DESIGN FOR RECYCLING OF ELECTRONIC PRODUCTS
STUDY ON SMART TVS

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Integrated Product Design
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Delft, May 2024

Master Thesis
MSc. Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Part of the NWO funded Circular Circuits project

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PREFACE

This thesis is my final project as a student of the Master Integrated Product Design at the Faculty of Industrial Design Engineering at the Delft University of Technology.

During my studies I have done many different projects in various fields of industrial design, but over the years interest in sustainability has grown. I am convinced that climate change is one of the biggest issues of our time, and as a designer I want to make at least a small contribution to its solution.

This led to a graduation project within the Sustainable Design Engineering department. For the past six months, I have been immersed in the complex and interesting world of e-waste recycling - a topic I was previously unfamiliar with. This project was very different from any other project I have worked on before, which is why it sparked my interest. What became very clear to me throughout this project is that the more you dive into this subject, the more complex it becomes. This project is only a small step towards more sustainable design practices, which I hope will be followed by many more.

Enjoy!

Doris

ACKNOWLEDGEMENTS

Before introducing the project, I would like to thank everyone who has helped or supported me during this project. First of all, I would like to thank my supervisors who helped me a lot by immersing me in the world of recycling. Thank you Ruud, for your expertise in this field, you always pointed out interesting observations and did not hesitate to give your feedback, I really appreciate that. Thank you Dorien, for all the hours of sorting, talking and laughing. Also for the trips to the recycling company, moving the TVs around and the insights you offered, it was much more fun doing it together.

I would like to thank everyone who helped me with my research by being interviewed, answering questions and giving their professional insights. Thank you Linda for your help with the recycling test, the sorting of the fragments and all the plastics you identified for me. I would also like to thank the staff at the recycling facility for their help with the shredding process and for taking the time to share their expertise and valuable insights.

Finally, I would like to thank my family, friends, housemates and fellow students for supporting me along the way and letting me know that you were there for me. Lastly, I would like to thank Daan for your constant encouragement and willingness to listen to my endless talk about the project. Your patience and support has been a huge help to me.

ABSTRACT

This thesis investigates how electronic products can be designed for effective recycling, which can reduce the demand for critical raw materials and mitigate environmental and human health risks through the safe removal of hazardous substances. In collaboration with an electronics recycling facility, this study provides practical insights into e-waste recycling through a shredding experiment. By conducting a shredding experiment with four brands of smart TVs the influence of product and part characteristics on the liberation and separation of materials are studied. The insights of this experiment, with a specific focus on connections and materials, are incorporated into Design for Recycling (DfR) guidelines and introduces a novel method to assess the tensions between repairability and recyclability, called: Recyclability Maps.

Key findings include the identification of connections that influence the separation of materials, such as the high liberation degree of snap-fits and the complex behaviour of screws and adhesives. This study demonstrates the critical role of product design in enhancing the recyclability of products and reducing its environmental impact. The developed DfR guidelines offer practical guidance for designers, integrating theoretical insights with empirical data from the recycling experiment. The Recyclability Map method provides a structured approach to evaluate how design choices affect the repairability and recyclability of a product. With this method the smart TVs were analysed on the tensions between these two circular design strategies.

The thesis concludes that effective integration of circular design strategies requires careful selection of connections and materials during the design phase, emphasizing the importance of informed design decisions to promote sustainability.

Keywords: Design for Recycling, e-waste recycling, DfR methods, smart TVs, Recyclability Maps, shredding, Design for Repair

TABLE OF CONTENTS

ABBREVIATIONS

E-waste - Electronic waste
BFRs – Brominated Flame Retardants
BoM - Bill of Materials
DfR – Design for Recycling
DM – Disassembly Map
E-waste – Electronic waste
FTIR – Fourier-transform infrared spectroscopy
PCB – Printed Circuit Board
RM – Recyclability Map

PLASTICS

ABS - Acrylonitrile Butadiene Styrene
PC – Polycarbonate
PC-ABS – Polycarbonate– Acrylonitrile Butadiene Styrene
PE – Polyethylene
PP – Polypropylene
PS - Polystyrene
PVC – Polyvinyl chloride
PBT – Polybutylene terephthalate

TERMINOLOGY

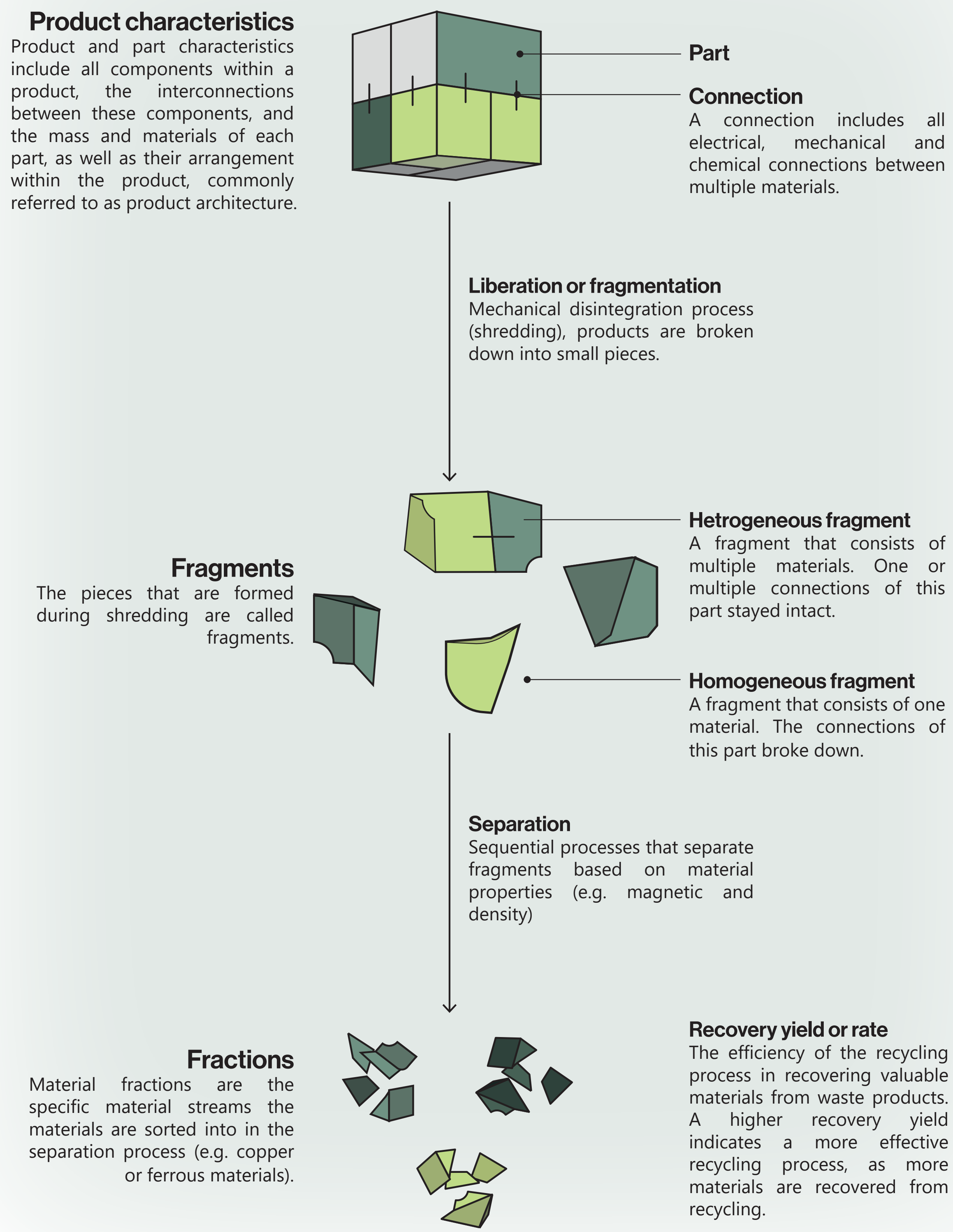


FIGURE 1 Terminology used throughout the project

CHAPTER 01

INTRODUCTION

The first chapter will outline the aim of this study, introducing the research question along with several sub-research questions that will be investigated in this study. Additionally, this chapter will provide a reading guide, detailing the structure of the thesis and summarising the content of each subsequent chapter. This introduction aims to clearly define the research focus, highlight the significance of the study, and prepare readers for the detailed analysis and findings that follow.

1.1 INTRODUCTION

E-waste is the fastest-growing solid waste stream in the world, growing three times faster than the global population (ILO, 2014). Electronics can contain scarce metals and valuable materials (Henckens et al., 2014). Many of these materials could be recycled, reducing the need for new raw materials. Recycling electronics can also reduce environmental and human health risks by safely removing hazardous substances (Ahirwar & Tripathi, 2021), (WHO, 2023). Notably, designers can play a pivotal role in reducing e-waste and designing electronic products for more effective recycling (Babbitt et al., 2021).

A solution for the e-waste problem can be solved by moving from a linear to a circular economy. A circular economy requires design strategies such as repairability and recyclability to minimise waste and keep materials in the economy. However, some design decision that are beneficial for recycling, can have a negative impact on the repairability of a product, and the other way around (Rijkswaterstaat, circulair ontwerp, n.d.). This can make it challenging for designers to identify the best and most impactful measures to take when the aim is to design for circularity.

Despite the importance of design strategies to keep products in circulation for as long as possible, the eventual need for recycling remains an inevitable part of the product lifecycle (Circular Economy, n.d.). This marks the importance of designing products for more effective recycling. Product characteristics such as materials, connections and product architecture have a significant impact on the recyclability of a product (Fakhredin, 2018). Existing DfR methods often lack experimental validation or adaptation for designers (van Dolderen et al., 2024). These methods are rarely tested with designers and have not been validated by recycling experiments. Therefore, there's an urgent need for DfR methods that are based on practical evidence and specifically tailored for designers. However, the influence of these design choices on other circular design strategies should also be investigated, to ensure design considerations that effectively enhance circularity.

The aim of this thesis is to investigate how electronic products can be designed for effective recycling. This will be investigated through a recycling experiment that will provide practical insights into design features that hinder the recyclability of electronics. This recycling experiment will be carried out using smart TVs. smart TVs are used as a test case because they contain high quality electronics and are expected to represent a variety of connections and materials. The knowledge gained from this experiment will be used to develop a comprehensive set of DfR guidelines for electronic products, as well as a new methodology to support designers in making informed design decisions by assessing the tensions between repair and recycling.

1.1 RESEARCH QUESTIONS

This resulted in the following research questions:

- How can electronic products be designed for effective recycling?
    - What are the product and part characteristics of a smart TV?
    - How do the product and part characteristics of a smart TV affect the liberation and separation during the recycling process?
    - What are effective DfR guidelines applicable by designers?
    - How can designers assess the tensions between recyclability and repairability?
    - What are the tensions between recyclability and repairability of a smart TV?

The first two sub-research questions focus on gaining practical insights into the behaviour of smart TVs during the recycling process. Particulary focusing on product and part characteristics such as materials, connections and product architecture. For the third sub-research question, the findings will be generalised into comprehensive guidelines for electronic products that can be used by designers. In addition to these guidelines, the fourth sub-research question proposes a new method that designers can use during the design process to assess the tensions between repairability and recyclability, focusing on the product and part characteristics. The fifth sub-research question will demonstrate the effectiveness of the new method by analysing the tensions between these two circular design strategies. The method will be applied on the smart TVs used throughout the study. The aim is to provide practical insights into how design choices can impact different circular design strategies.

Throughout the project, a combination of quantitative and qualitative research methods was used to answer the research questions. Each chapter describes the specific methodology used to answer the sub-research questions handled. The project outline in section 1.4 provides an overview of the methods used in each chapter and how the chapters relate to each other.

1.2 CIRCULAR CIRCUITS

This thesis is part of the Circular Circuits project, funded by the Dutch Research Council (NWO), which aims to achieve a fully circular production of electronics and eliminate e-waste (Circular Circuits, 2023). By leveraging expertise in technology, design, business modelling and systems analysis from various organisations, companies and universities, the project aims to co-create circular solutions for electronics. This is in line with the Dutch government's 'Netherlands Circular by 2050' programme, which focuses on consumer goods and manufacturing industries. The resulting innovations are expected to not only eliminate e-waste but also lead to significant savings in raw materials and energy while promoting sustainable employment opportunities.

1.3 PROMPT PROJECT

The smart TVs used in this study are obtained from the PROMPT project (Prompt Project, n.d.). In the PROMPT project these TVs were studied on their repairability, through among other things disassembly maps. The disassembly maps will also be used in this project.

1.4 PROJECT OUTLINE

This thesis is build up out of 5 sub-research questions, an introduction, background and conclusion.

CHAPTER 2 – gives background information on the e-waste problem and the current state of DfR methods. Next to this, the general recycling process for e-waste is discussed.

CHAPTER 3 – analyses the part and product characteristics of a smart TV. Mapping the type of materials and connections in the TVs and how these are structured in the product architecture. The product mapping is done for four different brands through disassembly.

CHAPTER 4 – conducts a shredding experiment with 20 smart TVs. The TVs are shredded and then analysed by sorting the fragments according to the connections that are still intact. The behaviour of the connections is thoroughly analysed, mapped and interpreted through qualitative and quantitative analysis of the data.

CHAPTER 5 – translates the insights into practical guidelines for designers. Together with existing literature a set of guidelines is developed. The literature is used to compare theory and practice to result in a comprehensive set of guidelines based on current recycling practices, applicable by designers.

CHAPTER 6 – develops a method to enable designers to assess the trade-offs between repairability and recyclability during the development of a product. The tool is based on insights from the experiment and is developed through an iterative design process by conducting user tests. Also, the method is demonstrated through applying it on the smart TVs and analysing the tensions.

CHAPTER 02

BACKGROUND

This chapter provides background information on the project. It explores the broad scope of the e-waste problem, its scale and the many factors that contribute to its complexity. It also explains the recycling process in detail. By addressing these interrelated factors, this chapter aims to provide a comprehensive understanding of the landscape in which the research is situated. This basic exploration provides the basis for a more in-depth examination of the recycling practice in the following chapters.

2.1 E-WASTE PROBLEM

Electronic devices seamlessly add convenience, comfort and luxury to our daily lives (Kumar, 2023). These devices not only improve our access to information and connectivity, but also provide tools that significantly increase our efficiency. However, due to the rapidly changing nature of technology and the increasing demand, driven by people's growing financial capability, many of these electronic products become waste withing a few years of their production. Factors such as limited repair options, the availability of better alternatives, the wide variety of products and the ever-increasing integration of electronic devices into daily activities, also contribute to this issue (Shittu et al., 2021), (Ahirwar & Tripathi, 2021). The amount of e-waste is growing every year. The annual worldwide generation of e-waste was 7,3 kg per capita in 2019 and is increasing at a rate of 3-5% a year (Statista, 2023), (Shittu et al, 2021). This growth is expected to continue, as people discard more and more electronics.

E-waste is an important waste stream, due to several factors. The most valuable materials are located in the PCBs of electronic devices. PCBs can contain precious metals, such as gold, platinum, palladium, ruthenium, rhodium, iridium, copper and silver. Also other valuable materials like iron, aluminium, cobalt, indium, germanium, bismuth and antimony are located in electronics (Ahirwar & Tripathi, 2021). Many of these materials could be recycled, minimising the need for new raw materials. Next to their environmental impact, they can hold significant economic value (Cayumil et al., 2016).

Besides the value in e-waste, proper e-waste recycling is essential for mitigating environmental and human health risks associated with unsafe disposal (Ahirwar & Tripathi, 2021). E-waste can contain various hazardous substances due to the presence of heavy metals (Hg, Cd, Pb, etc.), brominated flame retardants (BFRs), polychlorinated biphenyls and other harmful substances. If these hazardous substances are improperly managed, they can cause significant risks to humans and the environment (Kaya, 2016). These substances can contaminate groundwater, produce toxic fumes and gases after incineration, acidify soil, and release carcinogens into the air (Ahirwar & Tripathi, 2021). It is therefore important that e-waste is properly collected and recycled.

However, the management of e-waste presents complex challenges. Despite improvements in the collection and processing of e-waste, half of the e-waste generated in the Netherlands is still not properly collected and recycled (Baldé et al., 2020). This half is partly recycled by uncertified recyclers, partly dumped in regular waste bins and partly exported for reuse. When exported illegally to developing countries, regulations and labour reinforcement are not in place or are not effectively enforced (Lundgren, 2012). Resulting in the e-waste being dumped or recycled unsafely (Robinson, 2009), (Cayumil et al., 2016).

2.1.1 VARIETY IN E-WASTE

One of the challenges of e-waste recycling is the wide variety of products, which require different recycling processes. These products not only vary in size, but they also contain different qualities of electronics, resulting in different economic values for these products (Balde et al., 2015). Also, more and more materials are being used in a single electronic product, while they are becoming increasingly complex and smaller (Greenfield & Graedel, 2013). This variety adds complexity to the recycling process as these different products require different treatment.

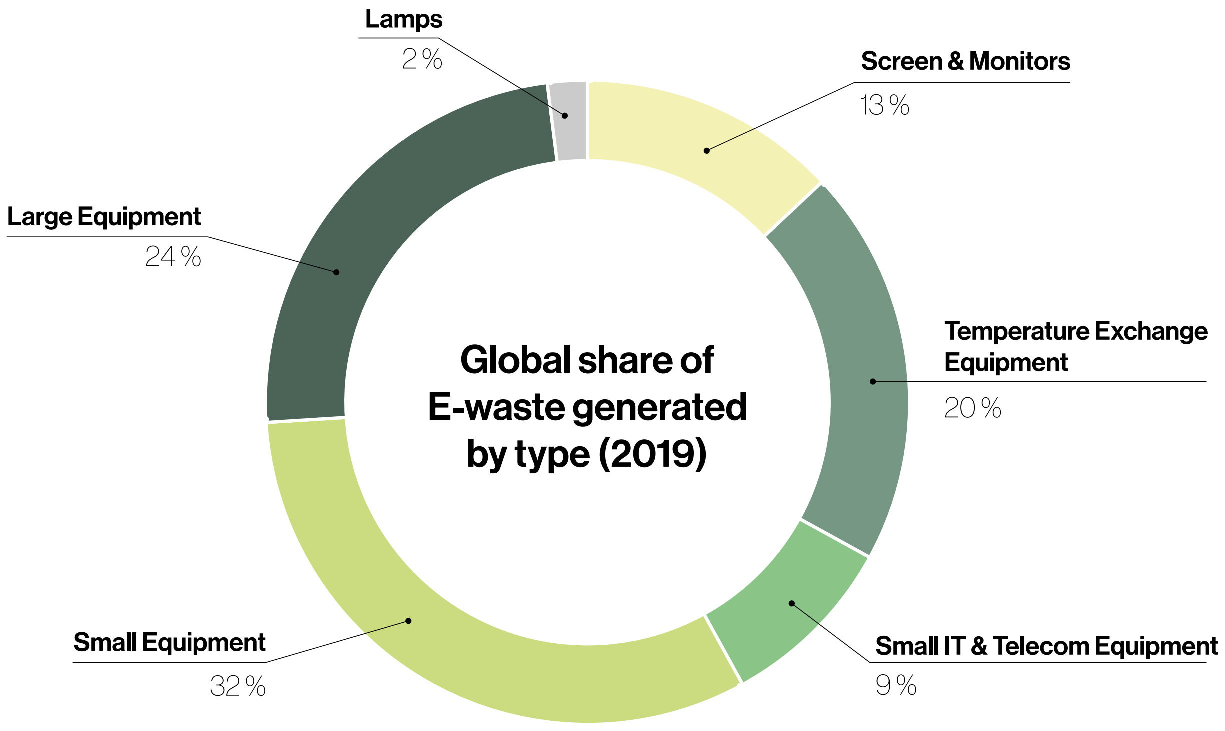


FIGURE 2 Categories of E-waste and their size (Statista, 2023a), (What Is e-Waste, n.d.)

2.2 RECYCLING PROCESS OF E-WASTE

The recycling process consists of several stages. A simplified overview, based on the process of an electronics recycling facility in the Netherlands, is shown in Figure 3. This overview focuses on the dismantling, liberation and separation phase, which are explained in more detail in the following sections. In addition, this section briefly outlines the key techniques used in the recycling process, focussing on the separation of materials.

As mentioned before, different types of electronics require different recycling processes. This process outline therefore focuses on televisions, providing context for understanding the recycling process of the products used in this study.

DISMANTLING

During the dismantling phase, also known as depollution, products are manually pre-sorted to remove any hazardous components or contaminants. In the case of TVs, screens are carefully checked for mercury content. This is done through random tests on large batches of screens. If mercury is detected, they are processed separately in a mercury-controlled line.

Occasionally, TVs also contain batteries, which are a potential fire hazard and therefore must be removed before shredding. In the depollution phase, workers use standard destructive tools such as hammers and screwdrivers. They extract contaminants, hazardous materials and valuable components from the products (expert interview, Appendix B).

LIBERATION

In this phase, the shredding (mechanical disintegration) of the products takes place. The shredder grinds the product into small fragments with its cutting knives. In this phase it is important that materials and connections liberate into homogeneous fragments, allowing for effective separation in the subsequent phase.

SEPARATION

During the separation phase, a vibrating conveyor belt transports the materials to the metal finder, where ferrous materials are separated from the rest of the fragments. This technique uses the magnetic properties of the ferrous metals.

A conveyor belt then transports the fragments to an Eddy Current separator. At this stage, fragments containing aluminium are removed from the material. Eddy current separation uses the different electrical conductivity of the metallic and non-metallic fragments to remove most of the non-metallic fragments, such as aluminium (Schlesinger et al., 2022).

The remaining metals are extracted in the subsequent separation step, induction sorting. This technique uses electric induction to separate the remaining metals, such as stainless steel and copper, from the other fragments (Vaško, 2015).

The other fragments are transported to an optical sorter, which separates the plastics from the rest of the materials. This machine uses a puff of air to sort the fragments into the correct material bin. Notably, black plastics are difficult for certain optical sorters to identify. The black colour absorbs (almost) all visual and infrared light, which means that the sensors cannot detect these fragments.

In the last separation step, plastics will be separated by sink-float technology. The high-density plastics will sink and the low-density plastics will float. While the low-density polymers are sent to a plastics recycling facility, the high-density polymers cannot be recovered and will end up as waste (expert interview, Appendix B).

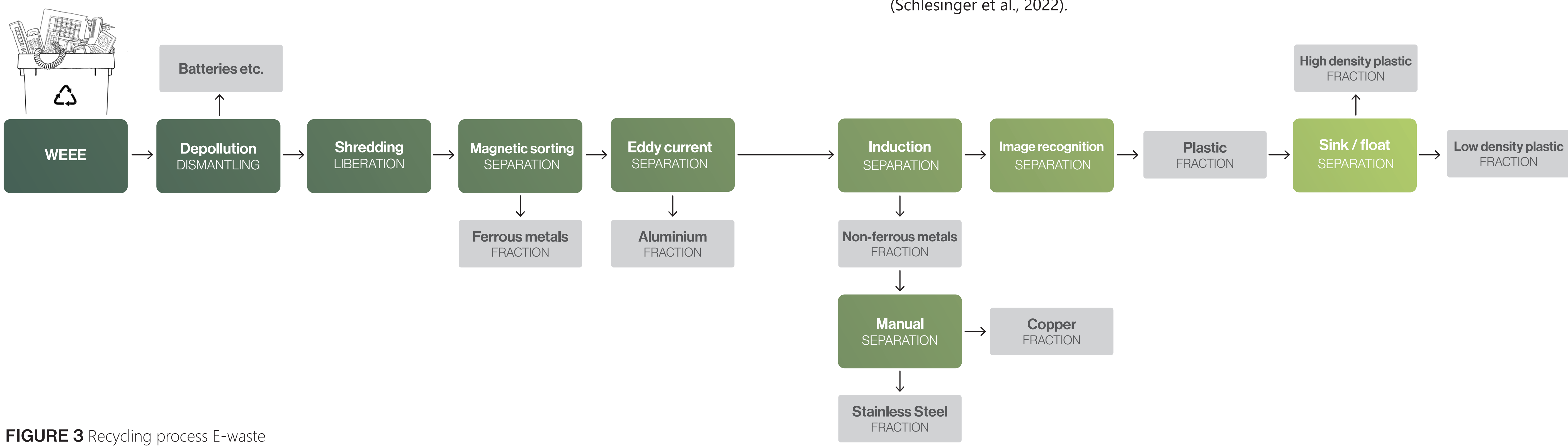


FIGURE 3 Recycling process E-waste

2.3 DESIGN FOR RECYCLING

As briefly mentioned in the previous chapter, design strategies in a circular economy aim to keep materials in continuous use, thereby minimising waste (Ellen MacArthur Foundation et al., n.d.). A circular economy prioritises maintaining maximum value from products and materials through methods such as reusing, repairing, remanufacturing and recycling (see Figure 4). Extending the life of products can significantly reduce the need for raw materials (Ellen MacArthur Foundation et al., n.d.).

While recycling is critical for closing material loops, it's also the stage where much of a product's value is lost. Maximising recycling value requires thoughtful design decisions that may conflict with other design strategies within a circular economy, such as repair.

Ideally, when electronic products are recycled, all materials end up in the correct material fraction and can be fully recovered. However, partly due to inefficiencies in recycling facilities and technologies, but more often due to complex designs, materials end up in an incompatible fraction (Fakhredin, 2018), (Lundgren, 2012). This not only reduces the recovery rate of materials, but also reduces the economic value for recyclers, making it less attractive to recycle these products (Cucchiella et al., 2015). During the shredding process, electronic products often break into heterogeneous fragments, resulting in materials ending up in an incompatible fraction, leading to material losses or contamination of material streams (Fakhrendin, 2018).

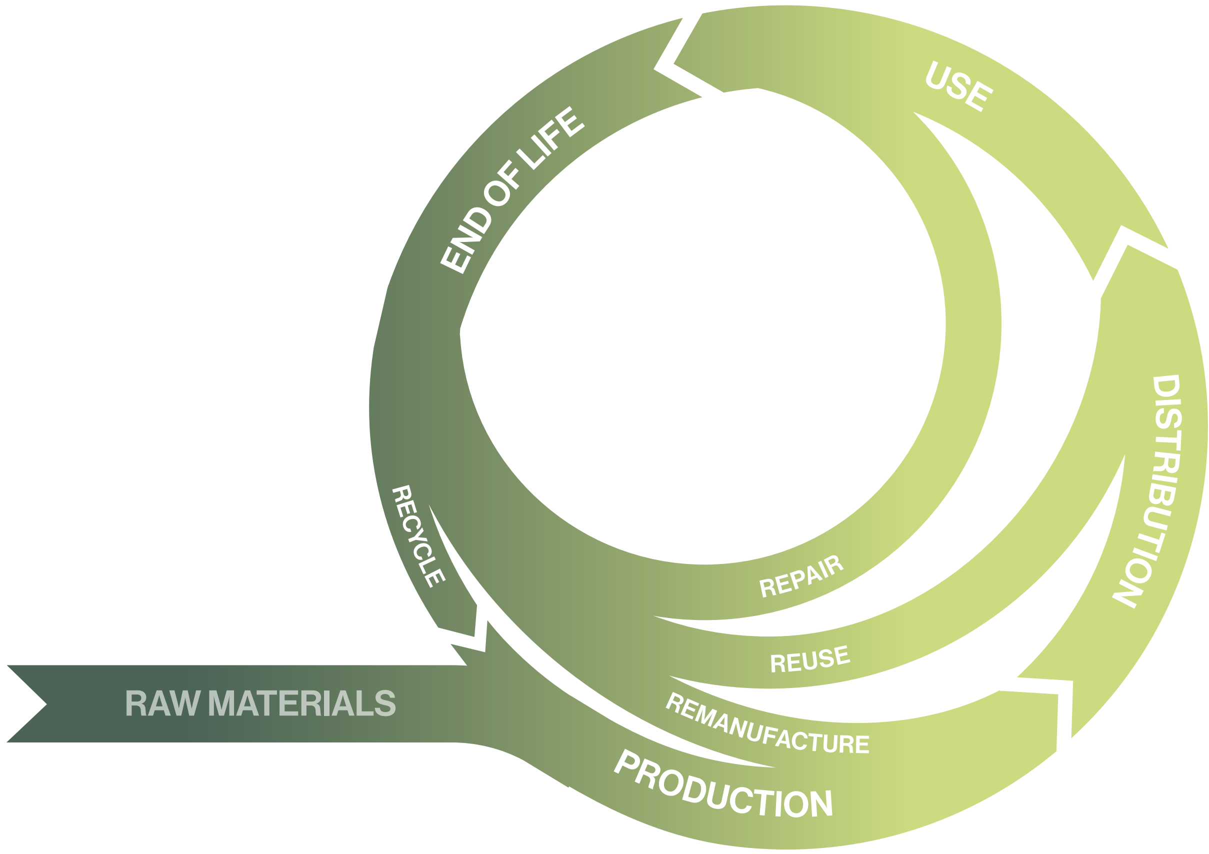


FIGURE 4 Circular economy

From a design perspective, products could be designed differently to ensure more efficient separation of materials during the recycling phase. In the literature, there is already some research found on how to design for recycling. However, looking at current recycling practices, many products are still not optimally liberated and separated (Fakhredin, 2018). Next to optimising products for recycling, it would also be important to investigate the impact of these design choices on other circular strategies, such as repair.

2.2.1 RECYCLABILITY EVALUATION METHODS

Current Recyclability Evaluation Methods often derive from Design for Disassembly methods (Kroll & Hanft, 1998; Bogue, 2007; Castro et al., 2005). Design for Disassembly is based on (partial) manual dismantling. These methods use ease of disassembly as a measure for assessing the recyclability of a product. However, in practice, products are rarely manually dismantled due to the lack of economic feasibility (Peeters et al., 2017).

There are models based on practical experiments, which often illustrate the relationship between product design and levels of liberation during shredding. These models simulate the behaviour of a product during shredding. They take factors into account, such as the type, quantity and dimensions of connections and assessing both the liberation and contamination levels of the recovered material streams (Castro et al., 2005; Van Schaik & Reuter, 2010). However, despite their effectiveness, these methods lack intuitiveness and accessibility, which limits their usefulness for design practitioners.

Therefore, this project focuses on researching product and part characteristics that influence the liberation and separation of electronic products. It aims to support designers by providing insights on how to consider these characteristics during the design phase. This is not only about optimising the recyclability of a product, but also about enabling designers to make informed design choices by evaluating trade offs between repairability and recyclability. Giving designers a deeper understanding of how design decisions impact different sustainability considerations.

CHAPTER 03

PRODUCT & PART CHARACTERISTICS

This chapter analyses four smart TVs in terms of their product and part characteristics. These characteristics include the materials and masses of the parts and the connections between them. Factors influencing recycling are identified through literature research. These factors are used as a framework for the analysis of the smart TVs.

3.1 INTRODUCTION

This chapter will dive into the product and part characteristics of smart TVs, as well as provide a theoretical framework of factors that influence the recyclability of a product, based on literature. To analyse which product and part characteristics have the most impact on the liberation process, it is necessary to map these characteristics before conducting the recycling experiment. This chapter addresses the sub-research question:

- What are the product and part characteristics of a smart TV?

Product and part characteristics refer to all components within the product, including their connections, masses, and materials. The study includes an analysis of four different brands of smart TVs, expecting to cover a wide range of connections and product architectures. Table 1 displays the specifications of the smart TVs analysed in this study. The TVs vary in size and specifications, in Figure 5 overview of the dimensions on scale and their price can be found. This reflects the variety of screens used in this study.

The following sections provide a more detailed description of the factors expected to affect product recyclability. As these factors could play a significant role in the results of the shredding experiment, they serve as a starting point for the analysis of the current product and part characteristics of the smart TVs. Following this relevant literature (section 3.2), the method for the analysis of the smart TVs is described (section 3.3). The results are presented in section 3.4 and discussed in section 3.5.

TABLE 1 specifications of the smart TVs used in this research (all specifications exclude the standard of the TV).

BRAND AND TYPE	**PANEL TYPE**	**SCREEN SIZE** (inch)	**SIZE W x H x D** (mm)	**MASS** (g)	**YEAR**
Panasonic TX-40JXW834	LCD	40"	904 x 524 x 65	7000	2021
Sony KD-43X80J	LCD	43"	972 x 567 x 70	10000	2021
Samsung GQ55QN95AAT	Neo QLED	55"	1227 X 706 x 26	16800	2021
LG OLED55C17LB	OLED	55"	1228 x 706 x 47	18900	2021

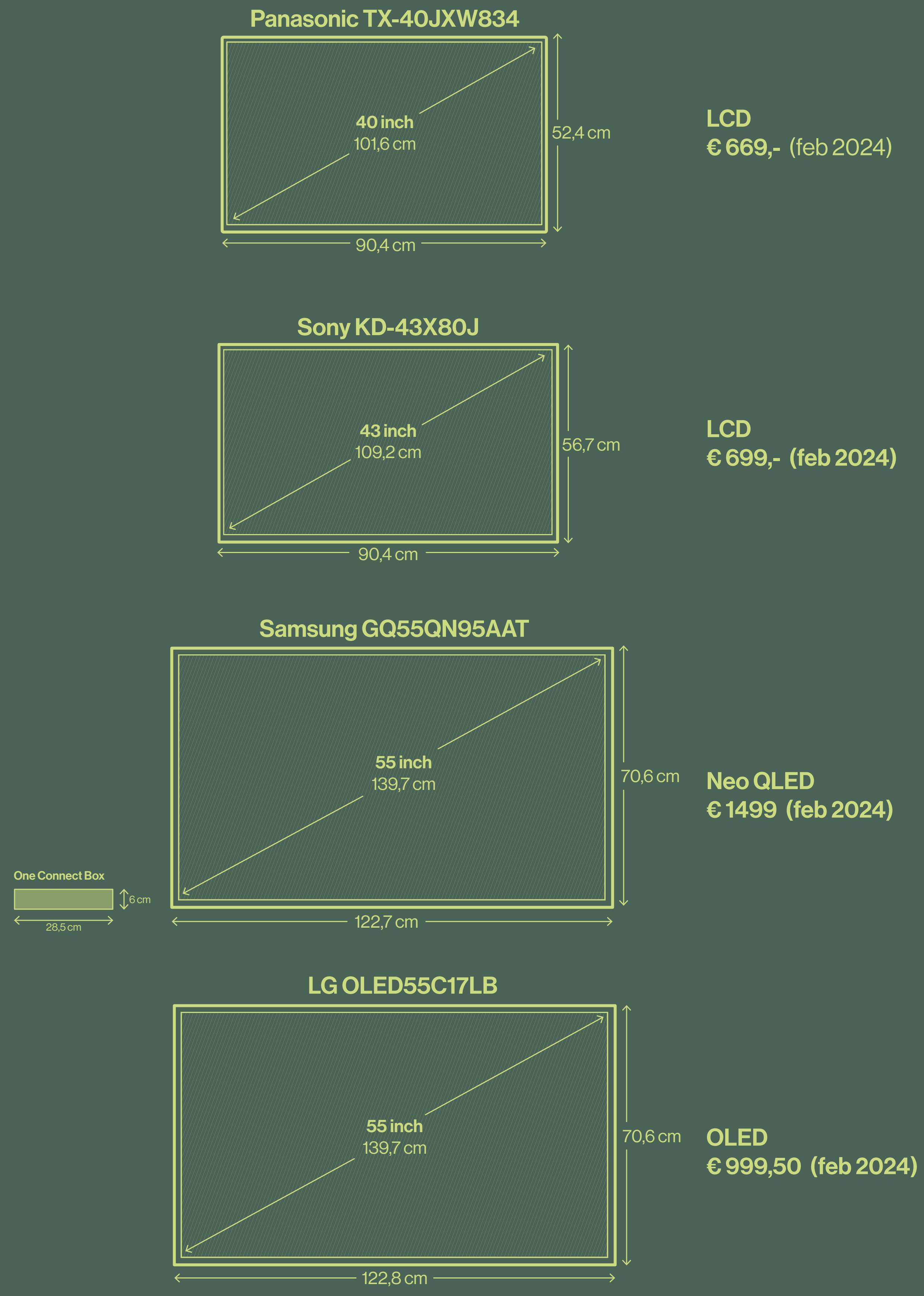


FIGURE 5 Relative sizes of the smart TVs used in the study (Tweakers, n.d.-a; Tweakers, n.d.-b; Tweakers, n.d.-c; Tweakers, n.d.-d

3.2 INFLUENTIAL PRODUCT AND PART CHARACTERISTICS IN RECYCLING

Influential product and part characteristics for recycling can be found in the literature. The combination of materials and connections used in a product, and how they are placed in the product architecture, largely determine the recyclability of a product. In the following sections, influential factors related to materials and connections are described.

3.2.1 MATERIALS

The material composition of a product has a strong influence on its recyclability (Xing et al., 2003). Some materials are hazardous or toxic and must be removed manually, some are not recoverable in existing recycling processes, and some are incompatible with other materials which may cause losses or contamination. For these reasons, careful material selection is crucial in Design for Recycling.

Recyclable materials
The recyclability of a material is determined by its properties (Henstock, 1998). Many materials are theoretically recyclable but lack the necessary recycling infrastructure. Recycling technologies are developed for specific materials, meaning that a material can only be recovered if the recycling technology is available (Sakundarini et al., 2014). Current recycling practices are influenced by the financial incentives for recycling facilities to develop the necessary technologies. This is often determined by the recyclability of a material and the frequency of its use in products. It is therefore advantageous to design products with materials that can be easily recycled using the existing recycling infrastructure.

Hazardous materials
E-waste can contain hazardous and toxic materials that pose a risk to the environment and human health. Hazardous materials may cause flammability, corrosiveness or reactivity (Zhang and Yu, 1999; De Aguiar et al., 2017). For example, batteries can explode and cause fires in recycling facilities, and brominated flame retardants, a filler used in certain plastics, have been linked to neurological damage, hormone disruption and cancer (Safer States, 2023). For this reason, some parts or materials must be manually removed or depolluted before products are shredded. European CENELEC standards specify how e-waste should be treated and what needs to be manually removed during the depollution process to ensure environmental and human safety (Sichting Open - CENELEC, 2023).

Compatible materials
Material compatibility is related to the effect of maintaining two or more materials together during recycling. When a connection between two different materials stays intact, the compatibility of the materials and the connection material plays an important role. Next to their individual recyclability, it is desired that those materials can be processed with the same recycling technology. For example, when a ferrous metal is connected to a non-ferrous metal, one of these materials will be lost in reprocessing. In a worse case, an incompatible material can pollute another material stream. This pollution could, for example, lead to difficulties in reprocessing, or to degradation of the mechanical properties of the recycled material (De Aguiar et al., 2017), (Shu et al., 1995). When two materials are compatible this eliminates the need to completely separate these materials for recovery.

3.2.2 CONNECTIONS

The recycling process's effectiveness is significantly influenced by the connections used to connect parts and materials to each other (Xing et al., 2003). Some connections break down easily during shredding, others might remain intact. Intact connections may result in ineffective separation, leading to material losses or pollution of material streams. To avoid this, the way materials are connected should be carefully considered when designing products. To improve recyclability, also the types and number of connections should be consistent and supportive for easy removal of hazardous components during dismantling.

Connection types
Different types of connections, have different behaviour during the shredding process (Fakhredin, 2018). In products, a wide variety of connections is used, which influences its recyclability. Considering the behaviour of connections is therefore important in Design for Recycling.

Connections can be grouped according to their bonding mechanism: form closure, force closure and material enclosure (Pahl & Beitz, 1996). Within these groups, or a combination of these, specific connections are identified based on the analysis of the smart TVs. (Figure 7).

Mechanical connections are mostly categorised under form and force closure, such as screws and snap-fits (Steinfelder et al., 2021). Material enclosure includes chemical bonds such as coating, welding and gluing. These connections initiate a chemical change at the interface of a part's material, forming the connection (Gibbons, 1992).

Special attential is given to the electrical connections. An electrical connector is a component that forms a detachable electromechanical connection between two parts of an electronic system, mostly through wires (Kyeong & Pecht, 2020).

Electrical connections can be formed through a variety of means, for example by using a connector housing, a screws or by soldering. Regarding these connections, wires with connector housings are the only ones identified in the smart TVs. This connection uses a combination of two bonding mechanisms: form and force closure. This mechanism is shown in Figure 6, where force closure is exerted by the pressure of the contact spring on the contact interface, and the form closure is created by the housing itself using a locking mechanism. Three types of locking mechanisms have been identified in the smart TVs: side lock, top lock and fold lock connections.

Quantity of connections
The number of connections should also be considered in product design. The strength required to break a connection during shredding depends on the quantity of connections between materials (Xing et al., 2003). During dismantling, the quantity and type of connections is directly related to the ease of removing valuable of hazardous components.

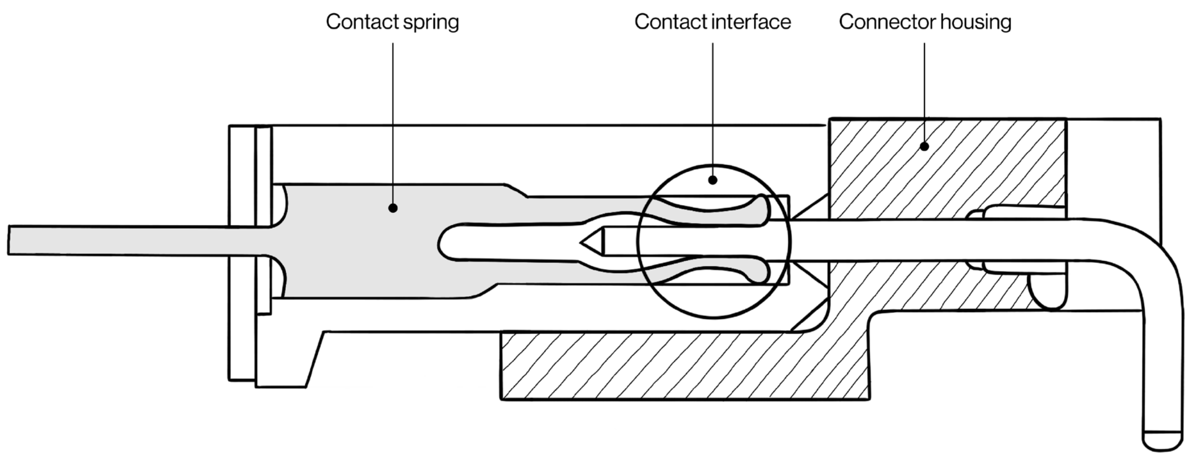


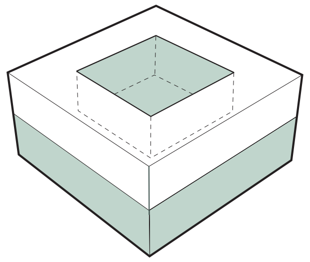
FIGURE 6 Components of an electrical connector (Kyeong & Pecht, 2020)

FORM CLOSURE

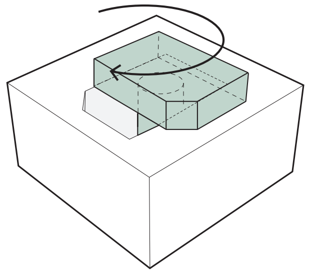
Establishing mechanical contact between joining surfaces of the components to be connected. By geometric constraints the components form a connection. The connection does not need a costant force acting on one of the surfaces in order to stay intact.

Other form closure connections:

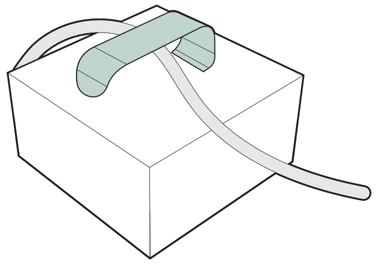
- turn-press connection
- press connection



Friction fit



Turn lock



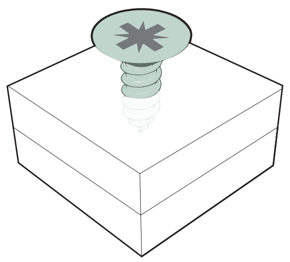
Hook

FORCE CLOSURE

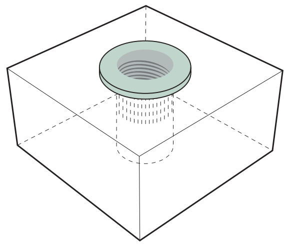
Establishing mechanical contact between joining components through an exerting force. When the force pressing the parts together is eliminated, the connection is no longer secured.

Other force closure connections:

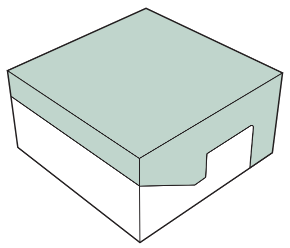
- Velcro
- Nut & Bolt



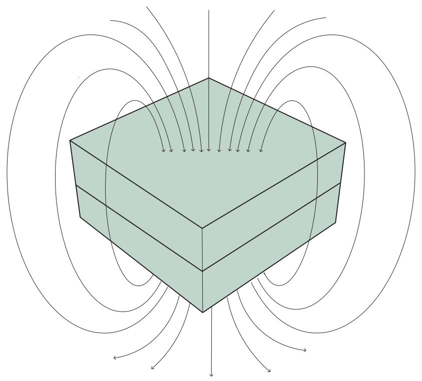
Screw



Insert



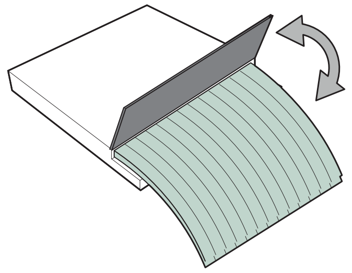
Snap fit



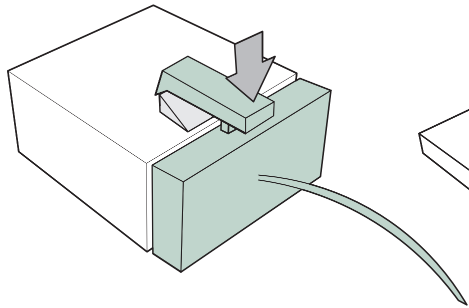
Magnetic attachment

FORM & FORCE CLOSURE

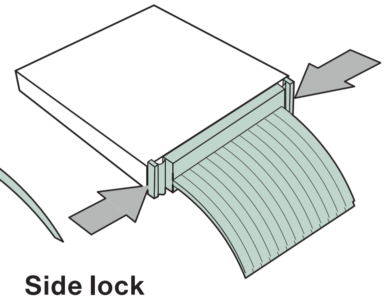
A combination of a form and force closure. Even when the geometric constraint is removed, the force of the contact spring remains active. The form closure is formed by the connector housing and can be removed by pressing on one of its sides. The direction in which the form closure can be removed depends on the type of lock used.



Fold lock



Top lock



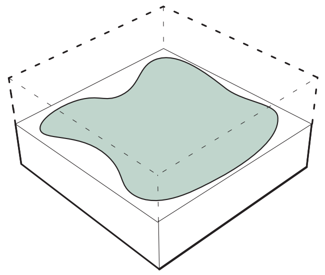
Side lock

MATERIAL ENCLOSURE

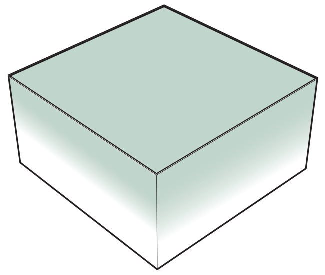
Establashing a connection by material fusion, which is characterised by a connection through atomic or molecular forces.

Other material enclosure connections:

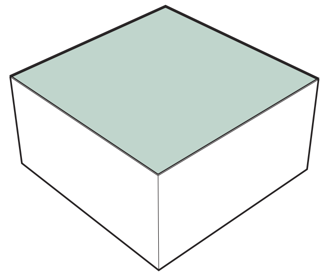
- Welding



Glue



2K injection moulding



Coating

FIGURE 7 Types of connections based on their bonding mechanism

3.3 METHOD FOR MAPPING PRODUCT CHARACTERISTICS

The product and part characteristics are analysed by disassembling one smart TV of each model. Subsequently, the smart TVs were mapped through product architecture maps, which will be presented in Chapter 6. In the following sections the disassembly procedure and the subsequent mapping of the product and part characteristics is described.

3.3.1 DISASSEMBLY PROCEDURE

The TVs were disassembled to component level using basic hand held tools, followed by a thorough documentation of each component. Throughout the process, two videos were recorded from different perspectives (top and side view) to serve as references for future stages of the project. Notable findings were documented by detailed notes and supporting images.

Following disassembly, each component was listed in a BoM, with its quantity, mass and material specified. In addition, the connections were examined and systematically categorised according to previously defined categories in section 3.2.2.

The following sections provides a more in-depth description of the methodology used to create the BoM and how the identification of the connections were identified. A list of all the tools and equipment used in this study is provided in section 3.3.5.

3.3.2 IDENTIFICATION OF MATERIALS

The materials were initially classified by visual identification into four main material groups: metals, polymers, electronics and glass (Figure 8). The electronics category included PCBs, wires and speakers. Due to the complexity of these parts, the electronics were not further disassembled and categorised as electronics, also aligning with the desired separation of electronics in the recycling process.

Metals
Metals were further identified using the magnetic properties of materials to distinguish ferrous from non-ferrous metals. Ferrous metals were considered to be steel, as this material is commonly used in this type of products. Non-ferrous metals were further differentiated on density.

Polymers
For polymers, material specifications were obtained either directly from the material or through Fourier Transform Infrared (FTIR) spectroscopy. The density of polymers identified through FTIR spectroscopy was also measured, supporting the identification process.

The aim of this material identification process was to determine the appropriate material fractions for the recovery of all the parts.

FTIR Spectroscopy
FTIR is an analytical technique identifying organic, polymeric, and sometimes inorganic materials. It uses infrared light to scan samples and observe their chemical properties. The instrument sends infrared radiation through a sample, the absorbed radiation is material specific and provides a unique spectral fingerprint. This fingerprint allows for the identification of different types of polymers.

Densimeter
A densimeter was used for measuring the density of non-ferrous metals and polymers. Metals can be easily distinguished through the density of the material (Understanding Product Engineering, 2023). In the case of polymers, it can be used in combination with FTIR spectroscopy to support identification.

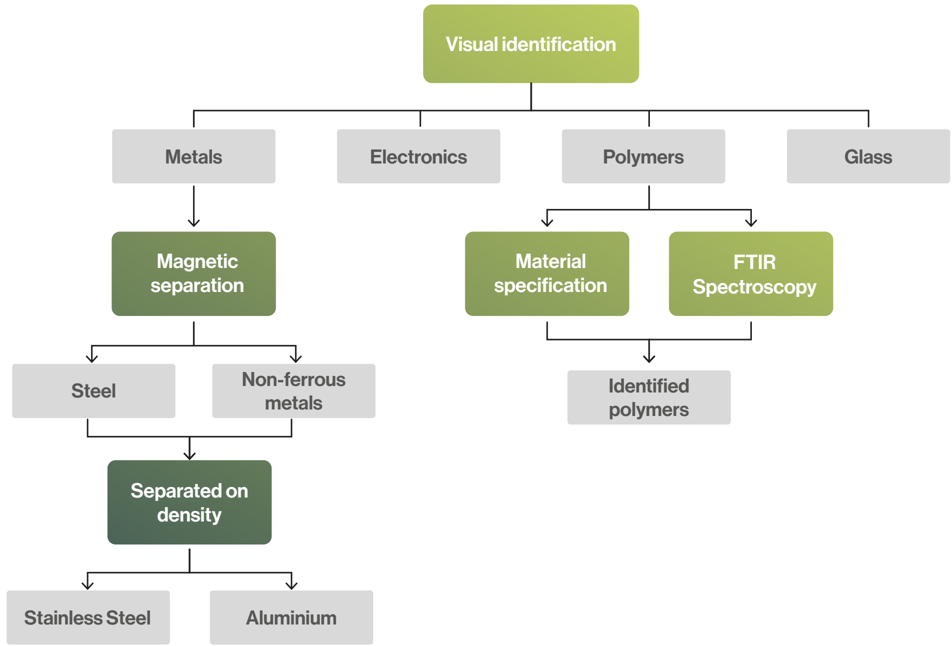


FIGURE 8 Material identification process

3.3.3 IDENTIFICATION OF CONNECTIONS

A combination of photos, videos and notes was used to document the connections within the smart TVs. This allowed them to be categorised according to the type of connection. It's important to note that electrical connections such as LVDS, jump wires, Molex cables and ribbon cables were not distinguished. Instead, all electrical connections were categorised according to their connector housing, as explained in section 3.2.2.

3.3.4 MASS OF PARTS

All components of the smart TVs were weighed using either a weighing scale or a mechanical force gauge. Fitting equipment was selected based on size and flexibility, considering components like screens, polarizing panels, and reflector panels. The BoM specifies the equipment used for each component.

3.3.5 EQUIPMENT AND TOOLS

TABLE 2 Tools and equipment used for the smart TV analysis

TOOL OR EQUIPMENT	SPECIFICATION	USE	METRIC
Scale	KERN 572 Max. 16100 g, d=0,2 g	Weighing parts	gram (g)
Digital Force Gauge	SH-500N	Weighing parts	Newton (N)
Densimeter	Hildebrand SG Resolution = 0,001 g/cm³ capacity =300 g	Measuring the density of a material	g/cm³
Phone Tablet Laptop and webcam	Apple IPhone 11 Apple IPad 9 Logitech capture	Photographing and recording the disassembly	-
FTIR	Perkin Elmer Spectrum 100 series	Identifying polymers	IR spectrum

3.4 RESULTS OF ANALYSIS SMART TVS

The results of the analysis are divided into three sections: product architecture (section 3.4.1), materials (section 3.4.2), and connections (section 3.4.3). The product architecture section relates to the structure of the smart TVs, the materials section analyses the material and its masses, and the connections section examines the type and number of connections in each smart TV. The BoM of each product documents the constituting parts, including their mass, quantity, and material and can be found in Appendix C.

3.4.1 PRODUCT ARCHITECTURE

The TVs vary in size and specifications, but a typical product architecture can be deduced from the disassembly procedures (Figure 9).

Generally, a smart TV is built up from several layers, including the screen assembly, a metal chassis to which the majority of electrical components are attached, a frame connecting the chassis to the screen assembly, and a plastic back cover for internal component shielding. The electronic components include a motherboard, a power board, one or multiple speaker assemblies, wires, and several other PCBs (e.g. buttonboard, IR sensor board).

In contrast to the integrated design of the other models, the Samsung TV is equipped with an external box that houses the majority of its electronic components.

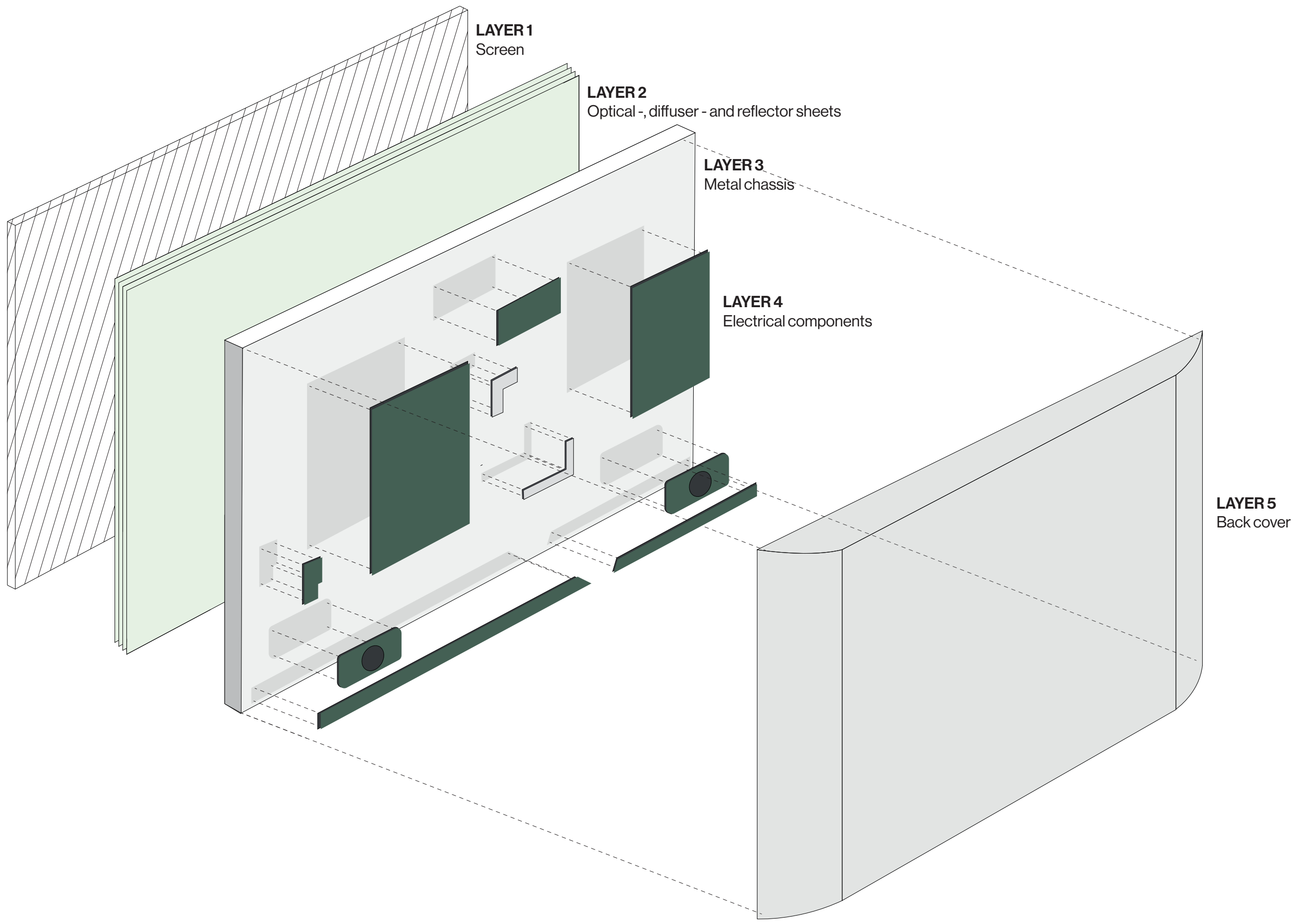


FIGURE 9 Typical product architecture of a smart TV

3.4.2 MATERIALS BEFORE SHREDDING

The materials were categorised according to their material groups: polymers, ferrous metals, non-ferrous metals, electronics, and glass. While the mass distribution of materials varies across models, interesting differences can be found. For instance, findings reveal that the LG TV predominantly consists of ferrous metals (63%) and some polymers (10%), whereas other TVs typically comprise around 30% ferrous metals and 30% polymers (see Figure 10).

Furthermore, the study reveals a general trend: as the overall mass of the TV increases, so does the mass of electronics utilised. For example, the Samsung TV, the heaviest model, contains the highest mass of electronics at 4,7 kg, constituting 24% of its total mass. Furthermore, the glass, derived from the screen, typically constitutes around 15% of a TV's total mass, although this amount rises to 20% (1,26 kg) for the Panasonic screen.

Non-ferrous metals are used in smaller quantities, with the Panasonic TV using the highest amount at 32 grams. Notably, aluminium is the primary non-ferrous metal used across the TVs.

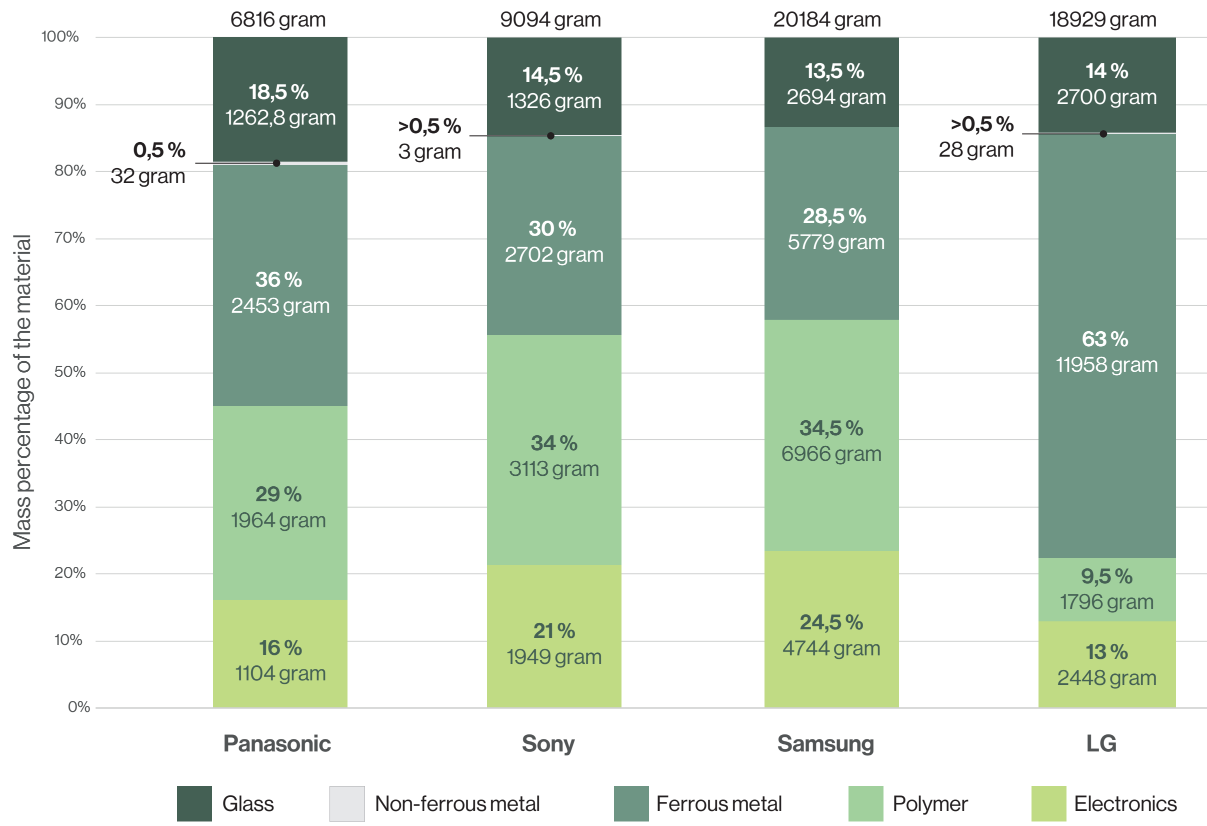


FIGURE 10 Material division per TV model

FTIR Results

The FTIR spectroscopy results indicate the amount of recyclable plastics in each TV (Appendix D & Appendix E). According to recycling experts, the common recyclable plastics are PE, PS, PP, ABS, PC-ABS. All other plastics are not recyclable with the current recycling infrastructure. Table 3 shows the masses of plastics in each TV and the FTIR identified plastics are listed in the last column.

TABLE 3 Plastics in the smart TVs

TV MODEL	RECYCLABLE PLASTICS	NON RECYCLABLE PLASTICS	UNIDENTIFIED PLASTICS	IDENTIFIED PLASTICS (FTIR)
Panasonic	**99,2%** 1783 gram	**0,4%** 7,6 gram	**0,2%** 3 gram	PA PDMS (with conductive fillers)
Sony	**65,7%** 1922 gram	**34,1%** 1000 gram	**0,2%** 4,8 gram	PA6.10 or PA6.12 PC PDMS (with conductive fillers) PA
Samsung	**42,5%** 3284 gram	**50%** 3861 gram	**7,5%** 578 gram	PC PDMS (with conductive fillers) PBT PA PDMS
LG	**99,3%** 1783 gram	**0,5%** 9,8 gram	**0,2%** 3 gram	PC PA PDMS

Looking at the results, the LG and Panasonic models in particular show that almost all of the plastics are recyclable. However, for the Samsung model, less than half of the plastics can be recycled. The plastics identified are mainly PDMS, with or without conductive fillers, PA, PC.

3.4.3 CONNECTIONS BEFORE SHREDDING

Connections were identified and compared based on their quantities (Figure 12). Among the form- and force closure connections, the majority was found to be screws and snap fits. In the material closure category, glue and coatings were identified as the most commonly used connections.

Notably, the Panasonic model has the fewest connections in total (138), whereas the Samsung model contains the most (195). With regard to electrical connections, fold locks are the most commonly used connection. Which are typically used for flat flexible cables (FFCs).

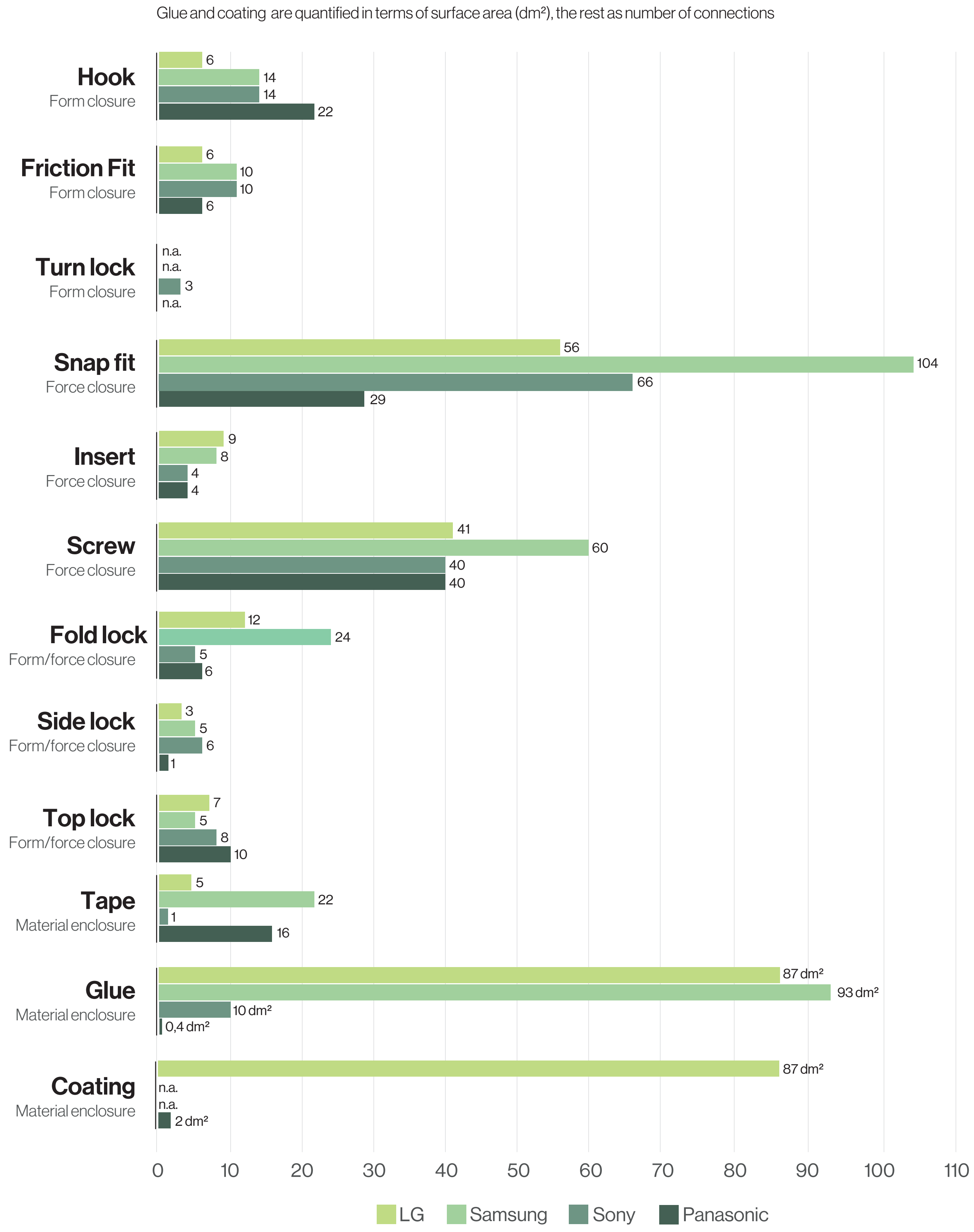


FIGURE 12 Connections before shredding in each TV model

3.5 DISCUSSION & CONCLUSION OF THE ANALYSIS OF SMART TVS

The sub-research question addresses in this chapter was:

- What are the product and part characteristics of a smart TV?

To answer this question, four different brands of smart TVs were analysed. This chapter identified the product and part characteristics to understand their influence on fragmentation during the shredding experiment. While these insights do not cover all potential material uses, connections, and product architectures for smart TVs, they provide a comprehensive overview of the relevant product and part characteristics for product design considerations.

In addition, the defined and quantified product and part characteristics provide a basis for analysing the results of the subsequent recycling experiment of the next chapter. The overview of product and part characteristics of the smart TVs resulted in a BoM for each model and an overview of the number of connections of each type.

3.4.1 LIMITATIONS

- Some connections are used in small numbers, it might be difficult to draw reliable conclusions on their behaviour after the shredding experiment.
- Stickers are not taken into account. The stickers do not connect parts to each other and are therefore left out of scope.
- Some polymers were not identified by FTIR spectroscopy and therefore remained unidentified in the rest of this research.
- Tape is not documented in BoM, since it has a weight of less than 0,2 grams, however the tapes are counted as connections.
- The screen is considered to only exist out of glass. In reality, the material also exists out of diodes, sometimes polarising panels and other layers. For the comprehensiveness of this analysis, this is left out of scope.

3.6 TAKEWAYS

- The most commonly used connections are snap-fits, screws and glue.
- The models typically exist out of steel, polymers and electronics, glass and a minor amount of aluminium.
- The amount of reyclable plastics used in each model differs widely (42,5%-99,3%)
- A smart TV typically exists out of a screen assembly, a metal chassis to which the majority of electrical components are attached, a frame connecting the chassis to the screen assembly, and a plastic back cover for internal component shielding.
- The electronic components in a smart TV include a motherboard, a power board, one or multiple speaker assemblies, wires, and several other PCBs, such as buttonboard and IR sensor boards.

4.

CHAPTER 04

SHREDDING EXPERIMENT

In this chapter the shredding experiment will be elaborated. Including its method, results and conclusions.

4.1 INTRODUCTION

This chapter presents an in-depth analysis of the current recycling behaviour of smart TVs, focusing on how product and part characteristics influence the liberation and subsequent separation of materials during recycling processes. By investigating these characteristics, the aim is to gain valuable insights into how to design electronic products for more efficient recycling. This chapter will address the following sub-research question:

- How do the product and part characteristics of a smart TV affect the liberation and separation during the recycling process?

The liberation of materials during the recycling process is crucial for accurate material separation. This means, when all connections between different materials have been broken down, fragments will be homogeneous and allow for more effective separation into clean material fractions. The composition and quality of the material fractions determine the yield of the material recovery. Therefore, the liberation and separation highly affects the recovery of materials.

In the previous chapter, the smart TVs' materials and connections have been mapped, resulting in an overview of the characteristics of each model. Now, the effect of shredding by comparing the resulting fragments with the initial product and part characteristics will be analysed. The method used for the shredding experiment and the subsequent analysis is elaborated in the following paragraph. To ensure accuracy of the results, the experiment involves shredding four smart TVs of each model. The results of the shredding experiment will be presented in section 4.3 and discussed in section 4.4. Finally, a list of takeaways will be presented, which will be used to create methods based on practical insights in the following chapters.

4.2 METHOD FOR THE SHREDDING EXPERIMENT

The study is divided in two parts (Figure 13). The first part focuses on the process towards the shredding experiment and the experiment itself. The second part focuses on the sorting of the fragments. Also, the method for analysing the fragments and for the interview with recycling experts is described. The tools and equipment used during the study can be found in section 4.2.5.

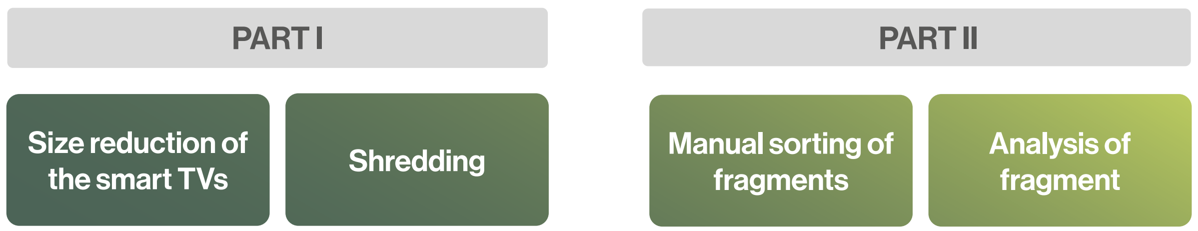


FIGURE 13 Shredding experiment build up

4.2.1 PART I LIBERATION

The first phase of the recycling process is the dismantling phase, focusing on the removal and treatment of hazardous materials. Since the LED illuminated screens contained no mercury, they did not require separate treatment in a specialised recycling line. Also, as the TVs did not contain batteries, there was no need for depollution.

Size reduction
Before shredding, the TVs were cut down in parts of a maximum of 45 x 45 cm to fit into the small-scale shredder. This task was carried out by three employees in the manual disassembly area of the recycling facility, using a jigsaw. Once cut to size, the parts were sorted into boxes separated by brand.

Shredding
The shredding process was conducted at a recycling facility for electronic waste in the Netherlands. Utilising a low-speed, high-torque, four-shaft, rotary shear industrial shredder, a smaller version of the main shredder typically employed for these type of products. The small-scale shredder was used for ensuring minimal contamination of the fragments and for the ability to collect all fragments directly from the shredder. Also, given the relatively limited scale of this experiment, the use of a larger shredder would risk the loss of numerous fragments in the subsequent recycling line. The working principle of the shredder is shown in Figure 14.

Prior to the experiment, the shredder was cleaned by running it empty until no residual fragments came out of the machine. This ensured minimal contamination during the experiment. The different brands of TVs were then shredded in separate batches and collected in a closed boxes. Between batches the shredder was cleaned, to prevent cross-contamination. The operation of the shredder and the placement of the TVs on the conveyor belt was managed by an employee of the recycling facility, ensuring consistency and safety throughout the process.

Documentation
The TVs were collected by brand in order to relate the product and part characteristics back to the original state. Throughout the experiment, videos and photographs were taken of the process and the resulting fragments, and notable observations were documented.

Limitation of the small-scale shredder
Due to the limitations of the small-scale shredder, only two LG TVs were shredded, as the shredder did not have sufficient power to cut through parts of this model. Therefore, some parts of the LG TVs were partially manually disassembled before shredding. This disassembly included the unscrewing of a metal bar. This created a distinction between LG TVs with and without this metal bar.

4.2.2 PART II SEPARATION

To understand the liberation of connections during shredding throughout the experiment, all fragments resulting from the shredding were analysed. Ideally, fragments would consist of a single material to facilitate separation and treatment in the appropriate material fraction. However, fragments containing multiple materials indicated that the connections were not fully broken down during shredding, resulting in (part of) the fragment being misplaced in an incompatible fraction. The following section describes the method for the manual sorting process and the subsequent analysis.

Sorting of the Panasonic TVs
The Panasonic fragments were sorted into different fractions, including metals, polymers, electronics, glass, screen panels (optical, reflector, and diffuser panels), dust (particles <1cm2), and mixed fractions. A fragment was sorted into a mixed fraction when a connection remained intact. After sorting, all particles smaller than 1 cm2, they were checked for homogeneity and then categorised as dust. Due to time constraints, handpicking these small particles was not feasible. The mixed fraction was further sorted into:

- Mixed: fragments with multiple materials still attached.
- Mixed homogeneous: fragments of the same material with an intact connection. E.g. a wire connected to a PCB.
- Mixed during the process: fragments with multiple materials that were not connected before shredding, often due to steel folding in other materials.

Further analysis of Panasonic's mixed fractions involved separating the mixed fractions by using basic tools (e.g. screwdrivers and hammers). This was done to determine the masses of all materials in the mixed fragments. Based on insights from an interview with recycling experts, the expected material losses of the mixed fragments due to incorrect separation, were determined. These considerations resulted in a mass balance of the Panasonic model, visualised in a Sankey Diagram (section 4.3.1).

SORTING OF THE OTHER MODELS

The sorting process for the remaining screens was done differently than described for the Panasonic model. For the Samsung, LG and Sony model, mixed fragments were sorted according to intact connections (e.g. snap-fit, friction-fit or screw), while homogenous fragments were not further sorted. This led to a more efficient sorting process, focusing on connections.

Fractions:
- Threaded connections (screws and inserts)
- Adhesives (glue, tape (also small pieces) and stickers)
- Force and form closure (friction fits, snap fits, hook connections)
- Magnetic material from the speakers
- Coating
- Mixed during shredding
- Multiple connections: a fragment that has multiple different connections and can therefore not be categorised into one fraction, for example a fragment where materials are connected with a screw connection and a glue connection.
- Homogenous

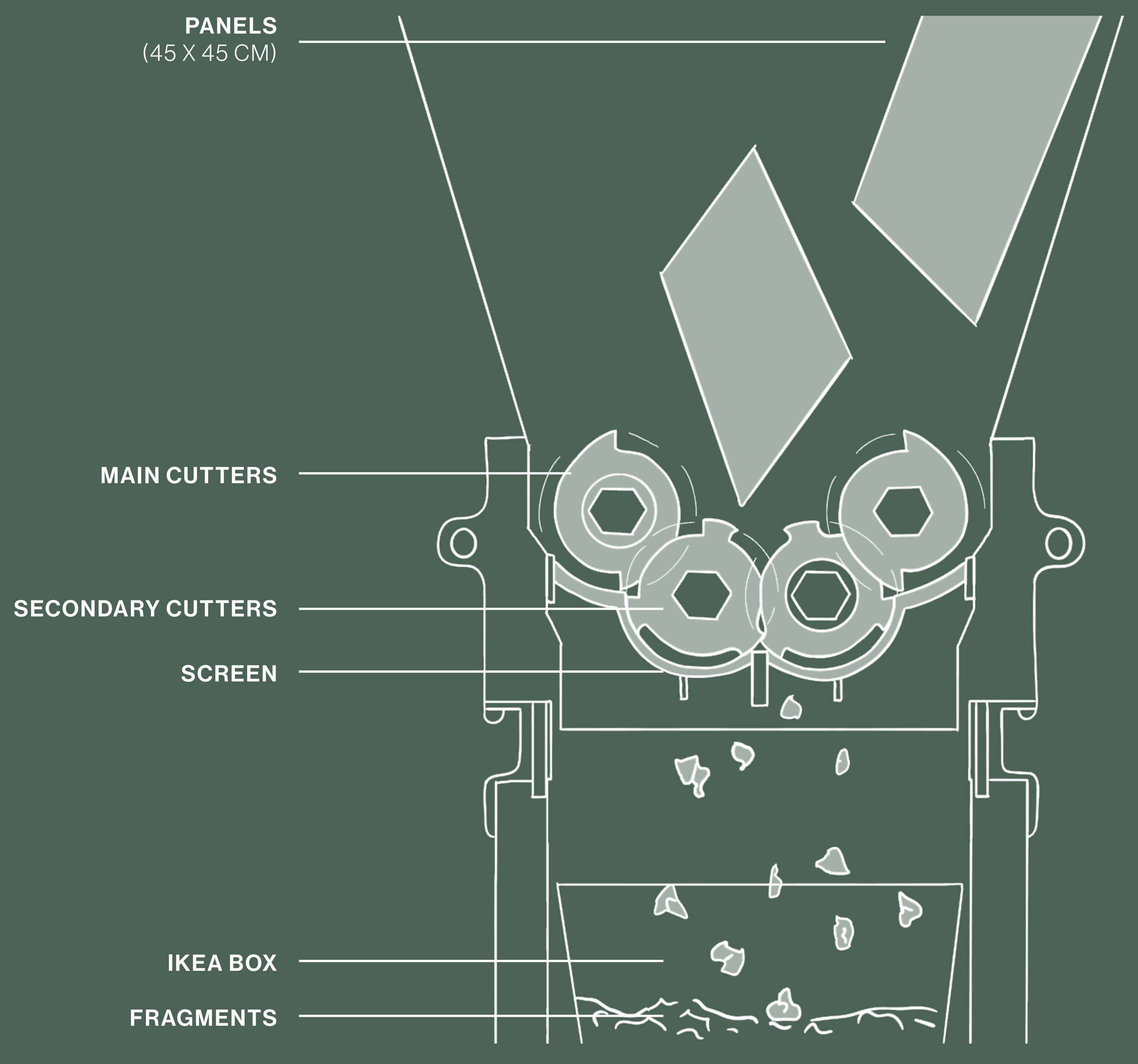


FIGURE 14 Working of the shredder

4.2.3 ANALYSIS OF FRAGMENTS

After manual separation of the fragments, all fractions were weighted. The resulting masses allowed for analysing the material involved in each fraction. Also, all intact connections for each connection type were counted. For connections quantified in terms of connected surface area - glue and coating - an estimation of the surface area of the intact connection was made. This estimation was based on a comparison of the mass of the heterogeneous fragments after shredding, with the original weight of these parts. All heterogeneous fragments were analysed.

A tape connection was considered broken if, after shredding, it no longer connected different materials. When a piece of tape is still connected to one of the two materials, the connection was considered broken down.

Some connections showed varying liberation degrees in the different models. A more detailed analysis was carried out to investigate these differences, taking into account the different materials used, as well as the physical shape of the connections and the parts connected to it.

Margin of error
The margin of error on the liberation data of the connections is calculated using formula 1. This formula is based on the number of connections that remained intact after shredding. It is important to note that this calculation can only be applied to countable connections and not to connections defined by connected surface area (such as glue). Adding this margin to the data allows a more accurate interpretation of the data.

$$\partial_n = \sqrt{n} \qquad (1)$$

Where:
- n - the number of connections after shredding
- ∂_n - the margin of error

LG and the metal bar
In total two LG screens were shredded. The TV without metal bar included 1,36 TV. It may give different results to the 0,64 TV with the metal bar (see Figure 15).

Combining the data from both groups was necessary to ensure equal representation of all connections, as relying solely on data from the 0,64 TV could distort the results. Several snap-fits were connected to the metal bar, so all screw and snap-fit connections from this model were excluded from the results. However, the results remains unreliable even after the TVs have been combined, and this must be taken into account when interpreting the results.

For this study, it is assumed that the intervention of the removal of steel bar of the LG, does not have significant influence on the behaviour on the rest of the connections. Next to the less reliable results of LG, the sample size of this model is also smaller, only containing two TVs.

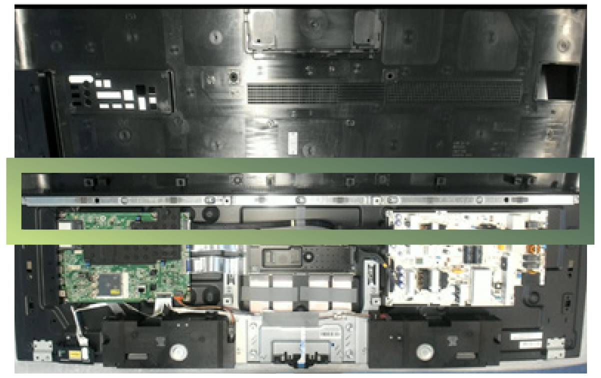


FIGURE 15 The metal bar in the LG TV

4.2.4 EXPERT INTERVIEW

Once all the fragments had been sorted, an interview was conducted with two recycling experts from an electronics recycling facility. During this interview, the heterogeneous fragments of the Panasonic TVs were discussed and it was predicted in which fractions the materials were likely to end up. The mass balance of the Panasonic TVs is based on these considerations. The interview was filmed and summarised (Appendix B).

4.2.5. TOOLS AND EQUIPMENT

In Table 4 all tools and equipment are listed with its specifications.

TABLE 4 Tools and equipement used for the shredding experiment and the subsequent analysis

TOOL OR EQUIPMENT	SPECIFICATION	USE	METRIC
Jig saw	Unknown	Cutting the TVs in parts of max. 45x45 cm	-
Shredder	A low-speed, high-torque, four-shaft, rotary shear industrial shredder	Shredding	-
Weighing scale fractions	KERN 572, max. 16100 g, d=0,2 g	Weighing fractions	gram (g)
Weighing scale boxes	KERN DE150K50N, max. 150 kg, d=50 g	Weighing boxes incl. fragments	kilogram (kg)
Camera	Canon DSLR camera	Photographing and recording the shredding process and the sorting of fractions	-
Boxes	IKEA Samla		
11L, 22L, 45L, 130L	Collecting fragments	-	
Hammer	-	Separate the heterogenous fragments of the Panasonic model.	
Screwdriver	Crosshead and flathead	Separate the heterogenous fragments of the Panasonic model.	
Dictaphone	Phone	Recording the interview	

4.3 RESULTS SHREDDING EXPERIMENT

The results of the shredding experiment focus on studying the effect of connections, materials and product architecture on the liberation and separation process. First, the mass flow of the Panasonic model is presented and analysed. Then, the results of the fragmentation process are described, focusing on the masses of the different fractions formed by the sorting on connections. This is followed by a quantitative analysis of the liberation of the different connections, followed by a more in-depth analysis of some connections with ambiguous results.

4.3.1 PANASONIC MASS BALANCE

The mass balance for the Panasonic TV is shown in Figure 16 (Appendix F). The initial masses represent the combined masses of the entire batch of Panasonic TVs, including 4 screens. Also, the masses of the most prominent and important parts of the TV are identified, to relate the materials to the design of the product. Additional considerations based on the interview with recycling experts are given at the end of this section.

MASS BALANCE (FIGURE 16)

After liberation and separation, 66 wt-% of the fragments end up in the correct fraction. This indicates their potential for recycling. However, 34 wt-% (including dust and small particles <1cm2) is either lost or contaminates other fractions, which indicates that this material will not be recycled.

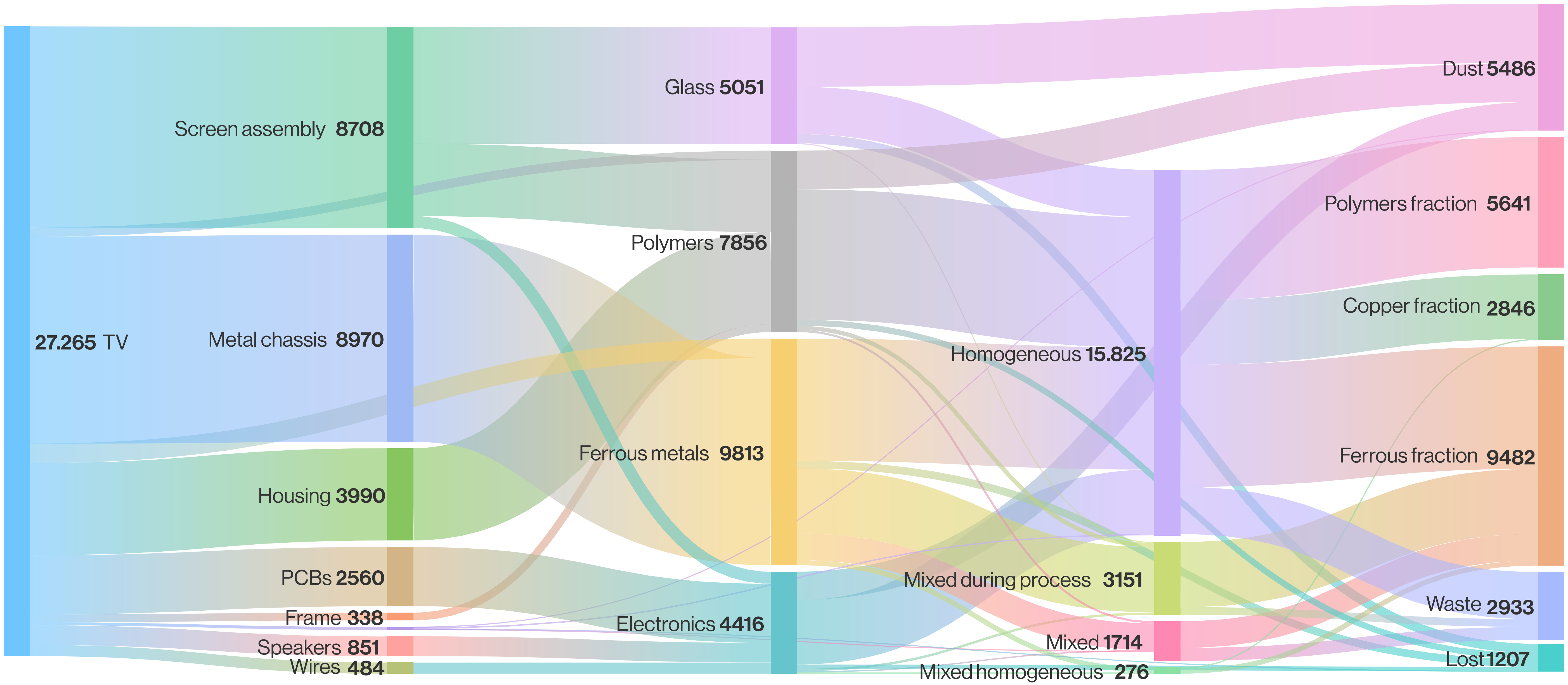


FIGURE 16 Mass balance of the Panasonic TVs (Flourish | Data Visualization & Storytelling, n.d.)

HOMOGENEOUS FRAGMENTS (FIGURE 17)

Even though a large part of the glass has liberated into homogeneous fragments, these fragmetns all end up as waste. This means, when designing electronic products, glass should be avoided.

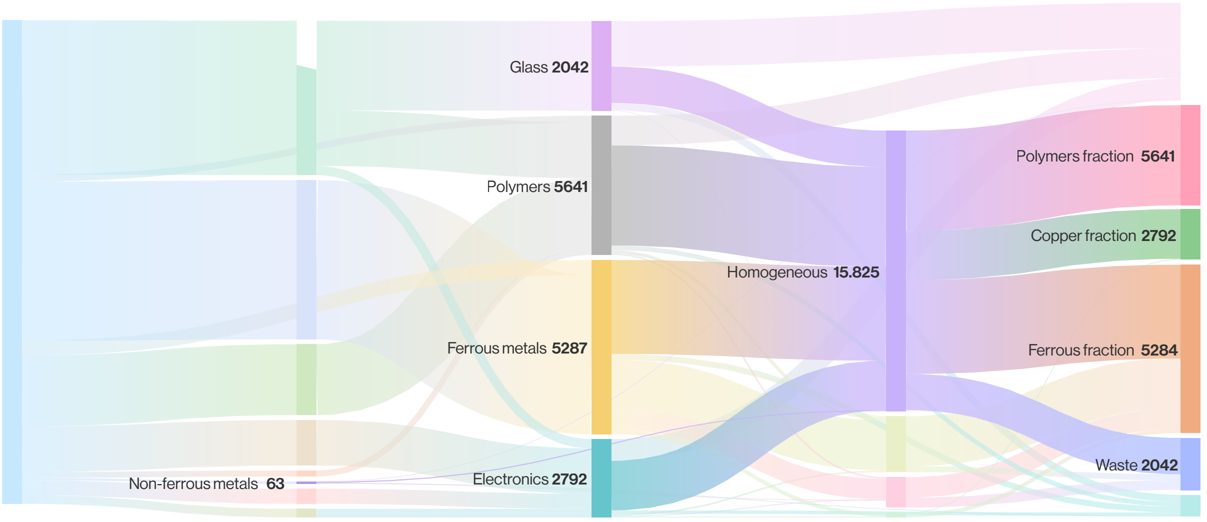


FIGURE 17 Mass balance homogeneous fragments Panasonic TV (Flourish | Data Visualization & Storytelling, n.d.)

MIXED FRAGMENTS (FIGURE 18)

The majority of ferrous metals in mixed fragments will be successfully separated into the correct fraction. Resulting in losses of other materials in these mixed fragments.

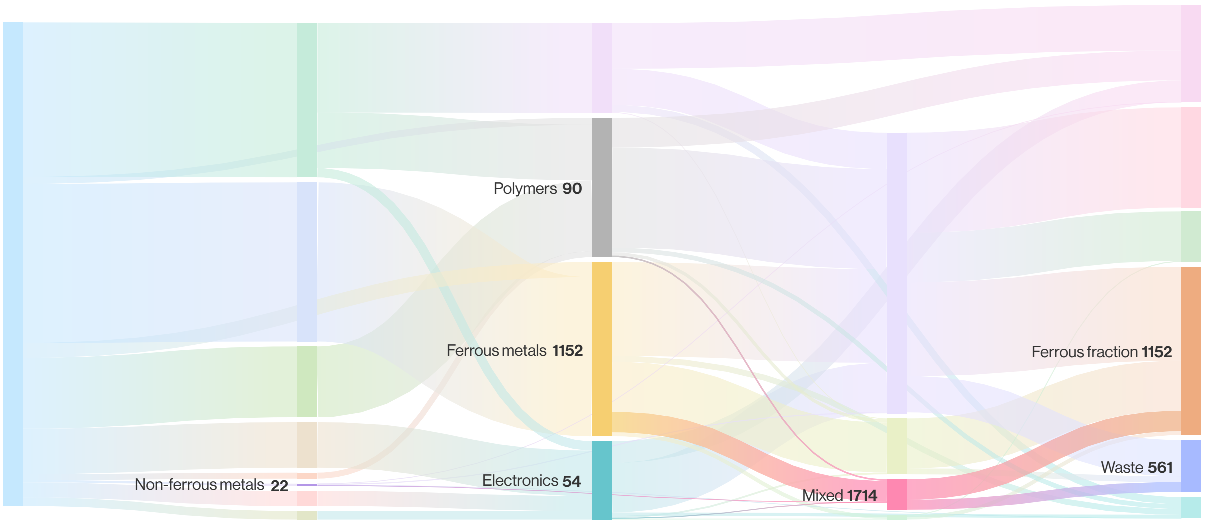


FIGURE 18 Mass balance mixed fragments Panasonic TV (Flourish | Data Visualization & Storytelling, n.d.)

FRAGMENTS THAT ARE MIXED DURING SHREDDING (FIGURE 19)

During the shredding process, some materials are folded in by steel. While the steel mostly ends up in the correct fraction, the folded in materials are often lost, including polymers, PCBs and glass.

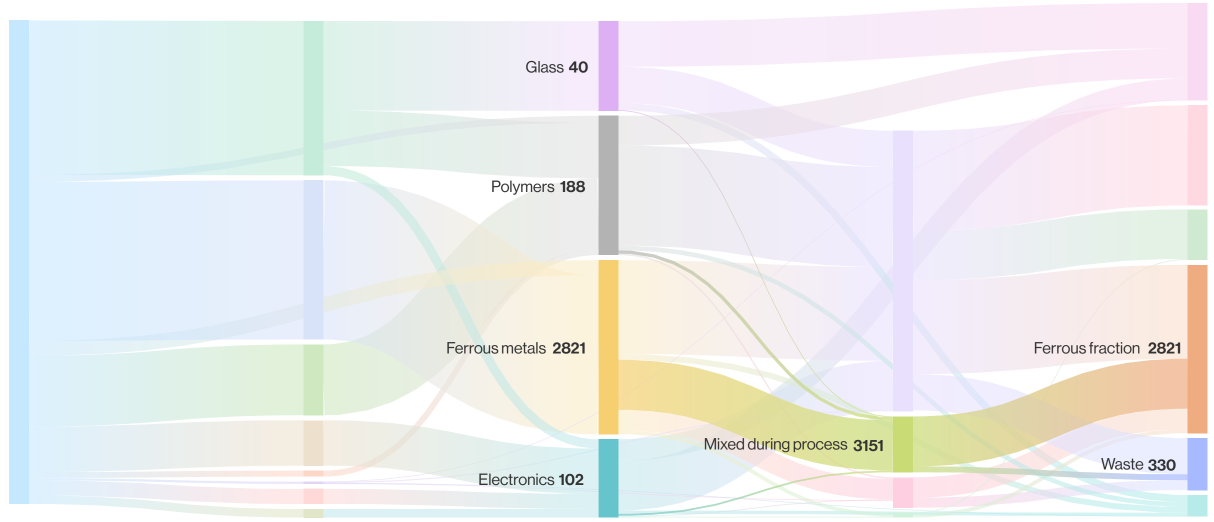


FIGURE 19 Mass balance mixed during process fragments Panasonic TV (Flourish | Data Visualization & Storytelling, n.d

FRAGMENTS OF THE SAME MATERIAL AND A CONNECTION INTACT (FIGURE 20)

If a connection remains intact but connects the same material (mixed homogeneous), this does not cause problems from a recycling point of view, as both materials can be recycled in the same fraction. However, it is still insightfu l to analyse which connections have remained intact. The most common connections found in these fragments are connections between wires and PCBs, and screws connecting ferrous metals.

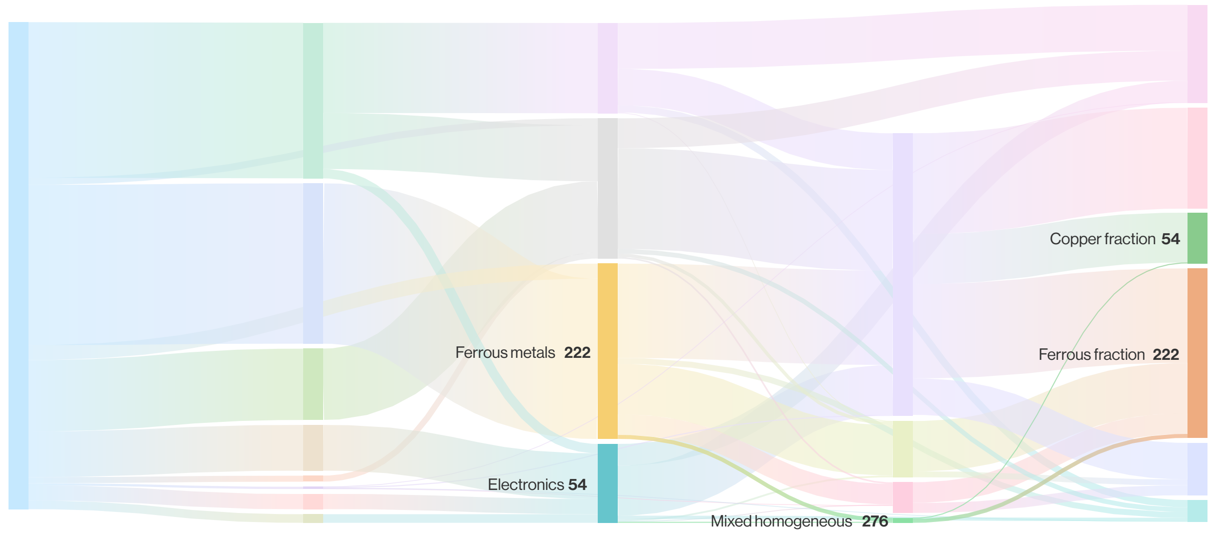


FIGURE 20 Mass balance mixed homogeneous fragments Panasonic TV (Flourish | Data Visualization & Storytelling, n.d.)

Considerations based on insights recycling experts regarding the mass balance
Based on recycling experts insights (Appendix B), choices have been made for determining in which fraction materials of mixed fragments end up.

Main material is ferrous metal (Figure 21)

- If steel is a significant part of the heterogeneous fragment, the mixed fragment will end up in the ferrous fraction, meaning that other materials are lost and the steel can be recycled. However, in practice, this is highly dependent on the precise setting of the magnet in the recycling line. It was mentioned that it is important to find a balance to avoid over-extraction of ferrous materials, which could potentially include PCBs, but still ensures extracting all the steel fragments is also important.

Main material is polymers (Figure 22)

- Mixed polymer fragments typically have different densities than homogeneous polymer fragments, presenting a challenge for their separation by density. As a result, mixed polymer fractions can either contaminate other fractions or end up in the high-density polymer fraction, where they will be incinerated.

Non-ferrous metals (Figure 23)

- If an insert remains attached to the plastic it is embedded in, it is expected to have insufficient induction for Eddy current separation. Recycling experts emphasise that the metal part must land precisely on the sensor surface for the Eddy current to be effective. Consequently, these fragments are not expected to end up in the aluminium fraction, but in the polymer fraction.

Lost materials

- Material that is not in the dust or any other fraction is considered lost. Lost means that it is not known where the mass has gone. It may still be in the machine, or it may have been lost during sorting.

Dust (Figure 24)

- The dust fraction contains an equal percentage of unidentified polymers, glass and electronics. Steel is not included in the dust (Figure 19).
- Experts mentioned that materials in the dust fraction could be separated to a size of 2 mm, meaning a significant part of this fraction will end up in the correct material fraction. To find out the exact number of particles that could be recycled, this dust fraction should be further separated into particles larger than 2 mm and smaller than 2 mm.

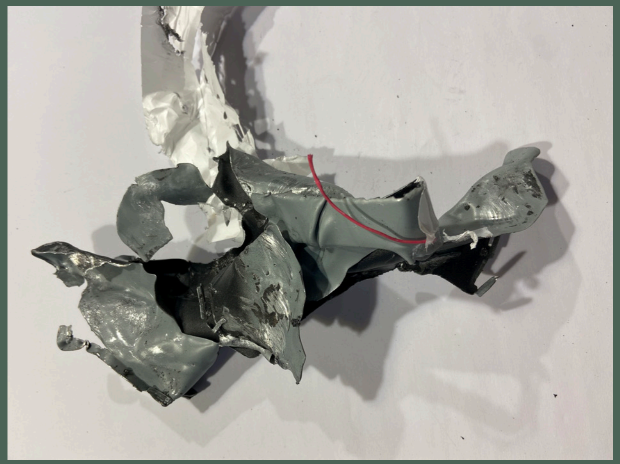


FIGURE 21 Main material is ferrous metal

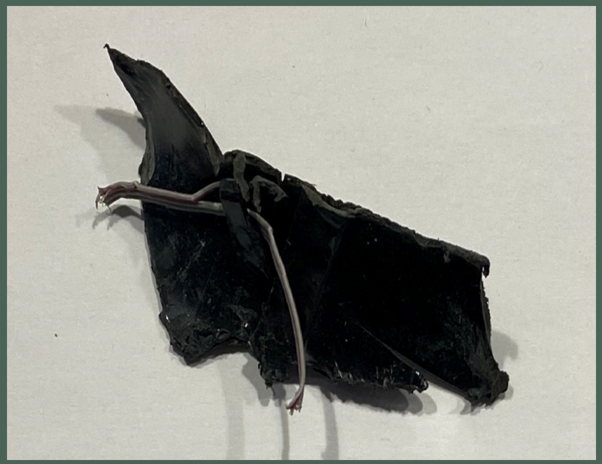


FIGURE 22 Main material is polymer

FIGURE 23 Small volumes of non-ferrous metal

FIGURE 24 Small particles (dust fraction)

4.2.3 MASSES OF FRACTIONS

Figure 25 shows the mass of the fractions that are formed based on sorting on the connections still intact. Since the Panasonic model was sorted differently, this model has been visualised in terms of homogeneous and heterogeneous fragments sorted.

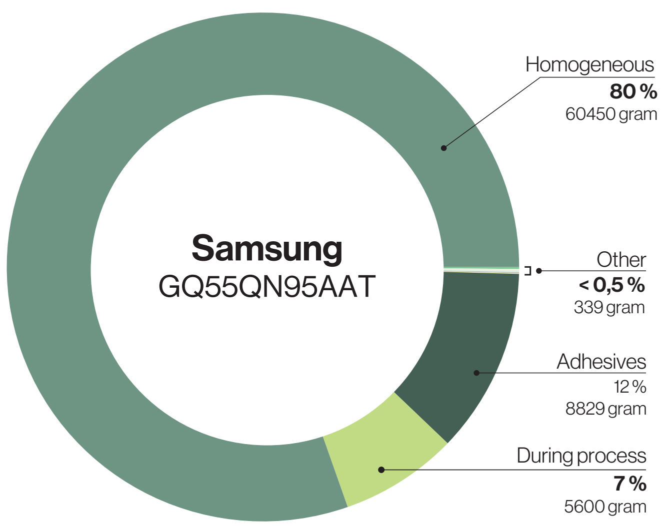
LG
The LG model has the highest mass of heterogeneous fragments (43 wt.-%), with a significant mass found in the fraction with fragments that have multiple different connections still intact. The connections in this fraction are mainly a combination of coating and glue, related to the design of the metal backplate. This metal backplate is coated and connected to another metal plate with glue. Together they form the TV's chassis.

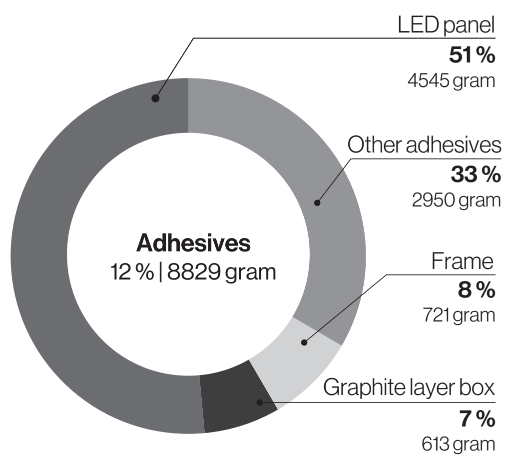
Sony
The Sony only contains one tape per model,. Looking at the adhesives fraction, it contains 8% of the weight of all the fragments. This means the connection in this fraction must primarily be glue.

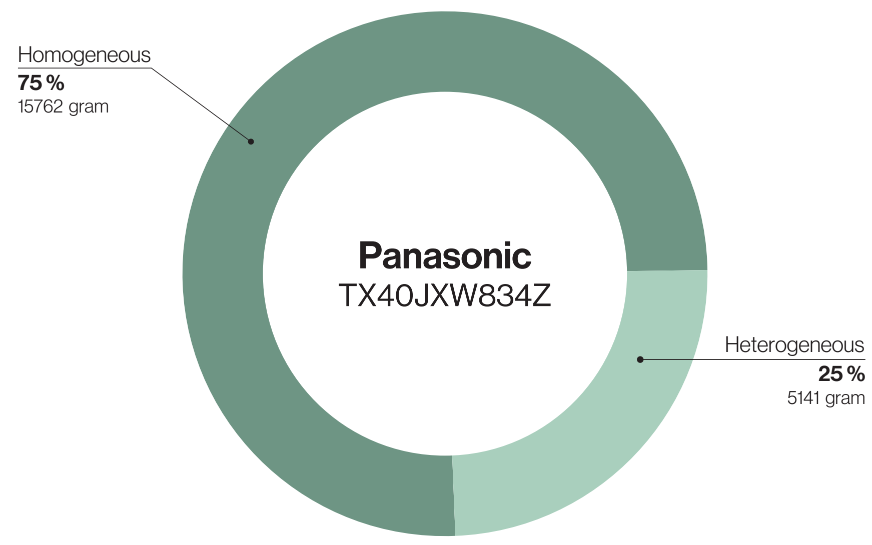
Samsung
The mass of heterogeneous fractions consists mostly of adhesives and attachments formed during the process. Within the Samsung adhesive fractions, a further division was made since the model had some parts with a glue connection which were often seen during sorting. Mostly, the LED panel, is a connection that connects a high mass of materials to each other. The glue connections of the LED panel will be further analysed in section 4.3.2.

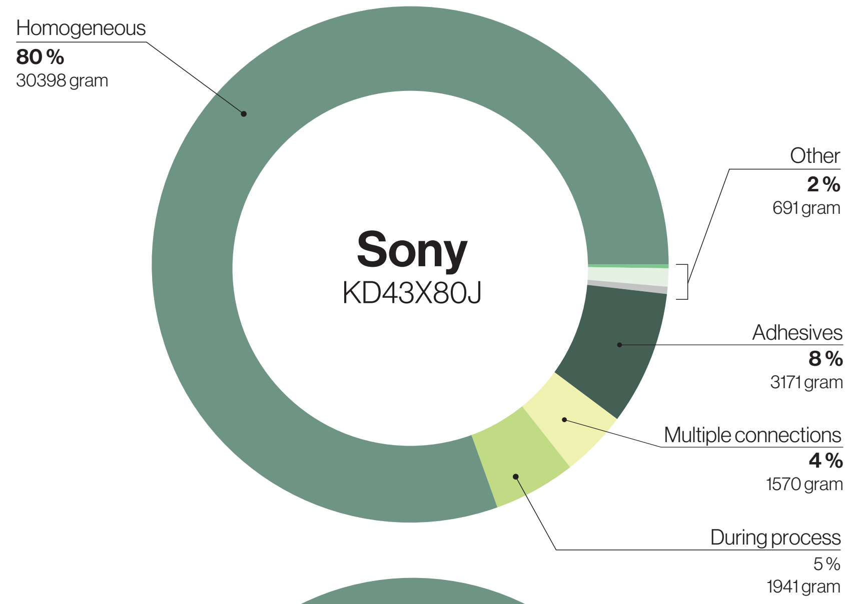
Mass of fractions with:

- Threaded connections (screws/inserts)
- Multiple connections
- Homogeneous fragments
- Force/form closure
- During process mixed
- Adhesives (glue/tape)
- Magnet









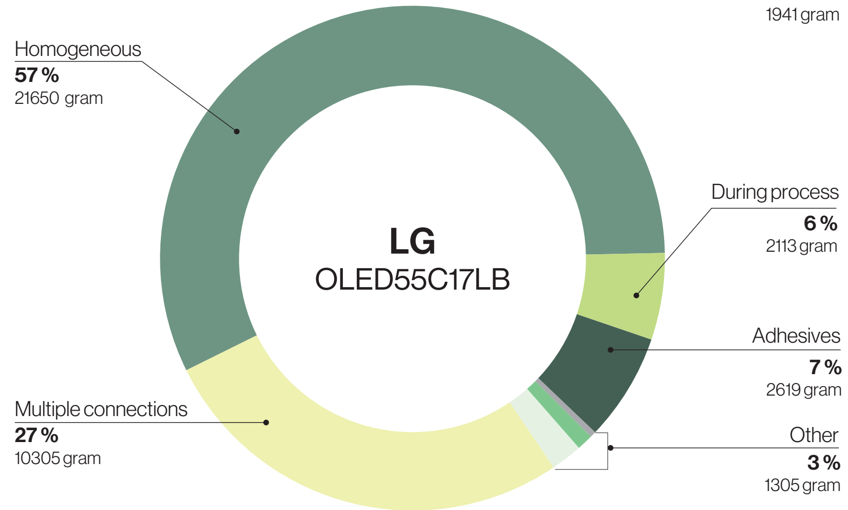


FIGURE 25 Masses of the sorted fractions

4.3.2 RESULTS LIBERATION OF CONNECTIONS

In Figure 27 the liberation behaviour of the connections is visualised, including their margin of error. Only a small number of snap-fits remained intact, with a maximum error margin of 1%. Contrarily, coatings did not break down at all. These two connection types displayed the most unambiguous liberation behaviour during the shredding process. Some of the more ambiguous results are analysed deeper in the next section.

Figure 26 presents an overview of the behaviour of the connections of all models combined. What should be noted here, is that these results do not show the nuances in different results per model, which should be carefully considered when using these results.

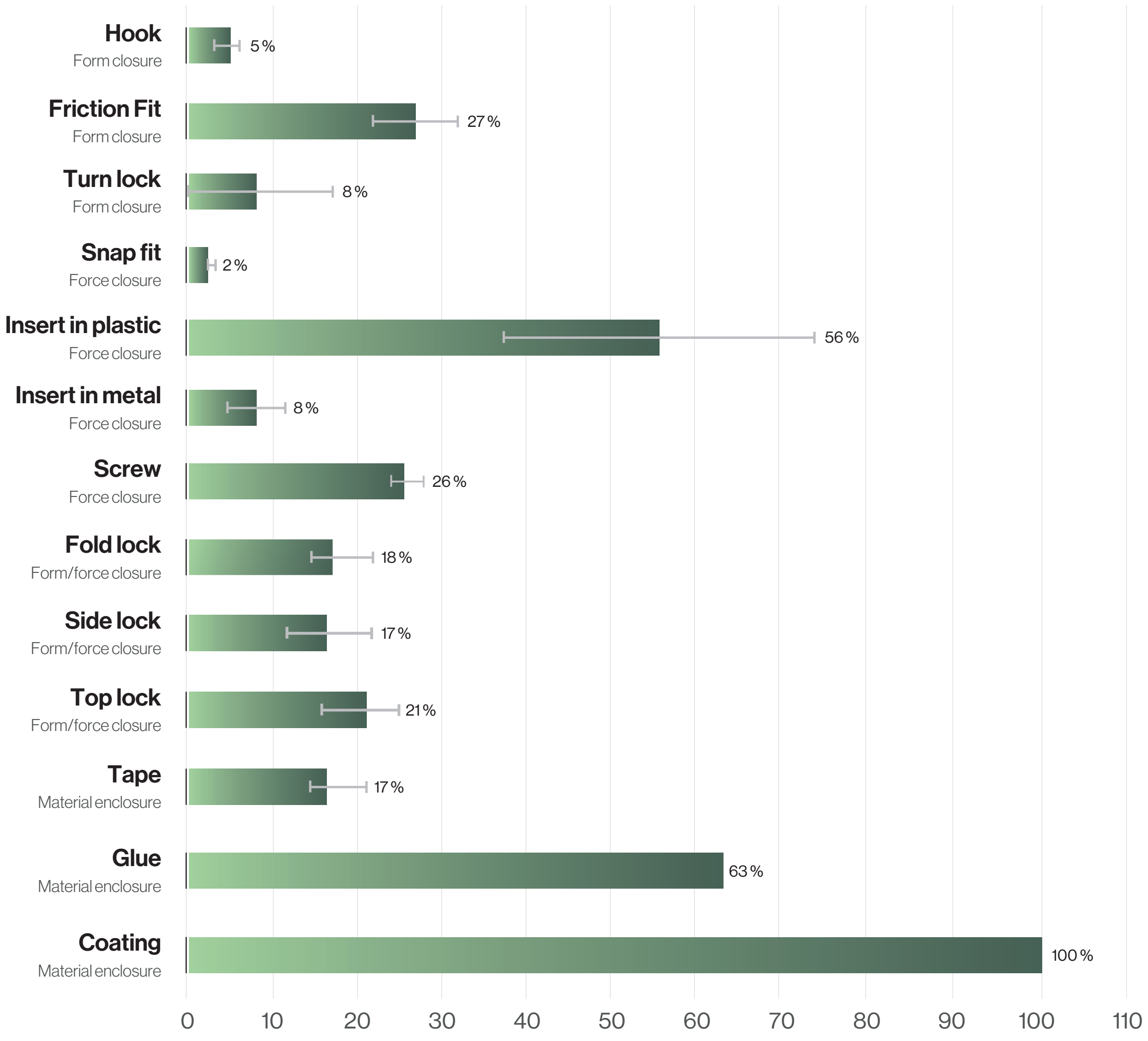


FIGURE 26 Connections intact after shredding total

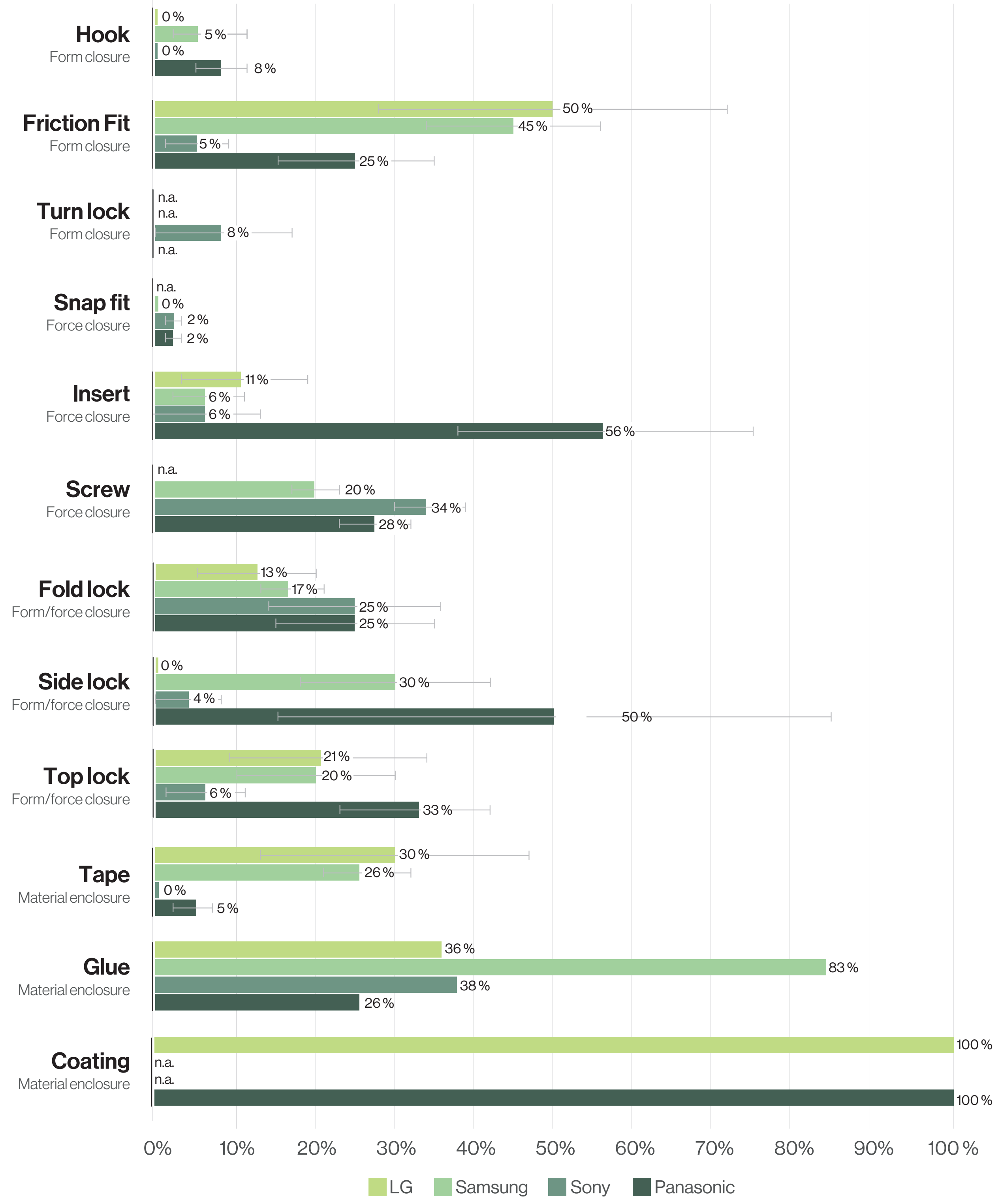


FIGURE 27 Connections intact after shredding per TV model (%)

FIGURE 28 Pulverised magnetic material

Magnetic attachment (Figure 28)
The magnetic material, ferrite, originating from the speakers have been pulverised in all models, resulting in small pieces of ferrite scattered over ferrous fragments, which then form new (temporary) connections. Although the connection itself is broken, all of the ferrite material ends up in the ferrous fraction, polluting it.

Adhesive connections
Overall, the glue connections often remained intact (63%). The Samsung model shows a great difference compared to the other models, with a significantly higher percentages of unliberated glue connections.

For this model, the LED panels are connected to a white reflective sheet with glue applied over its entire surface (see Figure 29). This connection remained intact 82% of the time, which highly influences the data for this model. From left to right: LED panel, white sheet with glue over its entire surface, the LED panel with the white sheet after shredding (connection still intact).

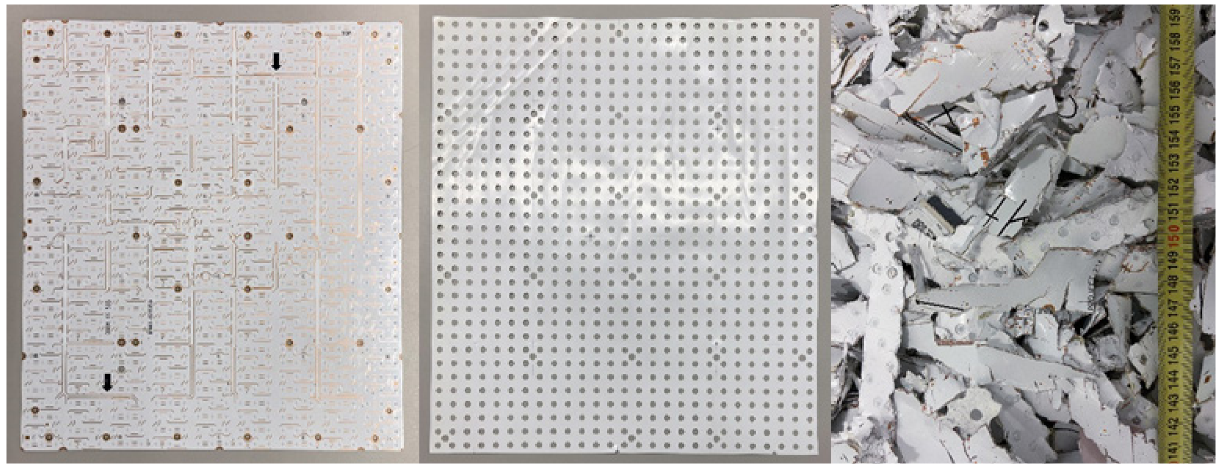


FIGURE 29 Glue connection of the LED panel of the Samsung model

Tape
Tape, although also an adhesive bond, liberates differently than the glue connections. While tapes occasionally remain intact, it is seen more often that only part of the tape will remain connected to one of the two materials it connects. Adhesive tapes are mainly used to adhere wires to the metal chassis, in order to supress electromagnetic radiation. This appeared out of insights from a designer working for a consumer electronics company (Appendix G).

Tapes vary in size, connected surface area, number and type of adhesive. In Figure 30 the scaled sizes of the tapes are visualised. To distinguish between them, the tape is qualitatively analysed (Table 5). The adhesive force ranges (low to high) are relative and based on a comparison of the tapes used in the four models.

In the Sony model, the only piece of tape broke down. The other three models used between 5 and 22 pieces of tape. The LG model had the highest percentage of tapes remaining intact after shredding. The tapes with a low adhesive force often break down during shredding.

TABLE 5 Tapes in each TV

	PANASONIC	SONY	SAMSUNG	LG
Surface Area (est.) (cm2)	5	10	9	8
Amount	15	1	22	5
Total surface area (cm2)	75	10	198	40
Intact after shredding (%)	5 %	0 %	26 %	44 %
Adhesive force	Low	Low	High	Medium

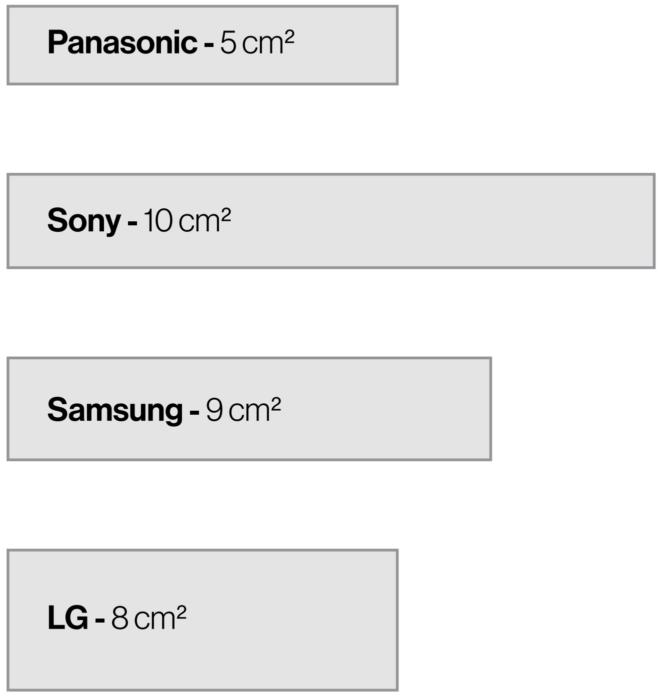


FIGURE 30 Surfaces of tapes relative from each other

Friction Fits

Friction fits can be divided into two categories: those used for speaker attachment and other friction fits (Table 6). The majority are friction fits for speakers. These connectors are anti-vibration rubbers, by placing them between the speaker and the chassis, they suppress the transmission of vibrations (insight from designer working for a consumer electronics company , Appendix G). Consequently, this connection is typically found in TVs.

In order to gain a deeper insight into the different behaviour of these friction fits for speakers, their position in the product architecture and the shape of the connection were analysed (Figure 31). The material for all connections is PDMS, therefore this is not analysed further.

The Sony model, has only 6% of these connections that remained intact. This model is the only TV with one relatively large speaker unit. Sony's friction fit is only enclosed by the speaker on three sides, unlike the other models. The Panasonic and LG model both have an opening in the connector that is clamped around a pin. Although Panasonic and LG share a similar design, the liberation results are very different. The speaker of the Samsung has a sort of hook that hooks into the friction fits, in addition the Samsung friction fits are also enclosed by the speaker of three sides. This friction fits remains intact most often, 50 %.

Analysing these results, clearly design choices regarding the shape and form of the connector play a key role in its liberation behaviour. Also, the size of the speaker and place in the product architecture could play a role. However, it is uncertain what product or/and part characteristics are most influential for the liberation of these friction fits.

Consideration

The connector is not only connected to the speaker, but also to the rest of the TV. When one of these two connections remained intact, the friction fit is analysed. In the case of Samsung, LG and Sony, the friction fit is attached to the speaker unit. For the Panasonic, however, they are attached to the plastic housing.

TABLE 6 Number of Fricion Fits (speakers and other)

	PANASONIC	SONY	SAMSUNG	LG
Total number of F.F.	28	36	36	12
Speaker F.F.	16	32	32	8
Other F.F.	9	4	4	4
Intact after shredding - speakers	5	2	16	5
Intact after shredding – other	1	0	0	0
Intact after shredding – speakers (%)	31 %	6 %	50 %	63 %
Intact after shredding – other (%)	8 %	0 %	0 %	0 %

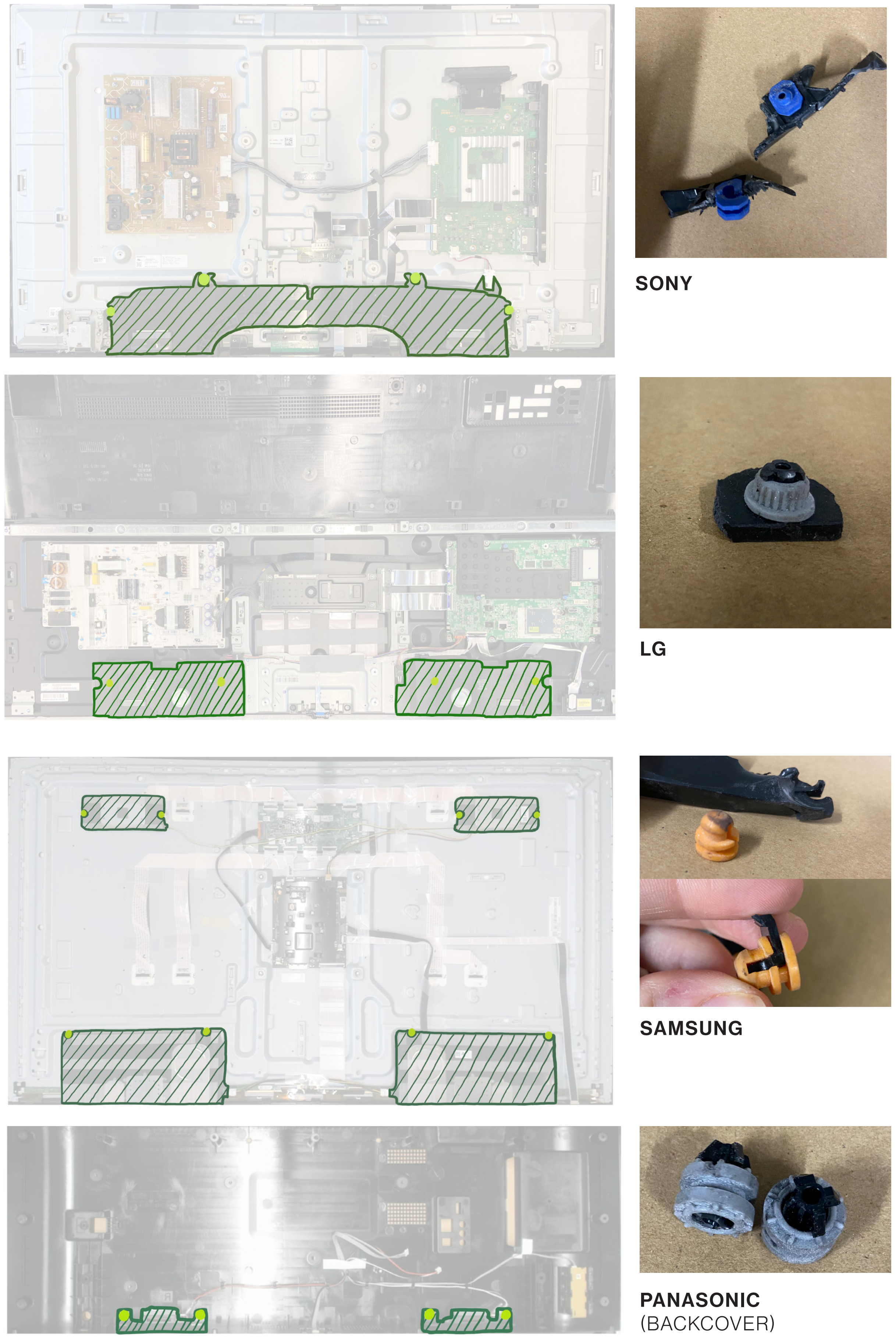


FIGURE 31 Speaker fricion fits

Inserts
For the inserts, a large difference between the TVs can be seen regarding the liberation of the connection (Table 7). The metal inserts in steel almost always broke down, with only a small percentage remaining intact: 6% - 11%. In contrast, the metal inserts in plastic often remained intact, with more than half of the inserts still connected to the plastic, 56%.

In Figure 32, an observation is made: the metal insert in plastic is surrounded by the plastic material, creating a large connected surface area between the insert and the plastic. In contrast, the metal insert is attached with only one side to sheet metal, resulting in a relatively smaller surface area between the insert and the sheet metal.

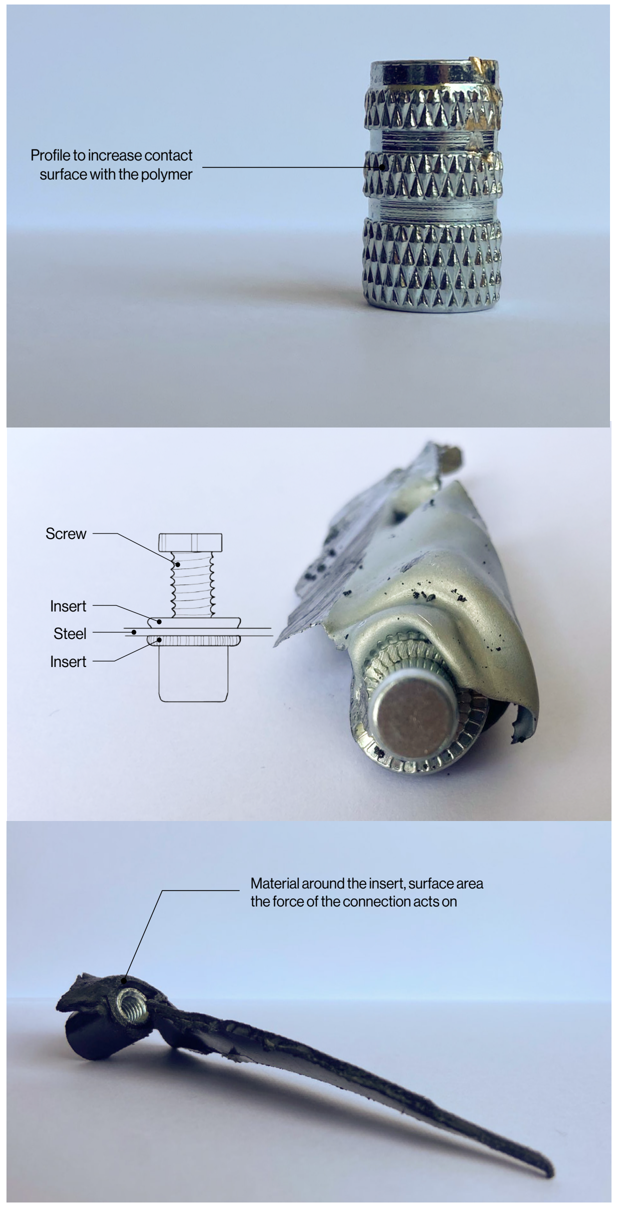


FIGURE 32 Inserts

TABLE 7 Comparison of metal inserts in plastic and in steel

	PANASONIC	SONY	SAMSUNG	LG
Inserts in plastic before shredding	16	0	0	0
Inserts in metal before shredding	0	16	32	24
Intact after shredding (%)	56 %	6 %	6 %	11 %
Intact after shredding (%)	5 %	0 %	26 %	44 %

4.3.4 NEW ATTACHMENT DURING SHREDDING

As mentioned before, during the shredding process, it was observed that the materials sometimes folded or pressed into each other. This was particularly the case with steel (Figure 33). Remarkably, this resulted in a relatively large volume ending up in the mixed fraction, even though these materials were not connected prior to shredding. This fraction varied between 5% and 12% of the total mass of all fragments. This category contained several materials, but mostly more lightweight materials were folded in by the sheet metal, for example, reflector and optical sheets.

It is expected that this folding in happens on a much smaller scale when products are shredded with the main shredder, which has 10 times the capacity of the shredder used for the experiment.

FIGURE 33 Steel folding in reflector sheet

4.3.5 MATERIALS DURING SHREDING

The small particle fraction resulting from the sorting of the Panasonic, contains many particles of reflector plates, polymers and other optical plates made of brittle materials. This means that, unlike ductile materials such as steel, these materials break easily during the shredding process, meaning these materials are easily liberated. However, there's a risk of losing these particles if they become too small during the process and dust is formed.

Dust
The particles are separated until they reach a minimum size of 2 mm. The dust contains many precious metals and is therefore sent to a smelter. Dust interferes with the process, so efforts are made to filter it out with a dust filter (expert interview, Appendix B).

4.4 DISCUSSION & CONCLUSION SHREDDING EXPERIMENT

This chapter provided an analysis of the shredding experiment conducted on 14 smart TVs, focusing on the following sub-research question:

- How do the product and part characteristics of a smart TV affect the liberation and separation during the recycling process?

One of the key findings is the importance of material liberation for effective recycling. The Panasonic model, which was thoroughly analysed, demonstrated that 66 wt-% of the fragments ended up in the correct material fraction, highlighting their potential for material recovery. However, 34 wt-% of the materials, including dust and particles smaller than 1 cm2, were either lost or ended contaminating incompatible fractions.

The analysis showed that different types of connections – such as screws, snap-fits, adhesives, and friction fits - exhibit varied liberation behaviours. For some connections, more research was needed to determine the factors that influence their behaviour during shredding. This was done for adhesive connections, friction fits and inserts. Even after this more in-depth analysis it was still unclear for some connections what product characteristics influenced this varying liberation behaviour. Conversely, connections, such as snap-fits and coatings showed consistent liberation results across all models.

Additionally, screws displayed varied behaviour across different smart TV models. Despite often remaining intact during shredding, they exhibited diverse liberation behaviour, which is expected to be related to the various types, sizes, lengths and materials used. To comprehensively understand this complex connection, further investigation into the type and material of screws, the material they are connected to, and the forces acting upon them is necessary to draw reliable conclusions.

Furthermore, additional research into the behaviour of electrical connections can give insights about influential design choices, however it was not prioritised in this study. Since electrical connectors should be separated into the same material fraction as the parts they are connected to (PCBs), materials will not be lost when these connections remain intact.

Materials behaved differently during shredding. The sheet metal often folded in other materials, resulting in a large mass of the heterogeneous fragments. However, this would most likely happen on a much smaller scale outside of this experiment, since the shredder normally employed for these products, has a capacity ten times higher. On the other hand, brittle materials, like those found in reflector plates and optical sheets, liberated easily, resulting in mostly homogeneous fragments. However, the downside of brittle materials is the potential formation of dust, which could lead to material losses of critical metals and the contamination of other material streams.

The interviews with recycling experts provided valuable practical insights, in particular regarding the expected separation of mixed fragments for the Panasonic model and details of the separation process. These insights have been incorporated into the interpretation of the fragmentation of the smart TVs and will be used in subsequent chapters.

Overall, this experiment shows the complexity of recycling electronics and the critical role of product design in facilitating material liberation and separation. By understanding the behaviour of different materials and connections during shredding, designers can design products that are easier to recycle, ultimately enhancing the efficiency of the material recovery process. Future research should focus on studying the factors determining the breakdown of some connections, such as screws, friction fits and glue. And on designing and validating design solutions that show more effective liberation and separation of materials.

4.4.1 LIMITATIONS

- It is possible that some dust and small particles may have been lost during the size reduction of the TVs in parts, as the sawing and breaking down of the TVs was not done in a space suitable for collecting the dust. However, it is assumed that the amount of dust and mass of materials lost is negligible. After shredding, the total loss (including loss in the shredder) was found to be <1,5% based on the Panasonic TVs.

- All fragments were manually sorted, which may result in different outcomes than automated sorting, due to variations in precision or human errors.

- The masses of the fractions based on connections give insight in the material involved for the intact connections, but not about the volume of material that will be lost. To conclude about volumes of materials lost, all connections should be broken and should be analysed on what materials would end up in an incompatible fraction, as done for the Panasonic model.

- The limitations of the small-scale shredder used in this experiment were evident. The inability to shred certain parts of the LG TVs and the occurrence of new attachments formed during shredding (e.g., steel folding into other materials) highlighted the need for experiments with the main shredder, typically used for these products. However, the sample size needed would be much bigger.

4.5 TAKE AWAYS

1. Between 20 wt-% and 43 wt-% of the smart TVs are separated into heterogeneous fractions.
2. Fold, side and top lock connections in the smart TVs only form connections with compatible materials (e.g. PCBs or speakers).
3. Large surfaces of steel in a design are unfavourable for the shredding of the product.
4. A significant volume of homogeneous fragments still end up as waste, due to the absence of recycling facilities for those materials.
5. Metal inserts in plastic will most likely end up in the polymer fraction, resulting in waste.
6. Snap-fits have a high liberation degree during shredding.
7. Coatings have a low liberation degree during shredding.
8. Glue connections often stay intact, especially when used over a large surface area.
9. Tapes with low adhesive force often broke down during shredding.
10. Magnets are pulverised during shredding and will end up contaminating the ferrous fraction.
11. Screws and friction fits show varying behaviour during shredding, but do occasionally not break down.
12. Hooks have a high liberation degree during shredding.
13. Brittle materials have a high degree of liberation, but with the risk of dust formation.
14. Particles formed in the shredding process smaller than 2 mm are not sorted further. These particles will be smelted.

CHAPTER 05

DESIGN FOR RECYCLING GUIDELINES

In this chapter DfR guidelines will be presented. Insights from the shredding experiment will be used as a basis. Also, DfR guidelines in the literature are explored.

5.1 INTRODUCTION

DfR guidelines have been proven to be effective when used in practice, leading to increased recyclability of electronic products (Fakhredin, 2018). However, given the current sub-optimal disintegration and separation of electronics, DfR methods are currently ineffective and not widely used in design practices. One of the reasons for this is that many DfR guidelines are insufficiently based on common recycling and design practices (van Dolderen et al., 2024). They are rarely tested with designers and often lack validation through recycling experiments. As a result, many DfR guidelines are ineffective and not in line with actual recycling practices.

A second reason is that DfR guidelines are currently not integrated into design practices. Design briefs often do not explicitly specify recyclability (Fakhredin, 2018). Only legal directives such as RoHS (Restriction of Hazardous Substances) are included, but these focus primarily on material selection to reduce toxicity. This lack of incorporation in design brief, means that there is little incentive for designers to incorporate DfR principles. This is worsend by the accessibility and complexity of DfR methodologies, particularly for those who lack expertise. Consequently, only those with sufficient knowledge can effectively navigate and integrate DfR strategies. This leads to the sub-research question:

- What are effective DfR guidelines applicable by designers?

This chapter aims to establish a comprehensive set of guidelines, that can be applied by designers and integrated into design practices. The methodology for developing this set is explained in the following section, followed by the full set of guidelines. The approach aims to bridge the gap between theory and practice, and support designers in adopting and implementing DfR principles effectively.

5.2 METHOD FOR CREATION OF GUIDELINES FOR RECYCLING

This section outlines the methodology used to develop DfR guidelines. The approach includes a synthesis of existing DfR methodologies from the literature, insights from recycling experiments and input from recycling experts. Next to this, I used insights from Fakredin's research, focusing on interviews with design practitioners, on how these guidelines should be communicated to be applicable for designers. By integrating this literature with practical insights, I aim to provide guidelines that are both based on practical evidence and usable for designers.

5.2.1 SYTHESIS OF DFR GUIDELINES

Van Dolderen et al. (2024) conducted a comprehensive literature review to identify existing DfR guidelines and methods in the field of electronics. The review used method content theory, as proposed by Daalhuizen and Cash (2021), to assess the research base of these guidelines. The review was used to identify a set of guidelines from the literature. Specifically, guidelines and methods supported by practical evidence, such as results from recycling experiments or collaboration with recyclers, were selected, while those without practical evidence were excluded. Similar guidelines I then combined to create a synthesised set of DfR guidelines derived from literature, all based on practical evidence. Guidelines that were unclear on their rationale or ambiguously formulated, where also excluded, to ensure clarity and effectiveness.

Conclusions from the shredding experiment and insights from recycling experts were incorporated into this synthesised set of guidelines. The guidelines from literature are compared to the shredding experiment insights, to ensure consistency. This results in a set of DfR guidelines, which incorporated insights from literature, experiments and expert perspectives, all derived from practical evidence.

5.2.2 APPLICABILITY OF DFR METHODS

The study conducted by Fakhredin (2018) was analysed to understand the needs and wants of designers. From this analysis, several factors regarding the wants and needs of designers in relation to DfR methods were listed. These findings are used as the foundation for the subsequent development of the set of guidelines.

Insights from designers (Fakhredin, 2018)
- The guidelines should be applicable by designers with different levels of expertise.
- The guidelines should be easily accessible for designers.
- The guidelines should be presented in a form applicable to the design stage they apply to.
- The guidelines should be applicable in the early design stages.
- The guidelines should not be company specific.
- DfR should be specifically mentioned in the design brief.

To take these requirements into account when creating the set of guidelines, a general design process is visualised in Figure 34. This design process is a simplified version of the product innovation process by Roozenburg & Eekels (1995), taking the four main phases into account. This design process serves as a framework in which the guidelines can be placed, loosely related to R3, R4 and R6.

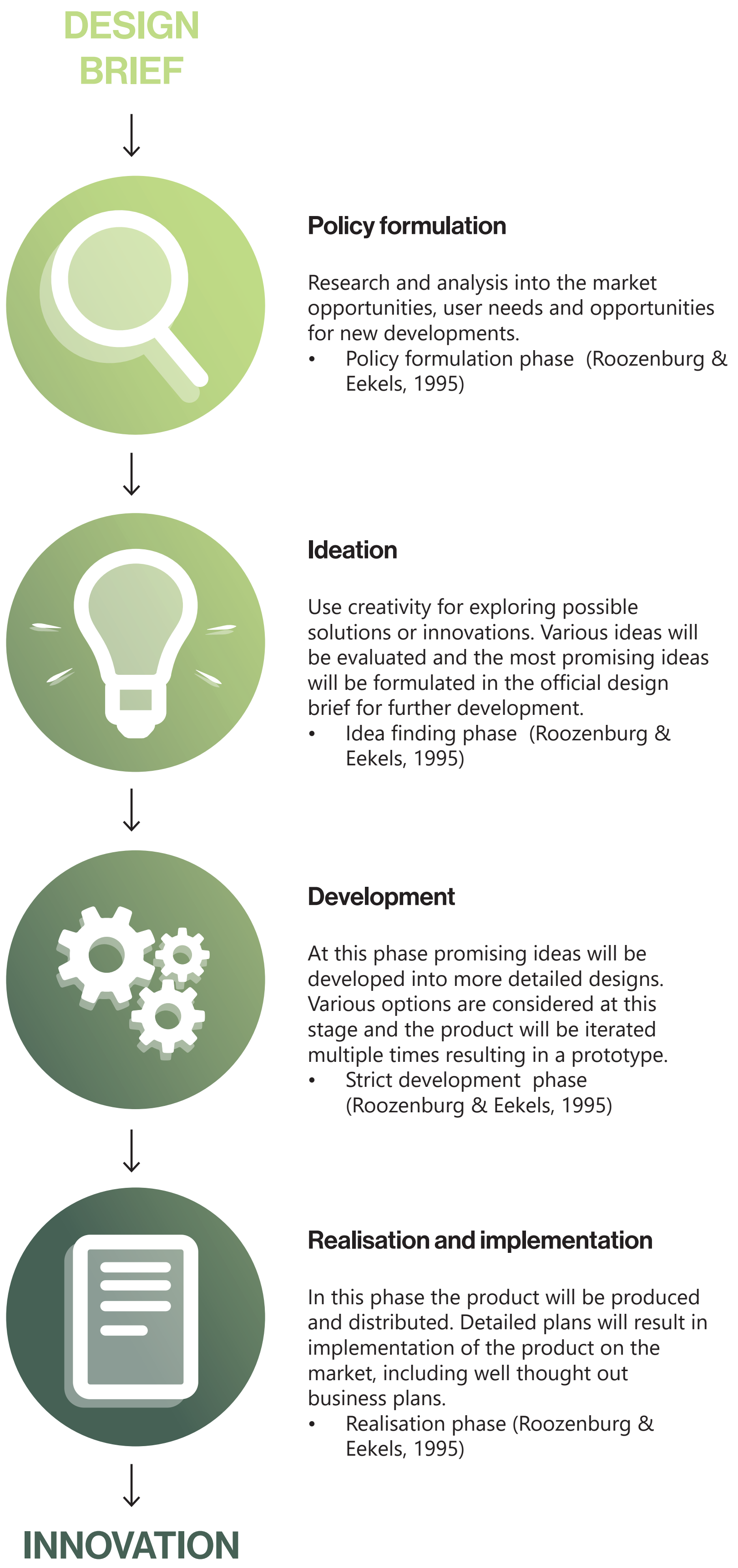


FIGURE 34 Design process

5.3 DESIGN FOR RECYCLING GUIDELINES OF ELECTRONICS

Taking into account the design process described in the previous section and the insights derived from the interviews conducted by Fakredin (2018), a concept for DfR guidelines for electronics is developed. The concept includes high-level and low-level guidelines, which should be applied in different phases of the design process. In addition, the implementation of the guidelines is briefly discussed, whereafter recommendations for further development are made.

5.3.1 LOW-LEVEL AND HIGH-LEVEL GUIDELINES

The ideation phase marks the peak of creativity in the design process and requires high-level guidance to encourage unrestricted exploration of ideas. During brainstorming sessions, it is crucial to facilitate an environment that is open to creativity, free from limitations (Rosso, 2014). These high-level guidelines are formulated with the aim to provide an overarching set of guidelines of DfR for electronics. They encourage innovative ideas that prioritise sustainability without becoming overly detailed.

As the ideation phase progresses and one or more ideas are selected for further development, there is a transition to the development phase, where low-level guidelines come to the fore. These guidelines provide detailed insight into issues such as material selection and the use of connections. By providing specific guidelines, designers gain a comprehensive understanding of how to improve product recyclability.

In essence, the ideation phase emphasises creativity, supported by high-level DfR guidelines, while the development phase delves into specific details to improve designs and enhance recyclability. This methodical approach ensures the seamless integration of sustainability considerations throughout the design process.

5.3.2 IMPLEMENTATION

Effective implementation of these guidelines involves ensuring accessibility and usability for designers with varying levels of expertise. This could be achieved by making the data available in an accessible digital format, for example a website. Next to this, designers are visual thinkers, so it would be informative to use visual representations or photographs to support the guidelines. The guidelines themselves should be clearly formulated, reasoned to provide context for making informed design choices, and organised in a logical structure to highlight the most impactful DfR guidelines. Also, suggesting alternative design choices by giving practical advice would enhance the understandability and applicability of these guidelines.

The iterative nature of a design process allows for the continuous integration of DfR methods into the design process. For example, a list of requirements is iterated and added to several times during a design process, providing the opportunity to add more specific DfR guidelines to the list as the design process progresses (Van Boeijen et al., n.d.).

5.3.3 THE CONCEPT

Together with these guidelines, an overview of the recycling process should be given, to inform designers on the basic principles of the liberation and separation in the recycling process. This is expected to improve their understanding of the guidelines and gives them more insight into how design choices influence the recyclability of the product.

High level guidelines:

1. Use recyclable materials.
2. Use connections that allow liberation.
3. Use the same or compatible materials for parts and connectors.
4. Do not use hazardous materials.

The low level guidelines are presented on the next pages.

GUIDELINE 1 | **Use materials that can be recycled with standard recycling processes.**

Materials can only be recovered if the recycling technology for that specific material is available. Therefore products should be designed with materials that can be recycled within the existing recycling infrastructure

- Beitz ,1993; Hultgren, 2012; Balkenende et al., 2014; Fakhredin, 2018; Van Schaik & Reuter, 2014, Recycling experts).

PLASTICS

GUIDELINE	RATIONALE	SOURCE
Use polymers that can be recycled with standard recycling processes. • ABS • PE • PP • PS • PC-ABS	The recycling process for these materials is well established, meaning these polymers can be recycle with the current existing recycling infrastructure.	Hultgren, 2018 Feenstra et al., 2021 Recycling experts
Do not use polymer blends, (except for PC-ABS).	Polymer blends are very hard to separate, they are either burned or end up polluting material streams.	Hultgren, 2018 Feenstra et al., 2021
Do not use thermosets, elastomers and foams. • When these materials are necessary, use materials outside the density range of common recyclable plastics.	Thermosets, elastomers and foams are not recyclable, they are either burned or end up polluting material streams. Choose thermoplastics or another alternative instead.	Hultgren, 2018 Feenstra et al., 2021
Minimise the additives in plastics. • Stabilisers • Fillers	Plastic streams with too high concentrations of certain substances cannot be used as recycled plastics but will be burnt instead. If you need to use an additive, use one that changes the density of the plastic outside the range of common recyclable plastics.	Hultgren, 2018 Feenstra et al., 2021

METALS

GUIDELINE	RATIONALE	SOURCE
Use metals that can be recycled with standard processes. • Steel/Iron • Copper • Aluminum • Stainless Steel	The recycling process for these materials are well established, meaning these metals can be recycled.	Recycling Experts

OTHER MATERIALS

GUIDELINE	RATIONALE	SOURCE
Do not use ceramics. • Cement • Concrete • Alumina • Silicon	Ceramics cannot be recycled and have to be manually removed before shredding. Otherwise it could pollute other material fractions.	Hultgren, 2018 Recycling experts
Do not use composites	Composites end up polluting fractions or as waste, since the different materials cannot be separated from each other.	Hultgren, 2018 Feenstra et al., 2021
Do not use paper, cardboard, wood and textiles.	These materials cannot be recycled in the e-waste recycling line and have to be manually removed before shredding. Otherwise they can cause problems during the recycling process.	Hultgren, 2012 Feenstra, 2021
Do not use magnets (especially not on PCBs).	Magnets get stuck on the machines used in recycling and can end up polluting the ferrous stream. PCBs contain many valuable non-ferrous metals. When magnets are connected to PCBs, the PCB might end up in the ferrous stream, leading to material losses and pollution.	Hultgren 2012 Feenstra, 2021 Recycling experts

GUIDELINE 2 | **Use connections that allow liberation.**

Connections that allow easy liberation during the shredding process, ensure materials to be liberated. This means these materials are more likely to be separated into the correct material stream, so that they can be recovered.

- Fakhredin, 2018; Balkenende et al., 2014; Feenstra et al., 2021; Hultgren, 2018
- Shredding experiment

For connections that are not expected to liberate use the same or compatible materials (Guideline 3).

GROUP 1 | **Expected to liberate during shredding**

CONNECTION	RATIONALE	SOURCE
1. Snap fits **2. Hook connections** **3. Turn lock connections** **4. Metal inserts in metal** **5. Tape** **6. Electrical connection: side lock** **7. Electrical connection: fold lock** **8. Electrical connection: top lock**	These connections showed liberation varying between 98 % and 21 % and are therefore highly likely to break down during shredding.	Shredding experiment

GROUP 2 | **Uncertain to liberate during shredding**

CONNECTION	RATIONALE	SOURCE
9. Screw **10. Friction Fit** **11. Metal inserts in plastic**	These connections showed liberation varying between 74 % and 44 % and are therefore uncertain to liberate during shredding.	Shredding experiment

GROUP 3 | **Not expected to liberate during shredding**

CONNECTION	RATIONALE	SOURCE
13. Glue **14. Coating**	These connections showed liberation varying between 37 % and 0 % and are therefore not expected to liberate during shredding.	Shredding experiment.
X. 2K or xk processes • Injection moulding • Over moulding	Materials that are moulded in together, will not be easy to separate. They will end op polluting other material streams or as a waste material. 2K is acceptable if it is with two colours of the same material.	Hultgren (2018) Feenstra et al., 2021

GUIDELINE 3 | **Use the same or compatible materials for parts and connectors.**

If two parts cannot be separated make them from the same or a compatible material, meaning the materials can be recycled with the same recycling process. When connections stay intact during shredding, they will be recycled together with the main component. In this case, the materials should be compatible to prevent pollution and material losses.

- Beitz, 1993; Castro et al., 2004; Hultren, 2018; Van Schaik & Reuter, 2012; Van Schaik & Reuter, 2014; Balkenende et al., 2014; Fakhredin, 2018; Feenstra et al., 2021

If two parts cannot be compatible use connections between them that are expected to liberate (Guideline 2).

GUIDELINE	RATIONALE	SOURCE
Avoid connecting materials to each other with different separation methods. • Avoid fixing ferrous materials to non-ferrous metals. • Avoid fixing metal to a component of plastic. • Avoid fixing different kinds of plastics to each other.	Fixing materials to each other with different separation methods, will end up in materials losses or pollution of material streams.	Hultgren, 2018 Feenstra et al., 2021 Recycling experts

GUIDELINE 4 | **Do not use hazardous or toxic materials that are harmful to humans or the environment.**

Hazardous materials may cause flammability, corrosiveness or reactivity. These materials must be manually removed or depolluted before products are shredded.

- Hultgren 2018; Feenstra et al., 2021
- Recycling experts

GUIDELINE	RATIONALE	SOURCE
Do not use halogenated plastics. • PVC • PTFE	Halogenated polymers degrade at the typical processing temprature of common plastics (ABS, PC, PC/ABS, PP, PE). The generated hydrochloride acid corrodes normal extruders and moulds. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future.	Hultgren, 2012 Feenstra et al., 2021
Do not use Brominated Flame Retardants (BFRs). • PBDEs • TBBPA • PBBs • HBCDs	Several BFRs are already restricted and it is likely that more will become banned. If these substances are used in materials today it is very likely that these material streams cannot meet the requirements to be recycled and reused in new products in the future. Plastics with BFRs will not be recycled.	Hultgren, 2012 Feenstra et al., 2021 Recycling experts
Do not use materials listed on the SIN/SVHC list.	The 'SIN list' is a list of substances that are not restricted yet, but are being pushed to go on the SVHC list in the future. SIN list substances are a good indication of substances to be restricted/banned in the future and therefore it is important to already now stop using them.	Feenstra et al., 2021

GUIDELINE 5 | **Enable easy access and removal of hazardous or polluting materials.**

When hazardous materials are present in a product, they must be manually removed before shredding. Otherwise, it can cause explosions, fires or contamination. Making these materials easy accessible and removable. The easier it is to take out these materials, the easier it is to keep the material streams clean.

- Feenstra et al., 2021; Hultgren, 2018
- Recycling experts

GUIDELINE	RATIONALE	SOURCE
Use drains for operating liquids and gases and easy removal of components (oil tanks, compressors and hoses).	Prevent the operating liquids and gasses from polluting the material streams or the air by making them easy to remove in the depollution phase.	Hultgren, 2012 Feenstra et al., 2021
Enable easy/fast detection of materials.	Components containing non-recyclable, toxic or valuable materials must be easily identified for easy dismantling.	Hultgren, 2012 Balkenende et al., 2014 Fakhredin, 2018
Use detachment possibilities for polluting components and materials. • Batteries • Dust bags • Lamps • Wood • Foams • Ceramics suspected devices • Toners • Drugs cylinders • Asbestos • Paper • Cardboard • Textiles • Foams • Glass	Depollution of hazardous/toxic/non-recyclable parts is mandatory. Enabling depollution saves time and money in recycling.	Hultgren, 2012 Feenstra et al., 2021

5.4 DISCUSSION & CONCLUSION DFR GUIDELINES

The sub-research question of this chapter was:

- What are effective DfR guidelines applicable by designers?

The development of effective DfR guidelines for electronics used a combination of literature insights and practical findings. The methodology integrates existing DfR methods, insights from interviews with design practitioners (Fakhredin, 2018), with practical insight from the shredding experiment. The guidelines from the literature were compared to the practical insights of the experiment to ensure alignment with the recycling practices described in this research. This synthesis resulted in a final set, based solely on practical evidence.

The guidelines provide both high-level and low-level guidelines, tailored to different phases of the design process. High-level guidelines should not interfere with creativity while promoting sustainability during the ideation phase. Moving on to the development phase, low-level guidelines provide specific recommendations on material selection and recycling considerations, ensuring practical applicability. Consequently, the guidelines should facilitate seamless integration into the design process.

Effective implementation of these guidelines involves ensuring accessibility and usability for designers with varying levels of expertise. Suggestions such as presenting the guidelines in a digital format with visual aids, aim to improve usability and understanding. In addition, the iterative nature of the design process allows for continuous integration of the guidelines as the design progresses.

In conclusion, the DfR guidelines provide a comprehensive method for integrating sustainability into the product design process. By combining practical knowledge with theoretical insights, these guidelines provide designers with effective guidelines to improve the recyclability of products during the design phase.

LIMITATIONS

- The guidelines are not tested with design practitioners to evaluate its applicability and effectiveness. Therefore guidelines should be thoroughly tested and iterated to validate their usability.
- This research did not focus on the implementation of the guidelines, therefore the accesibility of the guidelines and the usability for designers with different levels of expertise is ensured. This should be further researched and developed.

RECOMMENDATIONS

- The guidelines should be developed into an informative concept, where designers can explore recyclability and find examples and visualisations on the application of these guidelines.
- More direct suggestions or alternatives should be explored and added to the method, to give designers a more practical tool.
- The common plastics that are mentioned in the guidelines, must be researched further. It appeared out of insights from a plastic recycler that they only recycle: PP, PS, ABS and PE. Since this was not mentioned at the electronics recycling facility, this is not taken into account, but should be researched further.
- The plastic recycler also mentioned that labels do not pose such a problem for recycling, since all plastics are thoroughly washed before separating them. This should also be researched further.
- Further research should be performed on the compatibility of materials.
- As mentioned before, more research should be done on the occurrence of sheet metal folding in other materials. Guidelines on this phenomenon could be added to the set.

5.4 TAKE AWAYS

This chapter presents clear guidelines, summarised in the following take-aways:

- Use recyclable materials, which are:
  - PE
  - PS
  - PP
  - ABS
  - PC - ABS
  - Steel
  - Stainless Steel
  - Aluminium
  - Copper
- Use connections that allow liberation:
  - Snap fits
  - Hook connections
  - Turn lock connections
  - Metal inserts in metal
  - Tape
  - Electrical connection: side lock
  - Electrical connection: fold lock
  - Electrical connection: top lock
- Use the same or compatible materials for parts and connectors.
- Do not use hazardous or toxic materials, which include:
  - BFRs
  - Halogenated plastics
  - Materials on the SIN and SVHC list
- When hazardous or toxic substances are used, make them easy to remove.

CHAPTER 06

RECYCLABILITY MAPS

In this chapter a new method is developed that allows designers to evaluate the effect of design choices on the repairability and recyclability of the product. This new method is applied to the smart TVs is this project, resulting in the exploration of several tensions.

6.1 INTRODUCTION

All products eventually reach a point where they cannot be repaired, reused or refurbished, leaving recycling as the only option left. This step is critical to closing the material loop and moving towards a circular economy. However, before products reach this stage, other circular strategies, such as repair, can extend their lifespan and keep them in the economy longer, minimising the depletion of critical raw materials.

Design choices that improve the repairability of a product can affect its recyclability and vice versa. It is therefore crucial to balance these considerations in product design (Rijkswaterstaat circulair ontwerp, n.d.). This chapter addresses two closely related sub-research questions:

- How can designers assess the tensions between recyclability and repairability?
- What are the tensions between recyclability and repairability of smart TVs?

To answer the first sub-research question, a new method will be developed that enables designers to evaluate the tensions between these two circular strategies and make the most effective design choices for achieving circularity. Insights from the shredding experiment and recycling experts will be used to ground this method in practical evidence, ensuring its effectiveness. The second sub-research question will demonstrate the effectiveness of this method by applying it to the smart TVs used in this study. This will allow an analysis of the specific tensions between repairability and recyclability in these devices.

A method to evaluate ease of disassembly is already in place, called Disassembly Maps (de Fazio et al., 2020). This method is designed to help designers and engineers identify design features that facilitate or hinder the ease of disassembly of a product. According to the European standard, EN 45554 (CENELEC, 2020) and the scoring system developed by the Joint Research Centre of the European Commission (Cordella et al., 2019) ease of disassembly is the main product-related requirement for repair. The Disassembly Map visually represents a product's architecture and takes into account four disassembly-related parameters. By translating these parameters into an analysis and modelling tool, the Disassembly Map supports designers in evaluating how different design solutions affect disassembly and consequently repair (de Fazio et al., 2021).

This chapter introduces a new approach called Recyclability Maps, which builds on the foundation set by Disassembly Map. By applying this method to the smart TVs, I aim to identify specific design characteristics that embody these tensions.

6.2 METHOD FOR THE DEVELOPMENT OF THE RECYCLABILITY MAP

The methodology for answering the sub-research questions is divided into two parts. The first part outlines the process for developing the new method. The second part details the approach for analysing the tensions between recyclability and repairability.

6.2.1 PART I THE DEVELOPMENT OF THE RECYCLABILITY MAPS

The creation of the Recyclability Map followed an iterative design process, integrating important recyclability-related factors with the structure of the Disassembly Map method established by de Fazio et al. (2020). This resulted in a three-layer framework for visualising product repairability and recyclability (Figure 35):

- Layer 0: the product architecture.
- Layer 1: the Disassembly Map.
- Layer 2: the Recyclability Map.

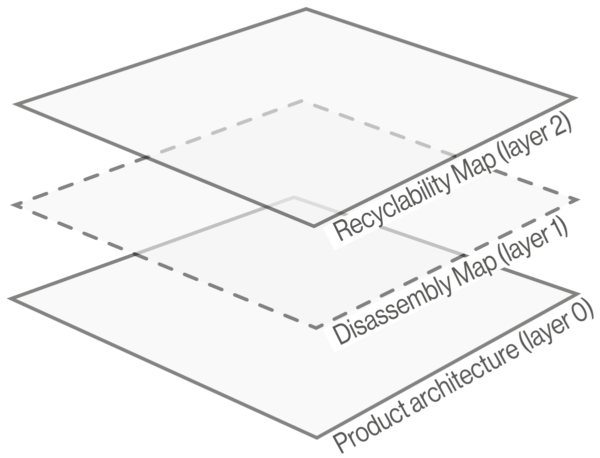


FIGURE 35 Three layer framework

For the first two layers, the method of de Fazio et al. (2020) was adapted to visualise the product architecture as a separate layer. This approach allows the Disassembly Map and the Recyclability Map to be used independently to analyse either the ease of disassembly or the recyclability of the product. But also by comparing the two maps it is possible to explore the tensions between these design strategies.

Recyclability-related factors were derived from the literature findings described in section 3.2 and insights from recycling practices. These factors were used to explore how the recyclability of a product could be visualised. The considered factors were:

- Liberation degree of the connections
- Recyclability of the materials based on current recycling processes
- Use of hazardous materials
- Compatibility of materials, referring to the ability to recycle connected parts together using the same recycling process

The method was iterated several times through testing and evaluation by mapping the smart TVs used in the recycling experiment. Also insights from evaluations with experts were incorporated. Through this iterative process, incorporating insights from literature and following the structure of the Disassembly Map, the Recyclability Map was designed.

6.2.2 EVALUATION METHOD

Once the method had been developed, two evaluation sessions were conducted, each involving a designer with previous experience working with the Disassembly Map method. These sessions included in-depth discussions about the new method, the existing Disassembly method, and their potential combination. The feedback from these sessions provided valuable insights and inspiration. Some of these insights were incorporated into the method itself, while others were documented for future recommendations.

Once the method was established, the Recyclability Map methodology was applied to the smart TVs. This involved constructing a base layer based on the disassembly performed, as described in Chapter 3. The disassembly maps were derived from the maps used in the PROMPT project (PROMPT, n.d.) and adapted to match the Disassembly Map method described by de Fazio et al. (2020). The new Recyclability Map method was then used to construct the third layer.

6.3.1 DISASSEMBLY MAPS SMART TVS

The changes made to the disassembly maps from the PROMPT project are listed below. It's important to note that in addition to the inconsistencies with Disassembly Map method, the naming conventions for the disassembly tools were also not aligned. Despite these differences in names, they were left unchanged as the exact definitions of the tools were unclear in both cases.

The alterations include:

- Changing the orientation of the PROMPT maps from horizontal to vertical. This adjustment was made to emphasise the depth of disassembly, which is a crucial factor related to ease of disassembly.
- Standardise the visualisation of action blocks and penalties according to the Disassembly Map method. For example, adding penalty icons for connectors with low visibility.
- Updating the representation of "Pry (H)" action blocks to "Pry (P)" to accurately reflect the use of a pry tool rather than simply indicating a hand action.

It's worth noting that while the maps may not comprehensively represent all components and disassembly steps, they fully illustrate the steps required to access priority parts. Therefore, although some tensions may not be fully explored due to this limitation, the effectiveness of the method can still be demonstrated by applying it and exploring the tensions.

6.3.2 ANALYSING THE TENSIONS

The tensions between repairability and recyclability were analysed by studying the most influential design choices for both circular strategies. This analysis also include findings from the research by Dangal et al. (2020), which assesses the repairability of various smart TVs. Although the TVs examined by Dangal et al. (2020) are not identical to those used in this project, they have similar specifications and dimensions. These insights can teach us more about the design choices that can create tensions between repair and recycling.

Table 8 outlines the product parameters essential for assessing the recyclability or repairability of a product. Understanding the influence of these parameters is crucial to understanding their impact on product design. These parameters served as a basis for identifying the tensions between the circular design strategies.

TABLE 8 Repairability and recyclability related parameters

REPAIRABILITY	RECYCLABILITY
Disassembly depth/sequence	Liberation degree of connections
Fastners reusability/reversibility	Recyclability of materials, based on current recycling practices
Type of disassembly tools required	Use of hazardous materials
Disassembly time	Compatibility of materials with the same recycling process

6.3 RECYCLABILITY MAP METHOD

The aim of the Recyclability Map is both to assess the recyclability of a product and to enable a comparison between the repairability and recyclability of a product. This allows for an analysis of the tensions that may arise between these end-of-life approaches, ultimately enabling designers to make informed design decisions for the intended circular strategy.

The Recyclability Map is explained in detail in the following sections. The Recyclability Map, maps all connections in the product including their expected liberation behaviour, the recyclability of materials and the presence of hazardous and valuable materials. Leading to insights on how to improve a products recyclability.

6.3.1 CONNECTION BLOCKS

Building upon the product architecture layer, the connection blocks contain information about the type of connection, the number of connections and their expected behaviour during shredding (Figure 36). Most importantly, the colour of the block indicates the expected liberation behaviour during the shredding process.

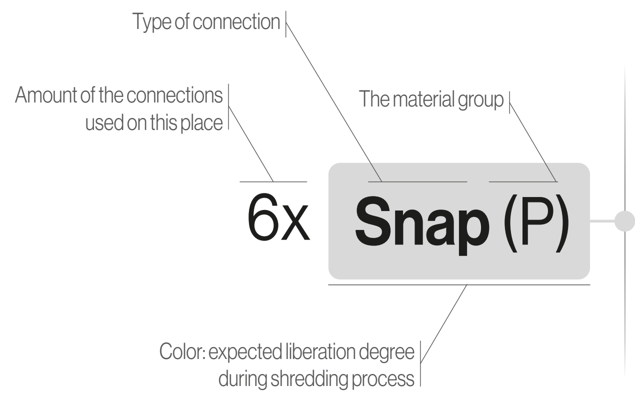


FIGURE 36 Connection block

Liberation behaviour
The liberation of connections is based on the results of the shredding experiment (Figure 37). Even though, some connections show ambiguous results, for the illustration of the method these results are still integrated for now. Later, when more research is done, these connections can be grouped according to these new insights. For now this results in the following:

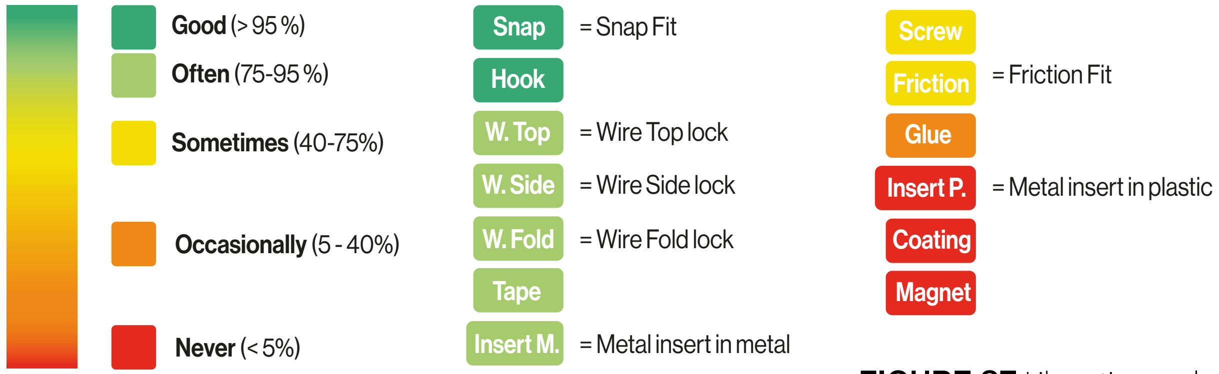


FIGURE 37 Liberation scale

Material group
In the connection block the material group will be indicated. This will allow the user to see whether the material group aligns with the main component it is connected to. It is expected this method is used in combination with a BoM, therefore the exact material of the connection will not be indicated. Also, the material of the connection is often the same as one of the two components it is connected to. For example, a snap-fit will often be made of the same plastic as the material of the main component.

- **F** - Ferrous
- **NF** - Non-ferrous
- **P** - Polymer
- **E** - Electronics
- **O** - Other

6.3.2 CONNECTORS

Sometimes materials are attached using connectors such as screws and wires. To visually represent these connectors as parts, their part numbers are shown in a component circle next to the connection block (Figure 38).

When connectors, such as wires, connect two or more parts, they form several separate connections using a single connector (Figure 39). For example, a wire connecting a PCB to the speaker unit forms one connection between the PCB and the wire, and another connection between the wire and the speaker. These connections may behave differently during the shredding process. A dotted line next to the component circle indicates that the connector connects multiple parts. As a result, this connector will appear multiple times on the map.

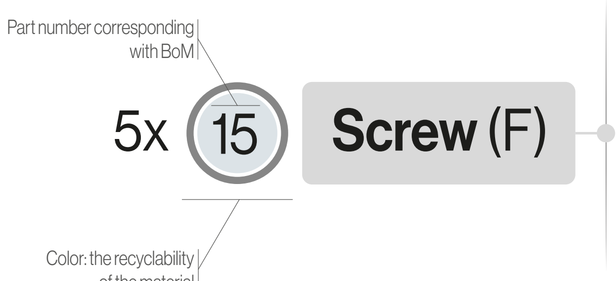
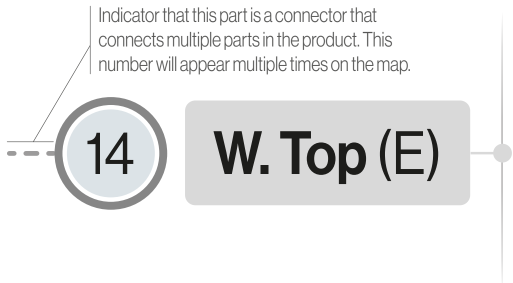


FIGURE 38 Connector



6.3.4 RECYCLABILITY OF A MATERIAL

The recyclability of a material is determined by a number of factors, including its properties and adjacent materials. However, the main determinant of whether a material can be recycled is the availability of appropriate technologies and infrastructure at recycling facilities. Therefore, the method uses a two-colour scale (red and green) to indicate whether the material can be recycled based on current recycling practices.

RECYCLABLE

- Electronics
- Aluminum
- Stainless Steel
- Steel
- PP
- PE
- PS
- PC
- PC + ABS

NOT RECYCLABLE

All other materials and mixture of materials are not recyclable in the current e-waste recycling process.

6.3.5 HAZARDOUS MATERIALS

Hazardous materials cause problems during the recycling process and must be manually removed before shredding. Therefore, easy access to these hazardous components is essential for efficient and safe dismantling. To indicate the presence of hazardous materials, use the symbol shown in Figure 40 next to the component circle. The symbol highlights that this part requires special attention.

FIGURE 40 Indicator Hazardous material

6.3.6 VALUABLE MATERIALS

The most valuable materials for recycling are often found on PCBs, such as copper, gold and silver. Proper separation of these parts is essential to maximise material recovery. To identify these valuable materials, the symbol shown in Figure 41 should be used next to the component circle. Design choices that improve the liberation of these valuable parts should be prioritised.

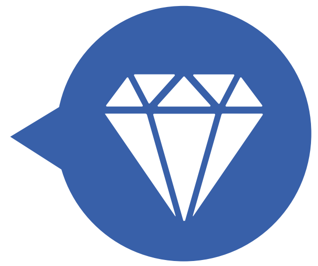


FIGURE 41 Indicator Valuable material

6.3.7 DESIGN CONSIDERATIONS RECYCLABILITY MAP METHOD

During the iterative design process of the Recyclability Maps methodology, several designs were explored. Some of the most important considerations are listed below, these considerations resulted in the final design of the method.

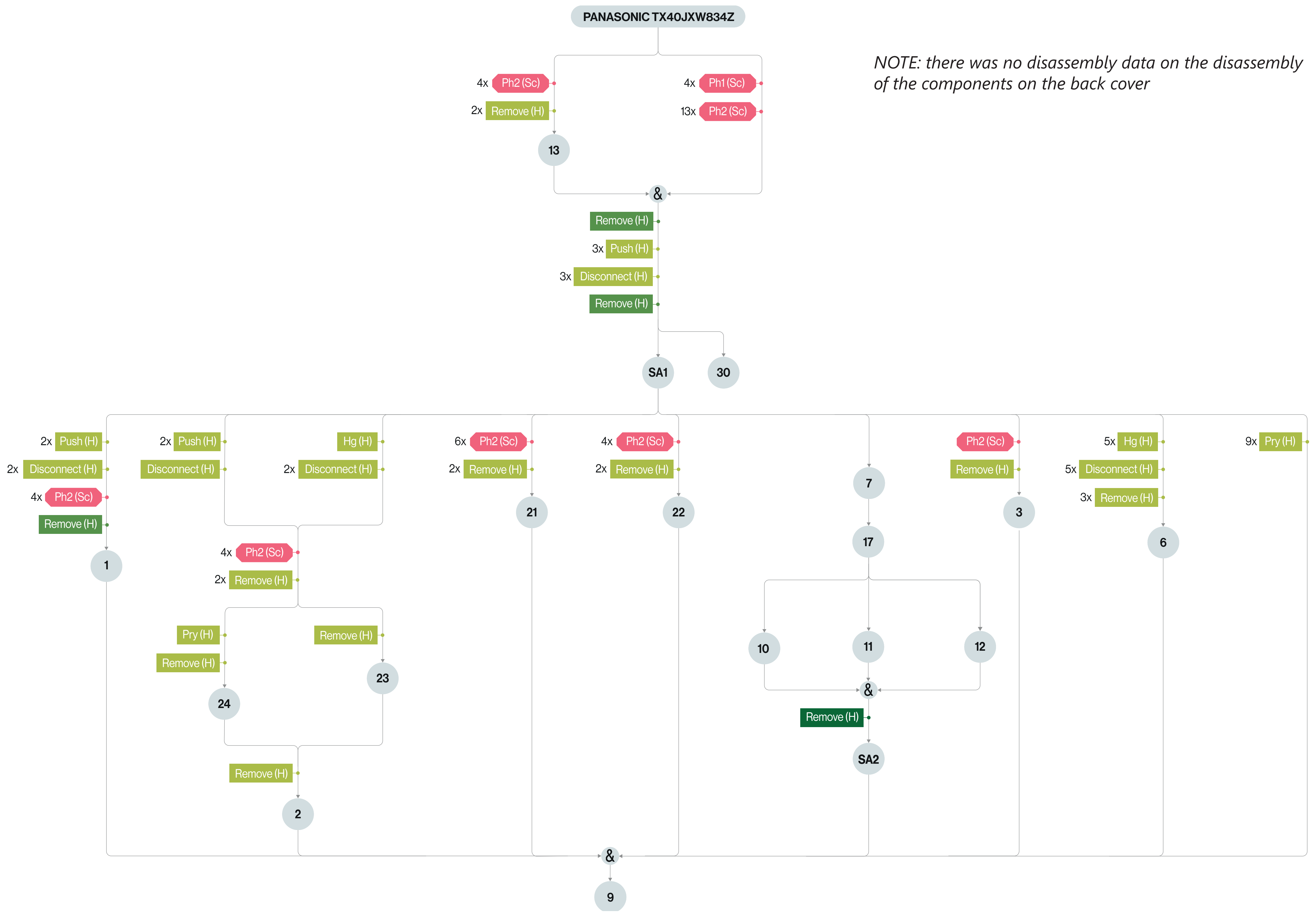
- To avoid confusion, it's decided not to display the disassembly and recyclability maps at the same time. Mixing these maps can be confusing and obscure the impact of design choices.
- To manage complexity, connectors are shown adjacent to connector blocks, instead of connecting them with a visible line. This resulted in many lines crossing and compromising the readability of the map.
- The number of connections is shown next to the connector blocks. For the connections that are quantified in terms of connected surface area (e.g. glue or coating), the amount is not shown. Given that this tool is used during the design phase, precise determination of these quantities is challenging and unnecessary.
- The colour range for the degree of liberation is based on the results of the shredding experiment. This non linear division resulted in the most informative scale at this moment. It also encourages designers to use connections with high liberation degrees, since the scale only has a few green connections.
- Material recyclability is influenced by material properties, adjacent materials and recycling practices. Throughout the design process, several iterations were explored, including different icons, colour scales and numerical values to represent a material's recyclability. This simplified visualisation with two distinct colours represents the most important determinant and ensures clarity and ease of interpretation.
- Subassemblies can be added in all maps, to keep the maps comprehensive and easy to interpret. When subassemblies are used to clarify the product architecture layer, make sure this is done correctly and aligns with the disassembly and recyclability layer.
- To ensure clarity it is recommended to visualise the entire product architecture, for all layers, ensuring a complete overview of the product. This means "clumping" used for disassembly maps, should not be done when comparing these two strategies.

6.4 THE SMART TV MAPS

The method was applied to the four different smart TVs analysed in this research. First, the PROMPT project maps are aligned with the product architecture layer. Then, the recyclability layer is created using the new method.

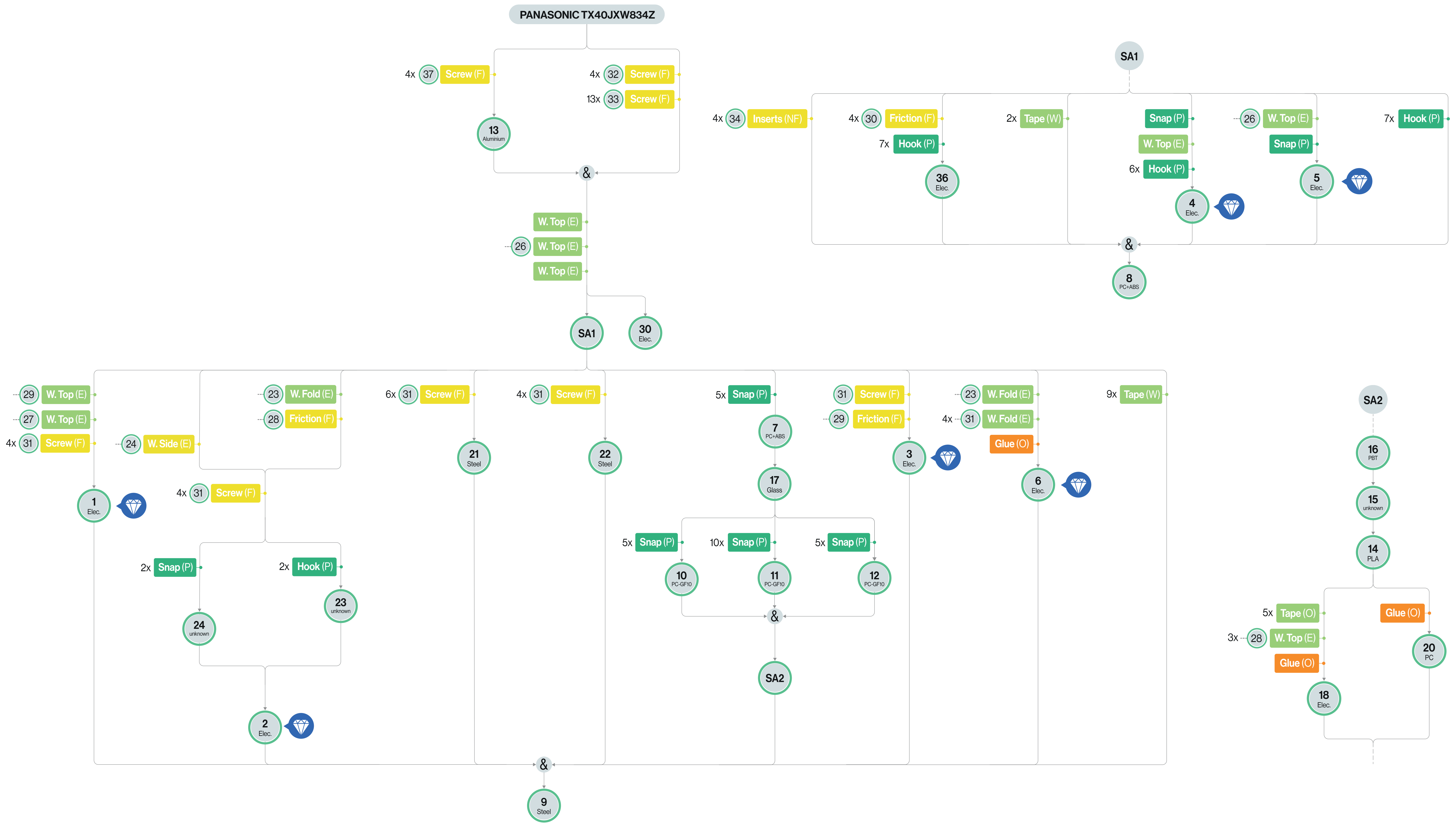
6.4.1 PANASONIC DISASSEMBLY MAP

NR.	COMPONENT
1	Powerboard
2	Motherboard
3	PCB
4	Button board
5	Contact sensor
6	Screen PCB small
	CHASSIS
7	Frame front
8	Housing back
9	Metal chassis
10	Frame part (short)
11	Frame part (bottom)
12	Frame part (top)
13	Tv standard
	SCREEN
14	Optical sheet
15	Diffuser plate
16	Reflector sheet
17	Screen
18	LED strip
19	LEDs
20	Placeholder spikes - transparent
	CONSTRUCTION/PROTECTION ELEMENTS
21	Bracket metal standard
22	Bracket metal - small
E	WIRES
23	Connection strip (L-shape)
24	Wire (grey)
25	Wires (black, multiple)
26	Wires (pink)
27	Wire (black, single)
28	Plug and cable
29	Connection strip (U-shape)
	CLIPS/PLACEHOLDERS
30	Silicone round
	SCREWS
31	Silver screws
32	Black screws (small)
33	Black screws (large)
34	Inserts
35	Screws (TV-standard)
	OTHER
36	Speakers



NOTE: there was no disassembly data on the disassembly of the components on the back cover

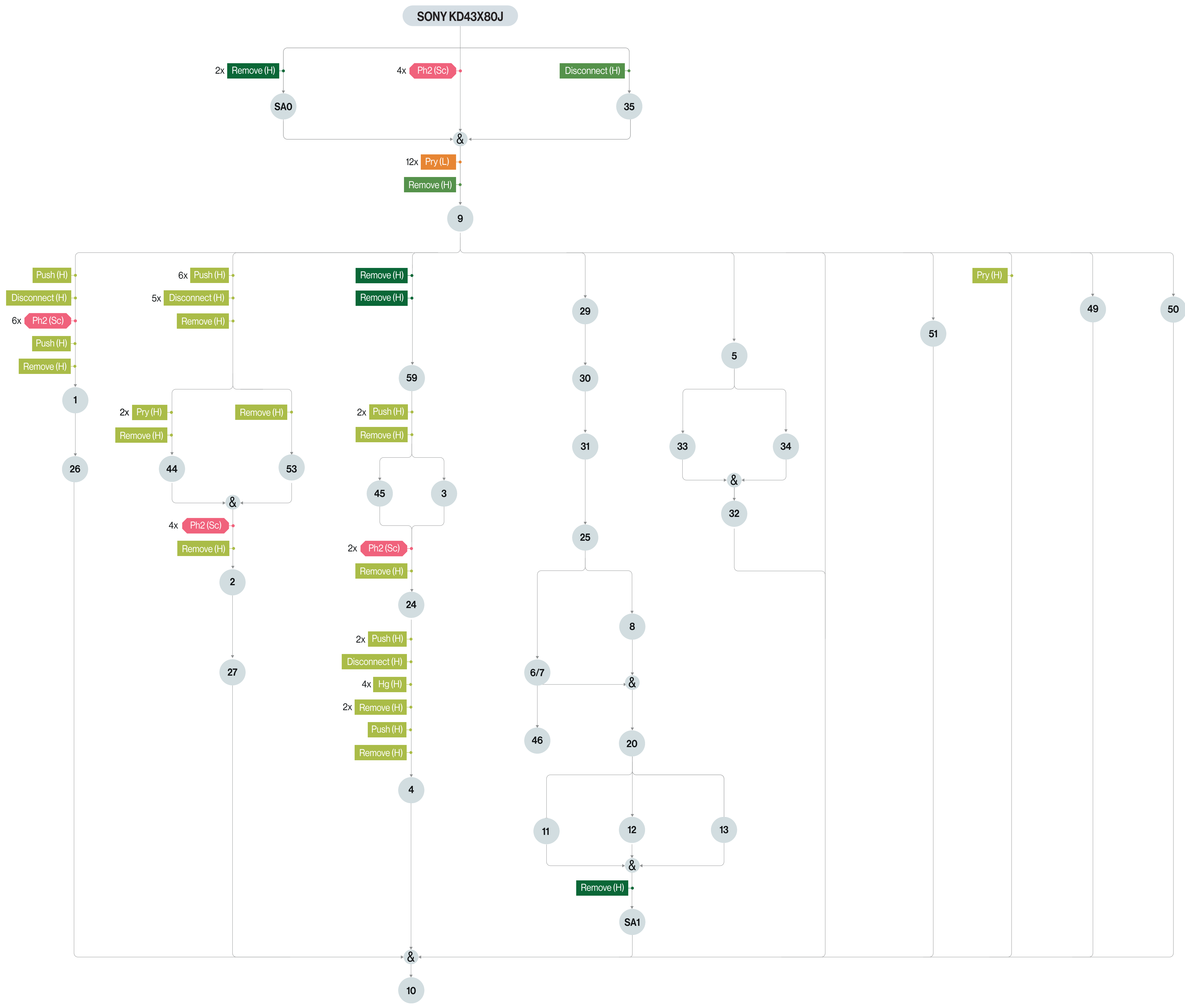
6.4.2 PANASONIC RECYCLABILITY MAP



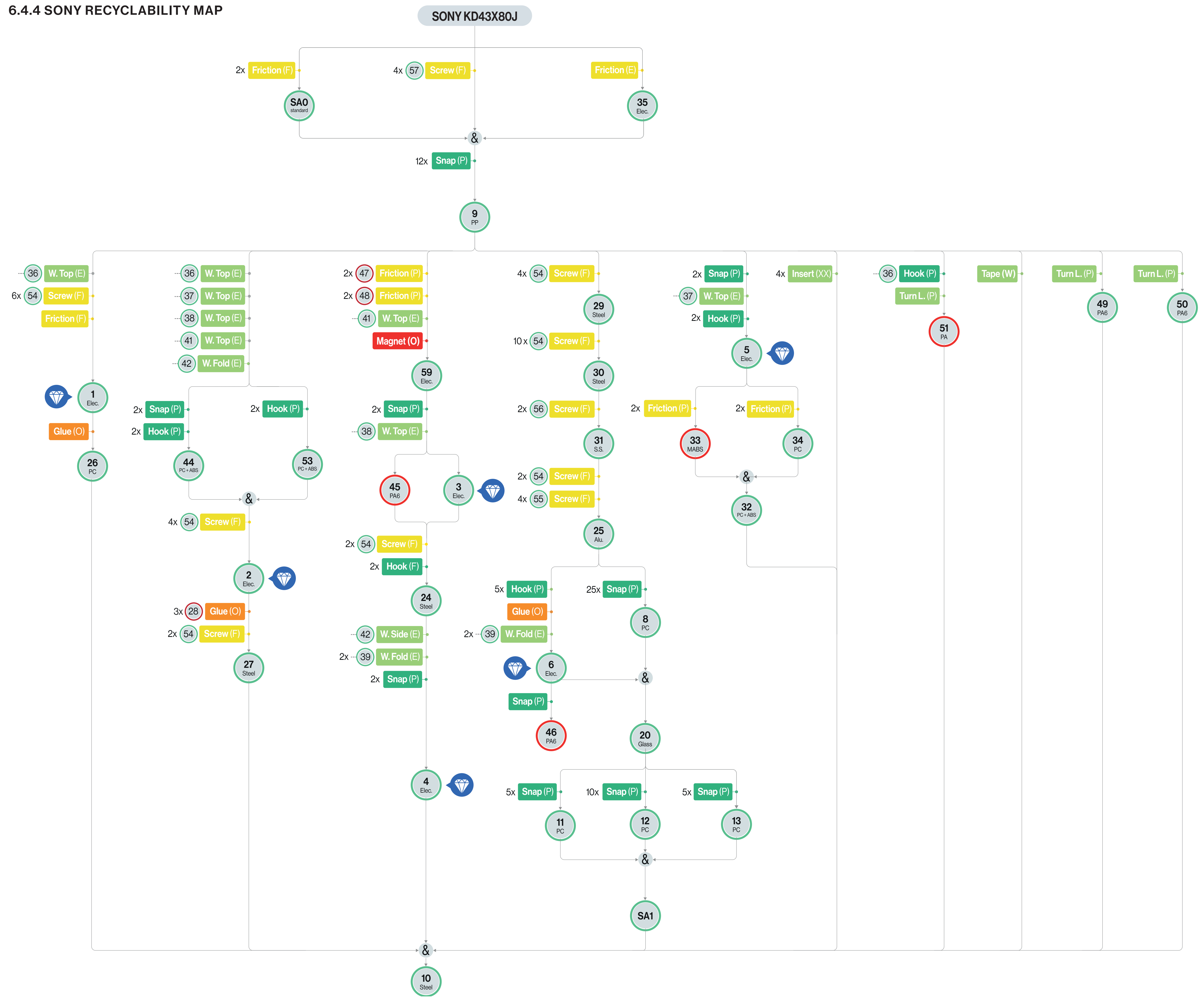
6.4.3 SONY DISASSEMBLY MAP

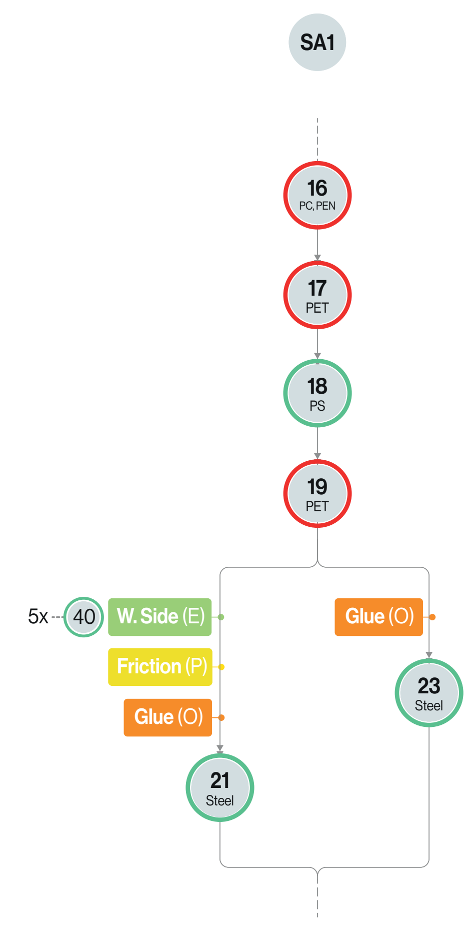
NR.	COMPONENT
	PCBs
1	Powerboard
2	Motherboard
3	PCB - small
4	PCB - large
5	Button board
6	PCB screen - small
7	PCB screen - large
	CHASSIS
8	Frame front
9	Housing plastic
10	Metal chassis
11	Bottom frame
12	Side frame
13	Top frame
14	Standard
15	Standard connection bracket
	SCREEN
16	Opt sheet top
17	Opt sheet bottom
18	Diffuser plate
19	Reflector sheet
20	Screen
21	LED strip
22	LED
23	Placeholders spikes - transparent
	CONSTRUCTION/PROTECTION ELEMENTS
24	Metal piece flat black tape
25	Housing screen PCB - metal
26	Transparent sheets under powerboard
27	Metal under plate motherboard
28	Sticky foam stickers
29	Metal bracket - small
30	Metal bracket - large
31	Metal spring in bracket
32	Housing button - black
33	Housing button - transparant
34	Housing button - milky white
	WIRES
35	Plug
36	Grey wire
37	Flat wire M shape - small
38	Flat wire M shape - large
39	Wire flat
40	Pink wire (multiple) & black plastic piece

See other page for the rest of the components →



6.4.4 SONY RECYCLABILITY MAP

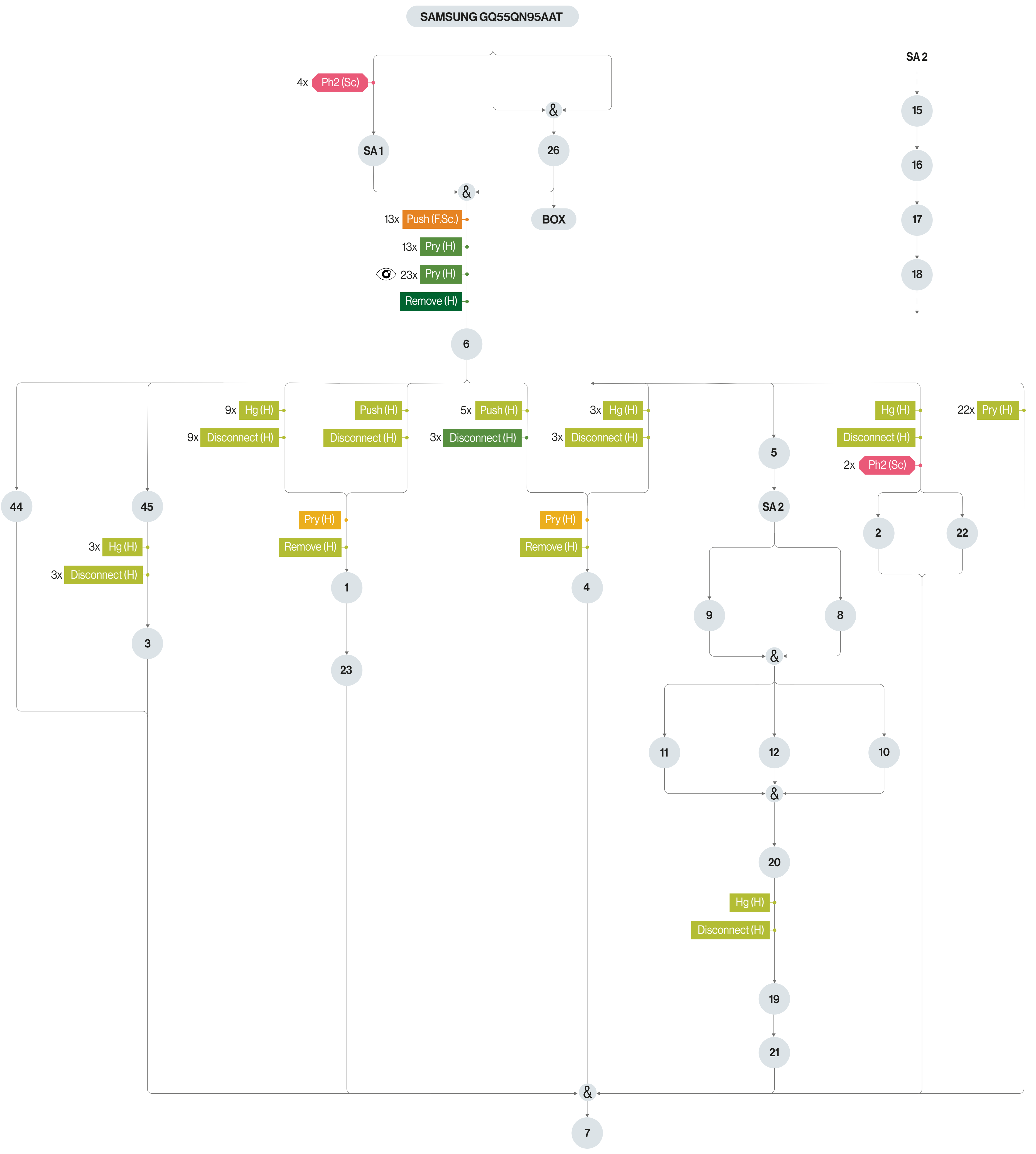




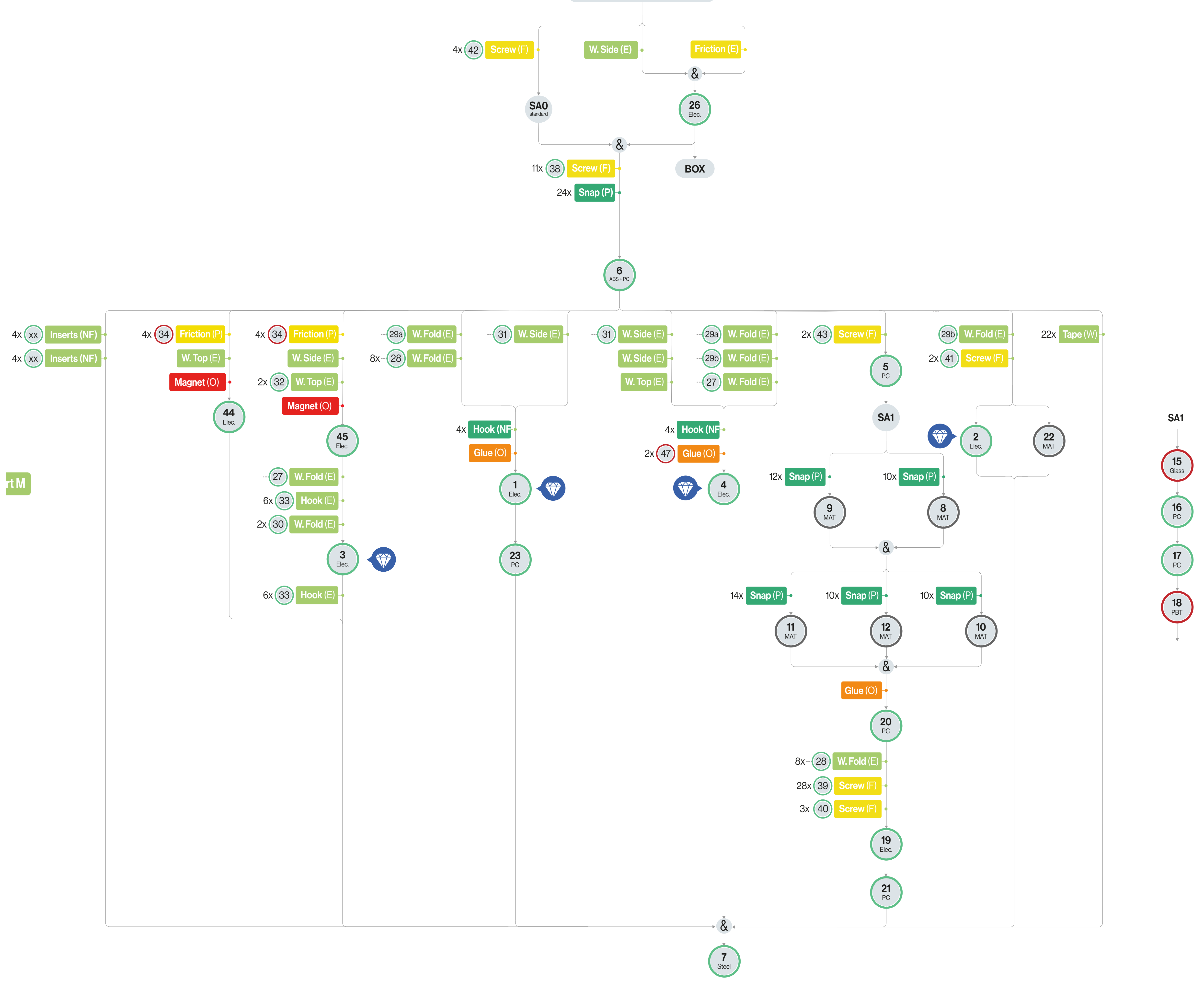
41	Red wire
42	Flat wire folded shape
	CLIPS/PLACEHOLDERS
43	Standard clips for socket
44	Motherboard housing - black
45	PCB back clip
46	Screen PCB clip - purple
47	Blue rubber
48	Black rubber
49	White PCB clip
50	Grey PCB clip
51	Black wire holder
52	Motherboard housing plug - piece inside
53	Motherboard housing plug
	SCREWS
54	Silver screws with ring - small
55	Silver screws flat - medium
56	Silver screws flat - large
57	Black screw with ring
58	Black screw with ring for standard
	OTHER
59	Speaker unit

6.4.5 SAMSUNG SCREEN DISASSEMBLY MAP

NR.	COMPONENT
	PCBs
1	Motherboard
2	Button board
3	Screen PCB
4	PCB black
	CHASSIS
5	Frame front
6	Housing plastic
7	Metal chassis
8	Top frame - black
9	Bottom frame - black
10	Bottom frame - white
11	Side frame - white
12	Top frame - white
13	Standard
14	Standard connection part
	SCREEN
15	Screen
16	Opt sheet top
17	Opt sheet bottom
18	Diffuser plate
19	LED plate
20	Protection sheet LED plate
21	Reflector sheet
	CONSTRUCTION/PROTECTION ELEMENTS
22	Housing button board
23	Black sheet under motherboard
	WIRES
26	Cable TV-BOX
27	Flat cable 52 mm
28	Flat cable 29 mm
29	Flat cable 15 mm
30	Flat cable black
31	Black cable - orange connection
32	Cable - red/green/yellow
	CLIPS/PLACEHOLDERS
33	Clips screen PCB - black
34	Rubber rounds
35	Wire clip outside
36	Cable cap
37	TV cable clip
	SCREWS
38	Black screws
39	Black screws flat
40	Black screws flat mini
41	Silver screws - mini
42	Black screws large
43	Black screws middle
	OTHER
44	Small speaker with wire
45	Large speaker with wire
46	Foam under PCB - black

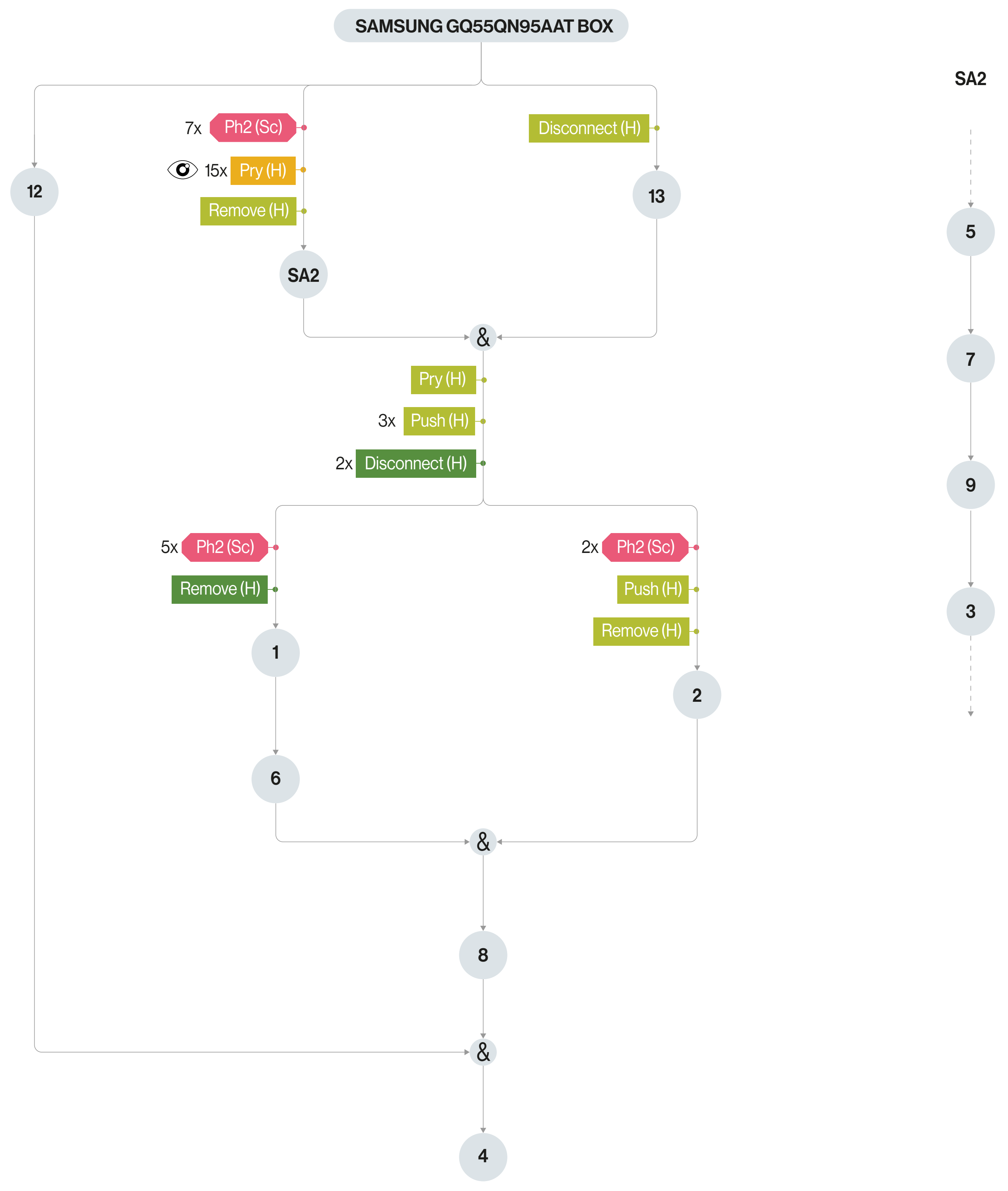


6.4.6 SAMSUNG SCREEN RECYCLABILITY MAP

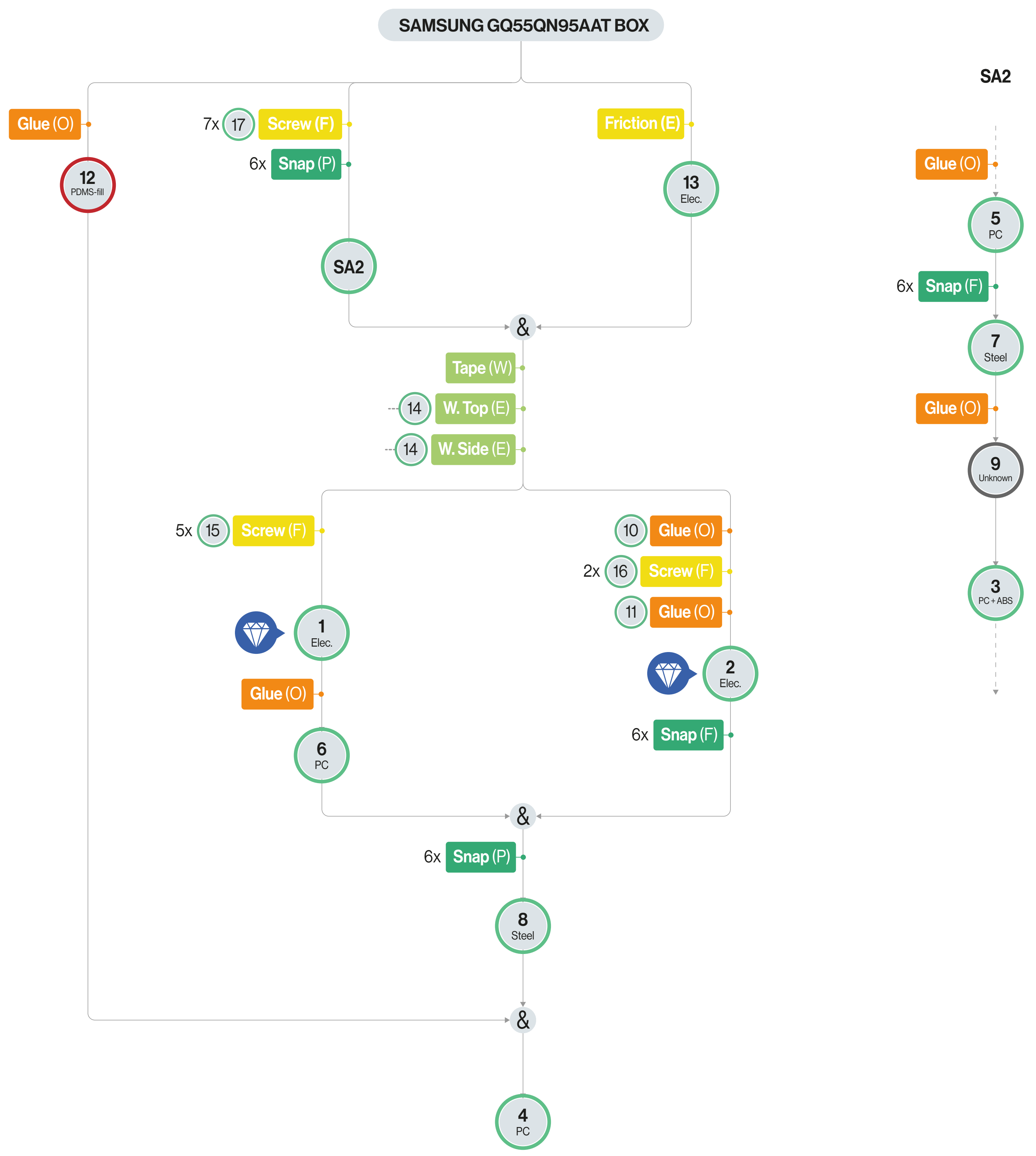


6.4.7 SAMSUNG BOX DISASSEMBLY MAP

NR.	COMPONENT
	PCBs
1	Powerboard
2	Motherboard
	HOUSING
3	Top housing
4	Bottom housing
	CONSTRUCTION/PROTECTION ELEMENTS
5	Black sheet top housing
6	Black sheet bottom housing
7	Metal sheet top housing
8	Metal sheet bottom housing
9	Plasticized graphite layer
10	Foam grey
11	Sticky foam stickers
12	Foam under housing
	WIRES
13	Plug
14	Black/blue cable - orange connection
	SCREWS
15	Silver screws
16	Silver screw - large
17	Black screws

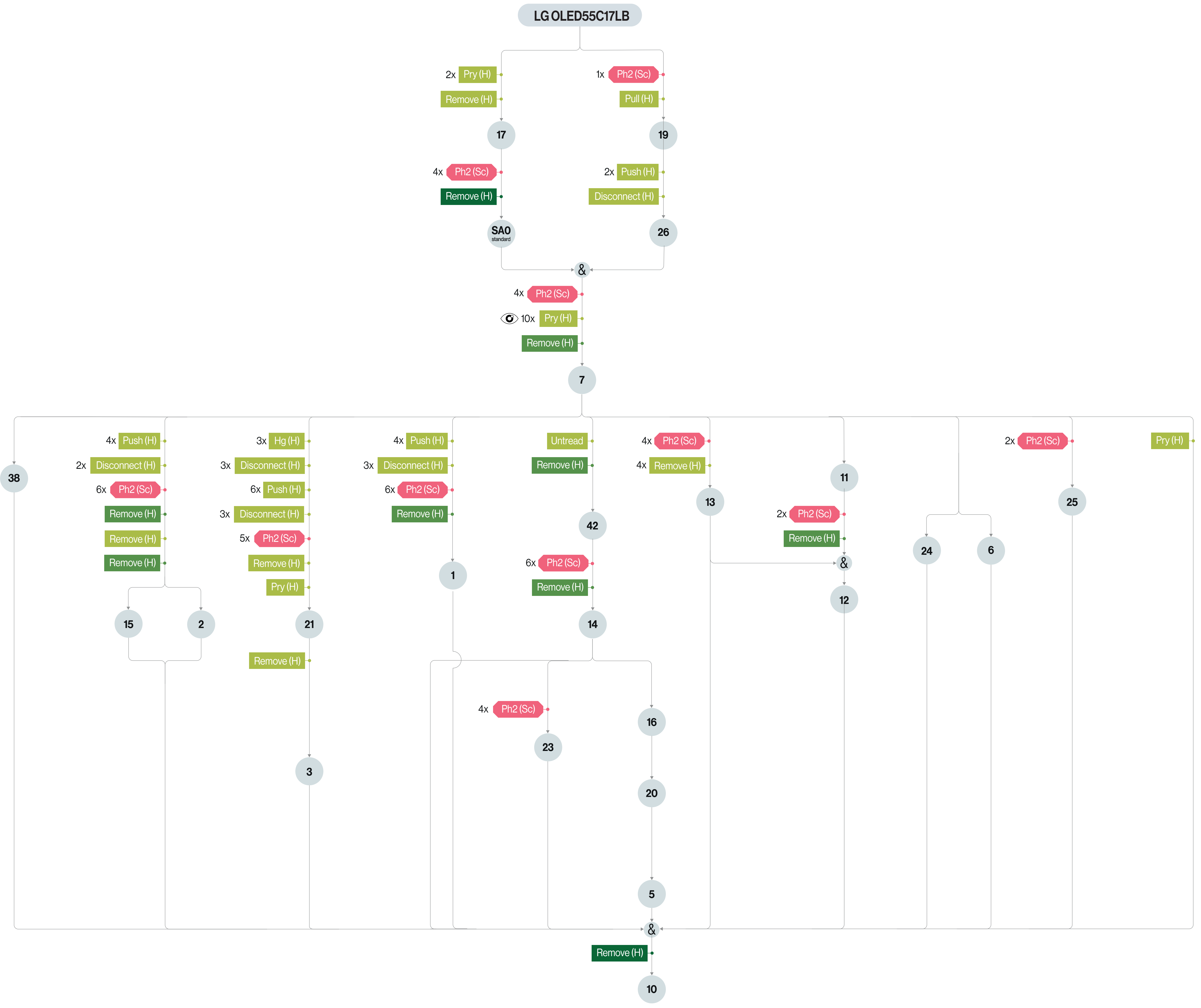


6.4.8 SAMSUNG BOX RECYCLABILITY MAP

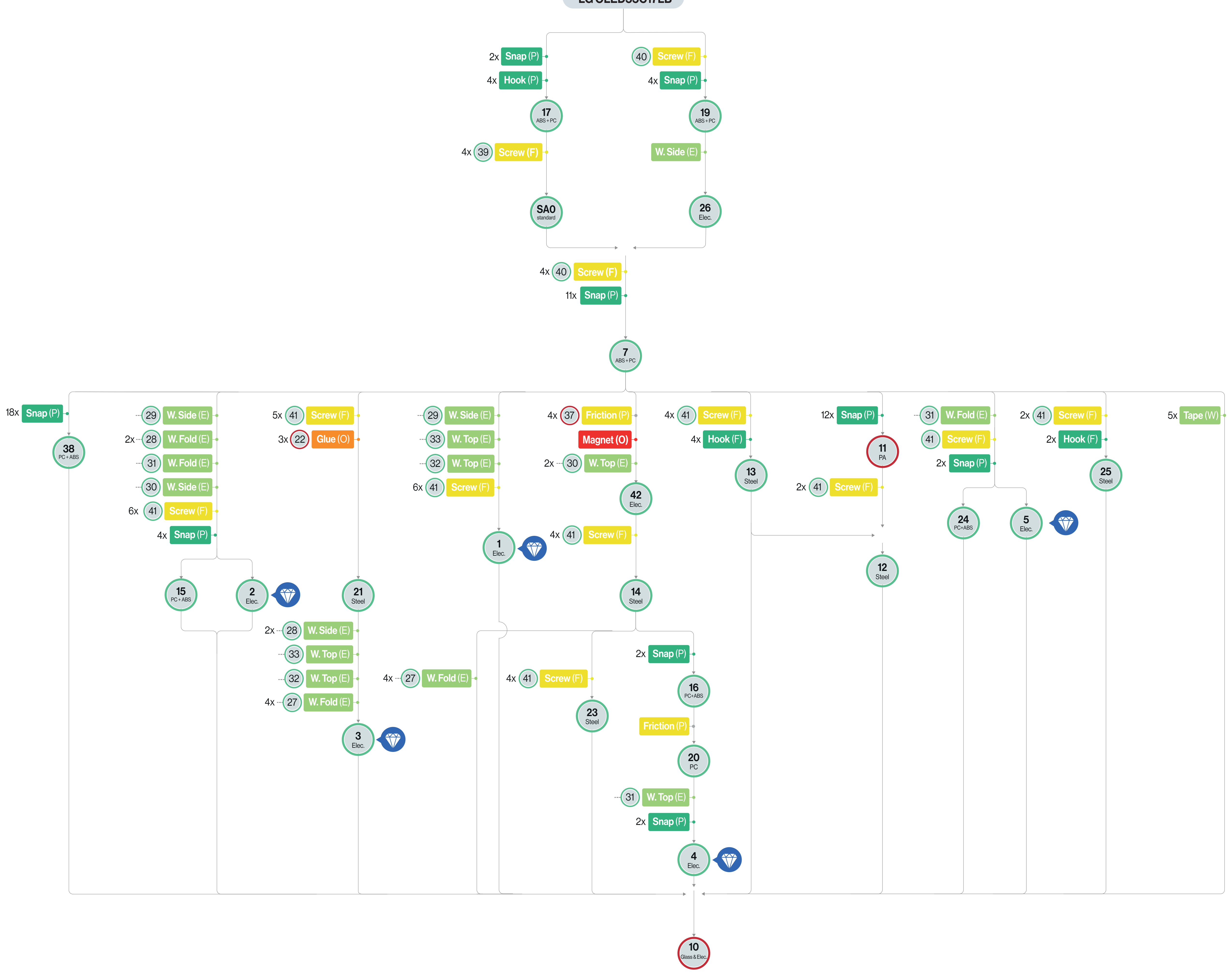


6.4.9 LG DISASSEMBLY MAP

NR.	COMPONENT
	PCBs
1	Powerboard
2	Motherboard
3	PCB - large
4	Screen PCB
5	Button board
6	PCB wifi
	CHASSIS
7	Housing plastic
8	Stand front
9	Stand back
	SCREEN
10	Screen (incl. screen PCB) and metal chassis
	CONSTRUCTION/PROTECTION ELEMENTS
11	Plastic piece inside (grey on metal)
12	Metal piece long top housing
13	Metal brackets for housing
14	Metal plate
15	Motherboard plastic connections
16	Housing buttonboard
17	Standard plastic cover
18	Plastic cover standard plug
19	Plastic cover power cord housing
20	Plastic front housing buttonboard
21	Small metal plate
22	Sticky foam stickers
23	Metal pieces for metal plate
24	Housing PCB wifi
25	Metal parts back cover bottom
	WIRES
26	Plug
27	Flat wire
28	Flat wire with connection part
29	Black wire
30	Blue/red wire
31	Silver/white wire
32	Grey/blue wire
33	Grey/blue wire 5 wires
	CLIPS/PLACEHOLDERS
34	Clip plug
35	Silicon rubber standard
36	Protection rubber bottom standard
37	Silicon rubber speakers
	SCREWS
38	Black screws with ring - large
39	Black screws - small
40	Silver screws
	OTHER
41	Speakers
44	Small speaker with wire
45	Large speaker with wire
46	Foam under PCB - black



6.4.10 LG RECYCLABILITY MAP



6.5 TENSIONS BETWEEN RECYCLING AND REPAIR

The tensions that are analysed, range from specific design choices within a particular TV model to broader product characteristics, such as the use of screws in general. The analysis is supported by previous research performed by Dangal et al. (2022), because the Disassembly Maps were not representive for the entire product architecture. With this analysis, I aim to point out several trade-offs involved in balancing recyclability and repairability of smart TVs.

6.5.1 GENERAL TENSIONS BETWEEN REPAIRABILITY AND RECYCLABILITY

Connections prone to breaking (Figure 42)

Recycle (pros)
- Use connections that break down easily during shredding and allow liberation of materials (e.g. snap-fits, hook connections).

Repair (cons)
- Avoid non-reusable fasteners or fasteners prone to breaking (e.g. glued components, on-way snap-fits and hidden high force snap-fits).

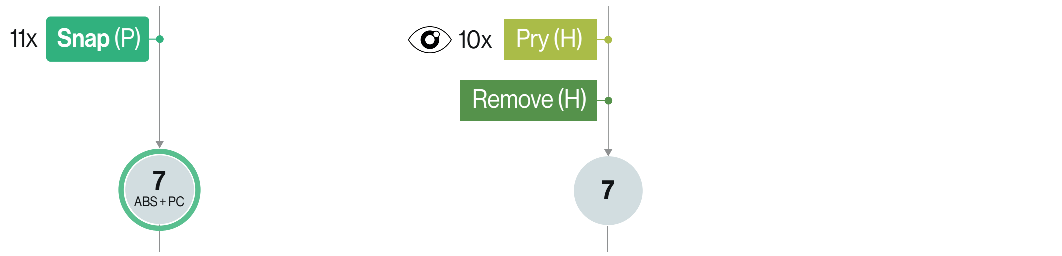


FIGURE 42 Snap-fit tensions (LG model map)

6.5.2 TENSIONS FOR SMART TVS

Attachment of the back cover (Sony, LG and Samsung) (Figure 43)

Recycle (pros)
- Snap-fits generally have a high liberation degree, meaning they rarely stay intact during shredding.
- Screws sometimes remain intact, but the back cover material, being relatively brittle, usually results in small fragments, allowing most material to be liberated and separated, except for small amounts around screws.

Repair (cons)
- Snap-fits are often invisible, non-reusable, and prone to breaking, making it very difficult to disassemble and reassemble the back cover without damage (Dangal et al., 2020).
- Multiple tools are needed, and the process is not straightforward (Dangal et al., 2020).

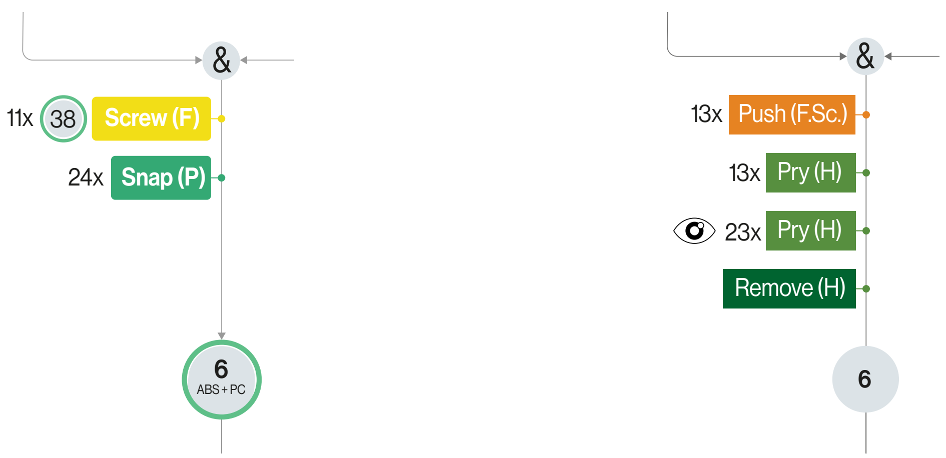


FIGURE 43 Attachment of the back cover tension (Samsung map)

Screen assembly (Sony, LG, Samsung, Panasonic) (Figure 44)
It should be noted that the screen is composed of several layers: optical sheet(s), reflector sheet, and the glass layer (with diodes, glass, and polymer films). The glass layer is considered one layer, even though it consists of multiple materials.

Recycle (pros)
- The fragility of the screen material ensures it breaks down into fragments, resulting in a high liberation degree, which is beneficial for recycling. The screen is often only enclosed by a frame connected with snap-fits; once the frame is liberated, all layers are no longer connected.

Repair (cons)
- The screen is very difficult to replace due to its large size, flexibility, and fragility, making the procedure highly complex and risky. Special care must be taken to avoid dust particles on the screen components (Dangal et al., 2020).
- *Not visible in the incomplete disassembly map, based on own experiences during the disassemblies and insights of Dangal et al. (2020).*

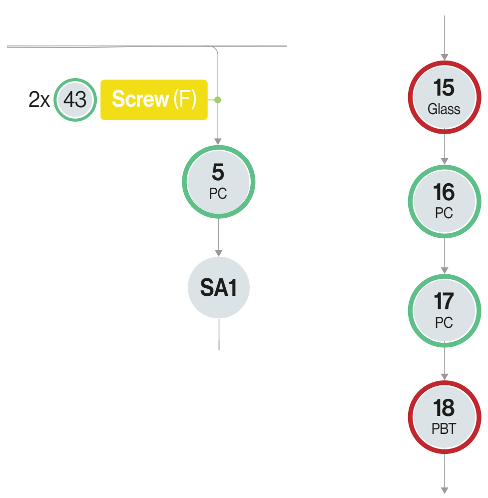


FIGURE 44 Screen assembly tension (Samsung map)

Magnets in speakers (Sony, LG, Samsung) (Figure 45)

Recycle (Cons)
- Speakers include a magnetic part that pulverizes during shredding, contaminating the ferrous materials stream.

Repair (Pros)
- The magnet in the speaker often connects to the TV's ferrous metal chassis, making the connection between the speaker and the rest of the TV very easy to disassemble and reassemble.

FIGURE 45 Magnetic attachment tension (LG model)

6.5.3 MODEL SPECIFIC TENSIONS

Sony – Screws for attaching multiple parts (Figure 46)

Recycle (Cons)
- Screws occasionally stay intact not favourable for recycling. Also many screws are used in this place and aluminium is connected to steel, which have different separation processes.

Repair (Pros)
- Using a low variation of fasteners minimizes tool changes and decreases disassembly time. Screws are also reusable fasteners.
- *These actions are not visualised in the disassembly map. It is however straightforward, that on the same locations as in the Recyclability Map, screws will appear.*

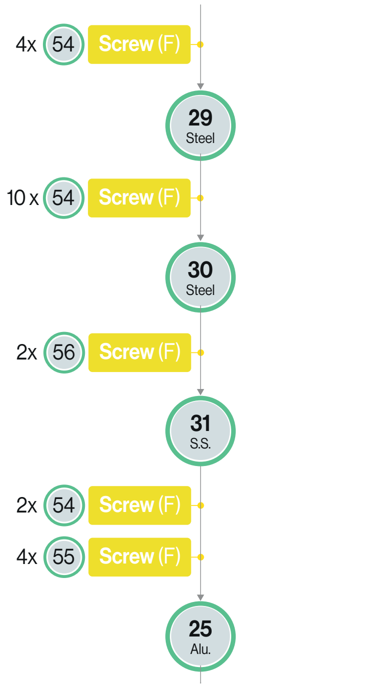


FIGURE 46 Screws tension (Sony map)

Sony - Snap-fits for frame assembly (Figure 47)

Recycle (Pros)
- The snap-fits used to connect the frame to the metal chassis have a high liberation degree.
- The material used is prone to breaking, leading to a high liberation degree.

Repair (Cons)
- Disassembly is difficult because some snap-fits break easily, making reassembly challenging.

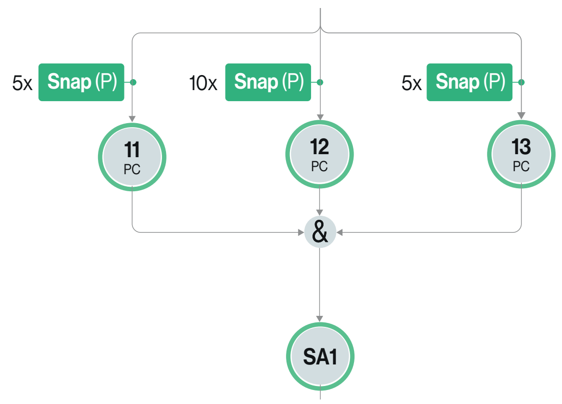


FIGURE 47 Snap-fit tension (Sony map)

Samsung – Hook connections for attaching PCBs (Figure 48)

Recycle (Pros)
- These connections are more favourable for recycling than screws, as they break down during shredding, enabling a high recovery rate of valuable materials.

Repair (Cons)
- Disassembly requires a tool and medium force. The connection differs from other models analysed, meaning the procedure is not straightforward, leading to longer disassembly times due to tool changes and different types of connections.

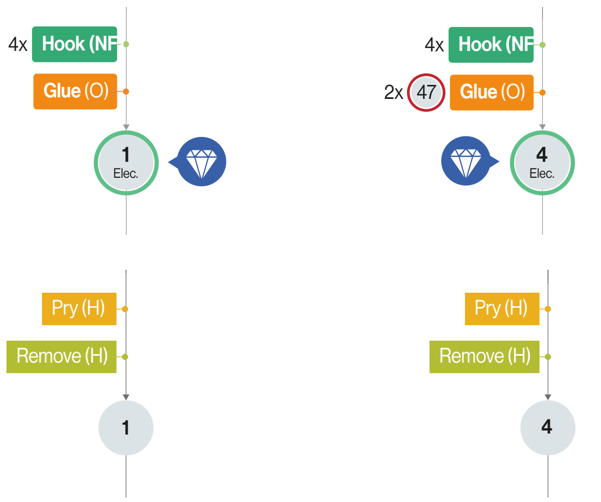


FIGURE 48 Hook tension (Samsung map)

Panasonic – Inserts (Figure 49)

Recycle (Cons)
- The metal inserts in the plastic back cover often stay intact during shredding, leaving plastic connected to the metal, leading to material losses during separation.
- *Not visualised in the disassembly map, based on insights of disassembly related parameters.*

Repair (Pros)
- These metal inserts facilitate easy disassembly and reassembly. They ensure fastener reusability and create threaded holes in plastic parts, resulting in stronger and more durable threads that are less prone to stripping or wear over time.

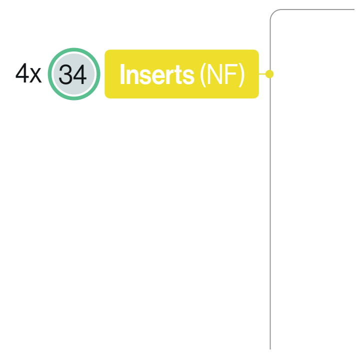


FIGURE 49 Inserts (Panasonic map)

LG – Disassembly depth of PCBs (Figure 50)

Recycle (Pros)
- Although there are many connections for the two PCBs, the liberation degree will mostly facilitate breakdown, not causing recycling difficulties.

Repair (Cons)
- Disassembling the PCBs requires many actions and different tools, leading to a relatively high disassembly depth and frequent tool changes.

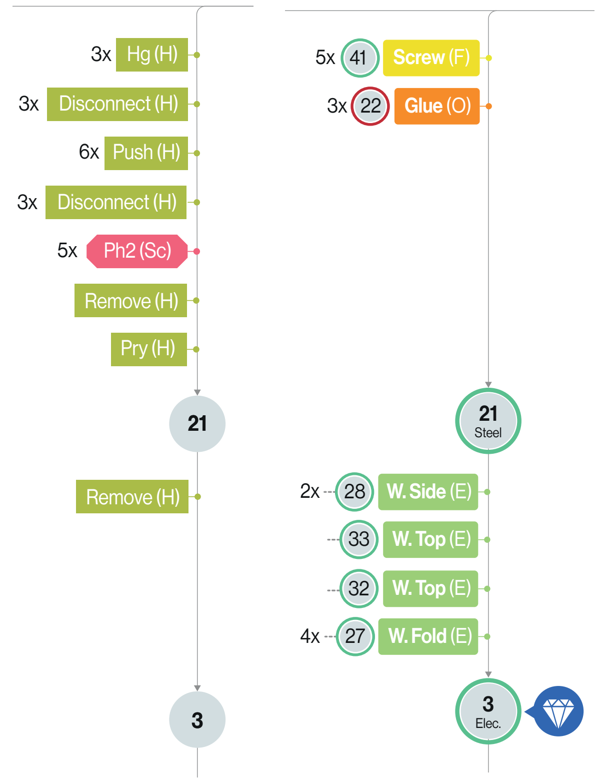


FIGURE 50 Disassembly depth (LG map)

6.5.4 LIMITATION

Unfortunately, due to some shortcomings and gaps in the disassembly maps it is hard to show the effectiveness of the method. However, looking at some snaps of the Recyclability Maps, it is sometimes straightforward what de Disassembly Map would look like. Therefore some tensions could be identified based on the Recyclability Map and the research of Dangal et al. (2020). Also, on the basis of my own experiences during the disassemblies I drew the conclusion for the "Sony - Snap-fits for frame assembly". Normally, these "non-reversible fastener" would be indicated in the Disassembly Map.

6.6 DISCUSSION & CONCLUSION FOR THE RECYCLABILITY MAP

In this chapter, the tensions between recyclability and repairability in the context of smart TVs is explored, by using a new method that integrates Disassembly Maps and Recyclability Maps. By addressing two closely related sub-research questions, I aimed to provide insights into how designers can assess and map these tensions effectively.

- How can designers assess the tensions between recyclability and repairability?
- What are the tensions between recyclability and repairability of a smart TV?

The first sub-research question focused on developing a methodology to assess the tensions. The iterative process allowed for the development of the methodology, incorporating insight from the recycling experiment and recycling experts. The evaluation with two designers familiar in this field, gave insight into improvements and recommendations, which were incorporated in the method. For the varying liberation degrees more research needs to be done to better understand the behaviour of connections during the shredding process and make more distinct options for these connections. However, for now the framework is set, in which the method can be further developed.

The second sub-research question aimed to demonstrate the effectiveness of the methodology by applying it to smart TVs. The Disassembly Maps, adapted for the PROMPT project and modified to align with the method developed by de Fazio et al. (2020), provided valuable insights into the disassembly process regarding priority parts. Additionally, the Recyclability Maps have been created for the TVs analysed in this study. The results show different problematic product characteristics for recyclability. Moreover, the use of the method represent an effective tool, by showing the problematic product characteristics for both recyclability and repairability. Allowing designers to make informed decisions during product design.

The analysis revealed several key findings regarding the tensions between recyclability and repairability in smart TVs. Snap-fits, commonly used for attaching components like the back cover and frame, demonstrated high liberation degrees during shredding, enhancing recyclability. However, their hidden nature and propensity to break posed challenges for repairability. Similarly, connectors such as hooks and screws showed trade-offs between ease of recycling and repair.

These findings have important implications for product design. Designers need to consider the interplay between recyclability and repairability when making design decisions. Balancing these considerations requires careful attention to the choice of materials, connections and product architecture.

There are some limitations to this study. The analysis focused solely on smart TVs, and the findings may not be generalizable to other product categories. This new method should be applied to different product to expand the scope to include a broader range of electronic devices and consumer products. Additionally, further refinement of the methodology and validation through real-world case studies would strengthen its applicability in practice.

Furthermore, the process of creating the maps with Adobe Illustrator, a visualization tool, was time-consuming. In the future, this process could be improved by automating it using online software. This would allow for quicker mapping of the product architecture and additional layers, facilitating more frequent updates throughout the design process and enabling designers to test design choices against circular strategies more efficiently. For instance, it could show connections between parts when hovering the mouse over certain components, making the method even more straightforward and accessible.

In addition to focusing on tensions, exploring the similarities between recycling and repair could reveal design choices that enhance both repairability and recyclability. This comprehensive approach would further promote sustainable product design practices.

6.7 TAKE AWAYS

The development of the Recyclability Map method represents a significant advancement in understanding and balancing the tensions between repairability and recyclability in product design. The key take-aways from this chapter are:

- The Recyclability Map method facilitates a balanced analysis of design choices, which is crucial to promoting circular economy principles.
- Designers need to consider the entire product lifecycle, carefully balancing repairability and recyclability.
- The iterative design process, based on practical experience and expert feedback, ensures the reliability and applicability of the Recyclability Map method.
- Applying the method to smart TVs reveals specific design features that impact repairability and recyclability, which could be considered in future design practices.
- Further refinement of the Recyclability Map method and exploration of evolving recycling technologies are needed to advance sustainable product design in the electronics industry.

CHAPTER 07

CONCLUSION

7.1 CONCLUSION

E-waste is the fastest growing solid waste stream in the world, creating an urgent need to address the design of electronic products. Circular design strategies can reduce the demand for critical raw materials and mitigate the environmental and human health risks associated with e-waste (ILO, 2014; Ahirwar & Tripathi, 2021; Fakhredin, 2018). Designers can have a major impact on the recyclability of electronics by making informed choices about materials, connections and product architecture. The impact of these choices on other circular design strategies, such as repair, should be considered. This thesis explores the influence of the design of electronic products and their recyclability, by addressing the following research question:

- How can electronic products be designed for effective recycling?

This study aimed to provide practical insights into the product and part characteristics that influence the shredding and separation process during recycling. These findings will be used to develop comprehensive methodologies to support designers in creating more sustainable products and making well considered design choices.

Chapter 1 analysed four smart TV models on their product and part characteristics, focusing on materials, connections and product architecture. The use of materials, such as steel, polymers and glass, and different types of connections (screws, snap-fits, adhesives and friction fits) offered a broad range of different characteristics. These characteristics form the basis for exploring how design features affect recyclability.

Chapter 2 investigated the liberation and separation of smart TVs through a shredding experiment. Different types of connections showed different liberation behaviour, with snap-fits and coatings showing the most consistent results. Screws, adhesives and friction fits showed more ambiguous behaviour. In addition, an interview with recycling experts provided many valuable insights. These practical insights were used to interpret the results of the shredding experiment and predict the separation behaviour of certain heterogenous fragments.

Chapter 3 developed a set of DfR guidelines for electronics by synthesising practical insights from the recycling experiment with existing guidelines from literature, which were filtered on their empirical evidence. These guidelines are focused on different phases of the design process, providing both high-level and low-level guidelines to improve the recyclability of electronic products and ensuring seamless integration into the design process. However, further testing with design practitioners is necessary to validate their usability and effectiveness.

Chapter 4 presented a newly developed method: Recyclability Maps, which effectively assesses the tensions between recyclability and repairability. The method, tested on smart TVs, revealed specific design features that causes tensions between these two circular strategies. Key findings, include that snap-fits in smart TVs, while beneficial for recycling, challenge repairability due to their hidden nature and tendency to break. Conversely, screws facilitate repair but complicate the recycling process. The Recyclability Map method offers a structured approach to evaluate the repairability and recyclability of products. By considering these two different design strategies, designers can make more informed decisions that balance these two essential aspects in a circular economy.

In conclusion, this thesis highlights the critical role of product design in facilitating effective recycling and moving towards a circular economy. By providing practical insights and developing comprehensive DfR guidelines, it offers a valuable insights into how to design for recycling. The Recyclability Map methodology represents a step forward in understanding and balancing the tensions between repairability and recyclability, enabling designers to make informed decisions that promote sustainability throughout the product lifecycle.

7.2 RECOMMENDATIONS

EXPANDING PRACTICAL RESEARCH AND COLLABORATIONS WITH RECYCLERS
To build on the insights gained from this thesis, future research should extend beyond smart TVs to include various electronic product categories. This will provide a broader understanding of how different products, connections, and materials impact the recycling process. Additionally, conducting shredding tests with larger sample sizes will ensure more reliable data and conclusions. Intensified collaborations with recyclers are essential to gather more practical data and refine recycling processes based on real-world conditions. Comparing the recycling processes of different recycling facilities will help identify differences in libaration and separation processes.

Encouraging collaboration between recyclers and designers is crucial. Interviews with recycling experts revealed their willingness to share knowledge and expertise on recycling. Facilitating contact between recyclers and designers can provide valuable insights, leading to more effective designs and better liberation and separation of materials. This, in turn, results in higher recovery rates of materials, which is financially beneficial for recyclers.

Next to e-waste recyclers, including plastic recyclers and smelters in these collaborations is also essential. Gaining more insight into the processes and techniques used, could enrich the DfR guidelines.

IMPLEMENTATION OF DFR METHODS
Developing an integrated tool that incorporates the DfR guidelines and the Recyclability Map method is essential for practical application. This tool should be accessible and usable for designers of all expertise levels. As new research and insights become available, the tool should be updated to reflect the latest knowledge. This will facilitate the creation of more sustainable designs and enhance designers' overall understanding of recyclability and repairability.

METHODS
Future research should focus on improving and iterating the methods. Specifically:

- **DfR Guidelines:** These guidelines need to be tested with design practitioners to validate their applicability and effectiveness. Applying the guidelines in practical design experiments will provide valuable feedback and insights into their real-world effectiveness and impact on design practices.

- **Recyclability Map Method:** This method should be tested on a broader range of product categories beyond smart TVs to evaluate its generalisability and effectiveness. Thorough testing and evaluation will help identify limitations and areas for improvement, ensuring the method is effective across different types of electronic products.

- **Disassembly Map Method (de Fazio et al., 2020):** This method could be improved for intuitiveness and usability. Integrating the Recyclability Map and Disassembly Map into one cohesive method would enhance their utility. Additional layers could be added in the future, such as layers regarding the safety or environmental impact of a product, to create an even more overarching method.

ONGOING RESEARCH AND DEVELOPMENT
The field of electronic product recycling is dynamic, with continuous developments in technology and recycling processes. Ongoing research is required to stay informed of these developments and to incorporate new knowledge into the DfR methods. Regular updates and iterations of these tools will ensure they remain relevant and effective in promoting sustainable design practices.

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APPENDIX A | DESIGN BRIEF

DESIGN FOR our future — TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Doris Versloot **Student number** 4,668,189

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

Project title Design for Recycling Guidelines for Electronic Products - A Smart TV Case Study

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

Introduction

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

Electronic waste (e-waste) is the fastest-growing waste stream, with an annual growth rate of 3-5% (Cucchiella et al., 2015). E-waste can contain precious metals such as copper, gold, silver and nickel. Many of these metals could be recycled to reduce the demand for new raw materials and mitigate environmental and human health risks by safe removal (Ahirwar & Tripathi, 2021).

In e-waste, Printed Circuit Boards (PCBs) contain the most substantial amount of precious metals, which, next to their environmental impact, hold significant economic value (Cayumil et al., 2016). Nevertheless, many products are currently not designed in a way that enables easy identification, separation and recycling of PCBs.

Designers can play a crucial role in reducing e-waste and designing electronic products for more effective recycling. Unfortunately, existing Design for Recycling (DfR) methods are underutilized and often lack experimental validation or adaptation for designers. DfR methods are frequently based on manual disassembly, whereas in current recycling processes, products are mechanically disintegrated (shredded). Even if these DfR methods are theoretically effective, the challenge lies in bridging the gap between theoretical effectiveness and real-world application for designers, implementing by ensuring widespread awareness and adoption of DfR methods.

The recyclability of electronic products depends on several factors, including the materials used, connections that enable easy breakdown into homogeneous fragments, and the product architecture that ensures the release of electronic parts as separate fragments. In the shredding process, homogeneous fragments are desired, since they improve the separation effectivity, leading to cleaner material flows and better recycling (Fakhredin, 2018).

Smart TVs are an interesting test case, as they are high-volume products containing high-quality electronics with valuable metals. Analysing the outcomes of the shredding experiment is expected to give valuable insights into the behaviour of these products in the shredding process.

Ahirwar, R., & Tripathi, A. K. (2021). E-waste management: A review of recycling process, environmental and occupational health hazards, and potential solutions. Environmental Nanotechnology, Monitoring and Management, 15, 100409. https://doi.org/10.1016/j.enmm.2020.100409

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DESIGN FOR our future — TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

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

Designing electronic products for recycling is challenging due to the absence of practical guidelines for designers. Existing Design for Recycling (DfR) methods frequently lack experimental validation or adaption for designers, which makes it challenging for designers to apply them in design processes.

During the shredding process, electronic products often break down into heterogeneous fragments, resulting in ineffective separation and making the material recovery and recycling difficult. The ineffective separation leads to the loss of precious metals and valuable materials during the recycling process.

The product features that influence a product's fragmentation are not well-established and often not based on practical experiments.

Assignment

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

Develop design for recycling guidelines for electronic products based on recycling experiments with Smart TVs and demonstrated through prototypes.

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

First, I will dive into the literature to understand current electronic product recycling processes and identify associated challenges.

Through a recycling experiment using 36 smart TVs, I will analyse the fragmentation, focusing on fragments of mixed composition and how this is related to product architecture and connections. Disassembly maps of smart TVs are a useful tool to analyse the product architecture and the connections within the product. They have been used to evaluate how changes within the product affect other characteristics of the architecture, for example the repairability of a product. I will expand this to include recyclability.

Based on findings from the literature and the experiment, a first draft of problematic design features and/or guidelines will be set up. With this first draft, I will create prototypes to explore how improvements can be made in connections or other design features to improve separation during shredding.

After evaluation and reflection on the prototypes and findings, a refined set of guidelines will be developed.

APPENDIX C | BILL OF MATERIALS OF THE SMART TVS

PANASONIC TX40JXW834Z

Nr.	Component	Quantity	Weight	Unity	Newton	Total weight	Unity	Material	
A	**PCBs**								
1	Powerboard	1	304,4	gram		304,4	gram	Electronics	Electronics
2	Motherboard	1	250,4	gram		250,4	gram	Electronics	Electronics
3	PCB	1	15,9	gram		15,9	gram	Electronics	Electronics
4	Button board	1	5	gram		5	gram	Electronics	Electronics
5	Contact sensor	1	1,2	gram		1,2	gram	Electronics	Electronics
6a	Screen PCB small	1	18,6	gram		18,6	gram	Electronics	Electronics
6b	Screen PCB large	1	44,6	gram		44,6	gram	Electronics	Electronics
B	**CHASSIS**								
7	Frame front	1	122,3	gram	1,2 N	122,3	gram	PC+ABS	Polymer
8	Housing back	1	997,6	gram	10,1 N	997,6	gram	PC+ABS	Polymer
9	Metal chassis	1	2242,6	gram	22,0 N	2242,6	gram	Steel	Ferrous metal
10	Frame part (short)	2	8	gram		16	gram	PC-GF10	Polymer
11	Frame part (bottom)	1	21,6	gram		21,6	gram	PC-GF10	Polymer
12	Frame part (top)	1	16,2	gram		16,2	gram	PC-GF10	Polymer
13	Tv standard	2	123	gram		246	gram	Aluminium	Non-ferrous metal
C	**SCREEN**								
14	Optical sheet	1	276	gram		276	gram	PLA	Polymer
15	Diffuser plate	1	438	gram		438	gram	unknown	Polymer
16	Reflector sheet	1	70	gram		70	gram	PBT	Polymer
17	Screen	1	1262,8	gram		1262,8	gram	PC and other r	Other
18	LED strip	3	30,6	gram		91,8	gram	Electronics	Electronics
19	LEDs	24	1,6	gram		38,4	gram	Electronics	Electronics
20	Placeholder spikes - transparent	4	0,8	gram		3,2	gram	PC	Polymer
D	**CONSTRUCTION/PROTECTION ELEMENTS**								
21	Bracket metal standard	2	70,8	gram		141,6	gram	Steel	Ferrous metal
22	Bracket metal - small	2	17,5	gram		35	gram	Steel	Ferrous metal
23	*Connector frame motherboard*	1	*Mass included in motherboard*						Polymer
24	*CI card holder*	1	*Mass included in motherboard*						Polymer
E	**WIRES**								
25	Connection strip (L-shape)	1	5,3	gram		5,3	gram	Electronics	Electronics
26	Wire (grey)	1	6,5	gram		6,5	gram	Electronics	Electronics
27	Wires (black, multiple)	1	9,4	gram		9,4	gram	Electronics	Electronics
28	Wires (pink)	1	2,8	gram		2,8	gram	Electronics	Electronics
29	Wire (black, single)	1	16,6	gram		16,6	gram	Electronics	Electronics
30	Plug and cable	1	79	gram		79	gram	Electronics	Electronics
31	Connection strip (U-shape)	2	0,7	gram		1,4	gram	Electronics	Electronics
F	**CLIPS/PLACEHOLDERS**								
32	Silicone round	4	0,8	gram		3,2	gram	PDMS	Polymer
G	**SCREWS**								
33	Silver screws	19	0,6	gram		11,4	gram	Steel	Ferrous metal
34	Black screws (small)	4	0,3	gram		1,2	gram	Steel	Ferrous metal
35	Black screws (large)	13	0,5	gram		6,5	gram	Steel	Ferrous metal
36	Inserts	4	8	gram		32	gram	Aluminium	Non-ferrous metal
37	Screws (TV-standard)	4	3,5	gram		14	gram	Steel	Ferrous metal
H	**Other**								
38	Speakers	2	106,4	gram		212,8	gram	Electronics	Electronics
	TOTAL					**7061,3**	**gram**		
	Expected weight					7	kilogram		

LG OLED55C17LB

Component	Quantity	Weight	Unity	Newton	Total weight	Unity	Material
PCBs							
Powerboard	1	729,2	gram		729,2	gram	Electronics
Motherboard	1	364,6	gram		364,6	gram	Electronics
PCB - large	1	69,6	gram		69,6	gram	Electronics
Screen PCB	1		gram		0	gram	Electronics
Button board	1	1,4	gram		1,4	gram	Electronics
PCB wifi	1	8	gram		8	gram	Electronics
CHASSIS							
Housing plastic	1	1631	gram	16	1631	gram	PC+ABS
Stand front	1	1089,8	gram		1089,8	gram	nvt
Stand back	1	2926,6	gram		2926,6	gram	nvt
SCREEN							
Screen (incl.screen PCB) and metal chassis	1	13183	gram		13183	gram	Glass + other
CONSTRUCTION/PROTECTION ELEMENTS							
Plastic piece inside (grey on metal)	6	0,8	gram		4,8	gram	PA
Metal piece long top housing	1	634,6	gram		634,6	gram	Steel
Metal brackets for housing	4	15,2	gram		60,8	gram	Steel
Metal plate	1	421,4	gram		421,4	gram	Steel
Motherboard plastic connections	1	15,8	gram		15,8	gram	PC+ABS
Housing buttonboard	1	6	gram		6	gram	PC+ABS
Standard plastic cover	1	52,6	gram		52,6	gram	PC+ABS
Plastic cover standard plug	1	47,8	gram		47,8	gram	PC+ABS
Plastic cover power cord housing	1	20	gram		20	gram	PC+ABS
Plastic front housing buttonboard	1	2,2	gram		2,2	gram	PC
Small metal plate?	1	28	gram		28	gram	Density test
Sticky foam stickers	3	nvt	gram		2,8	gram	PDMS(with conductive fillers)
Metal pieces for metal plate	2	109,2	gram		218,4	gram	Steel
Housing PCB wifi	1	7,8	gram		7,8	gram	PC+ABS
Metal parts back cover bottom	2	48	gram		96	gram	Steel
WIRES							
Plug	1	91,6	gram		91,6	gram	Electronics
Flat wire	4	2,6	gram		10,4	gram	Electronics
Flat wire with connection part	2	8,4	gram		16,8	gram	Electronics
Black wire	1	24,2	gram		24,2	gram	Electronics
Blue/red wire	1	7,6	gram		7,6	gram	Electronics
Silver/white wire	1	11,4	gram		11,4	gram	Electronics
Grey/blue wire	1	8	gram		8	gram	Electronics
Grey/blue wire 5 wires	1	4,4	gram		4,4	gram	Electronics
CLIPS/PLACEHOLDERS							
Clip plug	1	2	gram		2	gram	PE
Silicon rubber standard	2	0,4	gram		0,8	gram	FTIR
Protection rubber bottom standard	7	0,2	gram		1,4	gram	FTIR
Silicon rubber speakers	4	0,2	gram		0,8	gram	FTIR
Snaps on the back cover	9						PC+ABS
SCREWS							
Black screws with ring - large	7	2,4	gram		16,8	gram	Steel
Black screws - small	5	0,6	gram		3	gram	Steel
Silver screws	34	0,6	gram		20,4	gram	Steel
Other							
Speakers	2	550,2	gram		1100,4	gram	Electronics
TOTAL					**22942,2**	**gram**	
Expected weight					23	kilogram	

SONY KD43X80J

Nr.	Component	Quantity	Weight	Unity	Newton	Total weight	Unity	Material
A	**PCBs**							
1	Powerboard	1	424,2	gram		424,2	gram	Electronics
2	Motherboard	1	278,2	gram		278,2	gram	Electronics
3	PCB - small	1	9,4	gram		9,4	gram	Electronics
4	PCB - large	1	23,8	gram		23,8	gram	Electronics
5	Button board	1	8,6	gram		8,6	gram	Electronics
6	PCB screen - small	2	15,9	gram		31,8	gram	Electronics
7	PCB screen - large	1		gram			gram	Electronics
B	**CHASSIS**							
8	Frame front	1	254,84	gram	2,5	254,84	gram	PC
9	Housing plastic	1	1029,6	gram		1029,6	gram	PP
10	Metal chassis	1	2242,6	gram		2242,6	gram	Steel
11	Bottom frame	1	35,2	gram		35,2	gram	PC
12	Side frame	2	19,1	gram		38,2	gram	PC
13	Top frame	1	34,7	gram		34,7	gram	PC
14	Standard	2	213,6	gram		427,2	gram	ABS + steel
15	Standard connection bracket	2	64,6	gram		129,2	gram	Steel
C	**SCREEN**							
16	Opt sheet top	1	203,87	gram	2	203,87	gram	PC, PEN
17	Opt sheet bottom	1	214,07	gram	2,1	214,07	gram	PET
18	Diffuser plate	1	784,9	gram		784,9	gram	PS
19	Reflector sheet	1	91,74	gram	0,9	91,74	gram	PET
20	Screen	1	1326	gram		1326	gram	Glass, other materials
21	LED strip	5	42,8	gram		214	gram	Electronics
22	LED	40	1,2	gram		48	gram	Electronics
23	Placeholders spikes - transparent	8	0,8	gram		6,4	gram	PC
D	**CONSTRUCTION/PROTECTION ELEMENTS**							
24	Metal piece flat black tape	1	130,6	gram		130,6	gram	Steel
25	Housing screen PCB - metal	1	232,6	gram		232,6	gram	...+PET
26	Transparent sheets under powerboard	1	41,2	gram		41,2	gram	PC
27	Metal under plate motherboard	1	25,4	gram		25,4	gram	Steel
28	Sticky foam stickers	3	3,8	gram		11,4	gram	PDMS (with conductive fillers)
29	Metal bracket - small	2	39	gram		78	gram	Steel
30	Metal bracket - large	2	98,8	gram		197,6	gram	Steel
31	Metal spring in bracket	2	1,6	gram		3,2	gram	Stainless Steel
32	Housing button - black	1	45,6	gram		45,6	gram	PC+ABS
33	Housing button - transparant	1	6,4	gram		6,4	gram	MABS
34	Housing button - milky white	1	1	gram		1	gram	PC
E	**WIRES**							
35	Plug	1	72,6	gram		72,6	gram	Electronics
36	Grey wire	1	33,2	gram		33,2	gram	Electronics
37	Flat wire M shape - small	1	3,4	gram		3,4	gram	Electronics
38	Flat wire M shape - large	1	3	gram		3	gram	Electronics
39	Wire flat	2	1,6	gram		3,2	gram	Electronics
40	Pink wire (multiple) & black plastic piece	1	15,2	gram		15,2	gram	Electronics
41	Red wire	1	3,6	gram		3,6	gram	Electronics
42	Flat wire folded shape	1	7,8	gram		7,8	gram	Electronics
F	**CLIPS/PLACEHOLDERS**							
43	Standard clips for socket	2	3,2	gram		6,4	gram	PA66
44	Motherboard housing - black	1	33,8	gram		33,8	gram	PC+ABS
45	PCB back clip	1	2,8	gram		2,8	gram	PA6.10 or PA6.12
46	Screen PCB clip - purple	5	0,9	gram		4,5	gram	PA6.10 or PA6.12
47	Blue rubber	2	1	gram		2	gram	unknown
48	Black rubber	2	1,4	gram		2,8	gram	unknown
49	White PCB clip	1	0,6	gram		0,6	gram	PA6.10 or PA6.12
49	White PCB clip	1	0,6	gram		0,6	gram	PA6.10 or PA6.12
50	Grey PCB clip	1	0,2	gram		0,2	gram	PA6.10 or PA6.12
51	Black wire holder	1	0,6	gram		0,6	gram	PA
52	Motherboard housing plug - piece inside	1	4	gram		4	gram	PC+ABS
53	Motherboard housing plug	1	24	gram		24	gram	PC+ABS
G	**SCREWS**							
54	Screw with ring small	30	0,73	gram		21,9	gram	Steel
55	Silver screws flat - medium	4	0,15	gram		0,6	gram	Steel
56	Silver screws flat - large	2	0,4	gram		0,8	gram	Steel
57	Black screw with ring	4	0,8	gram		3,2	gram	Steel
58	Black screw with ring for standard	2	2,2	gram		4,4	gram	Steel
H	**Other**							
59	Speaker unit	1	769,2	gram		769,2	gram	Electronics
	TOTAL					9653,32	gram	
	Expected weight					10	kilogram	

SAMSUNG GQ55QN95AAT SCREEN

	Product	Quantity
	Samsung GQ55QN95AAT TV Scr	1
	Samsung GQ55QN95AAT TV Box	1

Samsung GQ55QN95AAT TV Screen

Nr.	Component	Quantity	Weight	Unity	Newton	Total weight	Unity		Material	
A	**PCBs**									
1	Motherboard	1	99,8	gram		99,8	gram		Electronics	
2	Button board	1	4	gram		4	gram		Electronics	
3	Screen PCB	2	19	gram		38	gram		Electronics	
4	PCB black	1	264,2	gram		264,2	gram		Electronics	
B	**CHASSIS**									
5	Frame front	1	226,4	gram		226,4	gram		unknown	PC
6	Housing plastic	1	2.378,80	gram		2378,8	gram		PC+ABS	
7	Metal chassis	1	5144,8	gram	50,5	5144,8	gram		Steel	
8	Top frame - black	1	29,6	gram		29,6	gram		FTIR	
9	Bottom frame - black	1	39	gram		39	gram		FTIR	
10	Bottom frame - white	1	43,2	gram		43,2	gram		FTIR	
11	Side frame - white	2	26,2	gram		52,4	gram		FTIR	
12	Top frame - white	1	49,4	gram		49,4	gram		FTIR	
13	Standard	1	3720,2	gram		3720,2	gram		Steel	
14	Standard connection part	1	531	gram		531	gram		PP	
C	**SCREEN**									
15	Screen	1	2694	gram	26,8	2694	gram		Glass + Electr	PC
16	Opt sheet top	1	407,8	gram	4	407,8	gram		PC	
17	Opt sheet bottom	1	275,2	gram	2,7	275,2	gram		PC	
18	Diffuser plate	1	1926,6	gram	18,9	1926,6	gram		PBT?	
19	LED plate	8	166	gram		1328	gram		Electronics	
20	Protection sheet LED plate	1	51,0	gram	0,5	51	gram		PC	PC
21	Reflector sheet	8	18,8	gram		150,4	gram		PC	PC
D	**CONSTRUCTION/PROTECTION ELEMENTS**									
22	Housing button board	1	3,6	gram		3,6	gram		PCB	
23	Black sheet under motherboard	1	10	gram		10	gram		PC	PC
E	**WIRES**									
26	Cable TV-BOX	1	205,6	gram		205,6	gram		Electronics	
27	Flat cable 52 mm	1	7,8	gram		7,8	gram		Electronics	
28	Flat cable 29 mm MB-LED panel	8	nvt	gram		33,8	gram		Electronics	
29a	Flat cable 15 mm MB-BPCB	1	0,8	gram		0,8	gram			
29b	Flat cable 15 mm	1	8	gram		8	gram		Electronics	
30	Flat cable black	1	0,8			0,8	gram		Electronics	
31	Black cable - orange connection	1	14,4	gram		14,4	gram		Electronics	
32	Cable - red/green/yellow	1	8	gram		8	gram		Electronics	
F	**CLIPS/PLACEHOLDERS**									
33	Clips screen PCB - black	6	1	gram		6	gram		PBT?	PBT?
34	Rubber rounds	8	0,6	gram		4,8	gram		PDMS	PDMS
35	Wire clip outside	1	1,2	gram		1,2	gram		unknown	
36	Cable cap	2	3,7	gram		7,4	gram		unknown	
37	TV cable clip	1	0,4	gram		0,4	gram		unknown	
G	**SCREWS**									
38	Black screws	11	4	gram		44	gram		Steel	
39	Black screws flat	28	0,2	gram		5,6	gram		Steel	
40	Black screws flat mini	3	0,1	gram		0,3	gram		Steel	
41	Silver screws - mini	2	0	gram		0	gram		Steel	
42	Black screws large	8	1,8	gram		14,4	gram		Steel	
43	Black screws middle	2	0,6	gram		1,2	gram		Steel	
H	**Other**									
44	Small speaker with wire	2	293	gram		586	gram		Electronics	
45	Large speaker with wire	2	379,9	gram		759,8	gram		Electronics	
46	Hook and loop TV cable	1	0,6	gram		0,6	gram		Nylon	
47	Foam under PCB - black	2	36	gram		72	gram		unknown	
48	Foam under standard	4	1,2	gram		4,8	gram		PDMS with conductive fillers	
49	Tape									
	TOTAL					**21255,1**	**gram**			
	Expected weight					21	kilogram	exl box	incl. standaard	

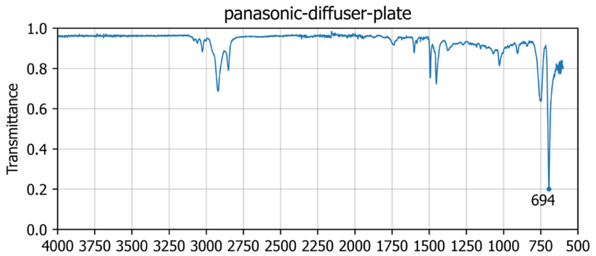
SAMSUNG GQ55QN95AAT BOX

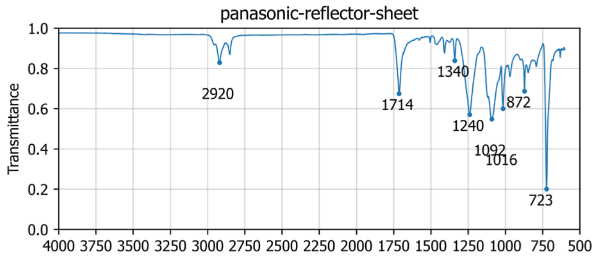
Samsung GQ55QN95AAT TV Box

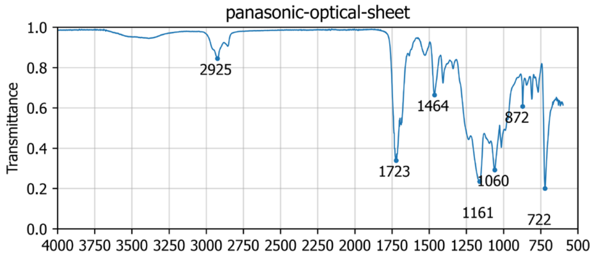
Nr.	Component	Quantity	Weight	Unity	Newton	Total weight	Unity	Material
A	**PCBs**							
1	Powerboard	1	1164,4	gram		1164,4	gram	Electronics
2	Motherboard	1	142,8	gram		142,8	gram	Electronics
B	**CHASSIS**							
3	Top housing	1	374,2	gram		374,2	gram	PC+ABS
4	Bottom housing	1	342,8	gram		342,8	gram	PC
C	**CONSTRUCTION/PROTECTION ELEMENTS**							
5	Black sheet top housing	1	35	gram		35	gram	PC
6	Black sheet bottom housing	1	50,8	gram		50,8	gram	PC
7	Metal sheet top housing	1	244	gram		244	gram	Steel
8	Metal sheet bottom housing	1	315,6	gram		315,6	gram	Steel
9	Plasticized graphite layer	1	57,2	gram		57,2	gram	unknown
10	Foam grey	2	nvt	gram		1,2	gram	PDMS with conductive fillers)
11	Sticky foam stickers	5	72,6	gram		363	gram	PDMS with conductive fillers)
12	Foam under housing	4	0,4	gram		1,6	gram	PDMS with conductive fillers)
D	**WIRES**							
13	Plug	1	67,2	gram		67,2	gram	Electronics
14	Black/blue cable - orange conne	1		gram		11,2	gram	Electronics
E	**SCREWS**							
15	Silver screws	6	0,6	gram		3,6	gram	Steel
16	Silver screw - large	2	1,2	gram		2,4	gram	Steel
17	Black screws	7	0,6	gram		4,2	gram	Steel
	TOTAL					**3181,2**	**gram**	
	Expected weight						kilogram	

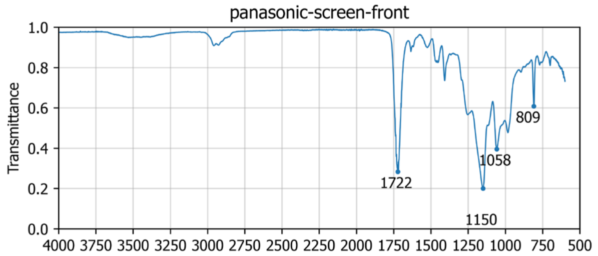
APPENDIX D | FTIR RESULTS

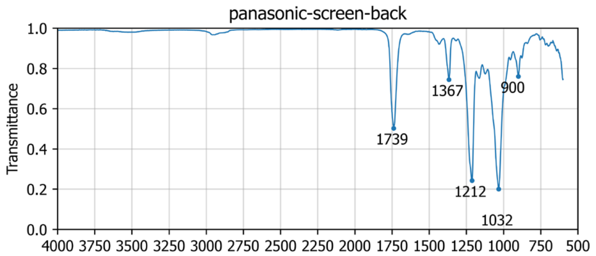
PANASONIC

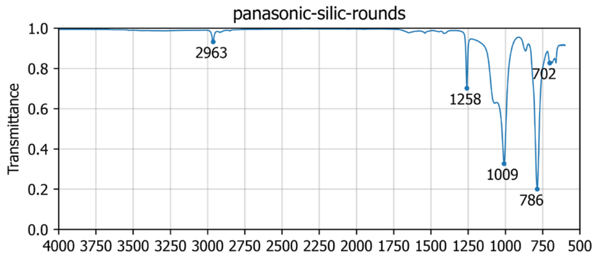




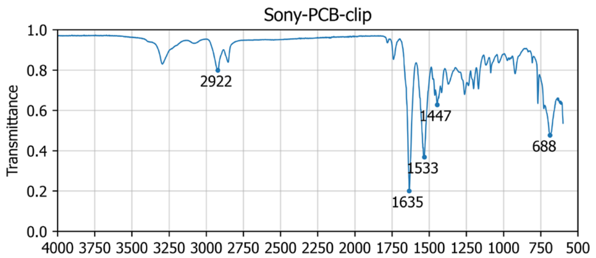


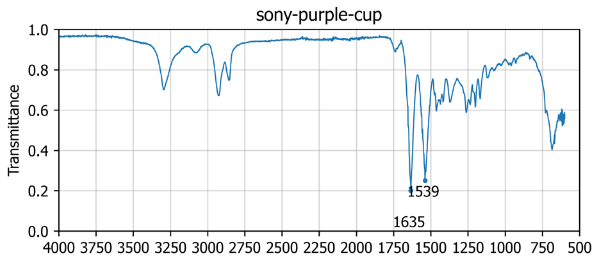


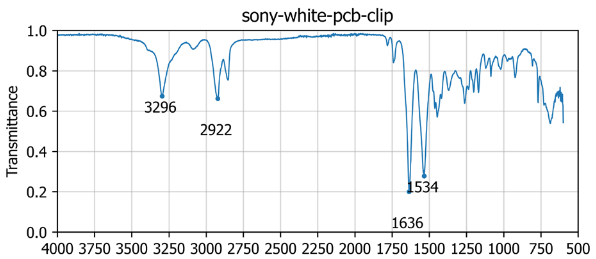


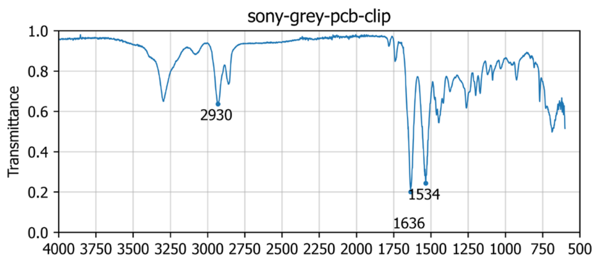


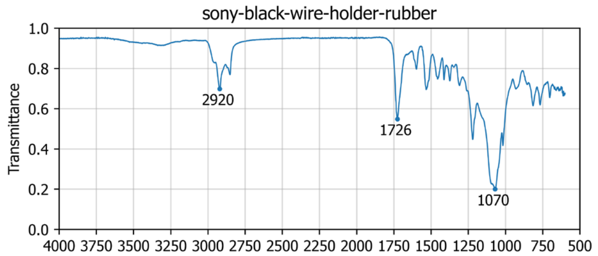
SONY

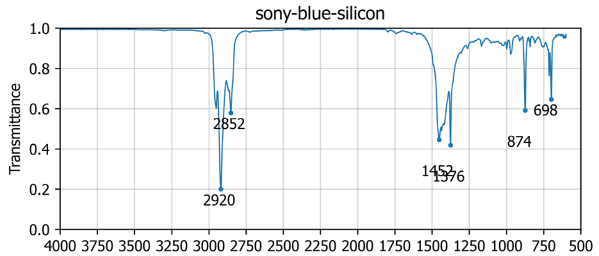


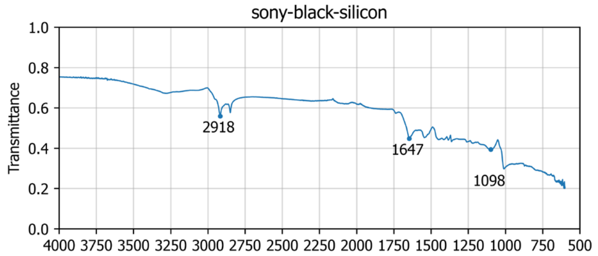


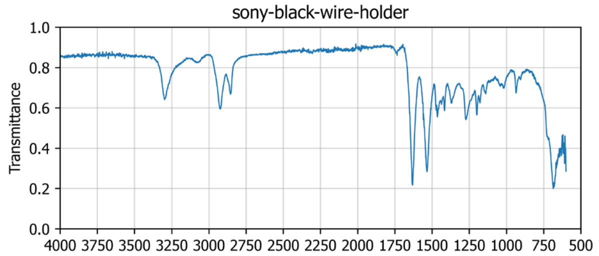


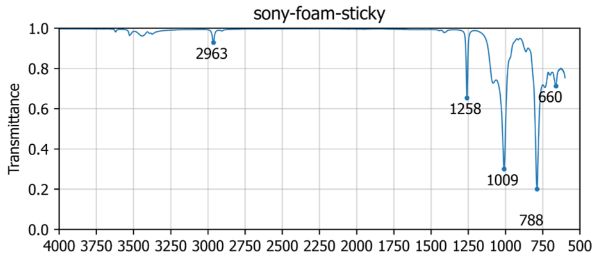


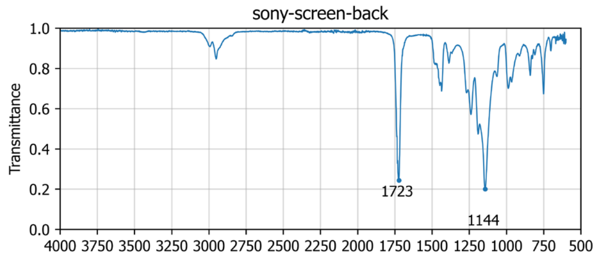


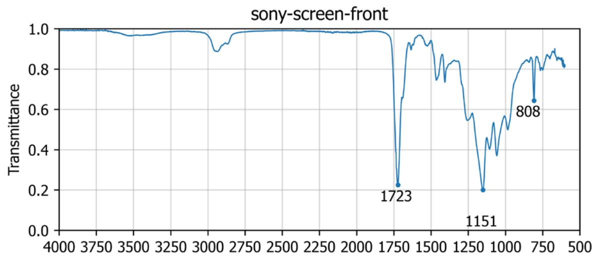


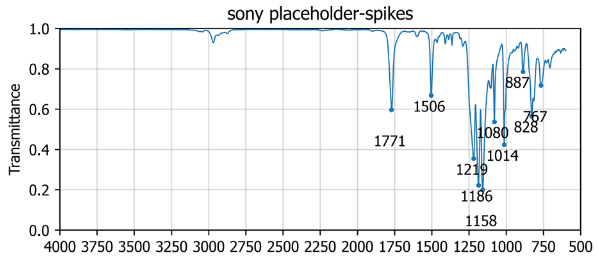




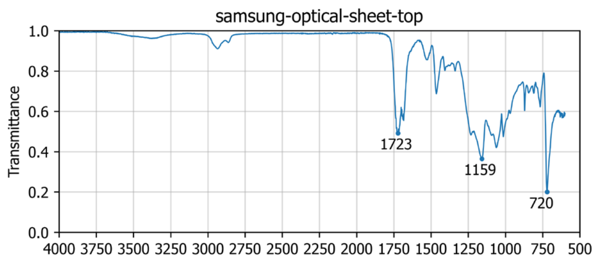


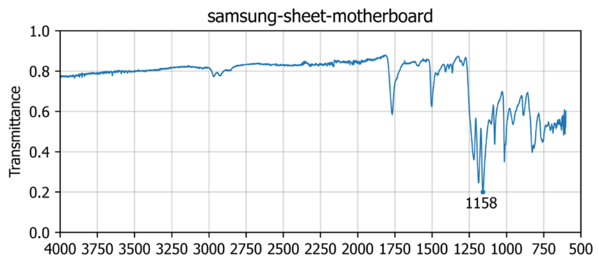


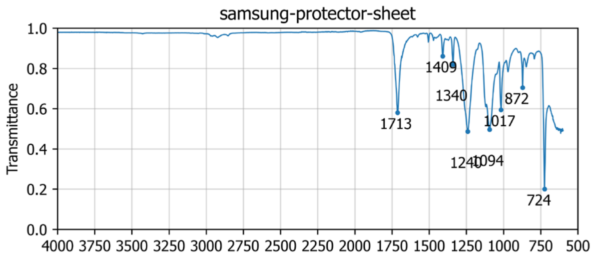


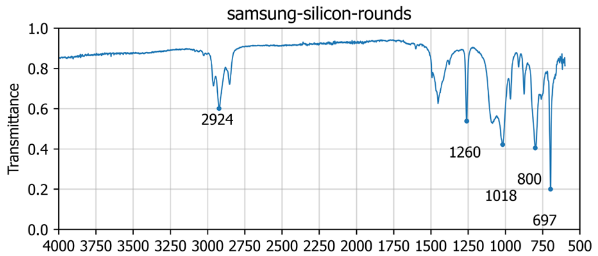


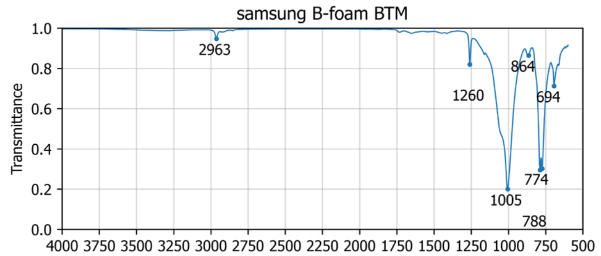
SAMSUNG

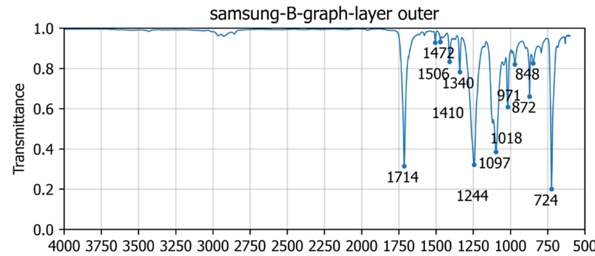


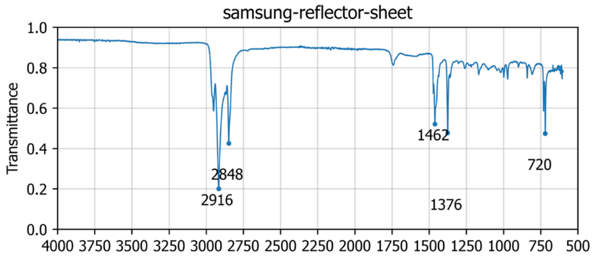


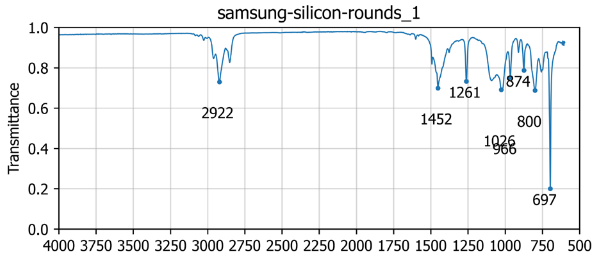


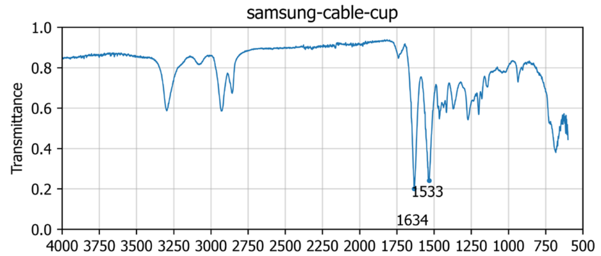


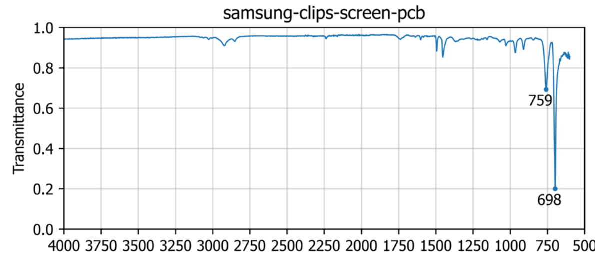


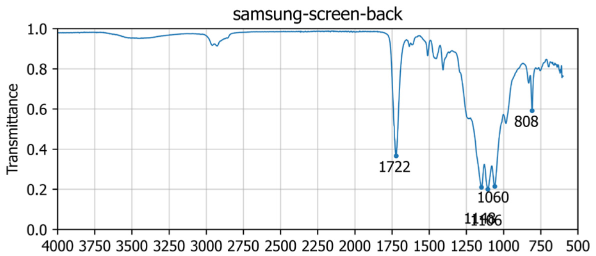


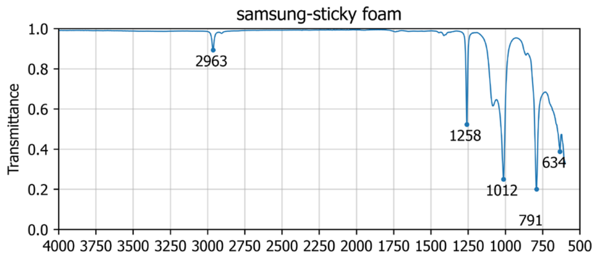


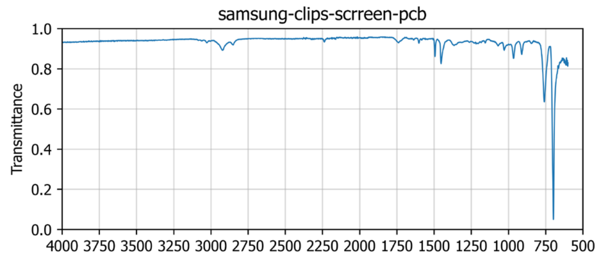


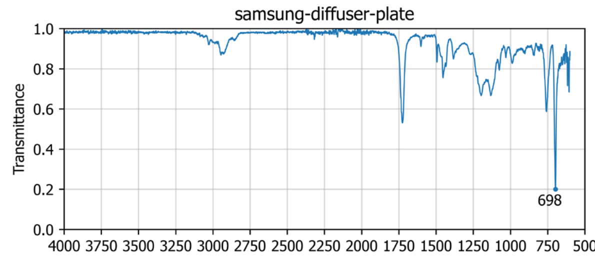


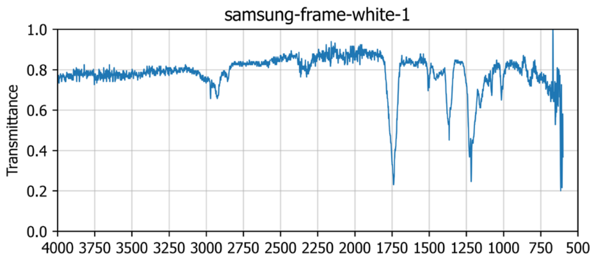


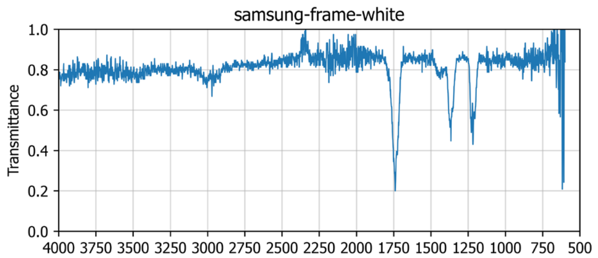


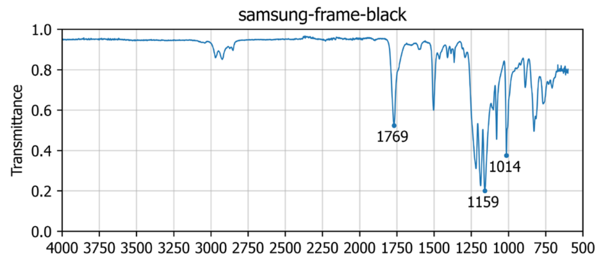


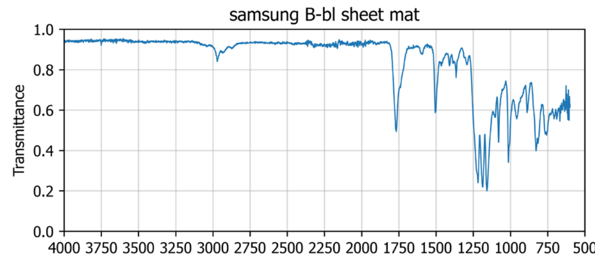


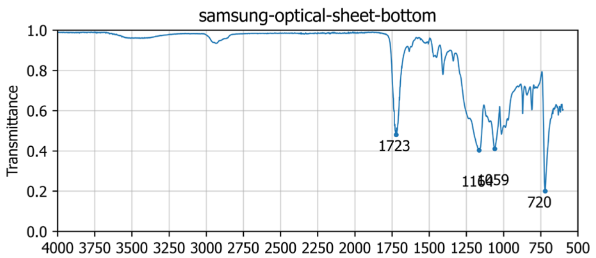


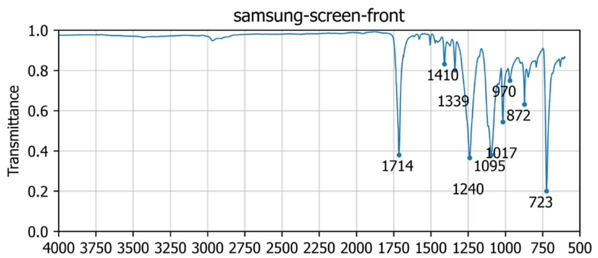


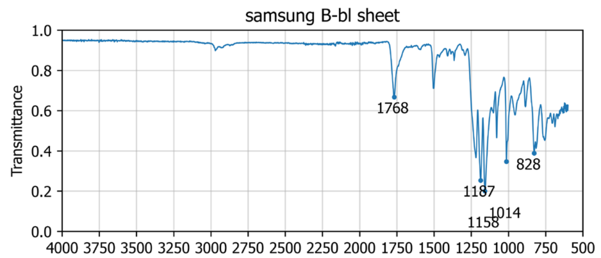


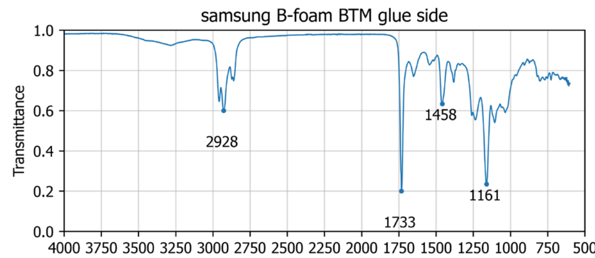








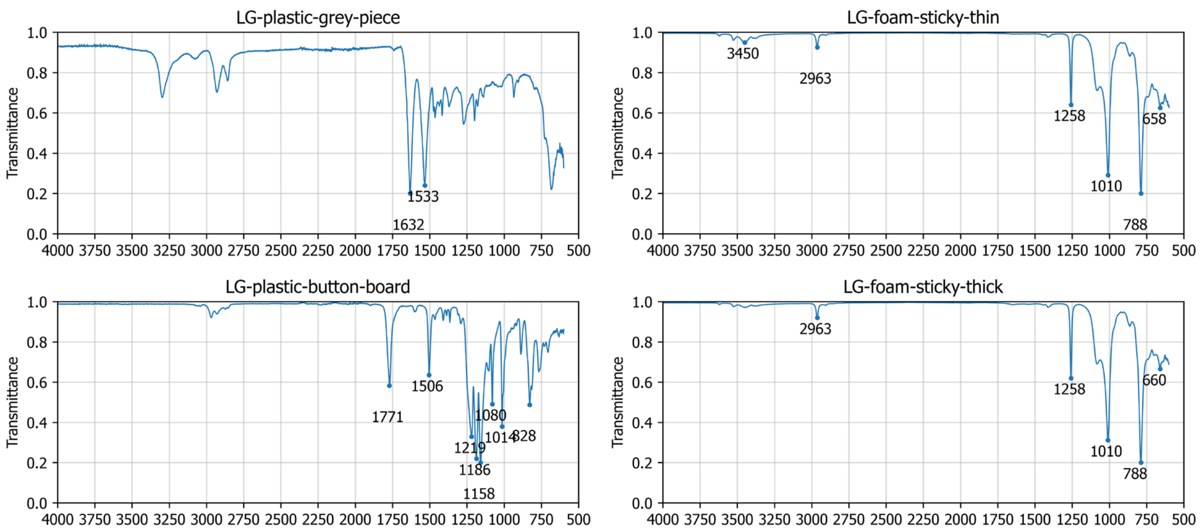




APPENDIX

DORIS VERSLOOT

LG



APPENDIX E | DENSIMETER RESULTS

	g/cm3	second test	FTIR	
sam - frame front	2,545		PC	
Sony PCB clip	0,999		PA6.10 or PA6.12	
sam-opt SH BTM	1,453		PC	
Sony purple clip	1,143	1,156	PA6.10 or PA6.12	
Sony placeh. spikes	1,198		PC	
Sony screen	2,115		PC or maybe glass	
Sam foam btm	1,548		PDMS (with conductive fillers)	
Sam b-bl. Sheet	1,249		PC	
Sam diff plate	1,108		Not sure, may be PBT?	
Sam opt sh. Top	1,228		PC	
Sam protect. Sheet	0,974		PC	
sam sticky foam thick	2,436		PDMS (with conductive fillers)	
sam sticky foam thin	2,593		PDMS (with conductive fillers)	
sam screen	2,007		PC	
sam clips scr. PCB	1,05		May be PBT?	Same as PH-wireholder
sam cable clip (no tape)	1,085		PA	
sam bl. Sheet motherb.	1,242		PC	
sam silicon rounds	0,999	0,997	PDMS	
sam frame black	1,241			
sam frame white	1,326			
sam reflect sheet	0,767		PC	
sony blue silicon	1,029			
sony black silicon	1,276			
sony white PCB clip	1,024		PA6.10 or PA6.12	
sony grey PCB clip	1,035		PA6.10 or PA6.12	
LG plastic button board	1,058		PC	
sony metal spring	7,854			
LG plastic grey piece	1,105		PA	
LG screen	no sample			
sony foam sticky	2,319		PDMS (with conductive fillers)	
lg foam sticky	1,844		PDMS (with conductive fillers)	
pana-silic rounds	1,119		PDMS	
pana screen	2,002		PC	
ph screen	fail	2,407	PC	
ph magnet	7,554			
ph silicon	1,132		PDMS	
pana opt sheet	1,234		May be PLA?	
pana diff plate	1,048			
pana refl plate	0,728		PBT	
ph-silicon large	1,052			
sony black wire holder	n.a. not in recycled material		PA	
ph? wire clip black	1,375			
ph? wire clip w/ white	1,129		PA	
ph button housing - 2K	1,184		PC	
ph wire holder	n.a. not in recycled material		May be PBT?	
ph silicon large	1,128		PDMS	
ph silicon small	1,137		PDMS	

APPENDIX F | SANKEY DIAGRAM DATA

Material	Fraction	Grams
Electronics	Pure	2792,2
Electronics	Mixed	54
Electronics	Mixed homogeneous	54
Electronics	Mixed during process	101,8
Electronics	Dust	1223
Electronics	Lost	191,3
Ferrous metals	Pure	5286,8
Ferrous metals	Mixed	1152,2
Ferrous metals	Mixed homogeneous	222,2
Ferrous metals	Mixed during process	2821
Ferrous metals	Lost	330,6
Frame	Polymers	337,5
Glass	Pure	2042,2
Glass	Mixed during process	40
Glass	Dust	2567,4
Glass	Lost	401,6
Housing	Polymers	3990,4
Metal chassis	Ferrous metals	8970,4
Mixed	Ferrous fraction	1152,2
Mixed	Waste	561,4
Mixed during process	Ferrous fraction	2821
Mixed during process	Waste	329,8
Mixed homogeneous	Copper fraction	54
Mixed homogeneous	Ferrous fraction	222,2
Non-ferrous metals	Pure	62,6
Non-ferrous metals	Mixed	23,8
Non-ferrous metals	Lost	21,6
Non-ferrous metals	Dust	20
PCBs	Electronics	2560,4
Polymers	Pure	5641
Polymers	Mixed	89,8
Polymers	Mixed during process	188
Polymers	Dust	1675,5
Polymers	Lost	262
Pure	Copper fraction	2792,2
Pure	Polymers fraction	5632,2
Pure	Polymers fraction	8,8
Pure	Ferrous fraction	5286,8
Pure	Waste	2042,2
Screen assembly	Polymers	3136
Screen assembly	Glass	5051,2
Screen assembly	Electronics	520,8
Speakers	Electronics	851,2
TV	Polymers	392,5
TV	Ferrous metals	842,4
TV	Non-ferrous metals	128
TV	Metal chassis	8970,4
TV	PCBs	2560,4
TV	Wires	484
TV	Speakers	851,2
TV	Screen assembly	8708
TV	Housing	3990,4
TV	Frame	337,5
Wires	Electronics	484

APPENDIX H | CONNECTIONS

Panasonic TX40JXW834Z (4x)

	Before shredding			After shredding			Afwijking	
CONNECTIONS	Amount 1 1	All TVs	Metric	Amount	Metric	Not break down (%)	Min.	Max.
MATERIAL ENCLOSURE								
glue	388,68	1554,72	cm²	400	cm²	26%		
glue - tape/sticker	16	64	cm²	3	tapes	5%	2%	7%
coating	2079,2	8316,8	cm²	8316,8	cm²	100%		
FORCE ENCLOSURE								
screw	40	156		43		28%	23%	32%
insert	4	16		9		56%	38%	75%
magnetic joint				0,00		100%		
snap fit	29	116		2		2%	1%	3%
FORM ENCLOSURE								
friction fit	6	24		6		25%	15%	35%
* friction fit speakers	4	16		5		31%	17%	45%
turn-lock	0	0		0		nvt		
top lock	10	40		13		33%	23%	42%
side lock	1	4		2		50%	15%	85%
fold lock	6	24		6		25%	15%	35%
hook	22	88		7		8%	5%	11%

Sony KD43X80J (4x)

	Before shredding			After shredding			Afwijking	
CONNECTIONS	Amount 1TV	All TVs	Metric	Amount	Metric	Not break down (%)	Min.	Max.
MATERIAL ENCLOSURE								
glue	1034,75	4139		1558,95	cm²	38%		
glue -tape/sticker	1	4		0	cm²	0%	0%	0%
coating	0	0		0	cm²	nvt		
FORCE ENCLOSURE								
screw	40	160		55		34%	30%	39%
insert	4	16		1		6%	0%	13%
magnetic joint				0,00		100%		
snap fit	66	264		5		2%	1%	3%
FORM ENCLOSURE								
friction fit	10	40		2		5%	1%	9%
* friction fit speakers	4	16		2		13%	4%	21%
turn-lock	3	12		1		8%	0%	17%
top lock	8	32		2		6%	2%	11%
side lock	6	24		1		4%	0%	8%
fold lock	5	20		5		25%	14%	36%
hook	14	56		0		0%	0%	0%

Samsung GQ55QN95AAT (4x)

	Before shredding			After shredding			Afwijking	
CONNECTIONS	Amount 1T	All TVs	Metric	Amount	Metric	Not break down (%)	Min.	Max.
MATERIAL ENCLOSURE								
glue	9271,5	37086	cm²	30652	cm²	83%		
glue - tape/sticker	22	88	tapes	23	tapes	26%	21%	32%
coating	0	0	cm²	0	cm²	nvt		
				10 during				
FORCE ENCLOSURE								
screw	60	240		48		20%	17%	23%
insert	8	32		2		6%	2%	11%
magnetic joint				0,00		100%		
snap fit	104	416		1		0%	0%	0%
FORM ENCLOSURE								
friction fit	10	40		18		45%	34%	56%
* friction fit speakers	8	32		16		50%	38%	63%
turn-lock	0	0		0		nvt		
top lock	5	20		4		20%	10%	30%
side lock	5	20		6		30%	18%	42%
fold lock	24	96		16		17%	13%	21%
hook	14	56		3		5%	2%	8%

LG

	Before shredding			After shredding		
CONNECTIONS	Amount 1T	All TVs (2)	Metric	Amount	Metric	Not break down (%)
MATERIAL ENCLOSURE						
glue	10483	20966	gram	7556,3	gram	36%
glue	8680,79	17361,58	cm²	2628,553	cm²	15%
glue - tape/sticker	5	10		3		30%
coating	8785,5	17571	cm²	11948,28	cm²	100%
FORCE ENCLOSURE						
screw						nvt
insert	9	18		2		11%
magnetic joint		0		0,00		100%
snap fit	56	112		14		13%
FORM ENCLOSURE						
friction fit	6	12		5		42%
turn-lock						nvt
top lock	7	14		3		21%
side lock	3	6		0		0%
fold lock	12	24		3		13%
hook	6	12		0		0%