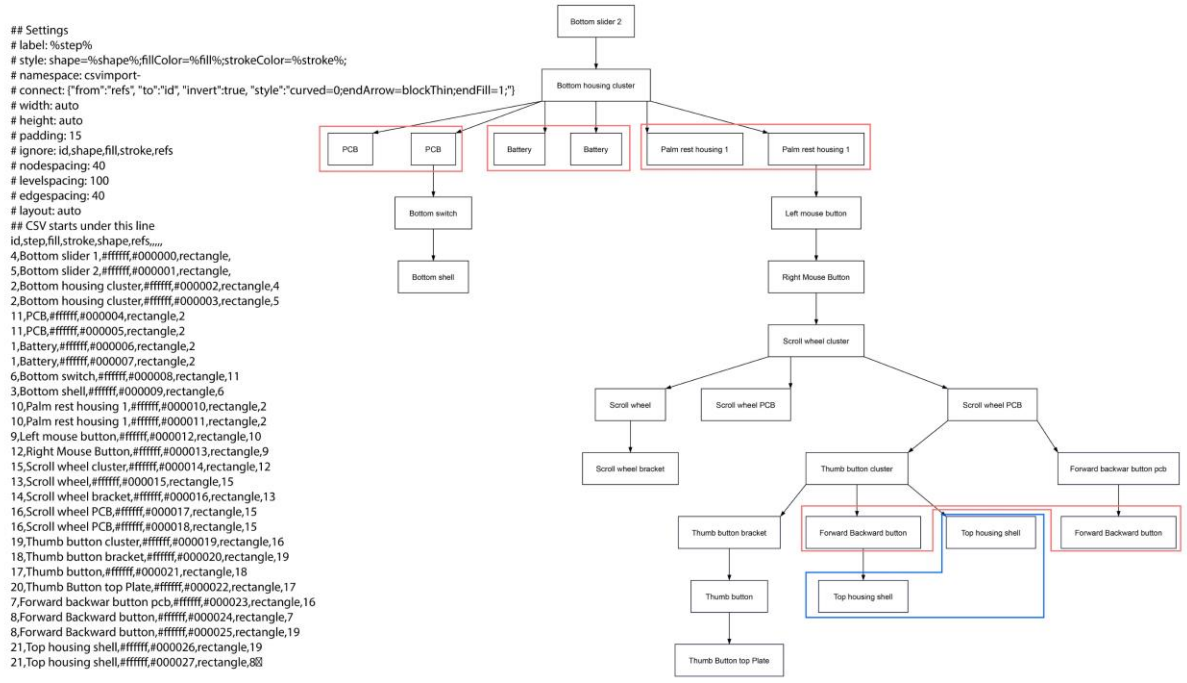


Figure 18 Input and the resulting output of diagrams.net.

Gephi

Gephi is an influential software tool designed to visualize and analyse graphs and intricate networks, including those found in social, biological, and internet-based contexts (Figure 19). Although it supports the importation of data related to edges and nodes, it is not adapted for displaying smaller graphs, focusing instead on the visualization of expansive networks. Additionally, Gephi lacks hierarchical layout options that would replicate the appearance and organization of the DM.

The software does offer an Excel import wizard; however, I faced challenges in importing Excel files without encountering errors. The import process in Gephi necessitates importing the same spreadsheet two separate times: once for the node list and again for the edge list. Moreover, users must manually define the data type (such as string, float, or integer) for each column. This requirement adds a layer of complexity, rendering the process more cumbersome and challenging to guide others through. Lastly, multiple activities are not possible between two components.

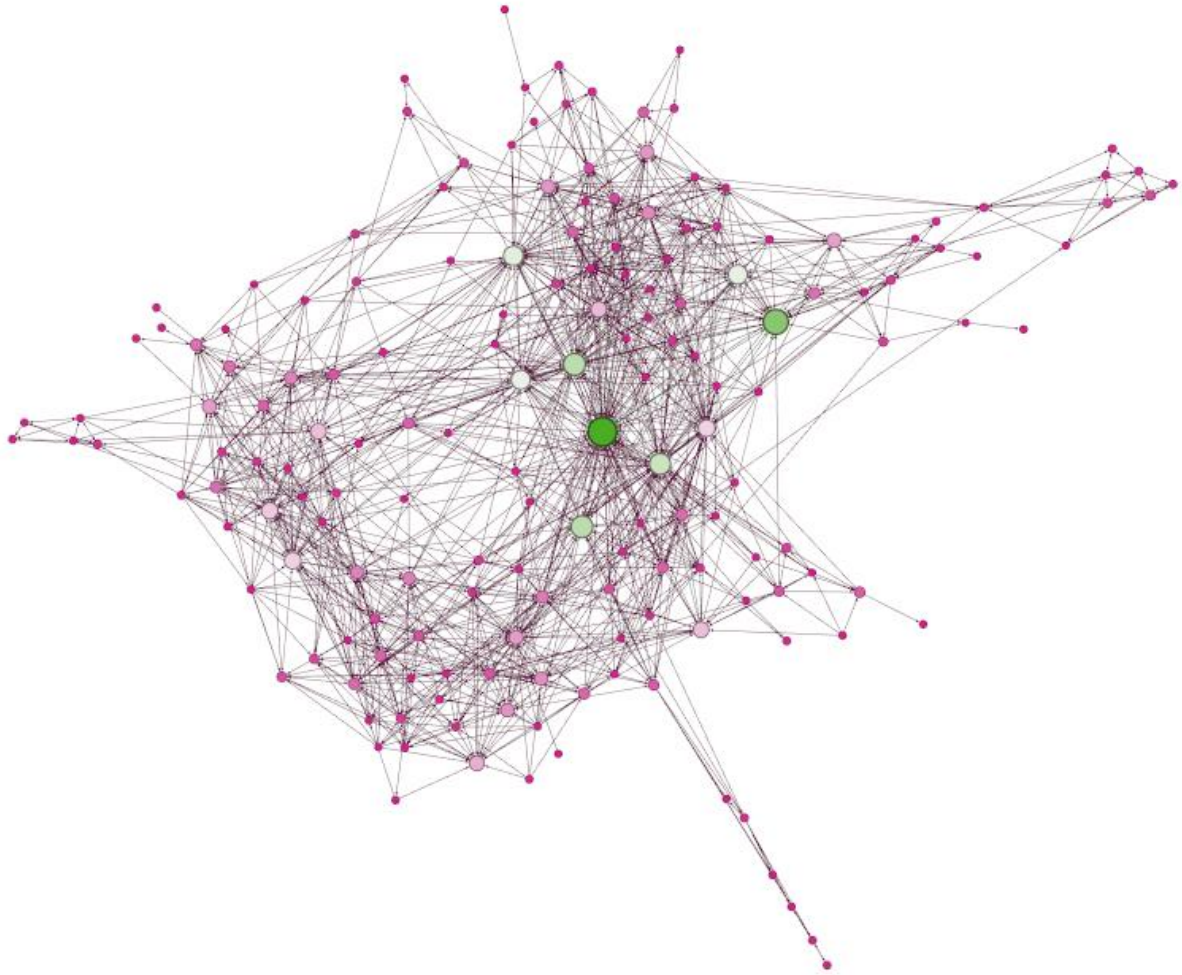
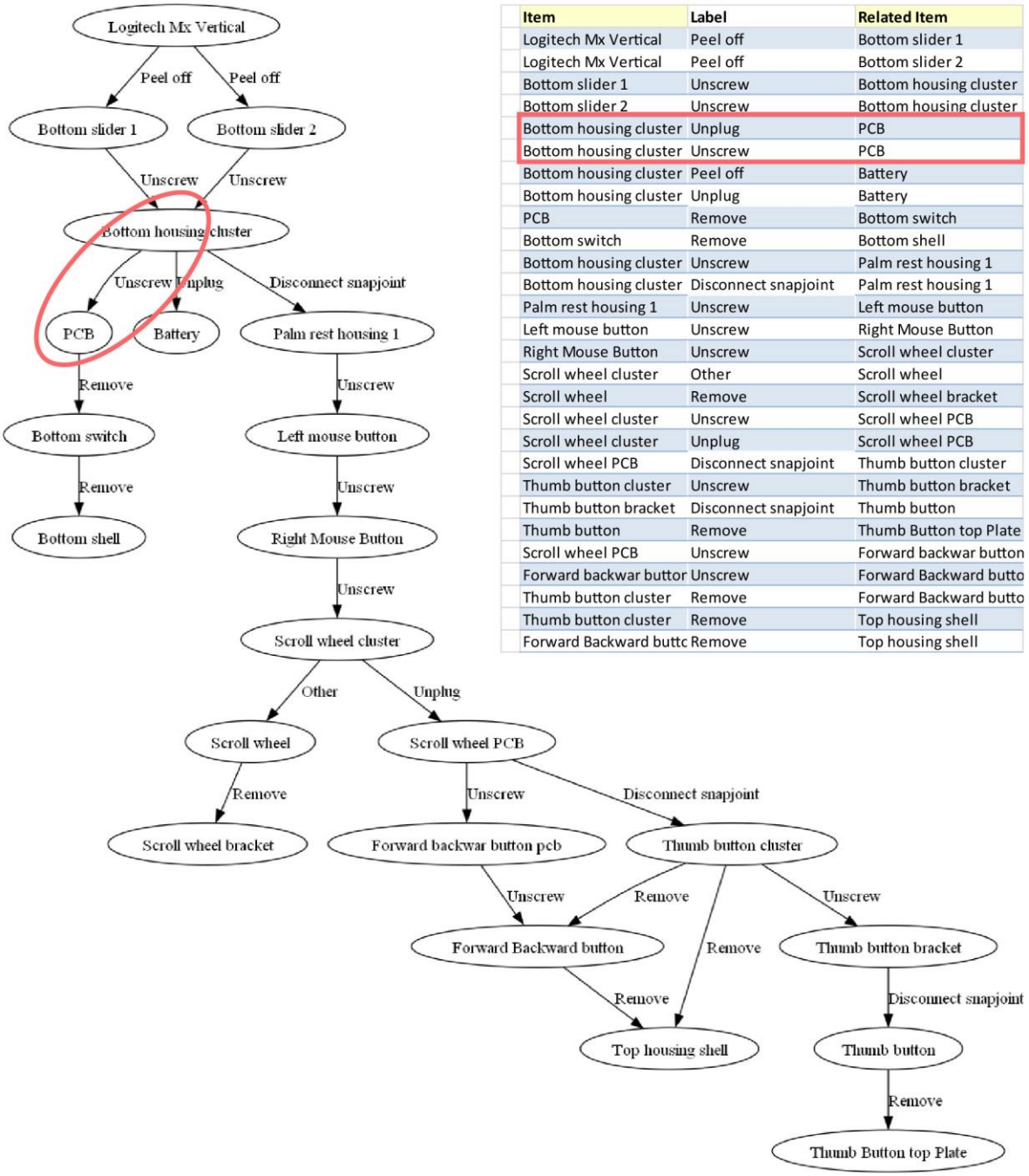


Figure 19 Example of network generated by Gephi (Gephi, 2009).

Graphviz

Graphviz is a language-based, specifically DOT language, graph visualization tool where graphs are entered using a command line format or can be programmed using other programming languages such as Python and Java. However, due to the lack of a visual user interface and the steep learning curve, it may not be suitable for use as a Disassembly Map generator.

There is a custom-built plugin available called Excel to Graphviz (Long, 2015) which integrates Graphviz into Excel. This plugin allows for a live updating map based on a data table, which would allow a user to get live feedback on the changes he/she is making. This solution seemed promising but was met with an inherent limitation within the Graphviz system. Specifically, Graphviz's inability to allow for multiple connections between two parts in a graph undermines its application for this purpose. As illustrated in Figure 20, the software only displays the last disassembly activity mentioned in the table, ignoring any previous connections between the same parts.



Item	Label	Related Item
Logitech Mx Vertical	Peel off	Bottom slider 1
Logitech Mx Vertical	Peel off	Bottom slider 2
Bottom slider 1	Unscrew	Bottom housing cluster
Bottom slider 2	Unscrew	Bottom housing cluster
Bottom housing cluster	Unplug	PCB
Bottom housing cluster	Unscrew	PCB
Bottom housing cluster	Peel off	Battery
Bottom housing cluster	Unplug	Battery
PCB	Remove	Bottom switch
Bottom switch	Remove	Bottom shell
Bottom housing cluster	Unscrew	Palm rest housing 1
Bottom housing cluster	Disconnect snapjoint	Palm rest housing 1
Palm rest housing 1	Unscrew	Left mouse button
Left mouse button	Unscrew	Right Mouse Button
Right Mouse Button	Unscrew	Scroll wheel cluster
Scroll wheel cluster	Other	Scroll wheel
Scroll wheel	Remove	Scroll wheel bracket
Scroll wheel cluster	Unscrew	Scroll wheel PCB
Scroll wheel cluster	Unplug	Scroll wheel PCB
Scroll wheel PCB	Disconnect snapjoint	Thumb button cluster
Thumb button cluster	Unscrew	Thumb button bracket
Thumb button bracket	Disconnect snapjoint	Thumb button
Thumb button	Remove	Thumb Button top Plate
Scroll wheel PCB	Unscrew	Forward backwar button
Forward backwar buttor	Unscrew	Forward Backward butto
Thumb button cluster	Remove	Forward Backward butto
Thumb button cluster	Remove	Top housing shell
Forward Backward buttc	Remove	Top housing shell

Figure 20 Live updating DM in Excel using Graphviz + Excel to Graphviz plugin.

Conclusion

The task of visualizing product architecture and its properties necessitated the exploration of a diverse collection of software programs, each with distinct features and capabilities. Key requirements, delineated in Section 6.2, provided a framework for evaluating the potential ability of each tool in representing Disassembly Maps.

Among the different software options, yEd Graph Editor emerged as the most suitable program, fulfilling all the criteria (Table 9), including the critical ability to visualize multiple disassembly activities between components. yEd's free and open-source nature, combined with its compatibility with Excel data, the flexibility to accommodate various configurations, and its capacity to generate hierarchical structures, set it apart. While Cytoscape presented a close competition, its limitations regarding importing Excel formulas and reliance on the yEd plugin for DM layout made it a less ideal choice.

	YED	VISIO	CYTOSCAPE	DIAGRAMS	GEPHI	GRAPHVIZ
EXCEL DATA/FORMULAS	Yes	No	No	Yes	Unknown	Yes
GRAPH VISUALIZATION	Yes	Yes	Yes	Yes	No	Yes
MULTIPLE ACTIVITIES	Yes	No	Yes	No	No	No
CONFIGURATIONS	Yes	No	Yes	Yes	Yes	Yes
HIERARCHICAL	Yes	Semi	Yes	Yes	No	Yes
ACCESSIBLE	Yes	Yes	Yes	Yes	Yes	Yes

Table 9 What requirements does each software program fulfil?

yEd integration

Integrating yEd with the HSM spreadsheet entailed a couple of aspects: creating a visual style in yEd, creating different profiles to dynamically show different information, and adjusting the HSM tool to contain hidden data which yEd can use to map different values to a colour scale.

To map the properties to visual elements, numerical outputs from the HSM tool are normalized in hidden columns. These normalized values, ranging from 0 to 1, are then used by yEd to map them onto a colour scale. Four configurations are programmed in yEd for both nodes (components) and edges (activities).

Nodes:

- Blank: This configuration does not assign any colour to the components, allowing for a simple overview of the disassembly sequence.
- Priority: Priority parts are highlighted using a red colour scale, with the highest priority part displayed in red and the lowest priority parts in white.
- Repairability focus: Priority parts are highlighted using a red colour scale, however now the disassembly depth is taken into account. So priority parts high up in the disassembly map will receive less attention while priority parts lower in the disassembly map are highlighted more.
- Economic: The economic value of parts is mapped onto the components, following the same principle as the priority parts.
- Environmental: The embodied environmental impact is mapped similarly to the priority and economic properties.

Edges:

- Blank: This configuration leaves the edge empty.
- Tool: Disassembly activities, required tools, and the number of activities are mapped as text on the edges.
- Tool + activity: The same text as the tool profile is mapped onto the edges, with the activity effort value determining the highlighting colour, ranging from white to orange.
- Activity time: This configuration projects the disassembly time of each activity on the edges with colour highlighting on a linear scale from the shortest to the longest duration.

Configurations for nodes and edges can be mixed and matched by the designer, to highlight what the designer wants to show or focus on. The original Disassembly Map shows all components as part numbers. In yEd parts can be displayed as part numbers, but also as part names, making it easier to read the Disassembly Map. Eliminating the need to reference a legend.

Throughout the integration, several colour schemes were tried. Figure 21 shows a disassembly map where the activities are highlighted on a stoplight-based principle on the left and a linear colour scale on the right. In the end, a scale from white to either orange (for the activities) or red (for the components) was chosen. This minimized the number of different colours and activities or components that do not need focus are not highlighted using this approach.

Instructions

As part of the integration process, a dedicated Instructions tab for how the yEd software can be used was incorporated into the HSM tool spreadsheet. These instructions provide a comprehensive guide for installing and setting up yEd, ensuring the successful implementation of the desired visual and dynamic outcomes. The instructions cover essential steps such as importing the required configuration and template files into yEd.

Once the yEd software is properly set up, users are provided with a step-by-step walkthrough. This guidance assists them in importing the relevant data from the HSM Excel file into yEd. Additionally, users are directed on how to apply the predefined configurations, select the appropriate hierarchical layout algorithm, and configure any miscellaneous settings required to achieve the desired visualization outcome.

In the zip file which contains the tool, an example populated HSM and DM are added the user can experiment and learn with. This allows the user to determine if their output is comparable to the output of the example files.

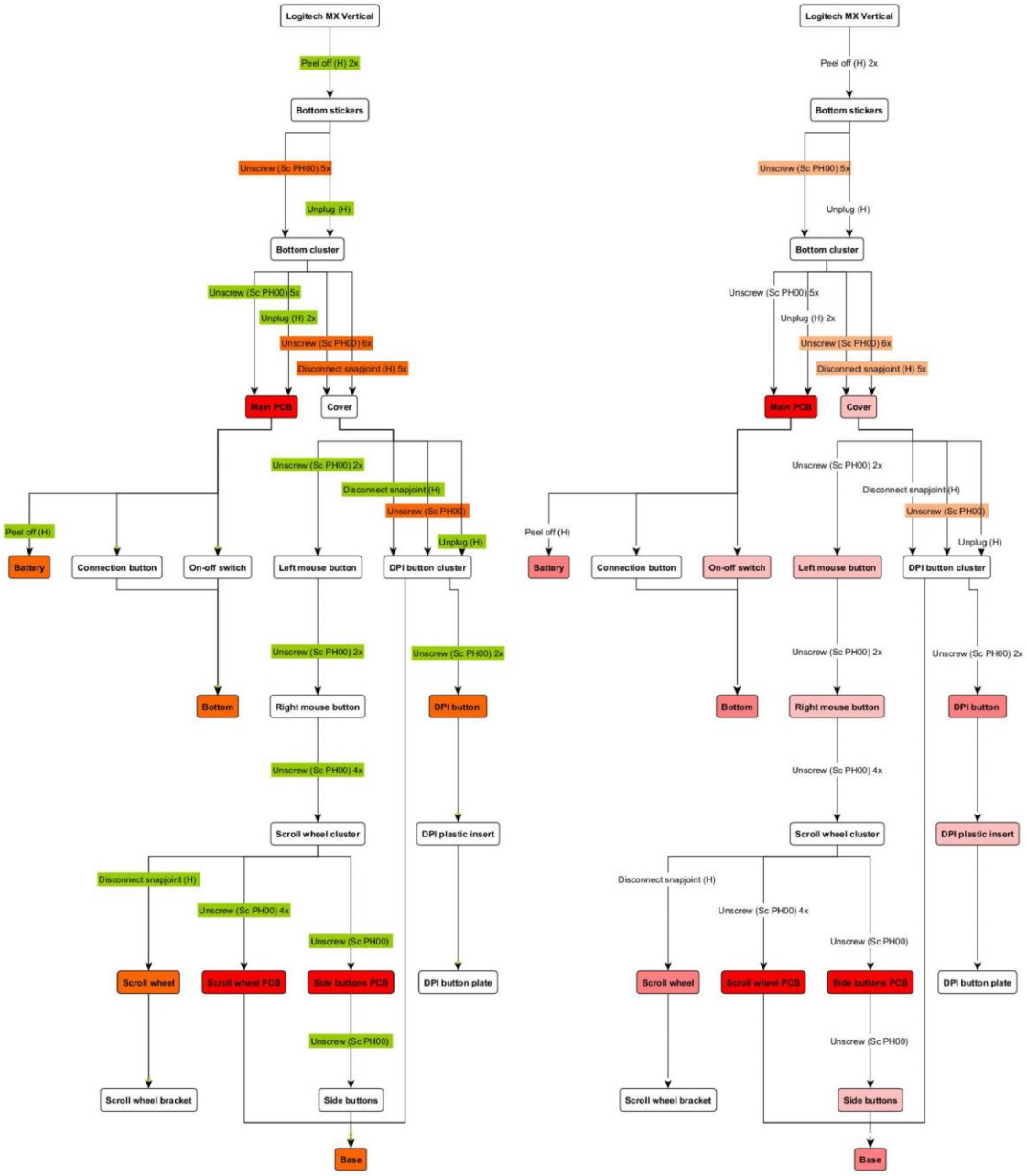


Figure 21 DM of Logitech MX Vertical with priority parts highlighted and activities highlighted. The left version displays the traffic light style, and the right version the linear one-colour scale style.

7.5 Iteration 4: Small improvements

In the previous iteration of the tool, significant modifications were implemented, leading to the need for refining and tidying up the current state of the tool. This involved several minor adjustments to enhance its usability. Firstly, a product summary section was incorporated, providing a comprehensive overview of key metrics such as total weight, environmental impact, economic value, and the number of parts (See Figure 22). Additionally, a tool counter and corresponding tool list were added to the dashboard. This new feature allows designers to easily identify the tools required for disassembly, aiding decision-making regarding tool selection and potential removal during redesigns. To ensure no parts are forgotten in the disassembly sequence, an indicator was introduced in the Bill of Materials table. This indicator highlights whether a part is used in the disassembly process, preventing any parts from being overlooked. Furthermore, instructions were integrated into the BOM and disassembly tables through the use of pop-ups. These pop-ups guide users on expected input formats and serve as reminders for the meaning of the various levels (see Figure 23 for example), aiming to facilitate a smoother user experience.

General project information

Product name	Logitech MX Vertical
Product category	Computer mouse
Authors	
Date	mei-23
Location	Delft

Overall HotSpot Results

Total:		
- time to disassemble	345 sec	
- number of tasks	50	
- number of steps	29	
- number of tools	1	
Average:		
- time per step	11,9 sec/step	
- force		2
- accessibility		2
- positioning		2
Product:		
- Weight	124,5 g	
- Environmental impact	3560 g CO2 eq	
- Economic material value	1387 ¢	
- Number of parts	19	
- Number of screws	33	
List of tools necessary for (dis)assembly		
Hands		
Screwdriver PH00		

Figure 22 General product data overview.

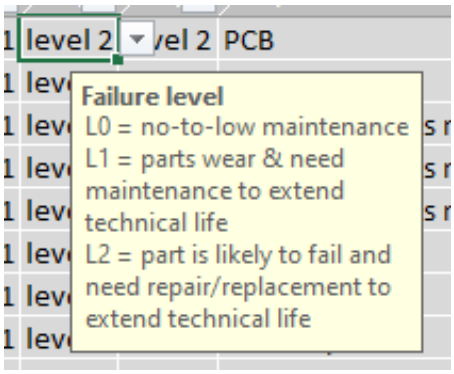


Figure 23 Popup of the meaning of the three different failure levels.

7.6 Iteration 5: Disassembly depth automation.

The assessment of disassembly depth is a critical factor for designers when considering the need to redesign components. If a priority part or a part with a high environmental impact has a low disassembly depth, redesign may not be necessary. However, if the part is deeply embedded within the product, the need to redesign becomes greater. Unfortunately, the Hotspot Mapping tool cannot currently display or indicate the disassembly depth of components.

The integrated edge/node lists describe every step that must be taken to remove each part. By aggregating all these steps, the disassembly depth of a component can be calculated. Through extensive experimentation, I was able to successfully determine the previous disassembly actions and associated parts for each entered component. This enables Excel to compute various metrics representing the disassembly depth, such as disassembly time, disassembly effort, the number of parts to be removed, and a list of all parts to be removed.

Nevertheless, the current calculation method shows certain limitations. It uses an iterative approach, wherein the disassembly activities from the target component are first determined, followed by a repetition of the same process to determine previous disassembly activities, and so forth. For instance, when Excel calculates the disassembly depth for the “Bottom” component depicted in Figure 24, during the initial iteration, it examines the disassembly steps between the Bottom and the components preceding it, specifically, the Connection button and On-off switch. Subsequently, in the second iteration, it determines the disassembly steps between the Connection button and Main PCB, as well as between the On-off switch and the Main PCB. This continues until the Logitech MX Vertical is reached.

Presently, this iterative process is confined to 15 iterations and a maximum of 10 disassembly steps per iteration. As a result, if the disassembly structure becomes too big or complex, Excel may be unable to calculate the disassembly depth.

The calculated disassembly depth data can now also be visualized in the generated disassembly map by adding another configuration. This gives a better indication of how deep a component is buried in the product architecture than the height of the component in the map. Figure 24 shows that the Cover is deeper than the Main PCB, while they are positioned at the same level.

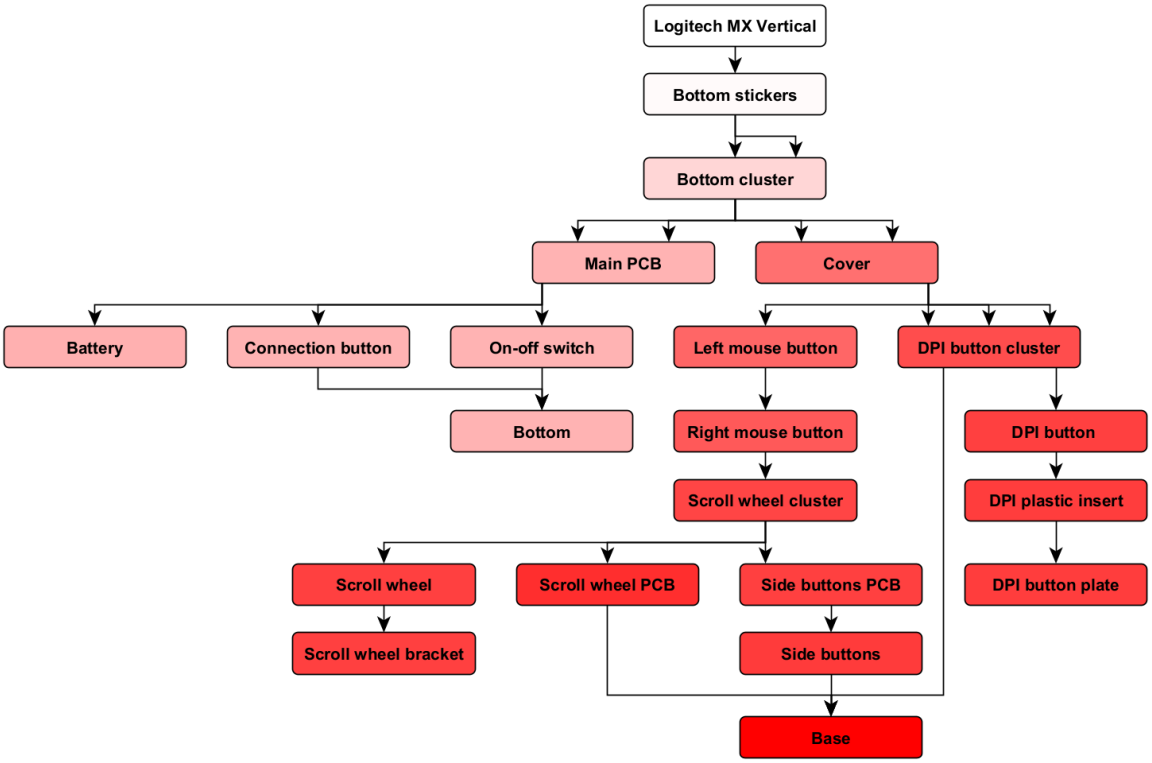


Figure 24 DM showing the disassembly depth.

Repair priority ranking.

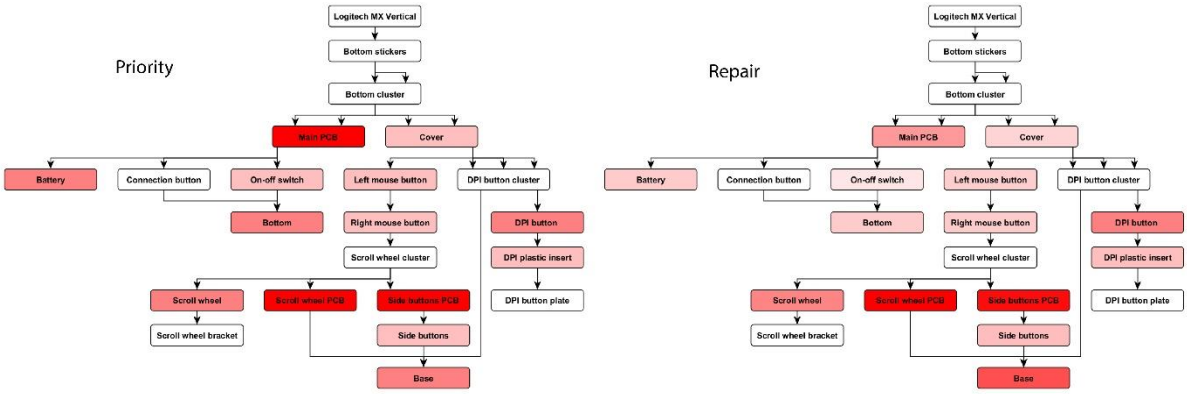


Figure 25 Comparing highlighting priority parts to repair priority parts.

The calculated disassembly depth provides a means to strike a balance between the priority value and the depth at which a component is situated within the product architecture. In the HSM tool, a ranking system has been incorporated to identify the parts that require greater attention during a redesign, taking into account both the priority assigned to a part and its disassembly depth. Figure 25 depicts the concept of repair priority in the Disassembly Map, highlighting priority parts in the left DM and repair focus parts in the right DM.

To determine the repair score, the priority value is multiplied by the combined values of disassembly depth and effort for each part. The resulting value is then min-max normalized and converted into a ranking. This approach enables the identification of parts that are high priority and located deep within the product, indicating a need for particular focus when redesigning to increase repairability. A similar ranking was added taking into consideration all the hotspots.

7.7 Iteration 6: usability and extra features.

With the integration of the node/edge list, automatic Disassembly Map generation and automatic disassembly depth calculation the main problems with the original tool have been solved. In this iteration step, a lot of smaller changes regarding visual aspects, usability and some extra features will be presented.

Hotspot indicators

The hotspot indicators from the original tool (see the black surrounded area in Table 10) are replaced in the updated version by a heatmap. This allows designers to see the individual differences between the parts better and see the associated values as well. For example, on the left side both the "PCB" and "Scroll wheel PCB" get red flags for Environmental and Economic impact, while there is a significant difference between the two parts, as can be seen in the heatmap values. Originally a designer was not able to distinguish between these when using the tool.

PartID	Part/Cluster	Is it a cluster?	Part of cluster...	Amount	Failure likelyhood	Functional relevance	Materialgroup	Total weight (g)	Time to reach part (s)	Effort to reach part	Priority	Environment	Economic	Disassembly depth (s)	Disassembly effort	Priority	Environment (gCO2e)	Economic
1	Battery	No	Bottom h	1 level 2	level 2	Battery		4,99 g						27	6	4	74,9	175
2	Bottom housing cluster	yes												21	6	0	0,0	0
3	Bottom shell	No	Bottom h	1 level 1	level 1	Thermoplastic		23,20 g						48	10	1	69,6	7
4	Bottom slider 1	No		1 level 2	level 1	Thermoplastic		0,87 g						3	1	2	2,6	0
5	Bottom slider 2	No		1 level 2	level 1	Thermoplastic		0,50 g						3	1	2	1,5	0
6	Bottom switch	No	Bottom h	1 level 0	level 0	Thermoplastic		0,27 g						47	10	0	0,8	0
7	Forward backwar button pcb	No	Top hous	1 level 1	level 1	PCB		1,12 g						91	26	1	179,2	67
8	Forward Backward button	No	Top hous	1 level 0	level 1	Thermoplastic		0,45 g						101	32	0	1,4	0
9	Left mouse button	No	Top hous	1 level 1	level 1	Thermoplastic		3,40 g						56	11	1	10,2	1
10	Palm rest housing 1	No	Top hous	1 level 0	level 1	Thermoplastic		20,80 g						51	10	0	62,4	6
11	PCB	No	Bottom h	1 level 1	level 2	PCB		13,70 g						46	10	2	2192,0	822
12	Right Mouse Button	No	Top hous	1 level 1	level 1	Thermoplastic		4,70 g						61	12	1	14,1	1
13	Scroll wheel	No	Scroll wh	1 level 1	level 1	Thermoplastic		4,90 g						74	16	1	14,7	1
14	Scroll wheel bracket	No	Scroll wh	1 level 0	level 0	Thermoplastic		2,44 g						74	16	0	7,3	1
15	Scroll wheel cluster	yes												71	15	0	0,0	0
16	Scroll wheel PCB	No	Top hous	1 level 1	level 2	PCB		4,06 g						88	22	2	649,6	244
17	Thumb button	No	Thumb b	1 level 0	level 1	Thermoplastic		0,36 g						100	27	0	1,1	0
18	Thumb button bracket	No	Thumb b	1 level 0	level 1	Mixed materials mainly plastics		1,45 g						98	25	0	4,4	0
19	Thumb button cluster	yes												93	24	0	0,0	0
20	Thumb Button top Plate	No	Thumb b	1 level 0	level 1	Aluminium		3,65 g						100	27	0	54,8	1
21	Top housing shell	No	Top hous	1 level 0	level 1	Thermoplastic		32,49 g						101	32	0	97,5	10

Table 10 Indicator comparison (black box shows heatmap including values)

Clusters

Clusters are defined as groups of components that can be collectively removed during the disassembly process. These clusters may encompass a complete subassembly or function as independent entities. Clusters are implemented into the new HSM tool the same way assemblies were integrated into the original HSM tool. To include clusters, they should be added as new entries in the BOM table, without any part properties. Upon categorizing a part as a cluster in the third column (see Table 10), the input fields for part properties are automatically greyed out, signalling to users that that information should not be entered. Additionally, in a hidden column, all the components that are part of a cluster are saved. This list of parts can be used in the Disassembly Map to show the individual components that make up the cluster.

This system has one limitation, a part cannot be assigned to multiple clusters, which does happen in products.

Material database

In the original HSM tool, the material database was inaccessible to users as it was embedded within hidden and locked sheets. However, to facilitate designers in incorporating their preferred materials and modifying corresponding values, a separate table was introduced specifically for the material database. This enables users to add their materials and customize the values to better suit their needs.

Reordering and filtering of parts

With the use of tables in Excel, the HSM tool now provides the capability to rearrange and filter components within the BOM table, as well as activities within the disassembly sequence table. This feature grants designers the

flexibility to prioritize their focus by reordering components based on factors such as disassembly depth, priority, or environmental impact.

Instructions on how to use the tool.

To guide users in how to use the tool a basic instruction sheet has been added to the HSM tool, detailing how to populate and use each sheet. Moreover, various popup instructions have been incorporated within the different tables to offer further guidance to users. Additionally, conditional formatting has been employed to aid users in identifying and rectifying incorrect data entries or non-existent parts. These instructions aim to make the tool as easy as possible to use. However, it is important to note that despite these efforts, the tool remains complex and may require time to fully comprehend. Therefore, I recommend following a course that offers proper instruction on the correct use of the tool. This will enable users to gain a thorough understanding and maximize the benefits of the HSM tool.

Mass-ECO2 graph

As an additional feature, a diagram has been incorporated into the dashboard to facilitate the assessment of components and their respective environmental and economic impacts. Although this addition was not based on literature findings or user feedback, I deemed it a valuable addition because it allows designers to quickly identify components or material groups with the most notable environmental or economic influence. The graph offers a comparative assessment, presenting weight, environmental impact, and economic value on both a per-part and per-material group level.

Figure 26 displays the Mass-ECO2 graph for the Logitech MX Vertical, showcasing that the PCBs significantly contribute to both the environmental impact and economic value of the product, even though they are only a small percentage of the total weight. Therefore, if the objective of a designer is to reduce a product's environmental impact solely through material usage, the most significant gains can be achieved by focusing efforts on minimizing the impact of the PCBs.

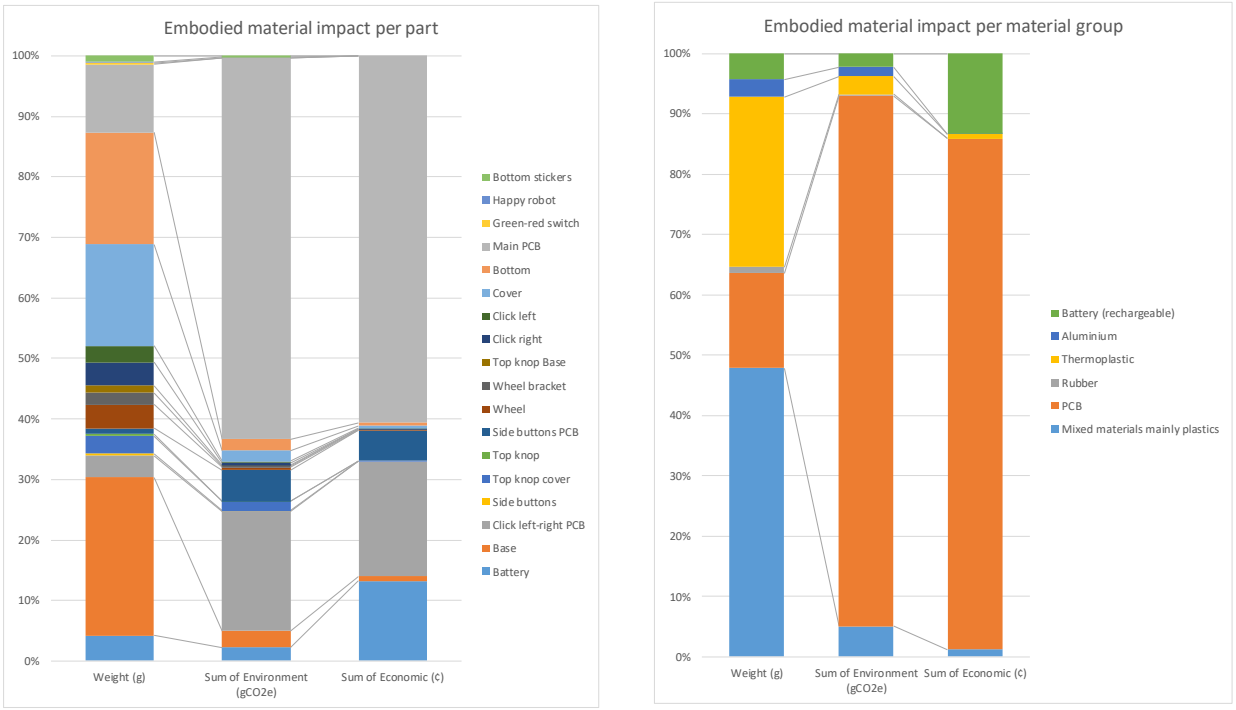


Figure 26 Mass-ECO2 graph Logitech MX Vertical

7.8 The final version

The new tool consists of six sheets for users to interact with and 3 hidden sheets required to calculate the outputs. Images of all the sheets including the hidden ones can be found in Appendix C.

- Instructions: A brief explanation of how the tool needs to be used.
- 1. Dashboard: An overview of the product is presented here including two Mass-ECO2 graphs.
- 2. BOM: All parts and clusters are entered here, and the most important outputs are shown here, such as the disassembly depth.
- 3. Disassembly: All disassembly steps/activities are recorded in this tab.
- 4. Disassembly Map: In this tab the instructions required to generate the Disassembly Map are presented.
- Material database: This tab allows users to create and manage their material database.

Tool limitations

Despite significant efforts in enhancing the tool's performance, there remain a few limitations.

Clusters: In its current form components cannot be part of multiple clusters. Even though this could be the case in the disassembly sequence, if for example, a small cluster is part of a bigger cluster.

Disassembly map: When multiple sequential disassembly activities are required to remove the next part, the order of the disassembly activities between two components is not automatically generated and must be finetuned manually by dragging the activities in the proper order in yEd.

Disassembly depth: The disassembly depth calculation in MS Excel is done through an iterative approach. This results in a limitation to the complexity the spreadsheet can manage. Currently, the spreadsheet has 15 iterations built in, which means from each part it checks 15 times which was the previously removed part. If it does not reach the product (origin of the disassembly tree) within those 15 iterations the calculation fails.

Microsoft Excel 365: Due to specific functions that are required for the tool that is only available in MS Excel 365, the tool, unfortunately, does not work properly when using a single-year office licence. These functions include SORT, UNIQUE, XLOOKUP, FILTER and SEQUENCE.

Different screws: The tool does record the number of different tools but does not keep track of the number of different screws that are used. For example, a product may contain three different lengths of Phillips head screws. By adding a record of this, designers may be able to reduce the different screw lengths and widths, reducing the need for users to keep track of where each screw belongs.

Evaluating the requirements

In Table 11 the tool is assessed based on the requirements set in Chapter 6. Almost all requirements are met, except for requirement four. This requirement can only be assessed by conducting a second System usability scale questionnaire, which is done in Chapter 8. Wish one and eight (Table 12) are also tested and discussed in Chapter 8.

	REQUIREMENTS
1	The tool needs a data structure that describes the product architecture.
2	The data structure needs to allow multiple properties to be attached to the components and disassembly activities.
3	The data structure needs to allow for visualization of the product architecture.
4	The tool needs to reach a minimum SUS score of 68, which is the average for all systems.
5	The tool needs to be capable of describing the three logic operations: sequential dependence, sequential independence (parallel) and multiple dependencies.
6	The data structure needs to allow for multiple disassembly activities between components.
7	The data structure needs to be compatible with MS Excel.
8	The tool needs to have at least the same features as the HSM tool.
9	The tool needs to record component properties, such as weight, material, failure likelihood, and functional relevance.
10	The tool needs to record disassembly activity properties, such as the activity, tool, task frequency, disassembly time, required force, accessibility, and tool positioning.
11	The tool needs to calculate the three component hotspots: Priority, Environmental impact, and Economic value.
12	The tool needs to calculate the two disassembly activity hotspots: Disassembly duration and disassembly activity effort.
13	The tool needs to calculate the disassembly depth in seconds and the total disassembly effort for each part.
14	The tool needs to keep track of the number of distinct types of fasteners and tools (Dangal, 2022; Lützen & Lissalde, 2020).
15	The tool needs to penalise non-reusable fasteners.
16	The tool needs to allow the generation of a DM based on the input in the HSM tool.
17	The tool needs to use self-recorded disassembly time.
18	The tool needs to display the calculated data instead of hotspot flags.
19	The tool needs to have coherent naming conventions between the HSM and DM.

Table 11 Does the tool adhere to the requirements?

	WISHES
1	The tool should be as user-friendly as possible considering the complexity of the tool.
2	The tool should give internal guidance to the user as to how the tool should be used and the data should be entered.
3	The tool should reduce the subjectivity of the Disassembly Map as much as possible.
4	The tool should allow clusters to be added, to represent the disassembly sequence more accurately.
5	The tool should allow for the reordering of components and disassembly activities.
6	The tool should allow users to add and adjust materials. This would allow for specific materials and sharing of the tool without proprietary data.
7	The tool should guide users in which components need focus in a redesign for different circular strategies.
8	The required time to use the tool should be in proportion to the value it provides.
9	The tool should include reassembly properties.
10	The tool should record if a component stays intact during disassembly.
11	The tool should separate the disassembly activities from the components.

Table 12 Does the tool fulfil the wishes?

Wish three is partly solved. The details of the subjective improvements and limitations are elaborated on in Chapter 9. Wish four is only partly achieved, as described in the limitation of the tool. It is possible to add clusters but not to add a component to multiple clusters, or have clusters be part of another bigger cluster. Reassembly properties were not integrated into the tool. In general, I assume that increasing the ease of disassembly also increases the ease of reassembly. However, this might not always be the case. For circular strategies such as repair, refurbish, remanufacture, and upgrade reassembly is necessary. Therefore, I recommend further development of the tool to look into properties that play a role in the reassembly process. Lastly, the tool does not record if a component stays intact during disassembly. If a component does not break depends on the skill and experience of the disassembler and is therefore difficult to integrate into the tool.

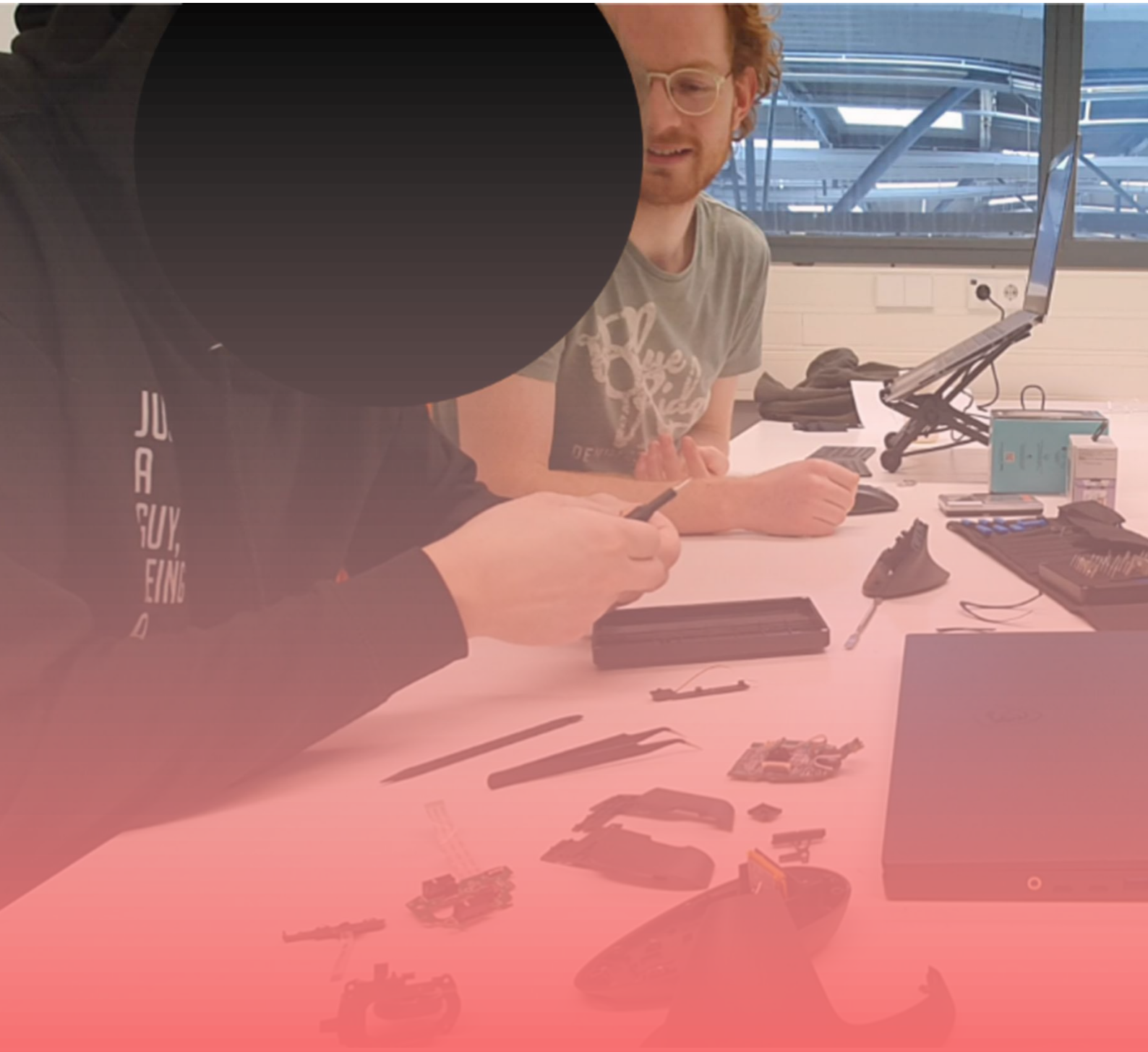
7.9 Conclusion

This chapter described the development of the new tool based on the analysis findings. The tool was created through an iterative process that involved disassembling Logitech products, evaluating different iterations of the tool, and making improvements along the way. The aim was to build a tool that complies with the requirements set in Chapter 6 and integrates the wishes as well as possible.

The primary objective of the project was to establish a connection between the HSM tool and DM, thereby reducing the need to use both tools separately. This integration was achieved using a node/edge data structure and employing the yEd Graph Editor software as a visualization tool for the Disassembly Map. Additionally, automatic disassembly depth calculations were incorporated, enabling designers to make more informed decisions regarding which parts to focus on in the redesign process. Furthermore, several minor usability improvements and additional features were implemented to enhance the overall usability and usefulness of the tool.

When comparing the result to the list of requirements most are checked, a couple are only partially met, and some will be validated in the next chapter. The subjectivity of the map has been reduced only slightly, clusters have been added but are limited in capability and reassembly properties are not integrated at all.

Overall, the development of the new tool followed a systematic approach, involving iterations, exploration of alternative methods, and refinement based on user feedback and findings. The resulting method, provides designers with a visual (DM) and data (HSM) representation of the disassembly process, facilitating easier analysis and decision-making during product redesign.



Validation

In the Validation part research objective five is addressed.

RO5: **Verify and validate the effectiveness and usability of the new tool.**

Chapter 8 evaluates the usability of the new tool and explores the strength and weaknesses. This is achieved through a SUS questionnaire plus open questions and a user test. Chapter 9 reflects the subjectivity of the tool. This chapter aims to discuss what subjective aspects persist in the tool and to what advantages and disadvantages this subjectivity leads. Finally in Chapter 10 a case study of the Logitech MX Master 3s is presented showing the effectiveness of the new tool.

8 User testing

The user test aims to answer the following research questions:

- RQ 1: Has the usability increased compared to the original HSM and DM method?
- RQ 2: What are the strong and weak usability features of the improved tool?
- RQ 3: What are the strong and weak features of the improved tool?
- RQ 4: Does the new system have added value compared to the original version?

To answer these research questions four participants were invited for a usability test. The participants were selected from students that participated in the repair course since knowledge of the original Hotspot Mapping and Disassembly Mapping tools is required.

8.1 Approach

To answer the research questions the participants, need to fill in the new tool. However, to fill in the tool they need to know the disassembly sequence and properties of a product. Therefore, the sessions were designed in the following manner. Since I want to evaluate the usability of the tool and not necessarily the learning process, I started the session by explaining how the tool is to be used and by giving the participants examples on how to fill in the tool. After the explanation, they could ask questions on how to use the tool.

After the tool introduction participants were asked to disassemble the Logitech MX Vertical. The disassembly itself was not part of the research and therefore I helped them with the disassembly where necessary. The disassembly process of each participant was video recorded to help them fill in the tool later. This video was not analysed.

When the participants finished the disassembly of the mouse, they could fill in the tool as previously instructed. This was followed by importing, generating, and adjusting the disassembly map in yEd Graph Editor. This stage of the process was captured through a screen recording accompanied by audio. This recording served as a valuable reference for later analysis, enabling easy identification of specific time frames during which participants made mistakes, accomplished noteworthy actions, or made important remarks.

To wrap up the session, the participants were asked to complete the same SUS questionnaire used for the original HSM and DM tools, which included open-ended questions. Additionally, an interview was conducted to gather their insights and experiences with the tool. During the interview, the following questions were asked, while leaving room for natural conversation to take place:

- In what way are the original tools better and why?
- In what way is the new system better and why?
- You might have noticed it takes more time to fill in the new system, is that worth it based on the results it provides? Why?
- What system (the original HSM and DM or the new version) do you prefer to use and why?

8.2 Results

The individual results of the system usability scale, open questionnaire questions and interviews can be found in Appendix F. The filled-in HSM and generated DM of the participants can be found in Appendix G. The most important findings are presented in this section.

System usability scale

To answer research question one, we compared the SUS score of the new system with the old method. The usability score of the new method is 68,13 with a standard deviation of 11,4 (n = 4). The original tools had a score of 50 with a standard deviation of 16,2 (n = 9). As can be seen in Figure 27 the new system has improved significantly. Where the old system only scored in the 15-percentile rank the new system is in the 50-percentile rank. This means the new system is now comparable to the average usability score of all systems.

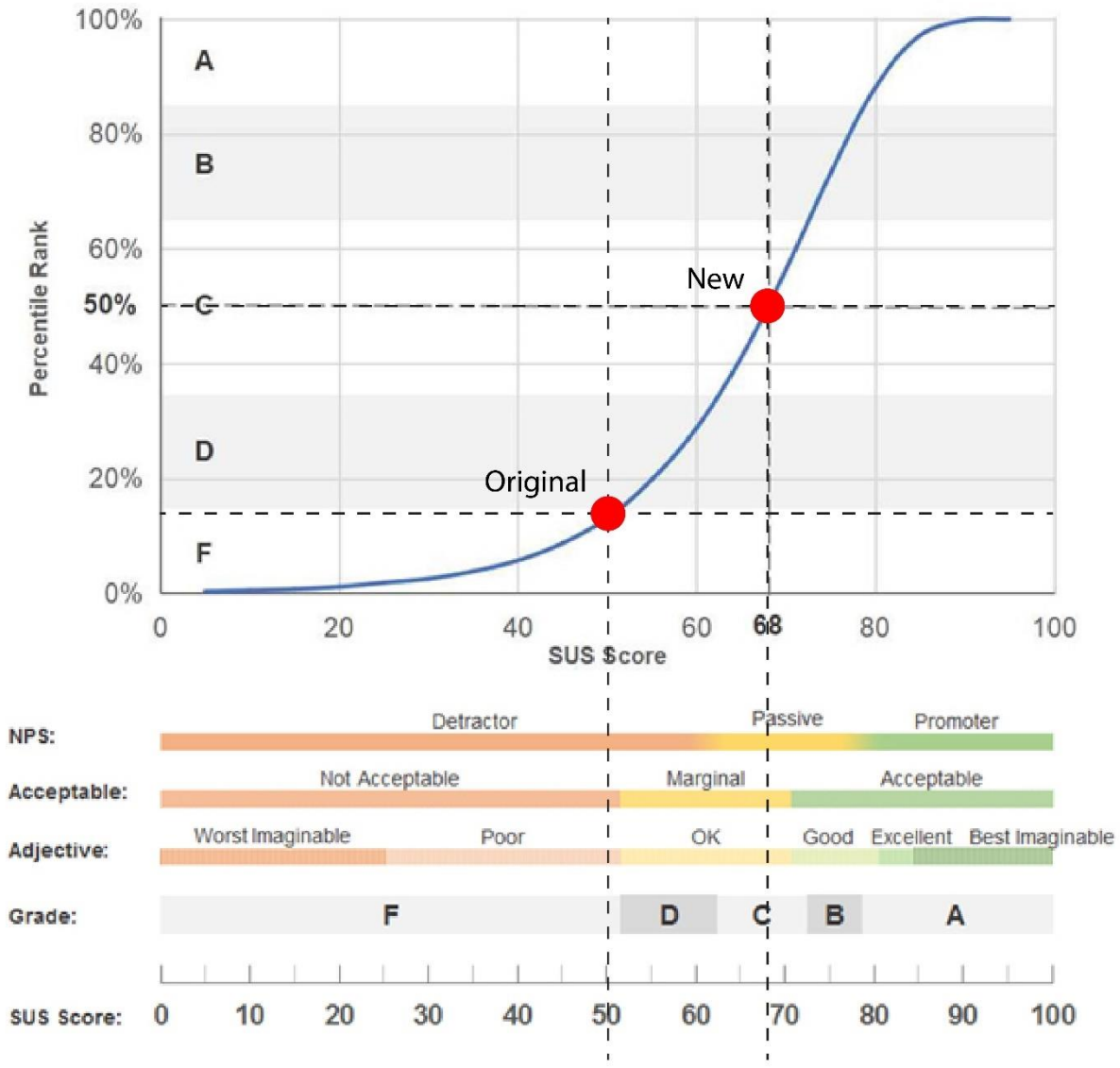


Figure 27 System usability scale interpretation and comparison

Questionnaire questions

Name one thing you liked about the adjusted Hotspot Mapping tool and why.
Participants liked the small popup explanations, the visual cues that help you keep track of parts used in the disassembly sequence, and the flexibility that was achieved because the order of the parts does not matter. They also liked that they could see the time it took to reach each part.

Name one thing you disliked about the adjusted Hotspot Mapping tool and why.
Most participants disliked the adjusted Hotspot Mapping tool because it still requires a lot of manual labour, data entry, and mental effort to fill in the disassembly table. They also struggled with the concept of how to use clusters and indicated they would prefer a more visual interface.

Name one thing you liked about the generated Disassembly Mapping and why.
The generated Disassembly Mapping was appreciated because of the automatic generation, saving them time, increasing consistency, and reducing errors. They also liked that the map gave a clear and simple overview while allowing them to change the input and filter the information in real time.

Name one thing you disliked about the generated Disassembly Mapping and why.
Participants found it difficult to be sure they filled in the tool correctly since they need to know exactly what the map should look like to check if it is correct. This also resulted in them not being sure if they generated a correct Disassembly Map. They also disliked that the map does not live update while filling in data and that the visual layout is not very appealing or suitable for presentation purposes.

Using the two tools in conjunction with each other, what worked well?
The increased integration between the Hotspot Mapping tool and Disassembly Map is appreciated by the participants. The fact that the Disassembly Map is now automatically generated significantly reduces time and effort. Furthermore, the separated parts and disassembly actions make the tool easier to fill in than the original. Moreover, after filling in all the parts in the BOM, parts were available in the disassembly sequence and were highlighted when not yet used. This helped the participants to create a complete Disassembly Map.

Using the two tools in conjunction with each other, what did not work?
Most participants found that using the two tools in conjunction with each other did not work well because they had to constantly think back or check the video for the sequence of parts, which was time-consuming and confusing. They also found that some parts did not pop up in the table when they typed them and disliked that they had to re-upload the Excel sheet if they made changes.

Interview

In what way are the original tools better and why?
From all the interviews there were a couple of points the participants preferred in the original tools. The original tool was described as simpler and more robust. Because there are fewer dependencies and automations, less can go wrong. Furthermore, multiple participants mentioned that they liked the visual representation of the original disassembly map better. Lastly, one participant mentioned that the flags in the original HSM tool were easier for the eye and made it clearer where to focus. However, this participant also mentioned that it lacked transparency because it was unclear what data was behind the flags.

In what way is the new system better and why?
The new version of the tool has its rules baked in, increasing consistency, removing human error, and reducing the time it takes to create a map. Unlike the original version, where parts had to be manually dragged and aligned. Furthermore, the information shown in the Disassembly Map can be limited and specific actions or parts can be highlighted. This makes it easier to use the map as argumentation and reduces the need to make different Disassembly Maps by hand. Creating the Disassembly Map following a row-based system also makes it more

systematic, whereas the original was sometimes perceived as chaotic, especially with many parts and complex interdependencies.

Next the order of entry of both the BOM and disassembly sequence does not matter, making it easier to fill in and correct. This solves the issue of needing to redo all your work if you find a mistake, as was previously the case. Furthermore, participants mentioned that the sorting (based on depth or priority) of both tables allowed them to get a better overview of the parts and disassembly activities.

Over the functionality of clusters, participants were divided, some found them intuitive to use while others found them hard to use and understand.

You might have noticed it takes more time to fill in the new system, is that worth it based on the results it provides? Why? The participants all agree that filling in the new tool takes more time when solely looking at the spreadsheet table. However, when also considering the automatically generated Disassembly Map, the new system saves time. Since all the data is transferred immediately and can be used in both. Furthermore, the MS Excel tool provides more relevant information than the original, such as disassembly depth.

What system (the original HSM and DM or the new version) do you prefer to use and why?
All participants prefer the new system over the old system. The most important reasons are time savings and a more intuitive interface. Suggestions and guidance such as instructional popups and parts colouring green help a lot in creating a complete disassembly sequence. The main reason the new system saves time is because there is no need any more to fill in the same information twice. Furthermore, participants notice the consistency between the improved HSM tool and generated Disassembly Map, since they now use the same naming conventions.

Experience using the tool
Besides the set interview questions, there are a couple of aspects participants mentioned during the interview about their experience using the tool. Even though, in total it takes less time to fill in the new system, it still requires a lot of data entry and mental effort. Specially creating the disassembly sequence was experienced as difficult for multiple participants. They mention that they need to keep a mental image of the target Disassembly Map in their head and require referencing the disassembly video a lot. A visual way of building the disassembly sequence is suggested by one of the participants. Lastly, multiple participants were doubting how to add the last two parts to a disassembly tree since both parts become free with one disassembly activity.

Interview takeaway
All participants preferred the new version of the Hotspot Mapping tool and Disassembly Map over the original one. They appreciated its flexibility, ease of use, efficiency, and ability to automatically generate a Disassembly Map with more information and features. However, they also acknowledged that it could take more time to fill in and that it can be challenging to check the connections between the parts. Some participants miss some of the colours and features of the original Disassembly Map. Overall, the new tool is seen as an optimized version of the original one that saves time in the long run and is more suitable for redesign purposes.

8.3 Conclusion

In conclusion, the user test conducted in this section aimed to answer four research questions regarding the usability and added value of the improved Hotspot Mapping and Disassembly Mapping tool. The four research questions were as follows:

- Has the usability increased compared to the original HSM and DM method?
- What are the strong and weak usability features of the improved tool?
- What are the strong and weak features of the improved tool?
- Does the new system bring added value compared to the original version?

Based on the findings from the user test, the usability of the improved HSM-DM tool has increased compared to the original method. The System usability scale (SUS) score for the new system showed an improvement from below-average usability to average usability compared to other systems. This indicates that participants found the improved tool to be more usable and user-friendly than the original version.

Regarding the strong usability features of the improved tool, participants appreciated the small popup explanations, visual cues to track used parts, and flexibility achieved through the order-independent nature of parts in the disassembly sequence. They also liked the ability to see the time taken to reach each part. On the other hand, the main weak usability feature mentioned by participants was the manual labour, data entry, and mental effort required to fill in the disassembly table. Some participants also struggled with understanding the concept of using clusters and expressed a preference for a more visual interface.

In terms of the generated Disassembly Mapping, participants liked the automatic generation, which saved time, increased consistency, and reduced errors. They also appreciated the clear and simple overview provided by the map, along with the ability to change inputs and filter information in real time. However, participants found it challenging to ensure they filled in the tool correctly and expressed a desire for a live-updating map during data entry. The visual layout of the generated map was also considered by some to be unappealing for presentation purposes.

The integration between the Hotspot Mapping tool and Disassembly Map was greatly appreciated. The automatic generation of the Disassembly Map significantly reduced the time and effort required to fill in the tools. Additionally, the separation of parts and disassembly actions made the tool easier to fill in compared to the original version. However, participants found it time-consuming and confusing to constantly consult the video for the sequence of disassembly steps. They also encountered issues with parts not appearing in the table when typing and expressed dissatisfaction with having to re-upload the Excel sheet to yEd after making changes.

Overall, participants expressed a preference for the new system over the original HSM and DM tools. The improved tool was considered more time-saving and intuitive, with features such as instructional popups and visual cues aiding in creating a complete disassembly sequence. The consistency between the improved HSM tool and the generated Disassembly Map, using the same naming conventions, was also noted. Despite the time required for data entry and mental effort, participants believed that the benefits provided by the new system, such as enhanced usability, efficiency, and relevant information, made it worthwhile.

8.4 Limitations

While the user test provided valuable insights into the usability and user perception of the improved Hotspot Mapping and Disassembly Mapping tool, several limitations should be considered:

Small sample size: The user test involved only four participants, which may not be representative of the broader user population. The findings from a small sample size might not capture the full range of perspectives and experiences that users with varying backgrounds and expertise may have.

Limited diversity: The participants in the user test were selected from students who had previously participated in a repair course (ID5422 at the TU Delft). This narrow pool of participants may not reflect the diverse range of potential users who could benefit from the tool. The findings might be influenced by the specific knowledge and skills possessed by the participants.

Personal connection bias: I have a personal connection with three out of the four participants. This familiarity varied in intensity among the participants. The presence of personal connections could have potentially influenced their behaviour and reactions during the study, consequently impacting the results.

Limited context: The user test focused on a specific product (Logitech MX Vertical) and its disassembly. The findings may be influenced by the characteristics of this product and may not be directly applicable to other products or contexts. The generalizability of the results to various products and industries should be approached with caution.

Lack of real-world conditions: The user test was conducted in a controlled environment, with participants given explicit instructions and guidance on how to use the tool. The absence of real-world constraints and pressures may have affected participants' perceptions and behaviours. The findings may not fully capture the challenges that users can encounter when applying the tool in actual design or repair scenarios, without being able to consult someone on the usage of the tool.

Potential learning effect: The user test started with an explanation of how to use the tool and provided participants with examples. While this was done to focus on the usability of the tool rather than the learning process, it is possible that participants' familiarity with the original Hotspot Mapping and Disassembly Mapping methods influenced their perceptions of the improved tool.

Subjectivity of feedback: The user test relied on participants' subjective feedback through questionnaires and interviews. The interpretation of their responses and reliability of their feedback may be influenced by individual biases, personal preferences, or an incomplete understanding of the tool's functionalities.

Time constraints: The user test might not have allowed participants sufficient time to fully explore and become proficient with the improved tool. The limited duration of the test sessions may have impacted participants' ability to uncover all usability strengths and weaknesses or fully grasp the tool's potential value.

Considering these limitations, it is important to interpret the findings of the user test with caution and recognize that further research and testing with a larger and more diverse user sample, in real-world conditions, and across various products and contexts would provide a more comprehensive understanding of the tool's usability and effectiveness.

9 Reflection on subjectivity

In this chapter, the subjectivity of the generated Disassembly Map is discussed and compared to the handmade Disassembly Map. First, the subjectivity that is inherently present due to the complex nature of product architectures is discussed. Then the visual differences between the handmade and generated Disassembly Maps are discussed. The subjectivity in the visual consistency of the representation of the product architecture is solved by the redesigned tool.

9.1 The subjectivity of product architecture interpretation

The new Disassembly Map is designed using the three logic principles: sequential dependence, sequential independence (parallel) and multiple dependencies explained in Section 3.2. Consequently, the new tool can effectively depict any disassembly architecture that the original method by Fazio and et al. (2021) can illustrate. However, it does not eliminate the inherent subjectivity present in the interpretation of the disassembly sequence itself. Products are often complex and have multiple disassembly paths (as per my personal experience).

For instance, to access the PCB of the Logitech MX Master 3s, one could describe two different disassembly procedures (Figure 28). The first approach involves removing the battery first, followed by the battery bracket, before accessing the PCB (left version). Alternatively, the battery and battery bracket could be removed as a unit, or cluster (right version). This decreases the disassembly depth of the PCB by more than 1.5 minutes while increasing the depth of the battery by just 12 seconds. Thus, while both disassembly sequences are possible, if the disassembler visualizes following the left example, there is a big difference between the actual disassembly time (269 seconds) and the visualized disassembly time (366 seconds) of the PCB.

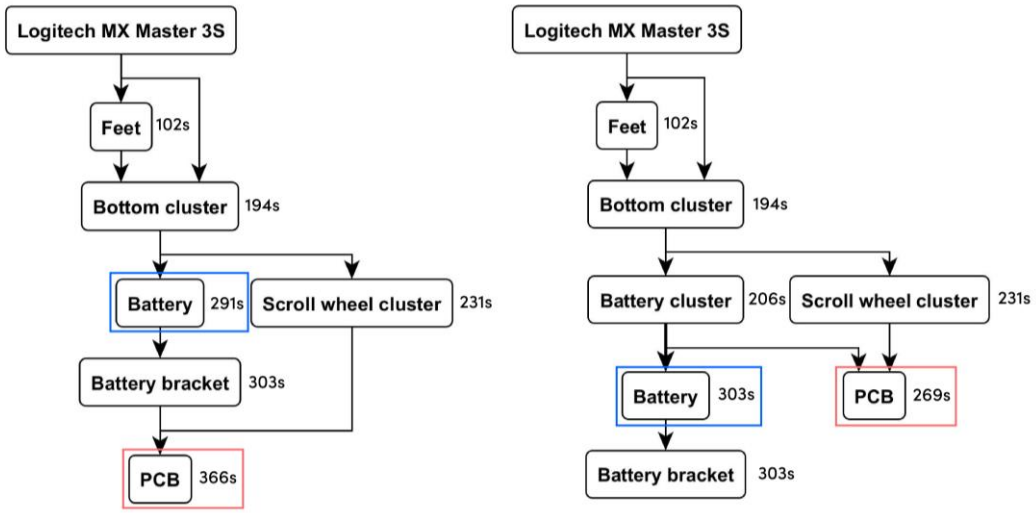


Figure 28 Two simplified alternative disassembly sequences of the Logitech MX Master 3s

The disassembler's interpretation of a product's disassembly can be affected by several factors, including their experience, the redesign objective, and even their personal preferences. A seasoned disassembler might examine all potential disassembly sequences, choosing one that best aligns with the redesign goal. In contrast, a novice disassembler might just document the product architecture based on how the initial disassembly unfolded.

The challenge with this subjectivity lies in quantifying the impact of choices made during disassembly, particularly when alternative sequences become more intricate than the simple example provided in Figure 28. Both disassembly sequences are possible when disassembling the product, but in the Disassembly Map, one version has to be selected, potentially leading to suboptimal results. If decisions are then based on these suboptimal results, the subsequent redesign might not yield the desired outcome.

Unless the tool is designed to accommodate multiple alternative disassembly sequences, it is impossible to completely avoid this subjectivity inherent in product architectures. While including multiple alternative disassembly sequences in the tool would enhance its objectivity, it would significantly complicate the process of input and analysis as components would have multiple disassembly depths. Furthermore, it would still be dependent on the disassembler being able to find every possible disassembly path available.

9.2 Visual differences

Approach

To illustrate the visual differences a handmade Disassembly Map was compared to a generated Disassembly Map. The handmade Disassembly Map was made by Klop and van den Boogaart (2023) (see Figure 30) for the course ID5422 Repair! in 2022/2023 at the TU Delft. They disassembled the Kinzo Table Fan shown in

Figure 29. I compared their Disassembly Map against one I created for the same product using the improved tool as depicted in Figure 31.



Figure 29 Knolled image Kinzo Table Fan by Klop and van den Boogaart (2023)

Differences

- The original Disassembly Map shows parts as part numbers, while the generated Disassembly Map can either show part numbers or show part names.
- The disassembly activity sequence is shown differently in the generated DM since multiple actions are not shown in order or sequentially compared to the original DM. To indicate a specific order of disassembly activities within the generated Disassembly Map, the activities must be dragged on top of each other manually.
- In the original, disassembly clusters are indicated by showing the different part numbers. In the new Disassembly Map, clusters receive their own name or can be visualised the same as the original by showing the individual part numbers (as shown in Figure 32).
- Highlighting of priority parts, environmental impact, or economic value is done on a linear scale in the generated Disassembly Map, compared to hotspot icons in the original Disassembly Map. The colour scale helps designers see the significance of the distinct parts compared to each other, instead of a binary visualisation of the hotspots.
- The penalty icons, motion-type shapes and colours that are shown in the original Disassembly Map are not present in the generated version. However, the four different penalties and the force intensity are considered in the highlighting of the disassembly activities. The new Disassembly Map misses the motion type information.
- A general difference is that spacing is consistent and the disassembly depth is always going down, while in the original Disassembly Map, this must be done by the disassembler. In the case of the manual DM of the Kinzo Table Fan, the disassembler sometimes chose to use arrows pointing up again, making the disassembly depth of parts hard to determine.
- The disassembly depth can be more accurately displayed in the generated Disassembly Map by scaling the highlight colour to the time it takes to reach each part, in addition to disassembly activity durations (See Figure 33).
- The original Disassembly Map shows all its information at once. This is not possible in the generated Disassembly Map. The generated Disassembly Map only shows for example priority parts, environmental impact, or economic impact.
- Visually the two versions are quite different, where the original tool makes use of different colours and shapes the redesigned version uses only two colours, red for highlighting parts and orange for highlighting disassembly activities.

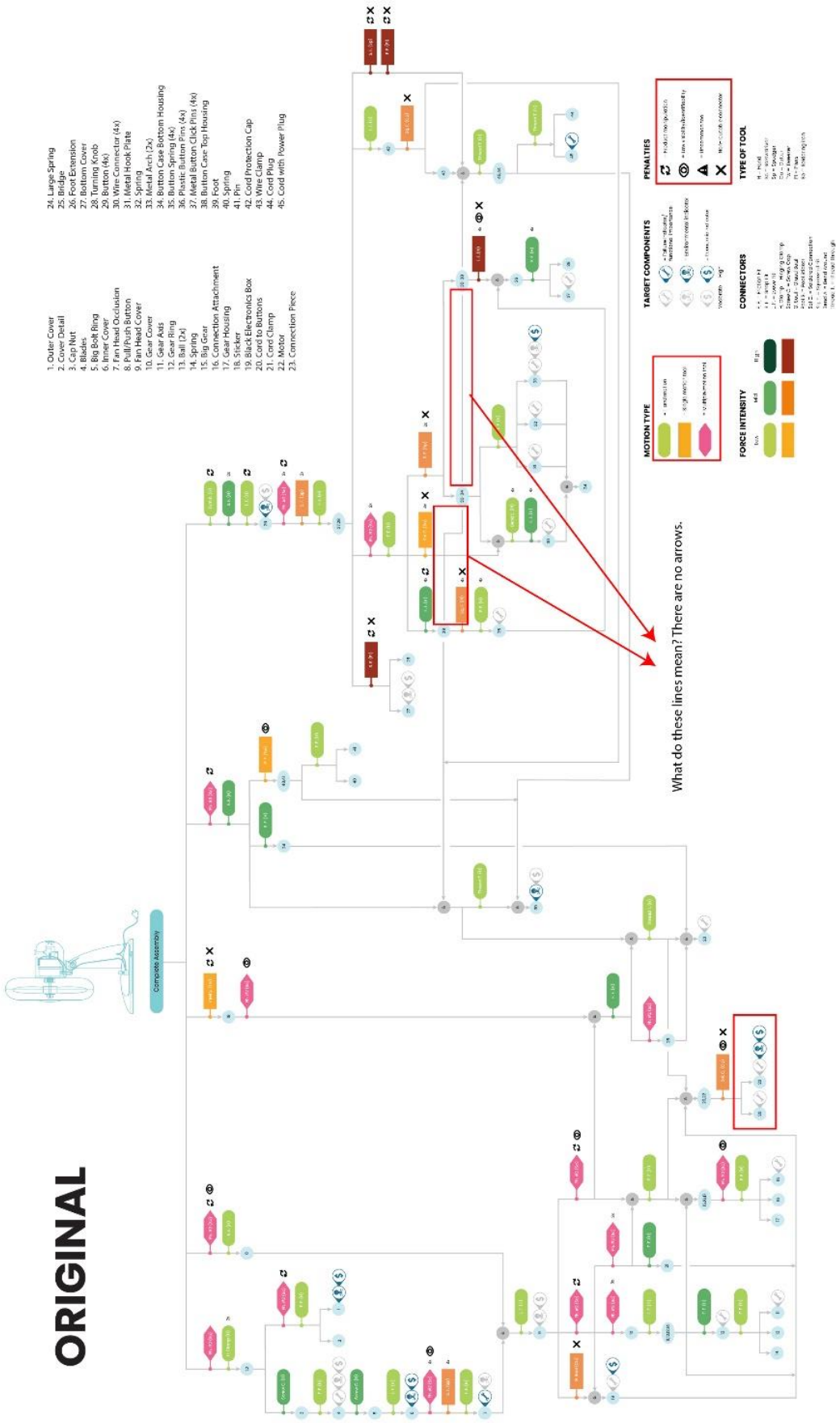


Figure 30 Handmade DM by Klop and van den Boogaart (2023) of Kinzo Table Fan

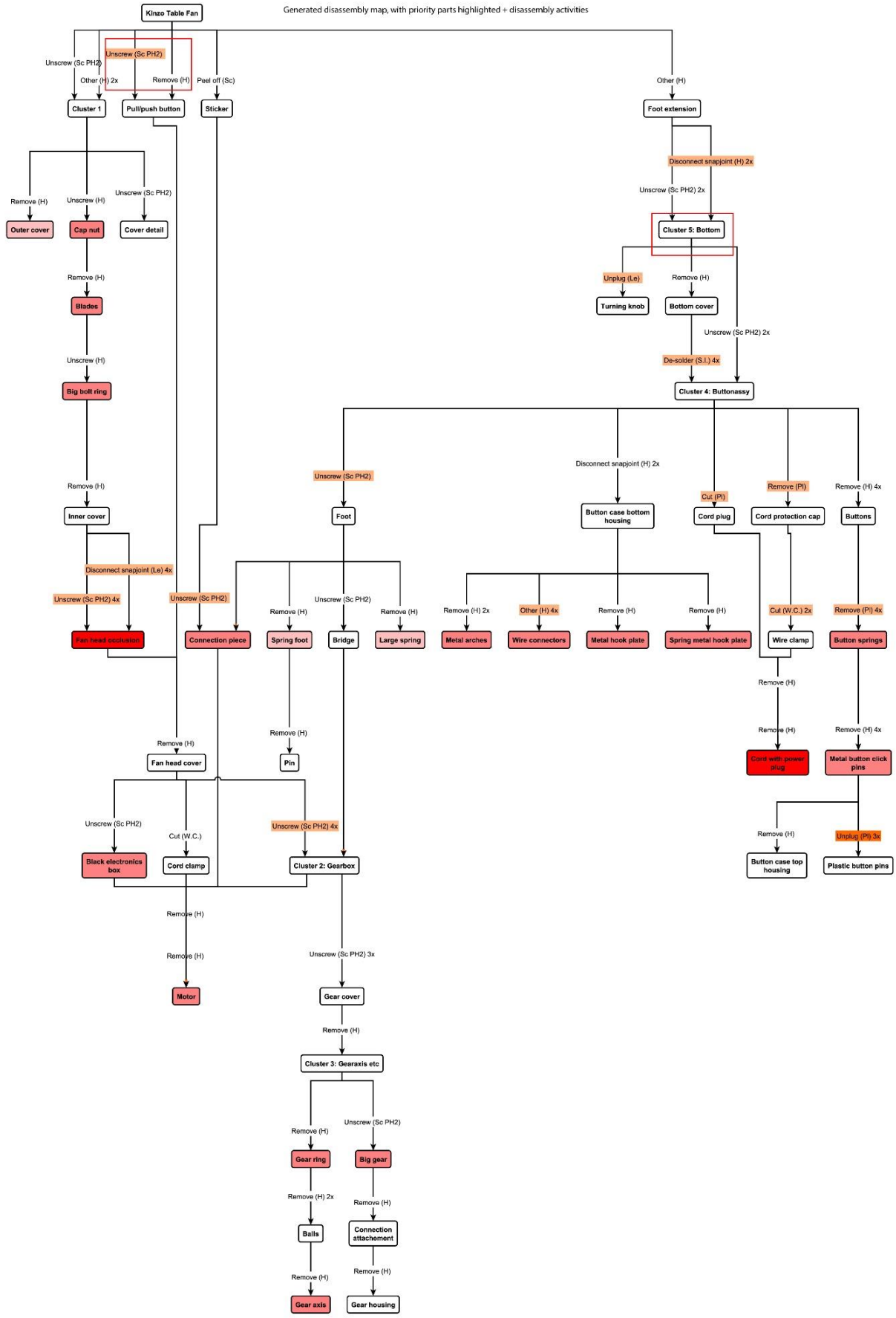


Figure 31 Generated DM of Kinzo Table Fan

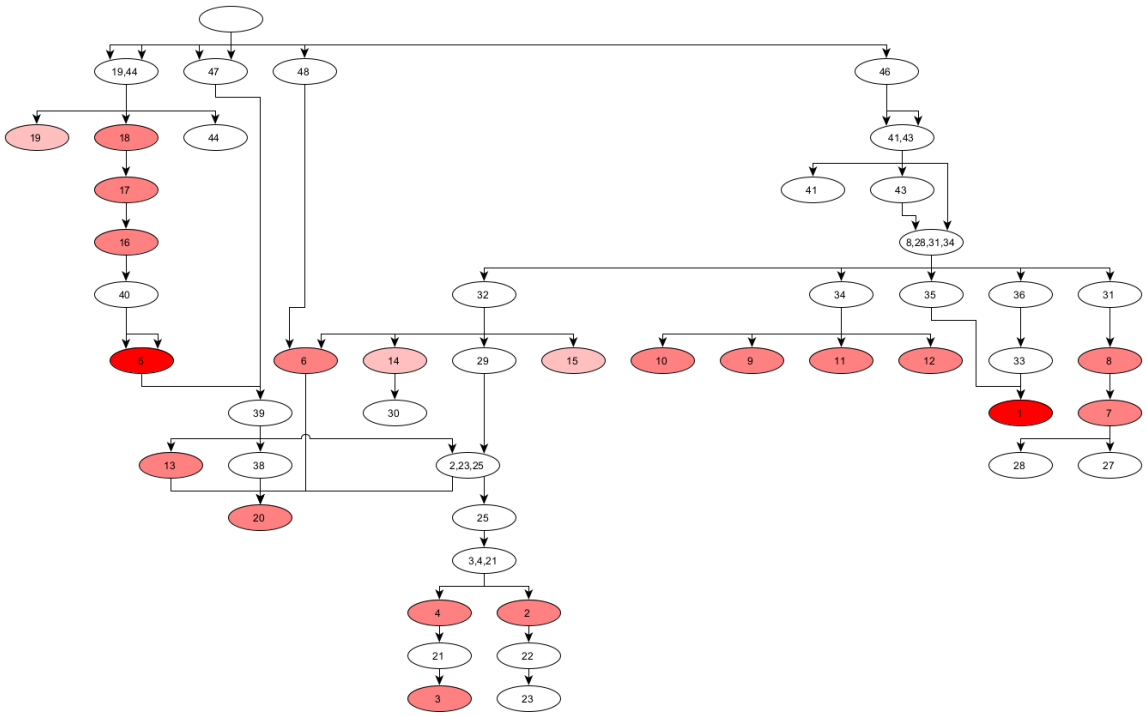


Figure 32 DM Kinzo Table Fan with part numbers instead of names highlighting priority parts.

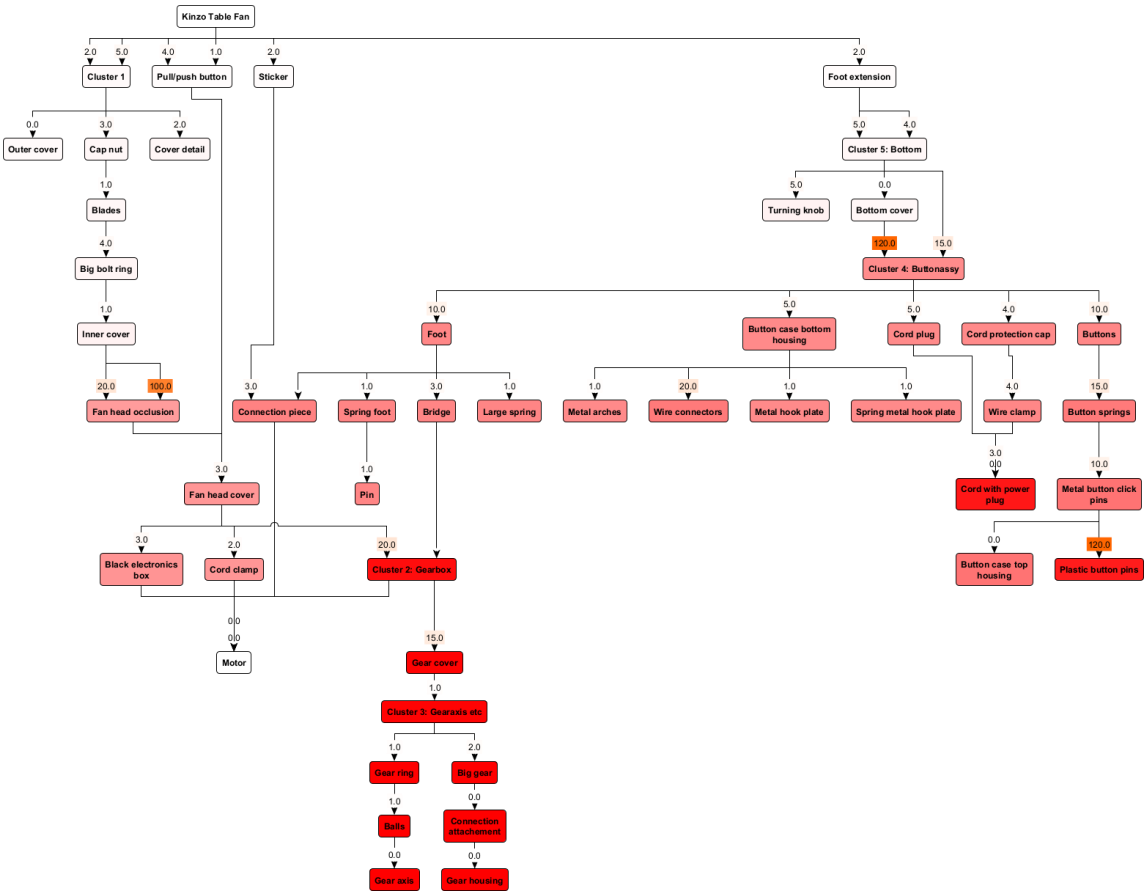


Figure 33 DM Kinzo Table Fan Highlighting disassembly depth and activity duration.

9.3 Conclusion

This chapter delved into the subjectivity of Disassembly Mapping and examined the visual differences between a handmade Disassembly Map and a generated one. The inherent subjectivity in interpreting product architectures was explored, and it was acknowledged that even with a well-designed tool based on logical principles, subjectivity cannot be eliminated. Products often have multiple disassembly paths, and the disassembler's experience, objectives, and preferences can influence the chosen sequence. While it may be possible to accommodate multiple alternative disassembly sequences in the tool to enhance objectivity, doing so would significantly complicate the input and analysis process and still not be completely objective.

The generated disassembly map enhances the objectivity in visualizing the spacing of the nodes and the direction of the disassembly activities. In the original DM, the consistency of the disassembler influenced this visualization. However, in the generated DM, the layout algorithm uniformly maintains this visualization.

Overall, the chapter highlighted the complexities of subjectivity in Disassembly Mapping and the benefits and limitations of the redesigned tool regarding the visual product architecture. As Disassembly Mapping continues to play a crucial role in product analysis and redesign, further research and improvements are required to address subjectivity concerns and enhance the objectivity of generated Disassembly Maps.

9.4 Limitations

The interpretation of the visual differences between the two Disassembly Maps is constrained by several limitations, particularly since the comparison hinges on product architectures (one made by Klop and van den Boogaart (2023), and the other by myself), which are inherently subjective by nature. The translations to a Disassembly Map are influenced by individual preferences, knowledge, and expertise, factors that could introduce bias into the resulting map. This bias may have influenced the comparison with the generated map, thereby affecting the conclusions reached. Moreover, it must be recognized that evaluating the Disassembly Maps is an exercise in subjective judgment and interpretation. Different evaluators might perceive and interpret the maps differently, leading to potential variations in the observed differences.

10 Case study: Redesign of the Logitech MX Master 3s



Figure 34 Logitech MX Master 3s

This chapter introduces the improved method through a case study focusing on the Logitech MX Master 3s (Figure 34). The Logitech MX Master 3s is a high-end wireless mouse known for its ergonomic design and productivity features, including silent operation and customizable options. One of its notable features is the MagSpeed electromagnetic scroll wheel, enabling users to switch between ratcheted and smooth scrolling. The mouse also boasts multiple programmable buttons, allowing users to tailor their experience to their preferences. The mouse is predominantly constructed from plastics, which (depending on the colour) is 22 to 27 per cent sourced from certified post-consumer recycled materials (Logitech, 2022).

Following the completion of the tool based on this mouse, the results of the method will be analysed and interpreted to develop and propose an improved design for the mouse. The primary objective of this redesign is to enhance the product's repairability and reduce its environmental impact. Emphasis will be placed on simplifying the disassembly process and enhancing access to essential parts. It is important to mention that the redesign will not encompass modifications to the mouse's visual aspects or features, as these are beyond the scope of this study. Additionally, the proposed design enhancements represent just a few suggestions to boost reparability. Numerous other solutions can yield comparable benefits.

10.1 Product selection

The Logitech MX Master 3s was selected since it has been redesigned already multiple times. Before the Master 3s, there were the Logitech MX Master, Master 2, Master 2s and Master 3. By redesigning a product that has been redesigned before, I can show that even at that point the tool will indicate points for improvements. The tool does not diagnose if a product is repairable or easy to disassemble, that is up to the designer to interpret.

10.2 Disassembly



Figure 35 Logitech MX Master 3s bottom(L) and top(R) clusters.



Figure 36 Logitech MX Master 3s disassembled.

The gentle disassembly starts with removing the stickers/feet the mouse slides on and removing the one and only Torx screw holding the USB-C port in place. These stickers block the five screws holding the mouse together. After removing the screws there are still a couple of snap fits which make it difficult to split the product into two clusters. When the connection cable is also unplugged, the mouse can be separated into two clusters of components as visualised in Figure 35.

From this point in the disassembly, a lot of parts become available for removal. They are generally easy to remove with just a few screws. Two disassembly activities take more effort. First, the removal of the battery since it is glued firmly in place. Secondly, removing the side cluster with the scroll wheel and side buttons, as they are held into the housing quite well by snap fits. The mouse consists of 26 parts as can be seen in Figure 36.

In general, the mouse is held together by a lot of snap fits and 40 screws, which are often used in redundancy with each other.

10.3 Hotspot Map & Disassembly Map

In this section, the results from the HSM and generated DM are analysed and interpreted for possible improvements to the product.

Dashboard

There are a couple of points that stand out from the dashboard in Figure 37. First, the high number of screws (40 screws) that are in a single mouse. It is a complex mouse, but several screws could be discarded using other connections, such as snap fits or even magnetic connections. Only two types of screws are used which is a good thing, however, there is only one Torx screw. Changing this would reduce the amount of tool switching during the disassembly. The last thing is the amount of impact of the PCBs, while they only account for about 15% of the weight of the product they produce more than 80% of the impact.

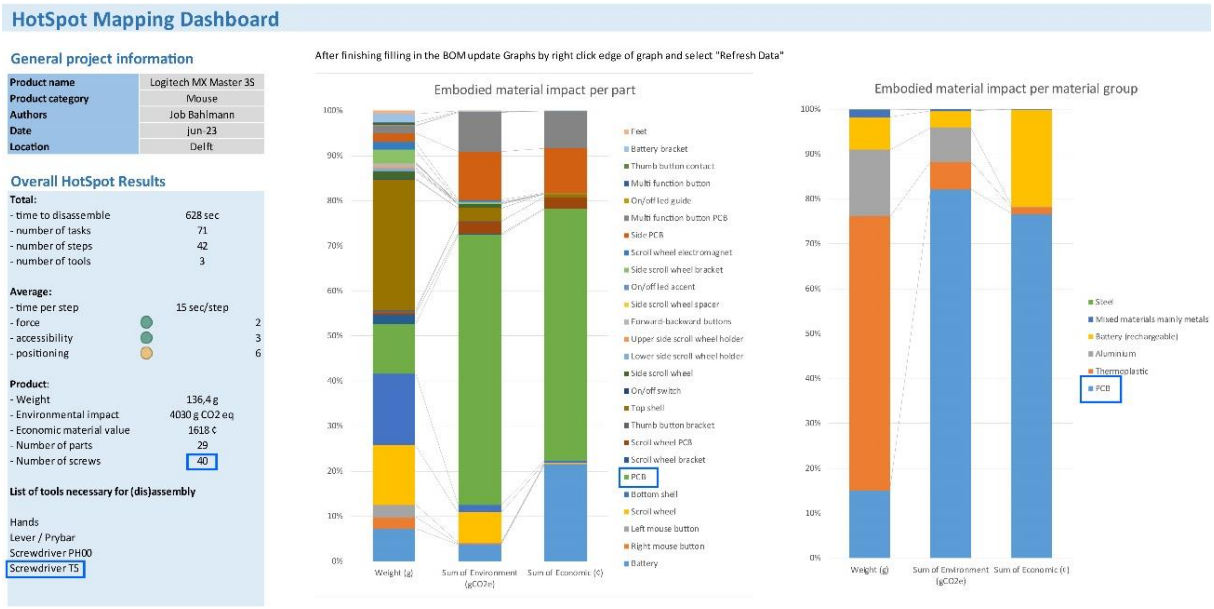


Figure 37 Hotspot Mapping dashboard

Bill of materials

The BOM (Figure 38) is sorted based on the repair focus rank. The components high in the list are the components that have a combination of high functional relevance, are likely to need replacement due to failure or wear and are buried in the product architecture.

In the redesign, I will focus on the following components (highlighted in Figure 38 and Figure 39).

Battery: The battery is critical for the products functioning, but over time, batteries tend to deteriorate and may require replacement. Unfortunately, it is currently firmly glued in place, which makes it challenging to replace. The battery also contributes to approximately 20% of the product's material value. Moreover, considering its chemical nature, proper recycling becomes imperative at the end of its life cycle, highlighting the importance of ensuring easy accessibility to the battery.

PCBs: Both the PCB and Side PCB are required for the product to function, have some chance of failure and are deep in the disassembly sequence. The mouse switches on the main PCB have a high chance of failure during the mouse's functional lifetime (according to a mouse and keyboard expert with in-depth disassembly experiences, personal communication, 01/08/2023). Furthermore, PCBs have a high environmental impact due to the different metals and components that are soldered on. Thus, for both repairability and recycling, they should be designed in a manner that ensures easy accessibility.

PartID	Part/Cluster	Is a cluster?	Part of cluster...	Amount	Failure likelihood	Functional relevance	Materialgroup	Total weight (g)	Disassembly depth (s)	Disassembly effort	Priority	Environment (gCO2e)	Economic (€)	nr of parts to remove	Circular focus rank	Repair f
1	Battery		Bottom cluster	1	level 2	level 2	Battery (rechargeable)	10,0 g	291	22	4	149,3	348	2	2	1
2	PCB		Bottom cluster	1	level 1	level 2	PCB	15,1 g	366	31	2	2414,4	905	5	1	2
3	Side PCB		Side cluster	1	level 1	level 2	PCB	2,7 g	327	33	2	432,0	162	8	3	3
4	Scroll wheel		Scroll wheel cl	1	level 1	level 2	Aluminium	18,0 g	254	25	2	269,4	4	5	5	4
5	Scroll wheel electromagnet		Scroll wheel cl	1	level 1	level 2	Mixed materials mainly metals	2,3 g	254	25	2	16,1	1	4	7	4
6	Scroll wheel PCB		Scroll wheel cl	1	level 1	level 2	PCB	0,7 g	236	22	2	110,4	41	3	7	6
7	Multi function button PCB			1	level 1	level 2	PCB	2,2 g	221	21	2	353,6	133	2	5	7
8	Lower side scroll wheel holder		Side cluster	1	level 1	level 1	Thermoplastic	0,6 g	283	26	1	1,7	0	5	11	8
9	Side scroll wheel		Side cluster	1	level 1	level 1	Aluminium	2,3 g	268	25	1	34,5	0	5	14	9
10	Upper side scroll wheel holder		Side cluster	1	level 1	level 1	Thermoplastic	0,5 g	268	25	1	1,5	0	4	14	9
11	Feet			4	level 1	level 2	Thermoplastic	0,8 g	102	4	2	2,5	0	0	28	11
12	Top shell			1	level 0	level 1	Thermoplastic	39,5 g	356	48	0	118,4	12	10	4	12
13	On/off led accent			1	level 0	level 1	Thermoplastic	0,2 g	299	34	0	0,6	0	6	13	12
14	Side scroll wheel bracket		Side cluster	1	level 0	level 1	Thermoplastic	3,9 g	327	33	0	11,7	1	9	11	12
15	Bottom shell			1	level 0	level 1	Thermoplastic	21,7 g	366	31	0	65,2	7	7	7	12
16	On/off switch		Bottom cluster	1	level 0	level 0	Thermoplastic	0,3 g	366	31	0	0,9	0	6	10	12
17	Side scroll wheel spacer		Side cluster	1	level 0	level 1	Thermoplastic	0,2 g	301	29	0	0,7	0	6	16	12
18	On/off led guide			1	level 0	level 1	Thermoplastic	0,3 g	276	28	0	0,8	0	5	17	12
19	Left mouse button			1	level 0	level 1	Thermoplastic	3,7 g	268	26	0	11,1	1	4	19	12
20	Forward-backward buttons		Side cluster	1	level 0	level 1	Thermoplastic	1,0 g	272	26	0	3,0	0	4	19	12
21	Scroll wheel bracket			1	level 0	level 1	Thermoplastic	2,8 g	251	25	0	8,5	1	3	21	12
22	Multi function button			1	level 0	level 1	Thermoplastic	0,8 g	229	24	0	2,5	0	3	23	12
23	Side cluster	Yes							260	24	0	0,0	0	3	21	12
24	Battery bracket		Bottom cluster	1	level 0	level 1	Thermoplastic	2,6 g	303	23	0	7,7	1	3	17	12
25	Scroll wheel cluster	Yes							231	21	0	0,0	0	2	24	12
26	Right mouse button			1	level 0	level 1	Thermoplastic	3,5 g	216	20	0	10,5	1	2	25	12
27	Thumb button contact			1	level 0	level 1	Steel	0,1 g	221	17	0	0,2	0	3	26	12
28	Thumb button bracket			1	level 0	level 1	Thermoplastic	0,8 g	216	16	0	2,3	0	2	27	12
29	Bottom cluster	Yes							194	15	0	0,0	0	1	29	12

Figure 38 BOM table of Logitech MX Master 3s.

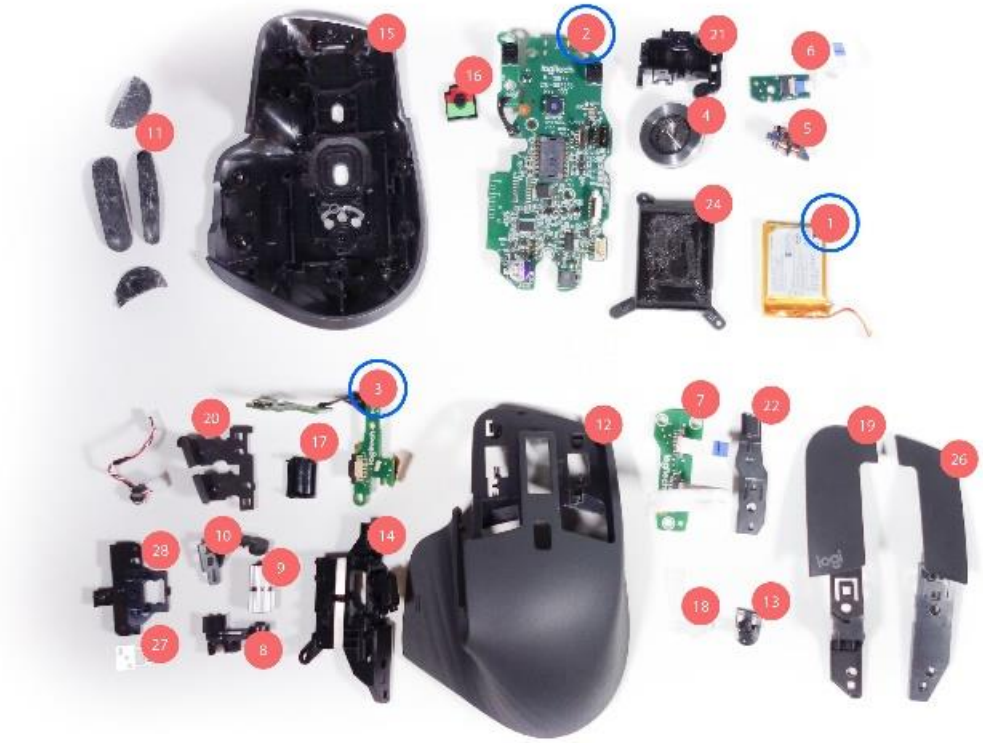


Figure 39 Knolled image of disassembled Logitech MX Master 3s highlighting the battery, main PCB, and side PCB.

Disassembly actions

The disassembly actions table in Figure 40 is sorted based on disassembly time per activity. This results in the activities that have the highest need for a redesign to be on the top. Removing the feet takes both a lot of time and precision and the glue connection cannot be reused. This means that for any repair to happen a user is forced to replace the feet since they give access to the rest of the disassembly. As described in the disassembly, the battery is also glued into place, making replacement unnecessarily difficult.

Lastly, to remove the bottom cluster after removing the feet, it is required to both unscrew 6 screws (of which one is a Torx T5) and unclip the snap joints. Added together it takes almost 3 minutes to remove the bottom cluster, giving access to the rest of the components.

Note: The properties in the rows at the bottom of Figure 40 are left empty, as they are dependencies. This means no disassembly activity is required, however, without removing the previous part it is not possible to remove the next part.

DisassemblyID	Previous step	Next step	Removal activity	Required tool	Tool size	Fastener reusable?	Task frequency	Total time (s)	Force	Accessibility	Positioning	Time	Activity
1	Logitech MX Master 3S	Feet	Peel off	Lever / Prybar		No	4	102	level 1	level 1	level 2	102	4
2	Bottom cluster	Battery	De-glue	Lever / Prybar		No	1	90	level 2	level 0	level 1	90	3
3	Feet	Bottom cluster	Unscrew	Screwc	PH00	Yes	5	60	level 0	level 1	level 2	60	3
4	Thumb button bracket	Side cluster	Disconnect sna	Hands		Yes	4	30	level 1	level 2	level 2	30	5
5	Scroll wheel cluster	PCB	Unscrew	Screwc	PH00	Yes	5	26	level 0	level 1	level 1	26	2
6	Bottom cluster	Multi function button PCB	Unscrew	Screwc	PH00	Yes	3	22	level 0	level 1	level 2	22	3
7	Bottom cluster	Thumb button bracket	Unscrew	Screwc	PH00	Yes	5	22	level 0	level 0	level 1	22	1
8	Bottom cluster	Scroll wheel cluster	Unplug	Hands		Yes	2	20	level 1	level 1	level 2	20	4
9	Scroll wheel cluster	Scroll wheel bracket	Disconnect sna	Lever / Prybar		Yes	3	20	level 1	level 1	level 2	20	4
10	Feet	Bottom cluster	Disconnect sna	Hands		Yes	5	20	level 1	level 1	level 2	20	4
11	Lower side scroll wheel hol	Side scroll wheel spacer	Disconnect sna	Lever / Prybar		Yes	3	18	level 0	level 1	level 2	18	3
12	Bottom cluster	Scroll wheel cluster	Unscrew	Screwc	PH00	Yes	2	17	level 0	level 1	level 1	17	2
13	On/off led guide	On/off led accent	Disconnect sna	Lever / Prybar		Yes	2	15	level 0	level 2	level 2	15	4
14	Upper side scroll wheel hol	Lower side scroll wheel hol	Unscrew	Screwc	PH00	Yes	2	15	level 0	level 0	level 1	15	1
15	Thumb button bracket	Side cluster	Unscrew	Screwc	PH00	Yes	2	14	level 0	level 1	level 2	14	3
16	Bottom cluster	Right mouse button	Unscrew	Screwc	PH00	Yes	2	14	level 0	level 1	level 2	14	3
17	Forward-backward buttons	Side PCB	Unscrew	Screwc	PH00	Yes	2	14	level 0	level 1	level 1	14	2
18	Side cluster	Forward-backward buttons	Unscrew	Screwc	PH00	Yes	2	12	level 0	level 1	level 1	12	2
19	Battery	Battery bracket	Unscrew	Screwc	PH00	Yes	2	12	level 0	level 0	level 1	12	1
20	Multi function button PCB	Multi function button	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 2	8	3
21	Bottom cluster	Right mouse button	Disconnect sna	Hands		Yes	2	8	level 0	level 1	level 1	8	2
22	Side cluster	Left mouse button	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 1	8	2
23	Left mouse button	On/off led guide	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 1	8	2
24	On/off led guide	On/off led accent	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 1	8	2
25	Side cluster	Upper side scroll wheel hol	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 0	level 1	8	1
26	Bottom cluster	Battery	Unplug	Hands		Yes	1	7	level 1	level 1	level 2	7	4
27	Logitech MX Master 3S	Bottom cluster	Unscrew	Screwc	T5	Yes	1	7	level 0	level 0	level 1	7	1
28	Feet	Bottom cluster	Unplug	Hands		Yes	1	5	level 0	level 1	level 2	5	3
29	Bottom cluster	Multi function button PCB	Unplug	Lever / Prybar		Yes	1	5	level 0	level 1	level 2	5	3
30	Scroll wheel cluster	Scroll wheel PCB	Unscrew	Screwc	PH00	Yes	1	5	level 0	level 0	level 1	5	1
31	Thumb button bracket	Thumb button contact	Unscrew	Screwc	PH00	Yes	1	5	level 0	level 0	level 1	5	1
32	Scroll wheel bracket	Scroll wheel electromagne	Remove	Hands		Yes	1	3	level 0	level 0	level 0	3	0
33	Battery bracket	PCB										0	0
34	PCB	On/off switch	Remove	Hands		Yes	1	0	level 0	level 0	level 0	0	0
35	On/off switch	Bottom shell										0	0
36	Scroll wheel electromagne	Scroll wheel										0	0
37	On/off led accent	Top shell										0	0
38	Multi function button	Top shell										0	0
39	Right mouse button	Top shell										0	0
40	Upper side scroll wheel hol	Side scroll wheel										0	0
41	Side scroll wheel spacer	Side PCB										0	0
42	Side PCB	Side scroll wheel bracket										0	0

Figure 40 Disassembly activities table Logitech MX Master 3s.

Disassembly Map

The Disassembly Maps in Figure 41 and Figure 42 show the product architecture with the priority parts and disassembly activities. From Figure 42 it is clear to see that peeling off the feet and unscrewing the first screws have an impact on the entire disassembly sequence that follows. Bypassing these activities would greatly reduce the disassembly time required to reach every part underneath it, including the priority parts. Furthermore, the map in Figure 41 shows that the placement of parts in the map is not representative of the disassembly depth, since the PCB takes 346 seconds to reach and the Side PCB only 307, while it is placed lower in the tree. Therefore Figure 42 gives a better visual representation of the disassembly depth by using a colour scale.

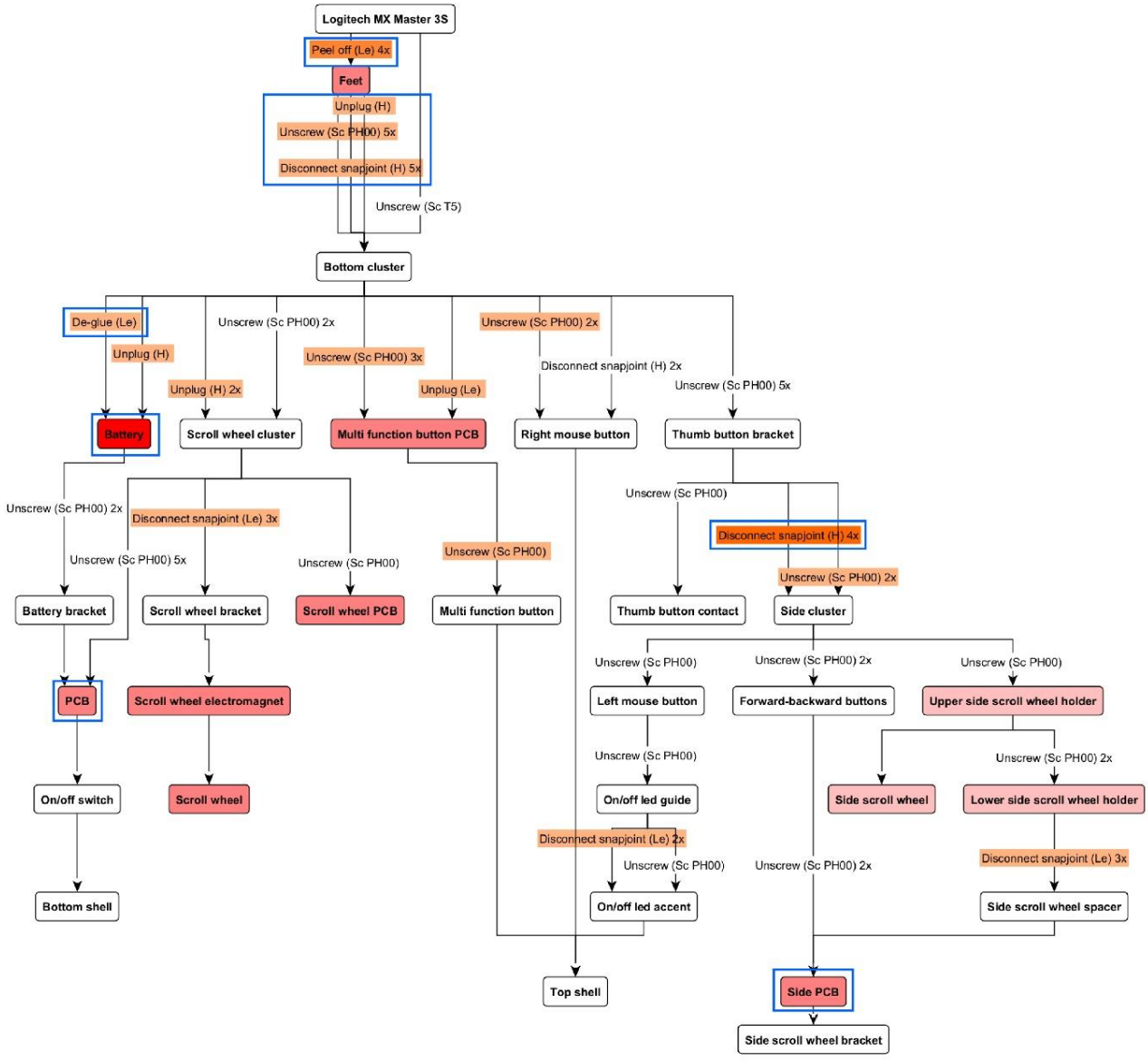


Figure 41 DM Logitech MX Master 3s highlighting priority parts and disassembly activities.

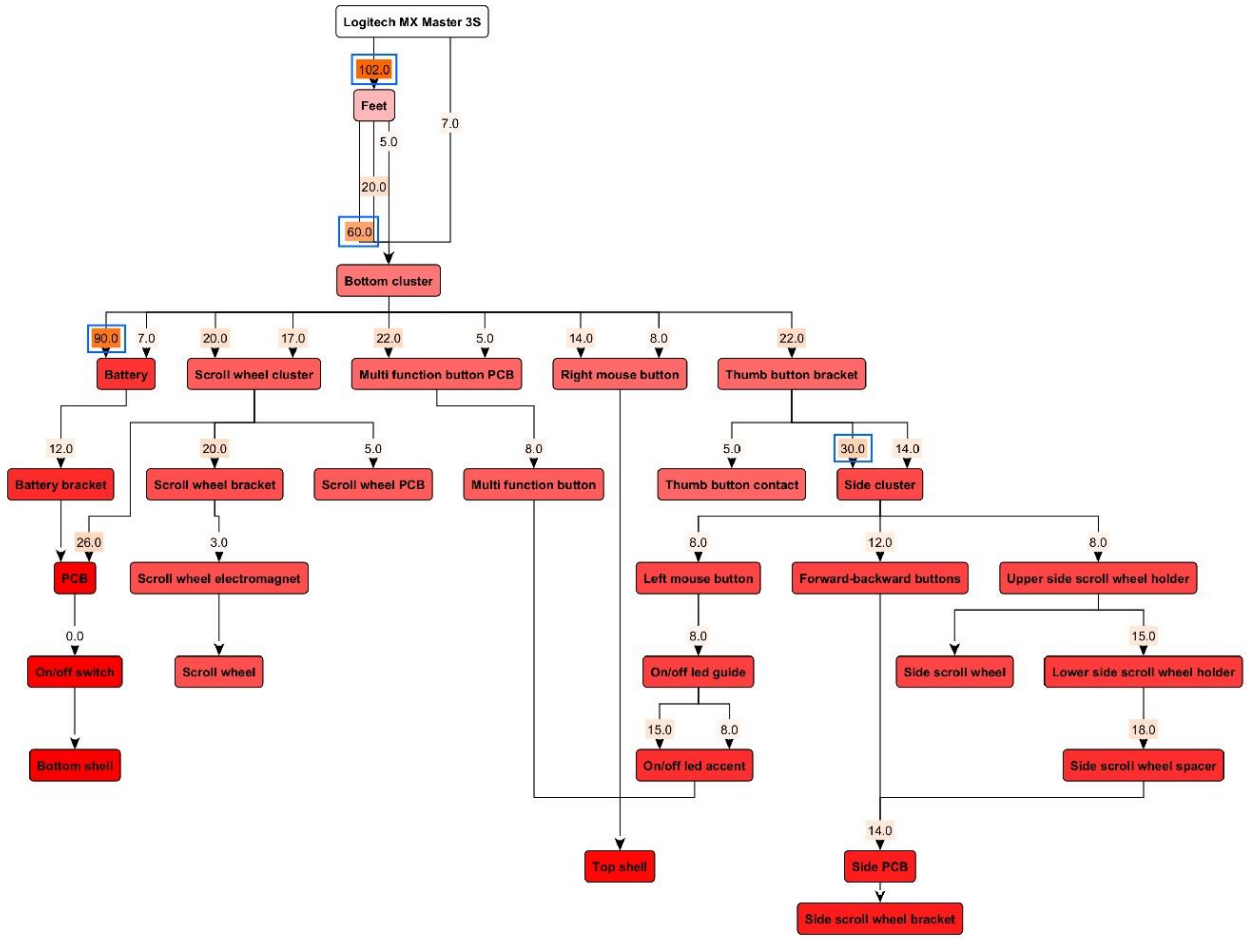


Figure 42 DM Logitech MX Master 3s focused on disassembly depth and activity durations.

10.4 Redesign

To come up with redesign ideas, I considered the aspects that stood out from the previous section and used the three techniques described by Flipsen (2020) to address them. The techniques are shortly explained hereafter. Furthermore, feedback from a mouse and keyboard expert with in-depth disassembly experiences was used to improve the design even further.

Surfacing: This technique involves relocating critical parts to the top of the Disassembly Map, reducing the number of steps required to access them. By evaluating the consequences of the redesign using a disassembly tree, it is possible to identify which critical parts can be placed closer to the top. In the case of the MX Master, I can focus on trying to get the three selected priority parts higher in the disassembly tree.

Clumping: Clumping involves grouping parts to form subassemblies/clusters that can be easily removed before accessing the critical part. The goal is to remove the cluster, freeing up the critical component of the sequential disassembly process. The critical component can both be part of the cluster itself or the next accessible part after the removal of the cluster.

Trimming: Trimming focuses on reducing the number of activities and time required to access critical parts. It involves rethinking the use of fasteners and replacing time-consuming and irreversible fastening techniques with reversible fasteners. By using none or common tools, the disassembly process becomes faster and more efficient. A perfect example for this regarding the mouse would be to replace the one Torx screw with a Phillips screw and reduce the number of duplicate connection techniques.

Overall, these techniques aim to enhance the ease of disassembly by strategically rearranging critical parts, grouping components, and optimizing fastening methods.

Increasing product accessibility

To enhance overall accessibility, the two disassembly activities that hinder the opening of the mouse must be redesigned. Figure 43 displays the locations of the screws, with five of the six screws concealed by the feet (as visible on the left side). Figure 44 highlights the positions of the snap fits, which complicate the user's reassembly of the product. The precise alignment required by these snap fits makes the process challenging, as it demands a high degree of accuracy.



Figure 43 Bottom shell MX Master 3s highlighting screw locations.

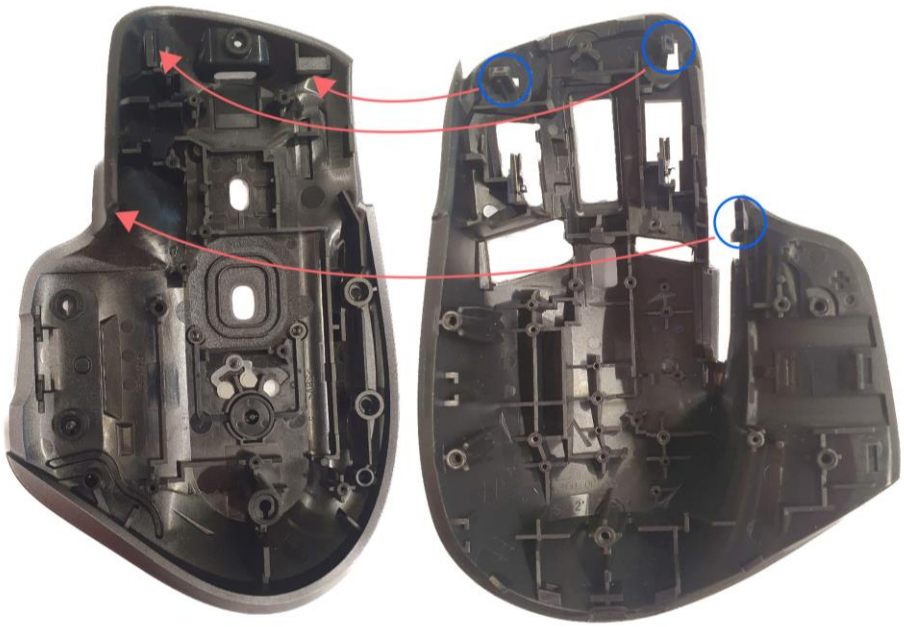


Figure 44 Bottom and Top shell MX Master 3s highlighting snap fits.

To address both these concerns, the snap fits are removed, and the screws are repositioned to be in visible locations rather than hidden underneath the feet. This alteration enhances accessibility and promotes the repairability of the product to the user. Several criteria must be met for the new screw placements. They must be easily visible, not conflict with existing components, and there must be sufficient space for the screws to fasten into the top shell. The Torx T5 screw depicted at the top of Figure 43 is substituted with a Phillips head screw. Two new screw locations are introduced just below the feet, as illustrated in Figure 45, all other screws are removed from the design.

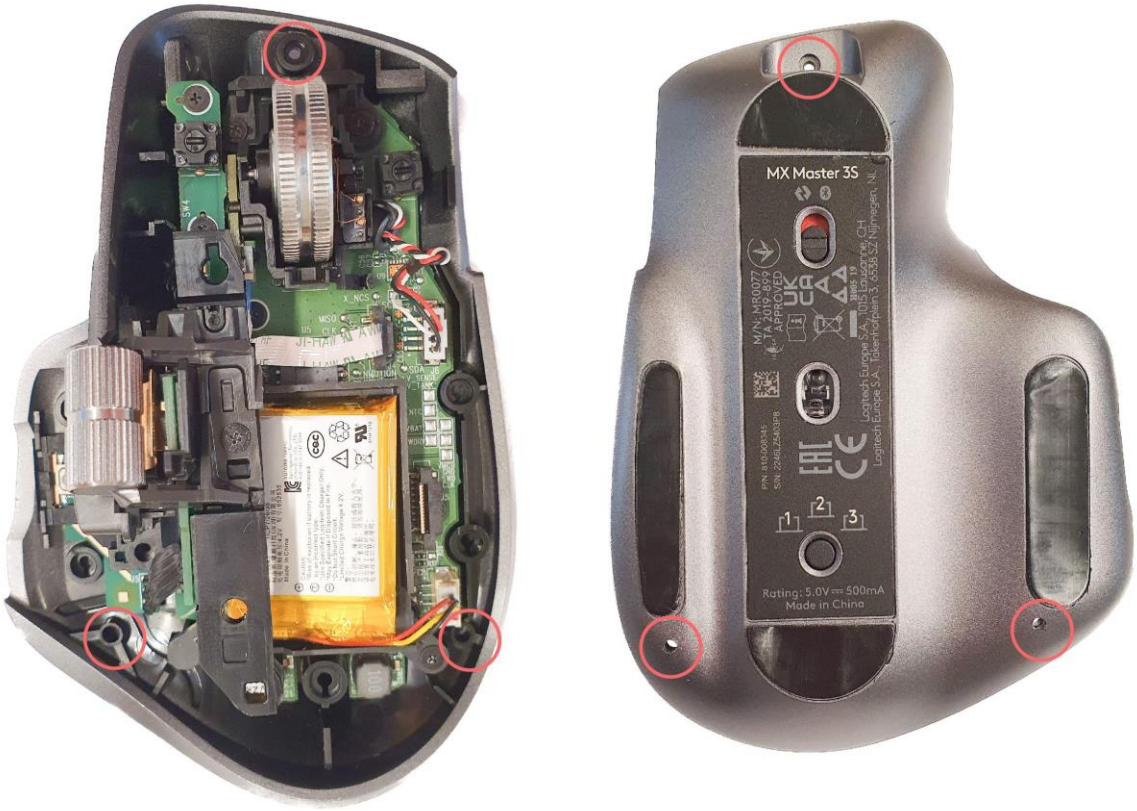


Figure 45 New screw locations Logitech MX Master 3s

Battery removal

The battery will still be glued in place (see Figure 46), however, now with stretch release pull tabs (see Figure 47). Stretch-release pull tabs allow a user to easily remove a battery without the necessity of chemicals or the risk of damaging the battery by bending or puncturing it with a pry tool (Purdy, 2020). These pull tabs lose their adhesive strength when they are stretched, thereby releasing the battery. This should reduce the amount of effort and time required in replacing the battery. Another option would be to have the battery replaced together with the battery bracket (proposed by a mouse and keyboard expert with in-depth disassembly experience, personal communication, 01/08/2023). However, this approach would complicate the recycling process of the battery, as it would still need to be detached from the plastic. Therefore, the stretch release pull tabs have been selected as the preferred option.



Figure 46 Battery placement in the mouse.



Figure 47 Example of stretch release pull tab in the iPhone 8 (Purdy, 2020).

Side PCB accessibility

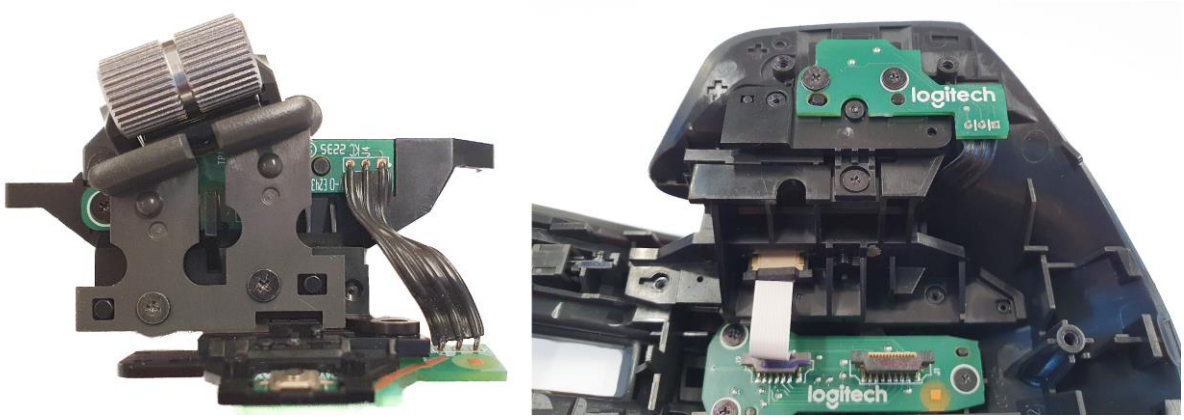


Figure 48 Side cluster (L) and how it is situated in the product (R).

The side PCB is embedded deep within the product's architecture, positioned in the product's scroll wheel bracket as shown in Figure 48. To enhance accessibility, the side scroll wheel bracket is merged with the thumb button bracket, as depicted in Figure 49. This combination not only reduces the component count but also forms a more extensive cluster. Consequently, there's no need to detach the side button bracket before removing the side cluster. As illustrated in Figure 49, both models are intricate components requiring injection moulding with sophisticated moulds, incorporating multiple side actions (Paulsen, 2021). While this design suggestion increases mould complexity and cost, it decreases the number of parts and assembly duration.



Figure 49 Original side scroll wheel bracket (L) and redesigned side scroll wheel bracket (R).

Secondly, the extraction of the side PCB is obstructed by the side scroll wheel brackets, as seen in the left image of Figure 50. These two brackets are secured by three screws, though only the first screw is essential to keep everything properly in place. To evaluate the feasibility of removing screws two and three, the mouse must undergo durability testing to ensure that these changes do not negatively affect the lifespan of the scroll wheel.

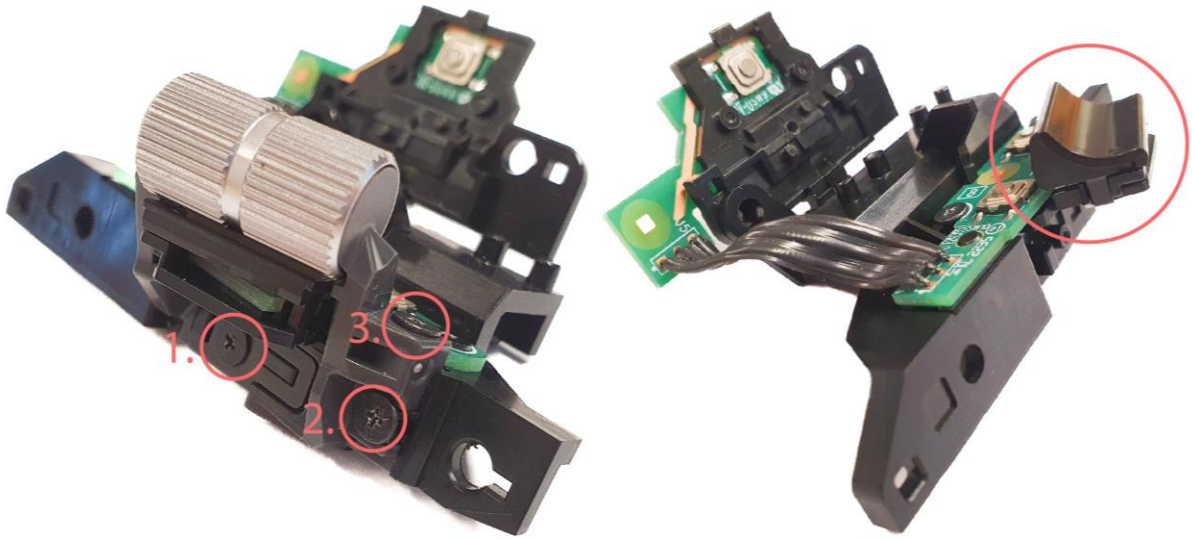


Figure 50 On the left the screws holding down the side scroll wheel brackets and on the right the side scroll wheel spacer is highlighted.

Lastly, as depicted in Figure 50 on the right, the side scroll wheel spacer is secured with three tiny snap fits, demanding significant precision during removal. To bypass this intricate disassembly phase, I propose to fuse the side scroll wheel spacer with the upper side scroll wheel holder, as illustrated in Figure 51. For Logitech to manufacture this modified part, new moulds are necessary. Even though the design is intricate, creating moulds for this component should be feasible since the incorporated spacer aligns with the draft direction of the round feature already present.

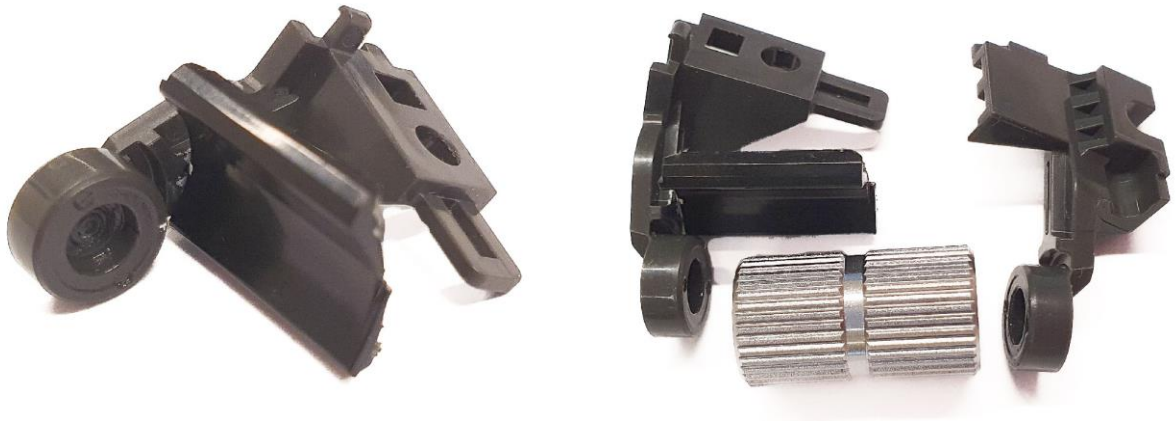


Figure 51 Upper scroll wheel holder combined with scroll wheel spacer.

10.5 Analysis of redesign

The redesign of the Logitech MX Master 3s can now be analysed by reusing the Hotspot Mapping tool and automatic Disassembly Map. After updating the data, the following findings were obtained.

Dashboard

In Figure 52 the main differences compared to the original dashboard are highlighted. The total disassembly time is reduced by two minutes, and the number of tasks (57 instead of 71) and steps (40 instead of 42) are also reduced, although only by a couple of steps. Lastly, the number of tools has been reduced by one, allowing a repair where just one PH00 screwdriver and a small prybar are required.

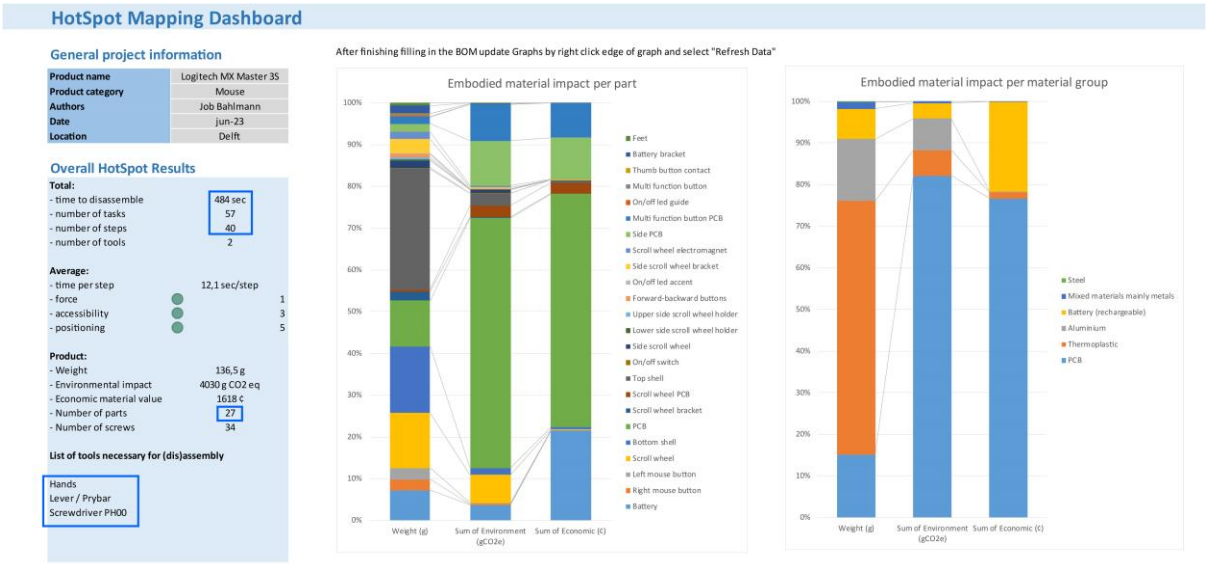


Figure 52 Dashboard of the updated design

Bill of materials

Figure 53 displays the key outcomes of the redesign, highlighting the significant improvements achieved in terms of repairability. Specifically, my focus was on enhancing the repairability of three priority components: the battery, the main PCB, and the side PCB. Through the restructuring of the product architecture, notable time savings have been accomplished, as outlined below:

Battery: The disassembly time has been reduced to 79 seconds from the previous 291 seconds. (0,27 x)

PCB: The disassembly time has been reduced to 154 seconds from the previous 366 seconds. (0,42 x)

Side PCB: The disassembly time has been reduced to 126 seconds from the previous 327 seconds. (0,39 x)

These time savings are a direct result of the product architecture restructuring. Additionally, the effort required for disassembling these components has significantly decreased because of the redesign. These time savings are only for the disassembly process, how much influence the changes have on the reassembly time was not measured.

PartID	Part/Cluster	Is a cluster?	Part of cluster...	Amount	Failure likelyhood	Functional relevance	Materialgroup	Total weight (g)	Disassembly depth (s)	Disassembly effort	Priority	Environment (gCO2e)	Economic (€)	nr of parts to remove	Circular focus rank	Repair
1	Battery		Bottom cluster	1	level 2	level 2	Battery (rechargeable)	10,0 g	79	12	4	149,3	348	1	2	1
2	PCB		Bottom cluster	1	level 1	level 2	PCB	15,1 g	154	21	2	2414,4	905	4	1	2
3	Side PCB		Side cluster	1	level 1	level 2	PCB	2,7 g	126	19	2	432,0	162	4	3	3
4	Scroll wheel		Scroll wheel cl	1	level 1	level 2	Aluminium	18,0 g	87	16	2	269,4	4	4	5	4
5	Scroll wheel electromagnet		Scroll wheel cl	1	level 1	level 2	Mixed materials mainly metals	2,3 g	87	16	2	16,1	1	3	7	4
6	Scroll wheel PCB		Scroll wheel cl	1	level 1	level 2	PCB	0,7 g	69	13	2	110,4	41	2	10	6
7	Feet			4	level 1	level 2	Thermoplastic	0,8 g	102	4	2	2,5	0	0	13	7
8	Multi function button PCB			1	level 1	level 2	PCB	2,2 g	54	12	2	353,6	133	1	7	8
9	Lower side scroll wheel holder		Side cluster	1	level 1	level 1	Thermoplastic	0,6 g	90	15	1	1,7	0	3	15	9
10	Upper side scroll wheel holder		Side cluster	1	level 1	level 1	Thermoplastic	0,7 g	90	15	1	2,1	0	2	15	9
11	Side scroll wheel		Side cluster	1	level 1	level 1	Aluminium	2,3 g	90	15	1	34,5	0	3	13	9
12	Bottom cluster	Yes							27	6	0	0,0	0	0	27	12
13	Right mouse button			1	level 0	level 1	Thermoplastic	3,5 g	49	11	0	10,5	1	1	26	12
14	Multi function button			1	level 0	level 1	Thermoplastic	0,8 g	62	15	0	2,5	0	2	24	12
15	Scroll wheel cluster	Yes							64	12	0	0,0	0	1	25	12
16	Side cluster	Yes							82	14	0	0,0	0	1	23	12
17	Scroll wheel bracket			1	level 0	level 1	Thermoplastic	2,8 g	84	16	0	8,5	1	2	20	12
18	Thumb button contact		Side cluster	1	level 0	level 1	Steel	0,1 g	87	15	0	0,2	0	2	21	12
19	Left mouse button			1	level 0	level 1	Thermoplastic	3,7 g	90	16	0	11,1	1	2	18	12
20	Battery bracket		Bottom cluster	1	level 0	level 1	Thermoplastic	2,6 g	91	13	0	7,7	1	2	21	12
21	Forward-backward buttons		Side cluster	1	level 0	level 1	Thermoplastic	1,0 g	94	16	0	3,0	0	2	18	12
22	On/off led guide			1	level 0	level 1	Thermoplastic	0,3 g	98	18	0	0,8	0	3	17	12
23	On/off led accent			1	level 0	level 1	Thermoplastic	0,2 g	121	24	0	0,6	0	4	11	12
24	Side scroll wheel bracket		Side cluster	1	level 0	level 1	Thermoplastic	4,7 g	131	20	0	14,1	1	7	11	12
25	Bottom shell			1	level 0	level 1	Thermoplastic	21,7 g	154	21	0	65,2	7	6	6	12
26	On/off switch		Bottom cluster	1	level 0	level 0	Thermoplastic	0,3 g	154	21	0	0,9	0	5	7	12
27	Top shell			1	level 0	level 1	Thermoplastic	39,5 g	178	38	0	118,4	12	8	3	12

Figure 53 BOM of the updated design

Disassembly actions

Compared to the original disassembly activities table, the primary distinction is that the duration of two out of the three selected activities has been decreased. The adhesive used for the battery has been substituted with stretch-release pull tabs, simplifying the removal process and making it quicker and less hazardous, as shown in Figure 54. Enhancements in removing the bottom cluster have been made by eliminating the snap fits, replacing the Torx T5 screw with a PH00 screw, reducing the overall number of screws, and allowing access to the screws without the need to remove the feet.

The process for removing the feet has not been enhanced; however, since the screws required to open the mouse are now accessible without the need to remove the feet, they do not impact the rest of the disassembly sequence. As a result, there is no need to replace them each time the mouse must be disassembled.

DisassemblyID	Previous step	Next step	Removal activity	Required tool	Tool size	Fastener reusable?	Task frequency	Total time (s)	Force	Accessibility	Positioning	Time	Activity
1	Logitech MX Master 3S	Feet	Peel off	Lever / Prybar		No	4	102	level 1	level 1	level 2	102	4
2	Bottom cluster	Battery	De-glue	Hands		No	1	45	level 1	level 0	level 1	45	2
3	Bottom cluster	Side cluster	Disconnect sna	Hands		Yes	4	30	level 1	level 2	level 2	30	5
4	Scroll wheel cluster	PCB	Unscrew	Screwc	PH00	Yes	5	26	level 0	level 1	level 1	26	2
5	Bottom cluster	Side cluster	Unscrew	Screwc	PH00	Yes	4	25	level 0	level 1	level 2	25	3
6	Forward-backward buttons	Side PCB	Unscrew	Screwc	PH00	Yes	4	24	level 0	level 1	level 1	24	2
7	Bottom cluster	Multi function button PCB	Unscrew	Screwc	PH00	Yes	3	22	level 0	level 1	level 2	22	3
8	Logitech MX Master 3S	Bottom cluster	Unscrew	Screwc	PH00	Yes	3	22	level 0	level 1	level 2	22	3
9	Bottom cluster	Scroll wheel cluster	Unplug	Hands		Yes	2	20	level 1	level 1	level 2	20	4
10	Scroll wheel cluster	Scroll wheel bracket	Disconnect sna	Lever / Prybar		Yes	3	20	level 1	level 1	level 2	20	4
11	Bottom cluster	Scroll wheel cluster	Unscrew	Screwc	PH00	Yes	2	17	level 0	level 1	level 1	17	2
12	On/off led guide	On/off led accent	Disconnect sna	Lever / Prybar		Yes	2	15	level 0	level 2	level 2	15	4
13	Bottom cluster	Right mouse button	Unscrew	Screwc	PH00	Yes	2	14	level 0	level 1	level 2	14	3
14	Side cluster	Forward-backward buttons	Unscrew	Screwc	PH00	Yes	2	12	level 0	level 1	level 1	12	2
15	Battery	Battery bracket	Unscrew	Screwc	PH00	Yes	2	12	level 0	level 0	level 1	12	1
16	Multi function button PCB	Multi function button	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 2	8	3
17	Bottom cluster	Right mouse button	Disconnect sna	Hands		Yes	2	8	level 0	level 1	level 1	8	2
18	Side cluster	Left mouse button	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 1	8	2
19	Left mouse button	On/off led guide	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 1	8	2
20	On/off led guide	On/off led accent	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 1	level 1	8	2
21	Side cluster	Upper side scroll wheel hol	Unscrew	Screwc	PH00	Yes	1	8	level 0	level 0	level 1	8	1
22	Bottom cluster	Battery	Unplug	Hands		Yes	1	7	level 1	level 1	level 2	7	4
23	Logitech MX Master 3S	Bottom cluster	Unplug	Hands		Yes	1	5	level 0	level 1	level 2	5	3
24	Bottom cluster	Multi function button PCB	Unplug	Lever / Prybar		Yes	1	5	level 0	level 1	level 2	5	3
25	Scroll wheel cluster	Scroll wheel PCB	Unscrew	Screwc	PH00	Yes	1	5	level 0	level 0	level 1	5	1
26	Side cluster	Thumb button contact	Unscrew	Screwc	PH00	Yes	1	5	level 0	level 0	level 1	5	1
27	Scroll wheel bracket	Scroll wheel electromagne	Remove	Hands		Yes	1	3	level 0	level 0	level 0	3	0
28	Upper side scroll wheel hol	Lower side scroll wheel holder										0	0
29	Battery bracket	PCB										0	0
30	PCB	On/off switch	Remove	Hands		Yes	1	0	level 0	level 0	level 0	0	0
31	On/off switch	Bottom shell										0	0
32	Scroll wheel electromagne	Scroll wheel										0	0
33	On/off led accent	Top shell										0	0
34	Multi function button	Top shell										0	0
35	Right mouse button	Top shell										0	0
36	Upper side scroll wheel hol	Side scroll wheel										0	0
37	Upper side scroll wheel hol	Side PCB										0	0
38	Side PCB	Side scroll wheel bracket										0	0
39	Lower side scroll wheel hol	Side scroll wheel bracket										0	0
40	Thumb button contact	Side scroll wheel bracket										0	0

Figure 54 Disassembly activities table of updated design MX Master 3s.

Disassembly Map

In the original Disassembly Map, the main problems were that the complete disassembly sequence was dependent on a couple of hard and time-consuming disassembly activities. These were the removal of the feet, and the separation of the bottom cluster. The redesign completely removes the feet from impacting any other parts and they only need to be removed if the feet themselves need replacement. This change alone reduces the disassembly time for any other part by 102 seconds.

When comparing the Disassembly Maps from the original design (in Section 10.3) to the redesign (Figure 55 and Figure 56) it is clear that the redesigned product has a wider, less deep map, meaning parts are generally closer to the surface. Therefore, they are easier to access, and this increases the repairability of the product.

The gradient disassembly depth representation in Figure 56 also indicates that the depth is increasing gradually, while in the original Disassembly Map, there was barely any gradient. Indicating that the original disassembly sequence was heavily dependent on a couple of time-consuming disassembly activities at the beginning of the disassembly sequence.

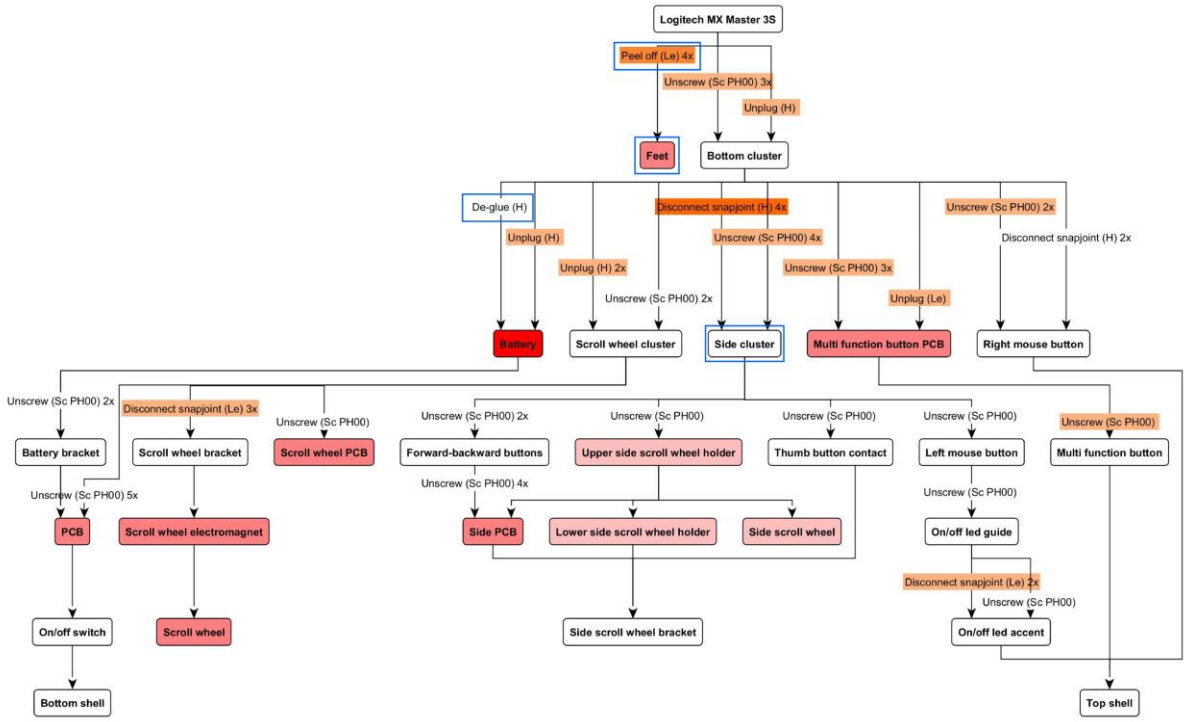


Figure 55 DM of updated MX Master 3s with priority parts and activities highlighted.

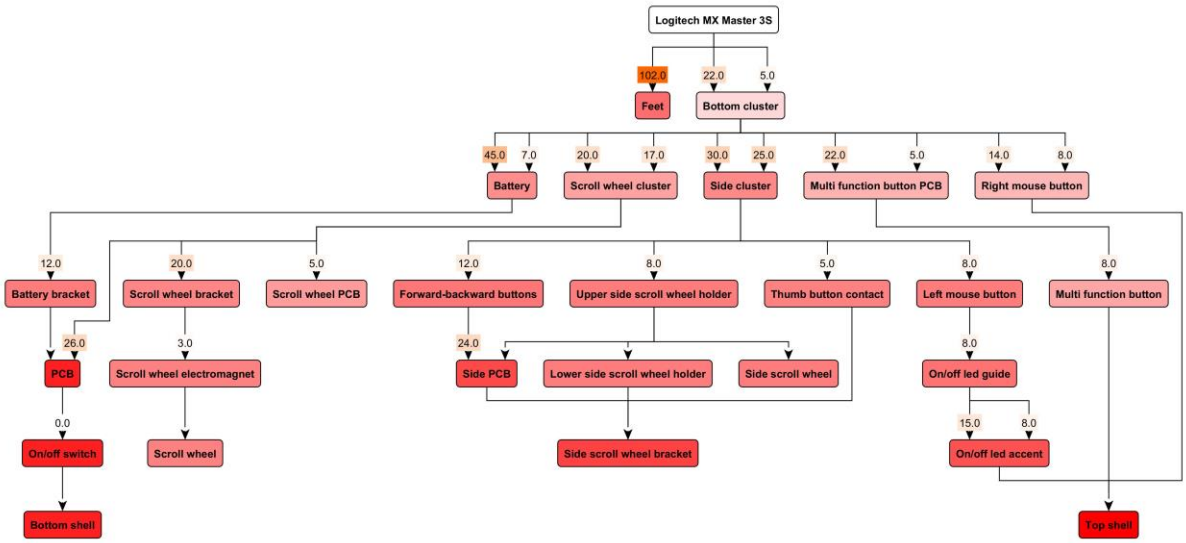


Figure 56 DM of updated MX Master 3s highlighting disassembly activity duration and disassembly depth.

For presentation purposes, a physical disassembly map of both the original and the redesigned Logitech mouse were made (See Figure 57). More pictures of the showcase can be found in Appendix I.

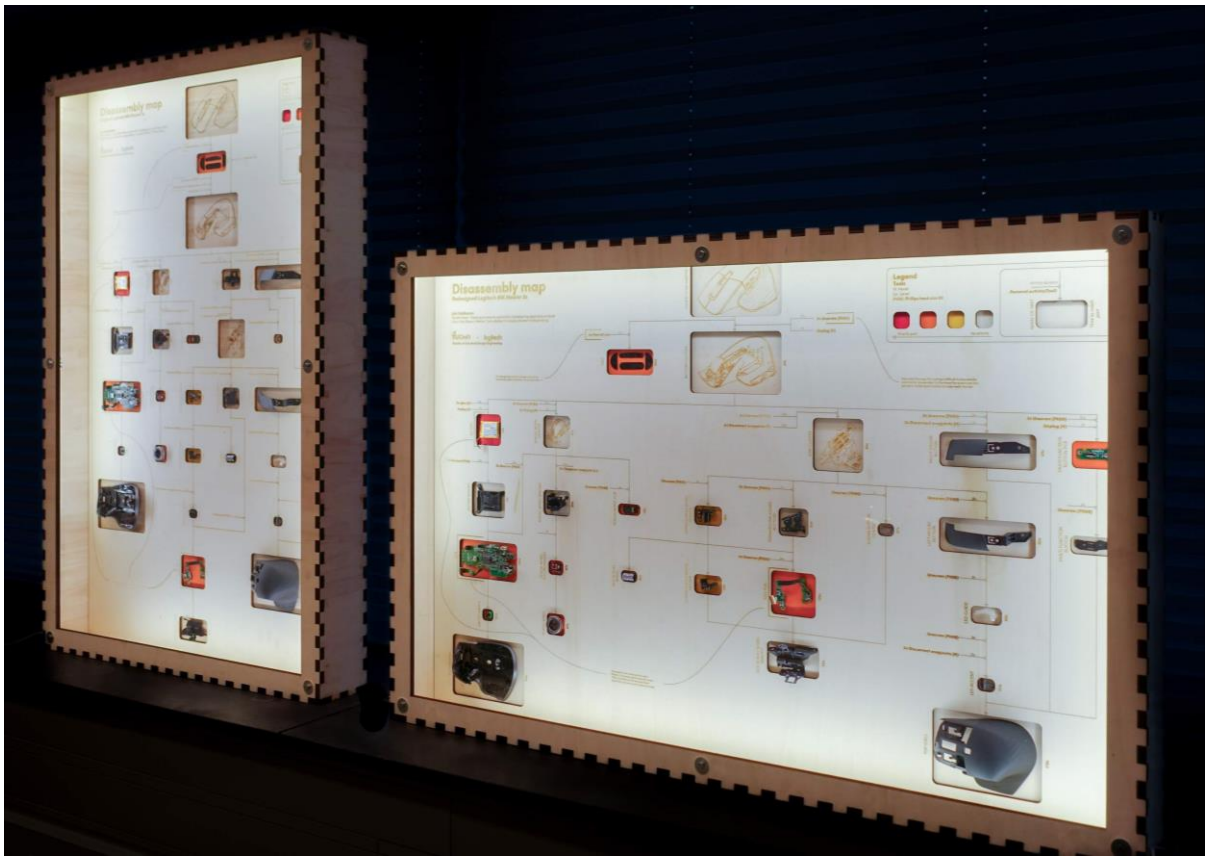


Figure 57 Showcase of both the original and redesigned product architecture of the Logitech MX Master 3s.

10.6 Conclusion

In this chapter, a case study of the Logitech MX Master 3s was conducted to demonstrate the effectiveness of the improved method. Through the analysis and interpretation of the results, an improved design for the mouse was developed, focusing on enhancing the ease of disassembly, resulting in increased repairability.

Through the Hotspot Map and Disassembly Map analyses, potential areas for improvement were identified. The Battery, PCB and Side PCB were selected as the main parts to focus on. Furthermore, a few disassembly activities were selected to be considered in the redesign.

Using techniques like surfacing, clumping, and trimming, ideas were generated for improvements. Clumping and trimming proved to be the most useful in this case. The goal was to strategically rearrange critical parts, group components into clusters, and optimize fastening methods to simplify the disassembly process. This was achieved by making the disassembly sequence independent from the disassembly of the feet since this was very time-consuming. Furthermore, the side bracket was combined with the thumb bracket, allowing to increase in the size of the side cluster. This results in quicker access to the side PCB, which is dependent on the side cluster. Additionally, replacing the battery glue with stretch-release pull tabs facilitated easier removal.

The developed redesign was prototyped and subjected to the same method to determine the significance of the redesign. The redesign showed a significant reduction in total disassembly time, specifically in reaching the three selected priority parts. The disassembly time to reach these three parts decreased on average by a factor of 0,36. Consequently, the time and effort to reassemble the product has also decreased, as experienced by me. However, because this is not recorded in the tool there are no objective measures that can substantiate this.

Reflecting on the tool it should be pointed out that the tool does not provide any metrics or guidance regarding the durability of the product. As the tool pushes towards simplifying and removing connections this could potentially decrease the durability of the product. Thereby possibly cancelling out the positive effect of increased repairability. Furthermore, the tool only indicates critical points in the disassembly sequence. It nudges the designer towards certain design choices by penalizing product properties hindering disassembly but does not provide explicit design recommendations.

In conclusion, the redesign of the Logitech MX Master 3s shows that using the improved method allows designers to select key areas for improvement. By identifying critical components and impactful disassembly activities, designers can achieve significant progress toward enhancing the ease of disassembly with targeted design changes. Nevertheless, designers must strike a balance between ease of disassembly and product robustness, which the current tool does not fully consider. Through the adoption of the improved method, designers can contribute to the creation of more sustainable and repairable consumer products.



Conclusion

In the Conclusions part I bring my thesis to a close. In Chapter 11 the research objectives are revisited and answered. Followed by a discussion about the limitation and lastly the recommendations. In Chapter 12 I reflect on my personal process during the project and the end results. This chapter is ended with acknowledgements.

11 Conclusion

11.1 Research objectives

The objective of this project was to establish a connection between the HSM tool and DM, eliminating the need for separate tool usage. To achieve this, several research objectives were formulated.

RO1: Explore the usability of the Hotspot Mapping tool and Disassembly Map.
The utility of both tools was analysed through a literature review, a user survey, and my personal experience. The System usability scale (SUS) indicated an unacceptable usability score of 50 for the current tools, highlighting a significant need for improvement. Several enhancement opportunities were identified, spanning scope, features, and usability.

Feedback pointed to the necessity for upgrades in specific features such as the required tools, materials database, and hotspot value displays. Usability shortcomings were evident in the complexity of reordering components, unclear input guidance, challenges in understanding varying levels, and weak visual and cognitive ties between the HSM and DM. Furthermore, the lack of automatic data synchronization, coupled with time-consuming and repetitive data entry, was also included in the list of usability issues.

RO2: Investigate data structures that describe the product architecture.
The data structure was required to meet several criteria, encompassing graph visualization, the ability to incorporate various properties and activities, allowing for multiple activities between two components, as well as compatibility with MS Excel. Four data structures, derived from the mathematical discipline of graph theory, were evaluated: the adjacency matrix, incidence matrix, adjacency list, and edge/node list. Of these, only the edge/node list satisfied all the requirements, allowing for graph visualisation, accommodating multiple properties, and maintaining compatibility with MS Excel.

RO3: Identify the requirements for the new tool.
From the analysis phase of the project, multiple requirements and wishes for both the tool and software packages were extracted. The requirements steered the design and development of the new tool.

RO4: Develop a new tool using the selected data structure that guides designers in increasing the ease of disassembly and reassembly.
Through an iterative approach, this objective was accomplished by implementing a node/edge list data structure and using the yEd Graph Editor software as the visualization tool for the Disassembly Map. Furthermore, the incorporation of automatic disassembly depth calculation empowered designers to make informed decisions regarding component prioritization. In addition, several minor usability enhancements and additional features were introduced to improve the overall usability and usefulness of the tool.

RO5: Verify and validate the effectiveness and usability of the new tool.
The developed tool underwent validation through a usability test, a discussion regarding the Disassembly Maps' subjectivity and a final case study showing the tool's effectiveness. The usability test demonstrated a significant improvement in the system usability scale score, elevating the tool from a below-average usability score to an average usability score compared to other systems. This validates the substantial enhancement in overall usability achieved by the system. Moreover, all participants expressed a preference for the new system over the old system, primarily due to the integration between the HSM and DM. This integration resulted in time savings, increased consistency between the tools, and improved usability.

The effectiveness of the combined tools was demonstrated through a case study involving the Logitech MX Master 3s. The dynamic tables and disassembly capabilities facilitated easy analysis and swift prioritization. With minimal changes, significant reductions in disassembly time for critical components were achieved.

In conclusion, the redesigned HSM and generated DM offer an improved workflow for designers in identifying focus components for a redesign. Overall, the improved tools enhance the design process and empower designers to create products with enhanced circularity and repairability.

11.2 Limitations

While the validation process yielded positive results, several limitations need to be addressed. Firstly, the validation tests themselves had a small sample size, which limited the information and validity of the results. To enhance the credibility of the tools, it is necessary to conduct these tests with a larger sample size.

Product category: The development of the new tool focused solely on small electronic products, potentially leading to a bias where the tool performs well for these specific products but may not be as effective for other product categories. To overcome this limitation, it is recommended to conduct case studies across multiple product categories to evaluate the tool's effectiveness more comprehensively.

The tool: The tool itself also has various limitations, including the inability of components to be part of multiple clusters, the lack of automatic assignment of a hierarchy for disassembly activities involving the same component, the inherent product architecture subjectivity and other limitations related to MS Excel. To address these issues and further enhance the tool, it is recommended to develop a dedicated software program that resolves these limitations and integrates the Disassembly Map directly into the software.

Ease of disassembly vs Durability: The tools developed are designed to improve the accessibility and ease of disassembly of products, consequently discouraging properties that make a product challenging to disassemble. However, these same characteristics frequently contribute to the product's durability. Consequently, the tool's output may guide a designer towards eliminating too many constructive elements, thus diminishing the product's overall strength. This could result in a product with a reduced lifespan, undermining the potential benefits of enhanced ease of disassembly.

Subjectivity of the product architecture: It is often not feasible to represent a product's architecture through a single disassembly tree as there can be multiple disassembly paths to access a specific component. For the tool, this implies that the Disassembly Map hinges on the disassembler's interpretation of the product structure. The decisions made by the disassembler could potentially impact the results and subsequently influence the design alterations for a product being redeveloped.

Instructions: Despite the redesigned HSM tool containing detailed instructions, it remains a complex tool to use. Therefore, it is recommended that designers undergo a training course that explains, demonstrates, and allows for practical application of the tool, with feedback provided. Alternatively, or in conjunction with the course, an instructional video would be a beneficial addition to assist users in effectively using the tool.

11.3 Recommendations

Reassembly properties: In general, I expect that the easier a product is to disassemble, the more straightforward its reassembly should be. Yet, this may not always apply. As pointed out by Kumar (2022), the sequence of reassembly might not exactly mirror the disassembly process in reverse. Additional complications such as keying or the absence thereof, and springs can make the reassembly more challenging than what the disassembly process suggests. Consequently, any further advancements in the tool should consider the influential factors in the reassembly process. This consideration is key to circular strategies such as repair, refurbishing, remanufacturing, and upgrading, where reassembly is a mandatory stage.

Digital product passport (DPP): A digital product passport is a concept related to digitally tracking the lifecycle of a product, from creation to end of life. It includes detailed information about the product such as its materials, manufacturing processes, usage history, maintenance, recycling or disposal details, and more (Walden et al., 2021). This data is stored and accessed digitally, potentially through technologies like QR codes, RFID tags, or blockchain. The aim is to increase transparency, improve product lifecycle management, promote sustainable practices, and facilitate circular economy strategies, such as reuse, repair, refurbish, and recycling. The BOM created in the HSM tool, along with the Disassembly Map produced, could potentially enrich the digital product passport. This is because they delineate multiple factors that affect the repairability and material attributes of all components. Furthermore, the Disassembly Map can serve as a guide for accessing and repairing a damaged part. I recommend that future research explores which aspects of the improved HSM tool could provide added value to the digital product passport and how those measures can be well integrated.

Tool awareness: For the enhanced Hotspot Mapping tool to truly contribute to environmental sustainability, it needs to be actively utilized by designers. Hence, its promotion and awareness are critical. To ensure designers are aware of the tool, several tactics can be employed. These involve partnerships with corporations, organizing webinars and workshops, publishing papers about it, presenting it at conferences, and incorporating it into academic courses.

12 Afterword

12.1 Personal reflection

I have always loved tinkering with physical products, disassembling them, exploring what makes them tick and then reassembling them. In the design field, I like the balance between working theoretically and practically, both doing calculations, arguing design choices, and then physically making prototypes. Without either, I get bored at some point.

However, I also always had in the back of my mind that I did not want to create yet another physical product and try to sell that to people. How do I combine my passion for the physical while trying to have a minimal or even positive effect on our planet? For this reason, I am very interested in consumer repair. Thus, for my graduation project, I wanted to do something that had to do with repair.

With this mindset, I came to Bas and asked if he had any ideas on a graduation project that had to do with repair. He had a project in mind which entailed working on a method to help designers increase the repairability of products. Although this meant a less physical project for me, I saw that the impact it could have would be far greater than when for example redesigning one specific product for increased repairability.

At the beginning of the project, I felt like I was working on the project in quite an unstructured manner. I was developing the tool while taking apart Logitech products. It felt a bit like a mess to me. However, my coaches instructed me early on to start reporting my progress. This helped me to see my progress and the iterations better, even when I had great difficulty with the reporting itself.

Throughout the project, the reporting became easier, as I had more material to write about. Furthermore, after making a planning and communicating with my coaches about the planning I felt like I got more in charge of the project.

Undertaking an individual project often presents challenges for me, particularly with maintaining motivation. There is a tendency to be hard on myself when I do not meet my expectations, which ironically leads to less productivity – an unfortunate downward spiral. At the start of this project, I decided to focus on time management and avoid this recurring issue. To accomplish this, I set several guidelines in place for myself.

First, I committed to going and working at the university daily since I get too easily distracted at home. Second, I committed to working together with other students, to motivate each other, discuss progress and help each other. Lastly, I decided to be less self-critical and not criticise myself for any perceived lack of productivity.

These guidelines were remarkably effective in keeping me focused. Naturally, there were days where productivity was lower than others, but the difference this time was my ability to contextualize these less productive days, avoid self-criticism, and start fresh the next day. A particularly useful strategy I found was to either switch to a physical task when writing seemed unproductive or simply take the rest of the day off to engage in a relaxing activity, such as cycling. These measures allowed me to mentally disconnect from the project and reset for the next day.

During my project I greatly enjoy taking apart the Logitech products and seeing their inner workings, wondering why certain parts were added, and being impressed by some while shocked by others. After the development of the tool, I also really enjoyed the user test. It was great to hear feedback from students and notice that the improved tool had a genuine impact on their workflow.

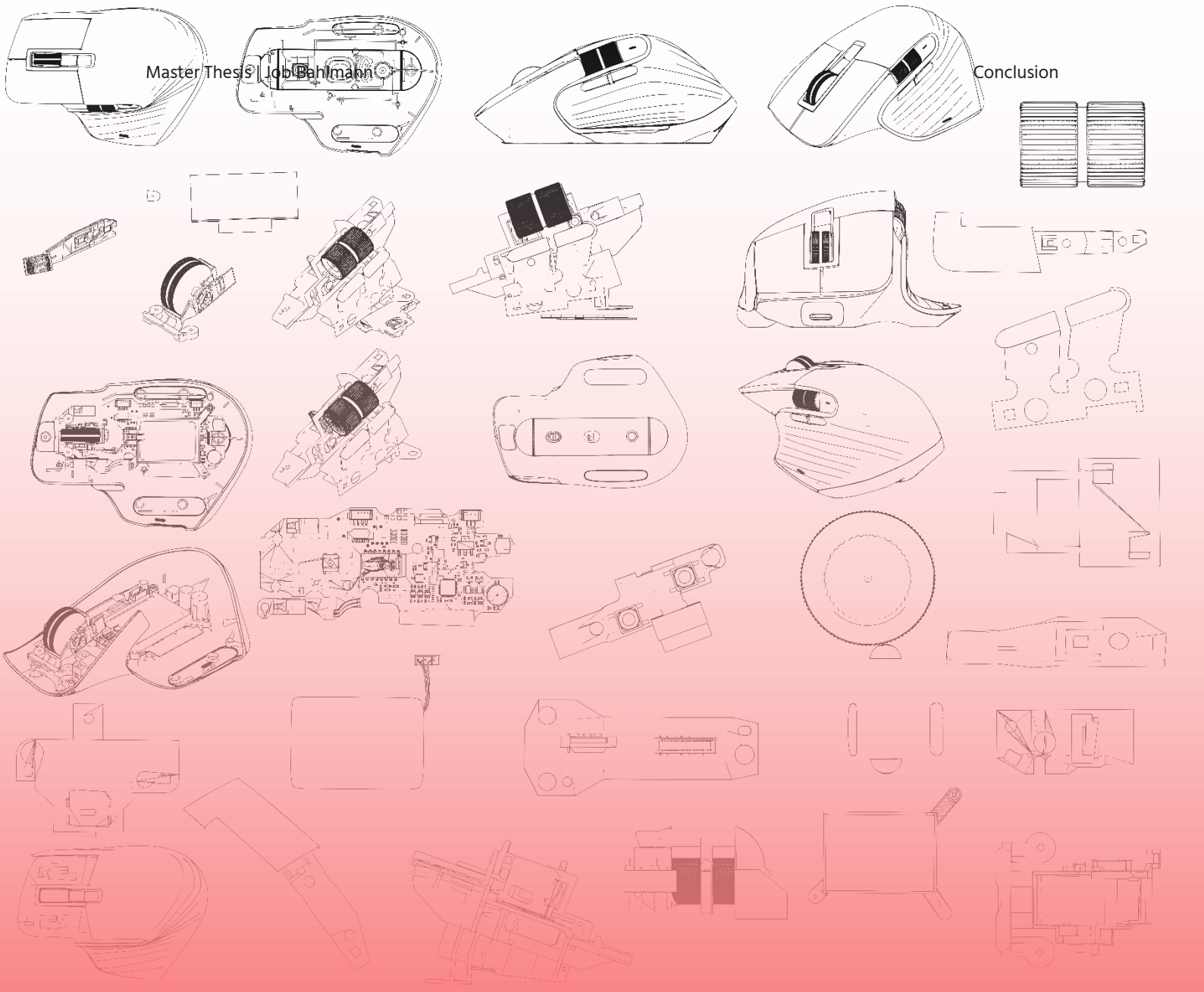
Overall, I am proud of the results I achieved, and I hope that this tool can be widely used to enhance the ease of repair for various products. My goal is to contribute to a world where repairability becomes a significant consideration in product design, ultimately leading to a more sustainable future.

12.2 Acknowledgement

My appreciation goes out to my mentors, Bas and Conny. Their constant support, constructive suggestions, and insightful feedback have been instrumental in steering my project on the right path, ensuring its academic integrity, and keeping me motivated throughout the process.

Additionally, I extend my gratitude to the users who provided their time and effort in testing both the initial and reengineered tools.

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Achterberg, E., Hinfelaar, J., & Bocken, N. (2016). Master circular business models with the Value Hill.

AT&T Labs Research. (2023). *Graphviz*. In (Version 8.1.0) https://graphviz.org/download/

Bang-Jensen, J., & Gutin, G. Z. (2008). *Digraphs: theory, algorithms and applications*. Springer Science & Business Media.

Bangor, A., Kortum, P. T., & Miller, J. T. (2008). An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction, 24*(6), 574-594.

Bastian, M., Ibañez, E. R., Jacomy, M., Bartosiak, C., Heymann, S., Bilcke, J., McSweeney, P., Panisson, A., Subtil, J., Suzuki, H., Skurla, M., & Patriarca, A. (2009). *Gephi: an open source software for exploring and manipulating networks*. In (Version 0.10.1) https://gephi.org/users/download/

Bracquené, E., Brusselaers, J., Dams, Y., Peeters, J., De Schepper, K., Duflou, J., & Dewulf, W. (2018). Repairability criteria for energy related products. *Study in the BeNeLux Context to Evaluate the Options to Extend the Product Life Time Final Report*.

Brooke, J. (1996). SUS-A quick and dirty usability scale. *Usability evaluation in industry, 189*(194), 4-7.

Cambridge Dictionary. (n.d.). Retrieved 11/04/2023 from https://dictionary.cambridge.org/us/dictionary/english

Cormen, T. H., Leiserson, C. E., Rivest, R. L., & Stein, C. (2022). *Introduction to algorithms*. MIT press.

Cytoscape. (2023). *Cytoscape*. In (Version 3.10.0) https://cytoscape.org/download.html

Dangal, S. (2022). Design for physical durability, diagnosis, maintenance, and repair

De Fazio, F. (2019). Enhancing Consumer Product Repairability: A case study on vacuum cleaners.

European Commission. (2020). *A new Circular Economy Action Plan For a Cleaner and More Competitive Europe*. Retrieved from https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

Fazio, F. D., & et al. (2021). The Disassembly Map: A new method to enhance design for product repairability. *Journal of Cleaner Production, 320*, 128552.

Finstad, K. (2006). The system usability scale and non-native English speakers. *Journal of usability studies, 1*(4), 185-188.

Flipsen, B. (2020). *Hotspot mapping - user guide: analysis of the circular readiness of your product.*

Flipsen, B. (2023). Repair! In.

Flipsen, B., Bakker, C., & de Pauw, I. (2020). Hotspot Mapping for product disassembly; a circular product assessment method. Conference of Electronics Goes Green 2020,

Gephi. (2009). *Features*. https://gephi.org/features/

Gomes, J. (2018). *Design Structure Matrix and its application in project communication*. Retrieved 11/04/2023 from http://wiki.doing-projects.org/index.php/Design_Structure_Matrix_and_its_application_in_project_communication

Hornbæk, K. (2006). Current practice in measuring usability: Challenges to usability studies and research. *International Journal of Human-Computer Studies, 64*(2), 79.

Introduction to DSM. (2019). DSMweb. Retrieved 11/04/2023 from https://dsmweb.org/introduction-to-dsm/

JGraph Ltd. (2023). *Diagram.net*. In (Version 21.3.8) https://www.drawio.com/

Kepner, J., & Gadepally, V. (2014). Adjacency matrices, incidence matrices, database schemas, and associative arrays. International Parallel & Distributed Processing Symposium Workshops (IPDPSW). IEEE,

Klop, S., & van den Boogaart, M. (2023). *Design for repair*.

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics, 143*, 37.

Kumar, S. (2022). *Investigating Metal 3D Printing of Spare Parts for Re-manufacturing Fuel Injection Pumps* Delft University of Technology]. https://repository.tudelft.nl/islandora/object/uuid%3Abb557e33-7f8d-4d15-b3cb-b020abd5f7d9

Laitala, K., Klepp, I. G., Haugrønning, V., Throne-Holst, H., & Strandbakken, P. (2021). Increasing repair of household appliances, mobile phones and clothing: Experiences from consumers and the repair industry. *Journal of Cleaner Production, 282*, 125349.

Lewis, J. R., & Sauro, J. (2009). The factor structure of the system usability scale. Human Centered Design: First International Conference, HCD 2009, Held as Part of HCI International 2009, San Diego, CA, USA, July 19-24, 2009 Proceedings 1,

Ligtelijn, S. (2021). The Circular Redesign Focus Point tool: A novel method to determine focus points for redesigning surgical devices for circularity.

Logitech. (2022). *MX MASTER 3S*. https://www.logitech.com/en-us/products/mice/mx-master-3s.910-006557.html

Long, J. J. (2015). *Excel to Graphviz*. In (Version 6.0.03 (Win + Mac OS))

Lützen, J. A., & Lissalde, C. B. (2020). *Circular Design Guidelines*. Retrieved 2-6-23 from https://circularproductdesign.org/

MacArthur, E. (2013). Towards the circular economy. *Journal of Industrial Ecology*, *2*(1), 23-44.

Microsoft. (2023a). *Microsoft 365*. In (Version 18.2305.1222.0)

Microsoft. (2023b). *Microsoft Visio Data Visualizer*. In (Version 1.0.0.4)

Muralikrishna Iyyanki, V. (2017). Life Cycle Assessment. *Environmental Management*, 57.

Paulsen, G. (2021). *Types of Injection Molding Side Actions*. https://www.xometry.com/resources/injection-molding/injection-molding-types-of-side-actions/

Purdy, K. (2020). *Ask iFixit: What Is Stretch Release Adhesive (and Why Do We Love It)?* https://www.ifixit.com/News/45779/ask-ifixit-what-is-stretch-release-adhesive-and-why-do-we-love-it

Representing graphs. (2014). Khan Academy. Retrieved 5-6-2023 from https://www.khanacademy.org/computing/computer-science/algorithms/graph-representation/a/representing-graphs

Sauro, J. (2016). Standardized usability questionnaires. *Quantifying the User Experience*, 185.

Singh, H., & Sharma, R. (2012). Role of adjacency matrix & adjacency list in graph theory. *International Journal of Computers & Technology*, *3*(1), 179-183.

Sodhi, R., Sonnenberg, M., & Das, S. (2004). Evaluating the unfastening effort in design for disassembly and serviceability. *Journal of Engineering Design*, *15*(1), 69-90. https://doi.org/10.1080/0954482031000150152

Tilstra, A. H., Seepersad, C. C., & Wood, K. L. (2012). A high-definition design structure matrix (HDDSM) for the quantitative assessment of product architecture. *Journal of Engineering Design*, *23*(10-11), 767-789. https://doi.org/10.1080/09544828.2012.706748

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research policy*, *24*(3), 419-440.

UNFCCC. (2021). The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement

Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. *Resources, Conservation and Recycling*, *135*, 323-334.

Vermaat, B. (2020). Design for refurbishment of child car seats–Towards circular safety critical products.

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital Product Passports as Enabler of the Circular Economy. *Chemie Ingenieur Technik*, *93*(11), 1717-1727. https://doi.org/10.1002/cite.202100121

yWorks. (2023). *yEd Graph Editor*. In (Version 3.23.1) https://www.yworks.com/products/yed/download#download



Creating an easy-to-use tool for (re)designing repairable products.