Towards guidelines for critical raw material efficiency in product design

Master thesis
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Towards guidelines for critical raw material efficiency in product design

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Preface

This thesis was carried out as part of the Master's programme in Integrated Product Design at the Faculty of Industrial Design Engineering, Delft University of Technology.

For my final master's project, I wanted to challenge myself to work on a topic with real world relevance and impact. With the increasing attention given to critical raw materials due to turbulent geopolitical times, I realised this was the direction I wanted to pursue.

This project explored the challenge of translating critical raw material policy ambitions into actionable product design guidelines. It allowed me to combine my interest in sustainability and circular product design with a focus on resource resilience.

Finalising my masters degree with a project on vacuum cleaners feels somewhat full circle. As a child, I was fascinated by vacuum cleaners and it is interesting to see that curiosity return in a completely different context at the end of my formal education.

I would like to thank my supervisors, Benjamin and Conny, for their guidance throughout this project. Your feedback and critical questions helped me to challenge my thinking and strengthen my work. I am grateful for your support and encouragement during the process.

To my friends in Delft, thank you for making my student years such a memorable experience. And to my parents and sister, thank you for your continuous support and trust in me, helping me navigate both the highs and lows of this graduation project.

Enjoy reading,

Ids Grupstra

Abstract

Critical Raw Materials (CRMs), such as neodymium, cobalt, and lithium, are essential for key technologies in the energy transition, yet their supply is highly concentrated and associated with significant environmental impacts. While recent European policies, including the Critical Raw Materials Act (CRMA) and Ecodesign for Sustainable Products Regulation (ESPR), establish targets for resource security and circularity, they lack actionable guidance for product-level design decisions. This creates a gap between regulatory ambitions and implementation in product development.

This thesis addresses this gap by developing a method to identify, prioritise, and act upon CRM-containing components within product architectures, by combining product teardowns, disassembly mapping and a CRM hotspot mapping method. CRM hotspot mapping combines material criticality (economic importance and supply risk) with component CRM mass relevance to prioritise components for design decision-making. The method is applied through two case studies: an exploratory washing machine study followed by a cordless stick vacuum cleaner case study to refine and evaluate the method.

The results demonstrate that product architecture strongly influences CRM efficiency. Components containing CRMs are often deeply embedded and difficult to access, limiting their recovery and reuse. Based on these insights, a set of CRM efficiency guidelines is developed, focusing on both CRM demand reduction (e.g., substitution, standardisation and pruning) and CRM recovery (e.g., modularity and improved accessibility through surfacing, clumping and clever fasten type usage). The guidelines are synthesised into a visual design decision booklet to support practical application.

The study shows that while the CRM hotspot mapping method is transferable across product categories, the effectiveness of CRM efficiency strategies depends on architectural constraints and product-specific trade-offs. By translating material criticality into design guidelines, this research provides a foundation for integrating CRM efficiency into product development and supports the implementation of circular economy policies.

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1. Introduction

1.1 Research context

Critical Raw Materials (CRMs), such as Lithium, Cobalt and Rare Earth Elements (REEs), are essential for renewable energy systems, digital infrastructure and advanced technologies such as electric vehicles, wind turbines and energy storage systems (Keersemaker, 2020). The European Union (EU) defines CRMs as materials that exceed thresholds for both economic importance and supply risk (European Commission, 2023). The EU assessment also distinguishes a group of Strategic Raw Materials (SRMs). These are materials considered important for future industrial development, even if they do not meet the criteria to be classified as Critical Raw Materials (CRMs). The SRM list includes materials such as copper and nickel, which fall below the CRM threshold but remain relevant due to their widespread use and expected demand. The outcome of the most recent CRM assessment is presented in Figure 1.

Results of the 2023 EU criticality assessment

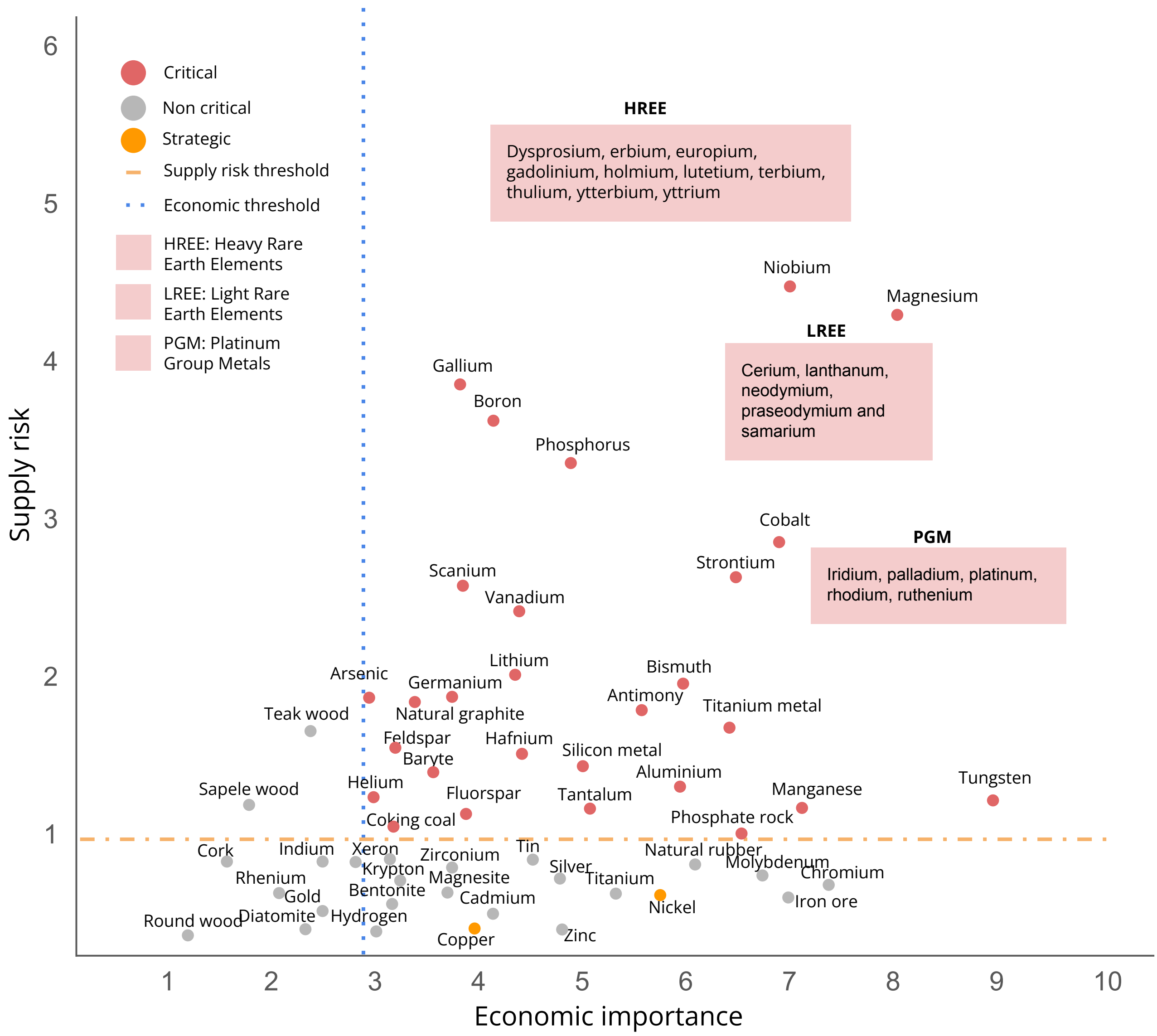


Figure 1. Results of the 2023 EU criticality assessment. (European Commission, 2023)

Many CRMs have limited substitutability due to their specific functional properties (Vafeas, Slezak, & Hitzman, 2024). In addition, their extraction and processing are geographically concentrated (van Gaalen & Slootweg, 2025), with China dominating global production and refining capacity (European Commission, 2023). This concentration creates structural supply risks and geopolitical dependencies, particularly for the EU, which relies heavily on imports to achieve its energy transition goals (Girtan et al., 2021).

As the global transition towards low carbon technologies accelerates, demand for CRMs is projected to increase substantially. For example, demand for rare earth elements is expected to grow sixfold by 2030 and sevenfold by 2050 (European Commission, 2024a). This projected demand growth adds to the pressure on already constrained supply chains.

At the same time, primary extraction and processing of CRMs are associated with substantial environmental impacts, including high energy use, land disturbance, and pollution (Manhart et al., 2019). Expanding extraction alone cannot provide a sustainable long-term solution to rising material demand. Together, supply risk, increasing demand and environmental impacts underline the need to reduce dependence on primary CRMs and improve material efficiency in products, thereby supporting a more circular use of critical resources.

1.2 Problem definition and research gap

In response to increasing supply risks and projected demand growth, the European Union adopted the Critical Raw Materials Act (CRMA) in 2024 (European Commission, 2024a). The CRMA establishes benchmarks for domestic extraction, processing and recycling capacities and promotes circularity as a strategy to strengthen supply security. One mechanism to moderate CRM demand is the integration of resource efficiency requirements within product regulation.

These objectives intersect with the Ecodesign for Sustainable Products Regulation (ESPR), which introduces horizontal product requirements related to durability, reparability, recyclability and information transparency (European Commission, 2024b). However, the ESPR does not provide CRM specific or product category specific design strategies. Its requirements remain largely general, limiting their direct applicability for improving CRM efficiency within concrete product architectures (van Gaalen & Slootweg, 2025).

Similarly, CRM related standards such as EN 45558 primarily address information exchange and material disclosure (Bundgaard et al., 2021). While increased transparency is a necessary step towards CRM efficiency, these standards do not provide operational design guidance for reducing CRM content, improving accessibility of CRM containing components, or enabling recovery through architectural design decisions.

Although the CRMA sets recycling and recovery targets for CRMs, it does not define how material criticality should be integrated into product design methods, such as design-for-X or circular design strategies (Institute for European Environmental Policy, 2023)(Hool, Helbig, & Wierink, 2024). Apart from general principles for specific applications, such as permanent magnet recovery, guidance on how CRM recovery should be enabled through product design remains limited (European Commission, 2024a).

The absence of product specific and operational design guidelines for CRM efficiency represents a gap in implementation, as product architecture directly determines CRM efficiency outcomes (Campbell-Johnston et al., 2022). Decisions regarding component placement, connection types, modularity and accessibility influence product lifetime extension, disassembly depth and the feasibility of targeted CRM recovery (Bundgaard et al., 2021)(European Road Transport Research Advisory Council, 2025). Bridging this gap requires product specific guidelines that integrate material criticality into design decision making in order to translate regulatory goals into concrete actions.

1.3 Research questions and objectives

The objective of this thesis is to develop and validate structured guidelines for improving Critical Raw Material (CRM) efficiency in product design. The research aims to bridge the gap between horizontal EU regulatory objectives and their practical implementation within concrete product architectures.

To achieve this, the study focuses on identifying CRM intensive components within products and translating these insights into actionable design guidelines. The research does not aim to quantify exact material flows or lifecycle impacts, but to establish a method for integrating material criticality into design decision making for CRM efficiency.

The central research question is:

> ***RQ***: *How can product specific design guidelines contribute to enhancing critical raw material efficiency?*

This question is addressed through the following sub-questions:

> ***SQ1***: *How can CRM containing components be systematically identified and prioritised within product architectures?*
>
> ***SQ2:*** *Which design strategies can improve CRM efficiency at the component and architectural level?*
>
> ***SQ3:*** *To what extent can CRM efficiency guidelines developed in one product category be transferred to other product categories?*

To answer these questions, two case studies are conducted. The first case study, focusing on a washing machine, serves as an exploratory study to develop and structure a method for CRM hotspot identification and initial guideline formulation. The second case study, focusing on cordless stick vacuum cleaners, functions as the primary case study. It refines the CRM hotspotting method and CRM efficiency guideline creation across a broader dataset.

Together, these case studies support the development and validation of product specific CRM efficiency guidelines and evaluate their transferability across product categories. The resulting guidelines are refined into a CRM efficiency guideline booklet that translates the research findings into an accessible format for designers, supporting the integration of CRM efficiency into product development.

1.4 Thesis structure

The thesis is structured as follows. Chapter 2 presents the theoretical background on Critical Raw Materials, relevant EU policy and circular design strategies. Chapter 3 describes the research methodology, including the CRM hotspotting approach and specific case study methods. Chapter 4 presents the results of the washing machine and vacuum cleaner case studies. Chapter 5 introduces the developed CRM efficiency guidelines showcase booklet.Chapter 6 discusses and evaluates the findings, including cross case comparison, trade-offs, limitations, recommendations for future research and a personal reflection on the project. Finally, Chapter 7 concludes the thesis by reflecting on the research questions and summarising the main contributions of the study.

2. Background context

2.1 Critical raw materials

Material criticality is dynamic. Technological developments, geopolitical shifts and evolving industrial priorities continuously influence both material demand and supply risk (Buijs, Sievers, & Tercero Espinoza, 2012). To monitor these changes, the European Union updates its Critical Raw Materials list at least every three years under the Raw Materials Initiative (Industrial Minerals Association Europe, n.d.). Materials are assessed based on two indicators: Economic importance and supply risk and are classified as CRM if they pass the threshold of 1.0 for supply risk and 2.8 for economic importance. Economic importance reflects the value added of relevant EU manufacturing sectors, adjusted for substitution potential, while supply risk accounts for global and EU-level supply concentration, governance factors, recycling rates and substitution parameters (European Commission, 2023). In the most recent assessment, 34 out of 87 screened materials were classified as critical. Copper and Nickel were included as Strategic Raw Materials (SRMs) due to their high importance to the EU's green, digital and resilience objectives, even though their quantitative risk scores fall below the formal CRM thresholds.

Changes in the CRM assessment illustrate the flexible nature of material criticality. For example, Indium was removed from the CRM list due to shifts in supply and demand patterns within the EU (European Commission, 2023). This demonstrates that material prioritisation needs to be adaptable over time. Design approaches addressing CRM efficiency should remain adaptable, as changes in a material's criticality status can require attention to shift toward different components or technologies containing other materials.

CRMs are embedded in a wide range of technologies. The EU foresight study (European Commission, 2020) visualises the relationship between materials and dependent technologies through a Sankey diagram, see figure 2 ,highlighting the role of CRMs in energy systems, digital technologies and mobility applications. For the purpose of this study, attention is directed toward technologies relevant to the selected case studies, particularly permanent magnet motors, electronic assemblies and battery systems, where CRMs are typically concentrated within the chosen product categories.

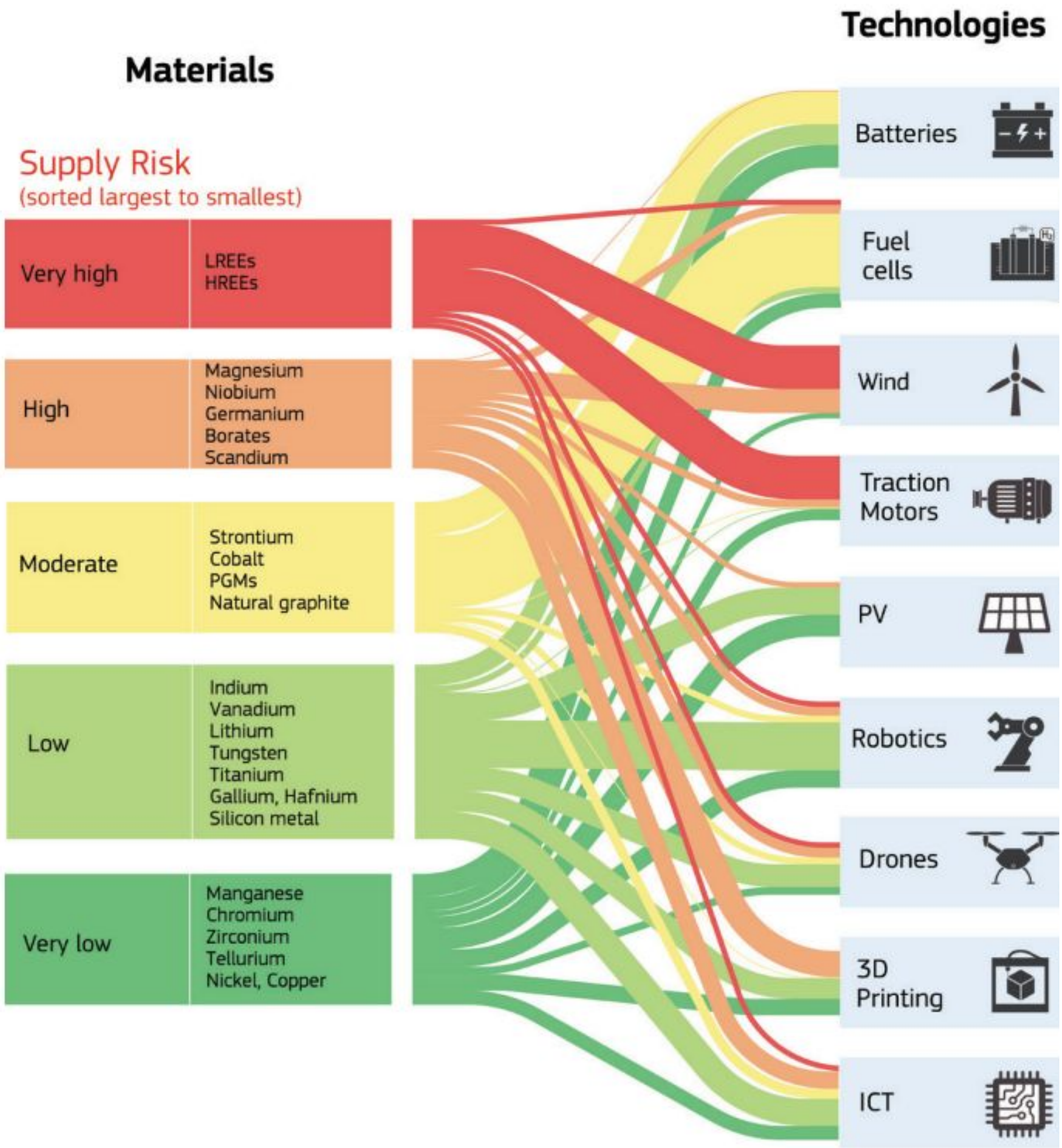


Figure 2. Sankey diagram showing the connection between materials and technologies (European Commission, 2020)

2.1.1 CRM in case study products

In the selected case study products of washing machines and cordless stick vacuum cleaners, CRMs are primarily concentrated in electric motors, electronic assemblies and battery systems. The type of motor design directly influences the presence of critical materials. Brushed DC motors are more likely to rely on ferrite magnets, which do not require rare earth elements, although they can still contain permanent magnets (Boules, 1990)). In contrast, Brushless DC (BLDC) motors typically rely on permanent magnets to function (Xia, 2012). These motors frequently use Neodymium-Iron-Boron (NdFeB) magnets, which contain rare earth elements such as neodymium, dysprosium and praseodymium (Tahanian, Aliahmadi, & Faiz, 2020). These elements are classified as critical due to their high supply concentration and limited substitution potential. An overview of the CRM content in permanent magnet motors is shown in figure 3.

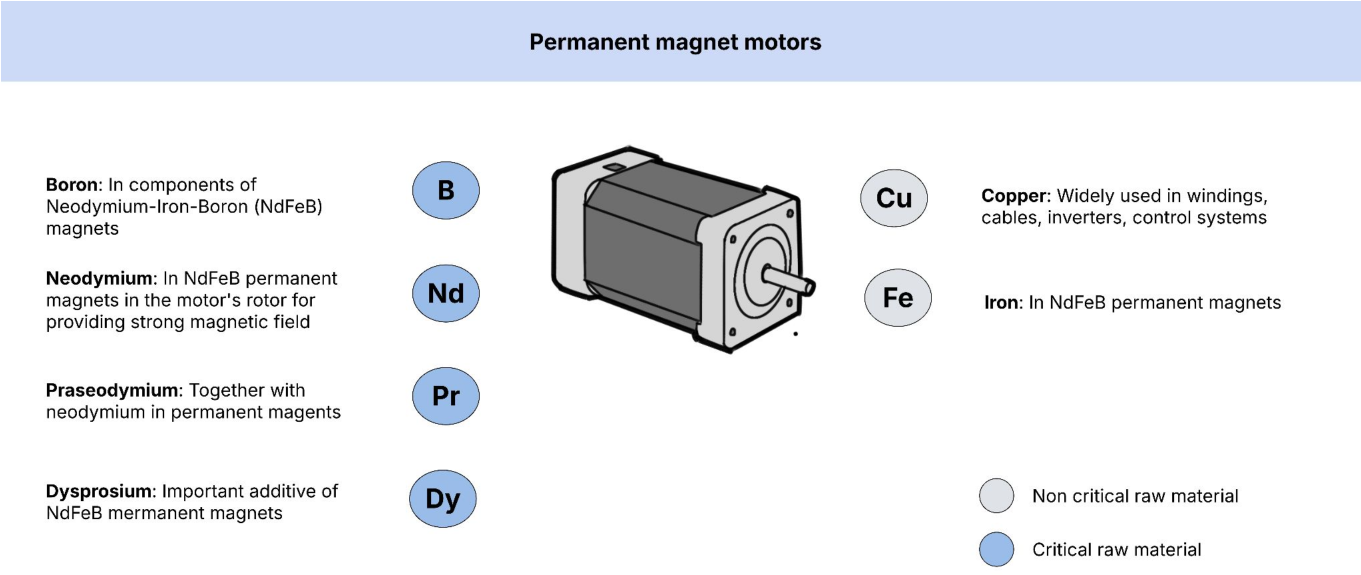


Figure 3. Critical raw material content in permanent magnet motors

Digital technologies, including printed circuit boards (PCBs), contain small quantities of critical materials such as palladium and tantalum. For example, vacuum cleaner PCBs contain approximately 0.01% palladium (European Commission, 2019), which is used to ensure conductivity and reliability. Due to this low material concentration and the structural complexity of PCB assemblies, recovery of CRM from these components remains technically challenging (Phiri, Chamunorwa, Kanhukamwe, & Goto, 2023). Figure 4 provides an overview of CRM commonly found in digital technologies such as PCBs.

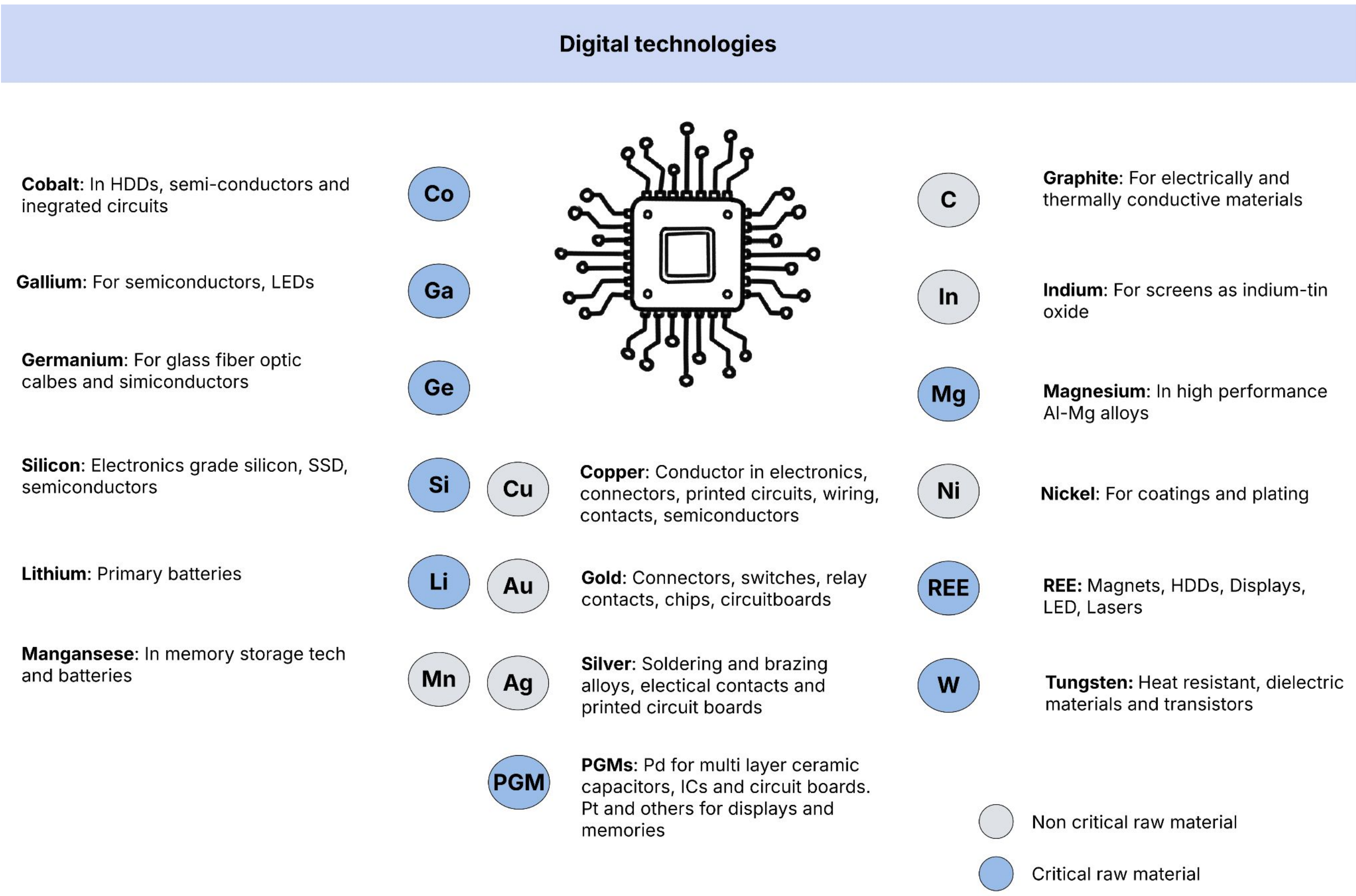


Figure 4. Critical raw material content in digital technologies

Rechargeable battery systems, particularly lithium-ion batteries, are another source of CRMs in the presented product categories, especially cordless stick vacuum cleaners. The cathode of these batteries typically contains lithium combined with metals such as cobalt, nickel or manganese, depending on the battery chemistry (Vranken, 2023). Lithium and cobalt are especially relevant from a criticality perspective due to their supply concentration and growing demand. The anode is commonly made of natural graphite, which is also included on the EU CRM list. Within lithium-ion batteries, the cathode generally represents the highest concentration of critical materials. (Wentker et al., 2019) Figure 5 shows an overview of CRM content in battery cells.

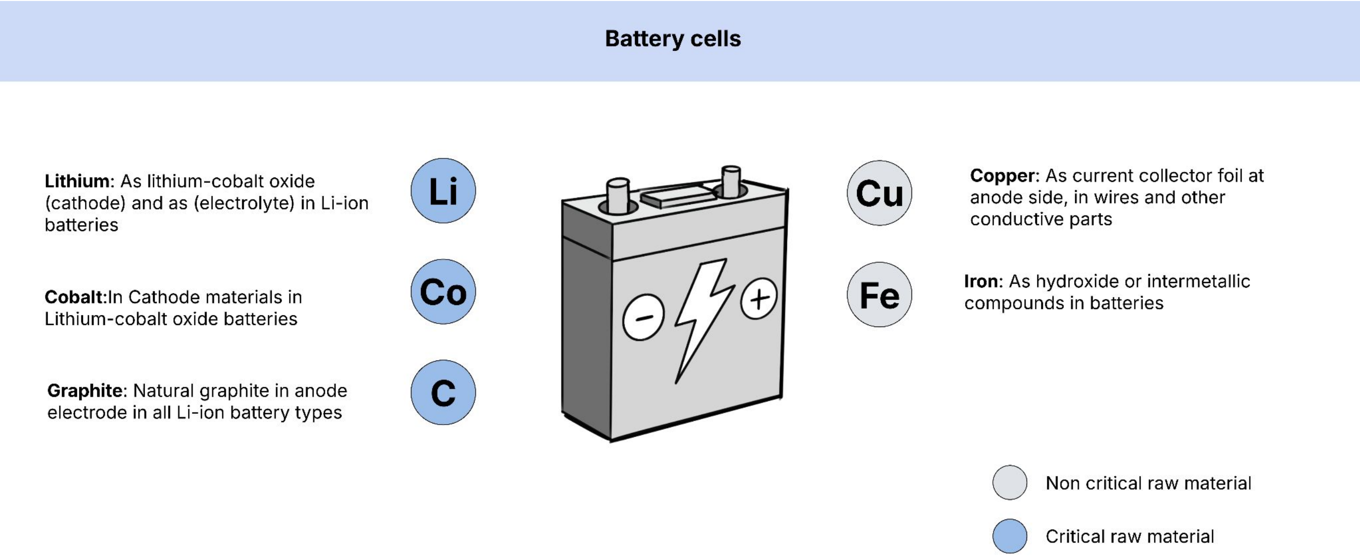


Figure 5. Critical raw material content in battery cells

In washing machines and cordless vacuum cleaners,these components represent the most likely to contain CRMs. Identifying how these components are positioned and connected within the product's architecture is necessary to evaluate possibilities for CRM efficiency.

2.2 Policy and regulations

The European Union addresses CRM supply risks and material sustainability through several policy instruments, including the Critical Raw Materials Act (CRMA), the Net Zero Industry Act (NZIA) and the Ecodesign for Sustainable Products Regulation (ESPR). Together, these initiatives aim to strengthen strategic autonomy, improve circularity and reduce reliance on primary raw material extraction. However, the effectiveness of these policies ultimately depends on their translation into product level design principles.(van Gaalen & Slootweg, 2025)

2.2.1 Critical Raw Materials Act (CRMA)

The CRMA was adopted in response to growing supply vulnerabilities and geopolitical dependency on concentrated raw material markets. The regulation establishes quantitative benchmarks for 2030, including targets for domestic extraction, processing and recycling, as well as limits on dependency on a single third country (European Commission, 2024a):

- At least 10% of the EU’s annual consumption for extraction
- At least 40% of the EU’s annual consumption for processing
- At least 25% of the EU’s annual consumption for recycling
- No more than 65% of the EU’s annual consumption from a single third country

In addition, the CRMA introduces measures to improve collection and recycling performance, including specific targets for permanent magnets (European Commission, 2024a)

While the CRMA defines supply chain targets at European level, it does not prescribe how product design should facilitate CRM reduction or recovery. Achieving the recycling and circularity benchmarks therefore requires product level strategies in order to reach the 2030 objectives.

2.2.2 Net Zero Industry Act (NZIA)

The NZIA aims to increase the EU’s manufacturing capacity for net-zero technologies and requires that at least 40 percent of annual deployment needs are met through domestically produced clean technologies by 2030 (European Commission, 2024c). Many of these technologies, including renewable energy systems and electric mobility infrastructure, depend heavily on CRMs (Sanseverino & Luu, 2022). Improving CRM efficiency within product design can reduce pressure on supply chains of CRM and support the feasibility of these deployment targets.

2.2.3 Ecodesign for Sustainable Products Regulation (ESPR)

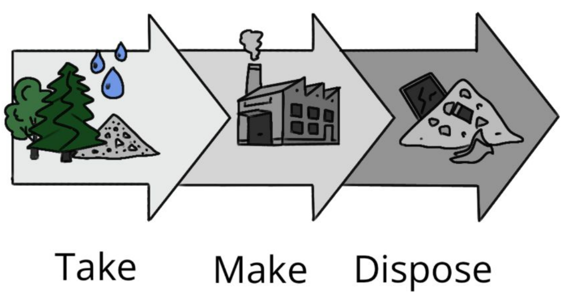
The ESPR seeks to improve the environmental performance of products by introducing horizontal ecodesign requirements related to durability, reparability, resource efficiency and information transparency (European Commission, 2024b). Future delegated acts will define product-specific requirements across major product groups.

Although the ESPR addresses several aspects relevant to circularity, specific criteria for CRM efficiency are not present. Requirements related to disassembly depth, component accessibility, modularity or targeted recovery of CRM-containing components are not yet concretely defined. As a result, there is a need for product design specific research to inform how CRM efficiency could be integrated into future product specific regulations.

Overall, EU policy sets clear targets for reducing material dependency and promoting circularity, but provides limited guidance on how CRM efficiency should be implemented at product level, reducing the practical actionability of these policies.

2.3 R-strategies as guidelines for the circular economy

The Circular Economy (CE) proposes a shift from linear resource extraction and disposal toward strategies that retain product and material value over time, see figure 6 (Ellen MacArthur Foundation, n.d.)(Ekins et al., 2019). Rather than focusing solely on recycling, the circular economy emphasises interventions that reduce material demand and extend product lifetime. For CRMs, such interventions are particularly relevant, as reducing the need for primary material extraction can mitigate supply risks and environmental pressures (Cimprich, 2022).



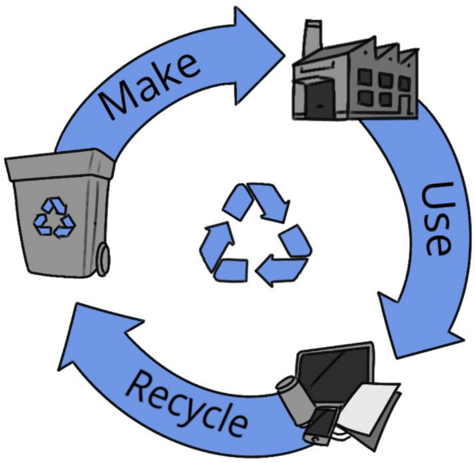


Figure 6. Overview of the linear and circular economy

To operationalise circularity, Potting et al. (2017) introduced the 9R hierarchy which categorises circular strategies according to their level of value retention, see figure 7. The framework distinguishes between:

R0–R2: Smarter product use and manufacturing
R3–R7: Extending product service life
R8–R9: Material recovery and recycling

9R Framework

Circular	Smarter products and manufacturing	R0 Refuse	Make the product unnecessary by discontinuing it or offering another product
		R1 Rethink	Make product use more intensive
		R2 Reduce	Use less natural resources and materials
	Extending product service life	R3 Reuse	Reuse of a used product that is still in good condition and performs its original function
		R4 Repair	Repair and maintenance of a damaged product so that it can continue to be used
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use of parts of a discarded product in a new product with the same function
		R7 Repurpose	Use of a discarded product or its parts in a new product with a different function
	Material recovery and recycling	R8 Recycle	Processing of materials to obtain the same or lower quality
Linear		R9 Recover	Combustion of materials with energy recovery

Figure 7. The 9R strategies framework (Potting et al., 2017)

Higher-order strategies, such as refuse, rethink, reduce, reuse and repair, preserve more functional value than lower-order recycling approaches. From a CRM perspective, these higher-order strategies are particularly important as many CRMs are used in small quantities and are difficult to recover efficiently at end of life (Phiri, Kanhukamwe, & Goto, 2023). Extending product lifetime or enabling component reuse can therefore be more effective than relying on material recycling.

From a CE perspective, products in use and at end of life are often described as part of the urban mine, representing a secondary source of raw materials (van der Voet et al., 2025). The accessibility of these materials depends on product architecture and disassembly characteristics. For CRMs, whose recovery can be technically complex and cost intensive (Bielowicz, 2025), design decisions determine whether this urban mine can be effectively utilized to mitigate supply risk.

Design-for-X approaches, such as design for repair, disassembly and modularity, provide practical means of implementing R-strategies within product architecture. However,they do not explicitly account for material criticality. Hotspot mapping (Flipsen, Bakker, & de Pauw, 2020) proposes a way to distinguish between components, allowing designers to prioritize the redesign of components with high failure indicators to ensure they are easily accessible.

For CRMs efficiency, such prioritisation is necessary. Not all materials embedded in a product contribute equally to supply vulnerability and economic importance. A CRM efficiency perspective therefore requires identifying which components contain the most critical materials and assessing where design changes can have the greatest impact. Integrating material criticality into circular design supports more targeted interventions and forms the basis for the guideline development presented in this study.

3. Methodology

The study presented in this paper used an explorative approach to identifying and prioritizing CRM components to develop CRM efficiency guidelines. The method structure is designed to bridge the gap between high level European policy objectives and practical product level implementation.

For this study, two product categories were selected: washing machines and cordless stick vacuum cleaners. Washing machines were chosen due to the presence of CRM containing components, particularly in motors and electronics, and the availability of the product at the start of the project. Cordless stick vacuum cleaners were selected because they are high-volume consumer products, readily accessible for teardown, and likely to contain CRM in motors, PCB assemblies, and battery cells. The washing machine case study served as an exploratory case to develop and structure the CRM hotspotting method. The cordless stick vacuum cleaner case study functioned as a validation case, refining the method and further developing the guidelines across a broader dataset of ten products.

Both case studies follow the same sequence of methodological steps, as summarised in Table 1. This structure ensures alignment with the research questions:

> ***RQ****: How can product specific design guidelines contribute to enhancing critical raw material efficiency?*
>
> ***SQ1****: How can CRM containing components be systematically identified and prioritised within product architectures?*
>
> ***SQ2:*** *Which design strategies can improve CRM efficiency at the component and architectural level?*
>
> ***SQ3:*** *To what extent can CRM efficiency guidelines developed in one product category be transferred to other product categories?*

Table 1. Research methodology tabel

Method step	Objective	Research question addressed	Type of data generated	Justification
3.1 Product teardown	Analyse internal product architecture and identify components	SQ1	- Overview of components in product - Knolled product pictures (vacuum cleaners)	Teardown enables observation of product architecture and material embedding, which is essential for evaluating accessibility and recovery potential in design research.
3.2 Disassembly mapping	Visualise disassembly sequence and accessibility of components	SQ1 + SQ2	- Disassembly maps	Disassembly maps provide a structured overview of product architecture and enable systematic assessment of accessibility barriers relevant to CRM recovery.
3.3 CRM focused BoM	Establish component material, weight and determine CRM components	SQ1	- BoM with component mass distribution and indication of CRM presence	BoMs indicate mass for relevant components and help to identify CRM presence in components.
3.4 CRM hotspot mapping	Prioritise CRM components suitable for CRM efficiency guidelines	SQ1 + SQ2	- CRM hotspot table prioritising CRM components for guideline creation	Combines supply risk, economic importance, and CRM mass relevance into a decision support method for CRM efficient guidelines.
3.5 CRM efficiency guideline creation	Translate component analysis into guidelines	SQ2	- Visual CRM efficiency guidelines	Creates a visual overview on how CRM efficiency guidelines influence product architecture.
3.6 Cross case comparison	Assess transferability of CRM guidelines across product categories	SQ3	-Assessment of CRM efficiency guidelines suitable across multiple product categories	Comparres two product category guidelines to increase robustness of created guidelines.
3.7 External validation	Assess feasibility and applicability of the developed guidelines	RQ	- Qualitative expert input	Expert validation enhances practical implementation for the CRM efficiency guidelines.

3.1 Product teardown

Product teardowns were conducted to analyse the internal product architecture and identify CRM-relevant components. Each selected product was disassembled as far as technically feasible. During the teardown process, several aspects were systematically documented, including the location of components within the product architecture, the order of disassembly, the types of mechanical fasteners used, the tools required for disassembly and whether disassembly steps were destructive or non-destructive.

This process enabled direct observation of component integration, accessibility and assembly logic. These observations provide insights into how CRM-containing components are embedded within the product architecture and help evaluate their accessibility, recovery potential, and opportunities for structural redesign.

3.2 Disassembly mapping

To structure the findings from the product teardowns, disassembly maps were created following the method described by De Fazio et al. (2021). Disassembly maps visualise the hierarchical structure of a product and the sequential removal steps required to access components. They indicate connection types, required tools, and the relative disassembly depth of components.

For this research, the method was adapted to support the identification of components containing CRMs. Elements of the original method were simplified to improve readability and focus on CRM-relevant components. Tool symbols, colour usage and penalty indicators were reduced to limit visual complexity. A CRM indicator was added to highlight components that potentially contain critical raw materials. In addition, component numbers were replaced with component names to improve interpretability of the maps. These adjustments allow the disassembly maps to focus on the accessibility of CRM-containing components rather than documenting the full technical detail of the disassembly process. Figure 8 shows the original legend for disassembly maps and the adjusted version showing the changes made for CRM component identification

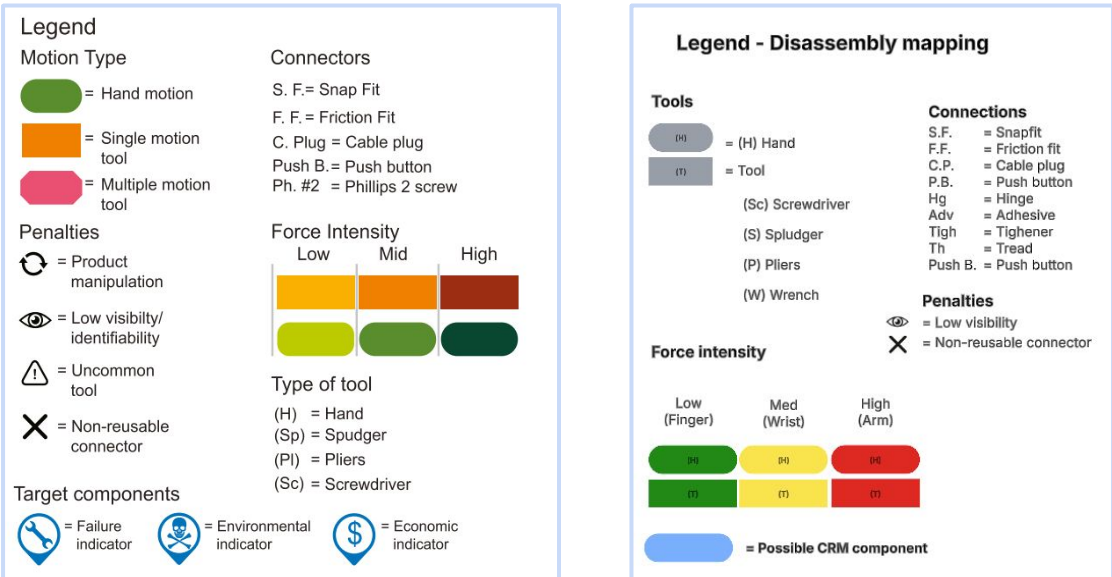


Figure 8. *Original legend for disassembly maps and the adjusted version for CRM efficiency*

Figures 9 and 10 show two examples of snippets of an original disassembly map as described by De Fazio et al. (2021) and of an adjusted disassembly map focused on CRM component accessibility. The maps represent different products and are shown for illustrative purposes only.

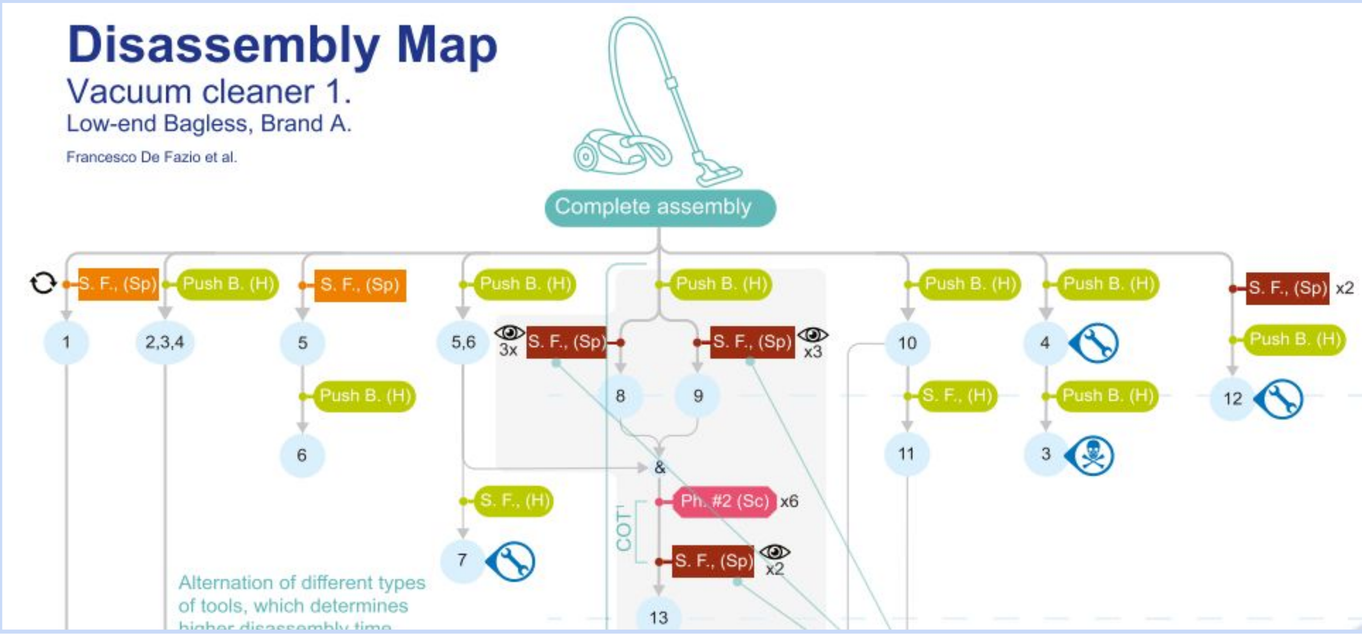


Figure 9. Snippet of original disassembly map example from De Fazio et al. (2021)

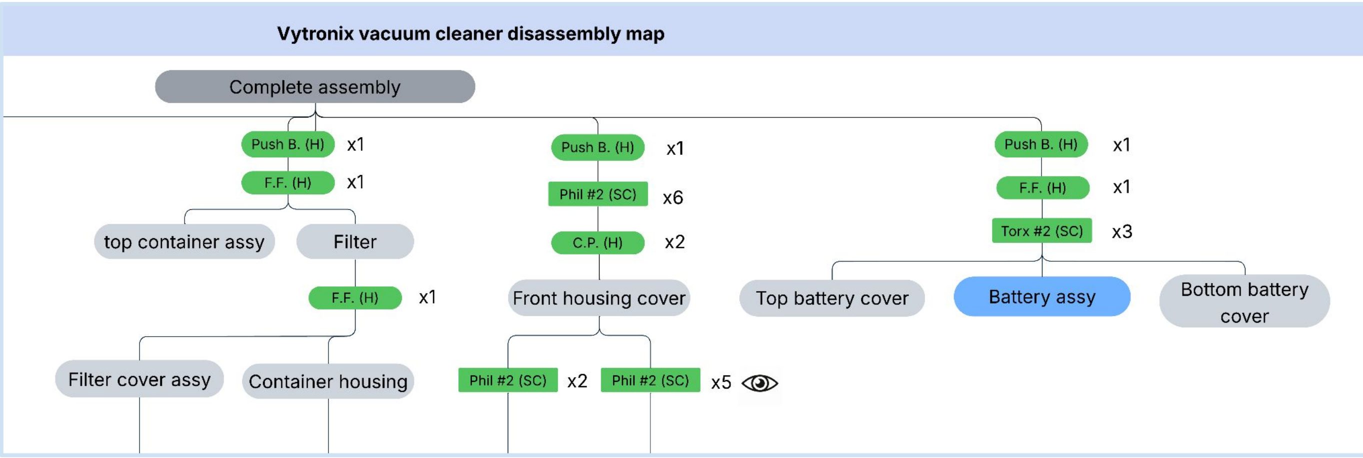


Figure 10. Snippet of adjusted disassembly map for CRM identification.

The resulting disassembly maps were used to analyse the accessibility and disassembly depth of CRM-containing components, where disassembly depth is defined as the number of steps required to remove a component from the product architecture.

3.3 CRM focused BoM

A CRM focused Bill of Materials (BoM) was created for each use case product. Instead of documenting all materials, the BoM focused on identifying components that potentially contain CRMs.

For each liberated component, the component name, weight, primary material indication, and if applicable: likelihood of CRM presence were recorded. Component weights were measured after disassembly using a digital scale. Material indications were based on component markings, visual inspection, and literature on typical material compositions.

The CRM focused BoM was used to identify components with a relatively high mass and potential CRM presence, supporting the CRM hotspot mapping method.

3.4 CRM hotspot mapping

A CRM hotspot mapping method was developed to prioritise components with the highest potential for improving CRM efficiency. The method combines Economic importance and Supply risk indicators from the EU assessment (European Commission, 2023) with estimates of CRM mass relevance at component level. It represents a simplified, design oriented adaptation of the EU criticality framework, intended for prioritisation of components rather than exact material classification.

Each CRM containing component was evaluated using three criteria to create hotspot scores:

Economic Importance (EI)
Economic Importance reflects the relevance of a material for the EU economy and is determined in the EU CRM assessment (European Commission, 2023). The score is based on the economic value of EU industrial sectors that depend on the material, taking into account how important the material is within those sectors and how easily it can be substituted. EI is expressed as a dimensionless numerical value, it should be interpreted as a relative indicator rather than an exact measurement. Higher EI values indicate greater economic relevance.

Supply Risk (SR)
Supply Risk represents the vulnerability of a material's supply chain and is also derived from the EU CRM assessment (European Commission, 2023). It is calculated based on factors including global supply concentration, governance performance of supplying countries, recycling rates and substitution potential. SR is also a dimensionless numerical value that should be interpreted as a relative indicator rather than an exact measurement, where higher values indicate greater supply risks.

CRM mass relevance
CRM mass relevance represents the estimated presence of CRMs within a component. It was determined by literature-based estimates of CRM content in specific components. The CRM mass relevance score links material criticality to product components by prioritising components where CRMs occur in substantial quantities rather than trace amounts.

To enable comparison and prioritisation, EI, SR and CRM mass relevance were categorised into three levels (low, medium, high) using defined cutoff points (Table 2). The thresholds were chosen to create a relative distribution of values across the dataset.

Table 2. Criteria cutoff points

Criteria	Low	Medium	High
Supply risk	< 2.0	2.0 - 3.5	> 3.5
Economic importance	< 4.0	4.0 - 6.0	> 6.0
CRM mass relevance	< 0.01%	0,01% - 1%	> 1 %

Economic Importance (EI) and Supply Risk (SR) were combined to determine overall material criticality. A matrix diagram was used to reflect how they influence each other (Table 3). This ensures that materials are only classified as highly critical when both economic relevance and supply risk are high.

Table 3. combining SR and EI into CRM criticality

	Low SR	**Medium SR**	**High SR**
Low EI	Low criticality	Low criticality	Medium criticality
Medium EI	Low criticality	Medium criticality	High criticality
High EI	Medium criticality	High criticality	High criticality

To determine the overall CRM hotspot score, material criticality was combined with CRM mass relevance to prioritise components with both high criticality and substantial CRM content for guideline creation. (Table 4)

Table 4. Determination CRM hotspot score

Criticality	CRM mass relevance	CRM Hotspot score
High	High	High
High	Medium	Medium
High	Low	Low
Medium	High	High
Medium	Medium	Low
Medium	Low	Low
Low	High, Medium, Low	Low

The final CRM hotspot scores are presented in a table to create an overview of the outcome. The table includes the component name, the estimated CRM content, the estimated CRM mass concentration and a “chance of CRM presence" column, see table 5 for an example .The “chance of CRM presence" column was introduced to address limited transparency regarding component CRM content. Because product technologies vary (e.g., Brushless DC versus brushed DC motors) and due to limited component data, CRM content could not be precisely quantified. The likelihood classification accounts for uncertainty by indicating the likely presence of CRM in the component.

Table 5. Example of a motor component in the CRM hotspot table

Component name	CRM content	Component CRM mass	Chance of CRM presence	CRM hotspot
Motor	Nd, B, (Dy, Pr), Cu	>1%	High	High

3.5 CRM guidelines creation

The CRM efficiency guidelines were developed by adapting existing circular design strategies to the context of critical raw materials. Relevant design strategies were selected from literature and translated to support CRM efficiency. The selection was based on their relevance to the CRM hotspots identified in Section 3.4 and their potential to reduce CRM demand or improve CRM recovery. Strategies from De Fazio et al. (2021), such as clumping and surfacing, were included to improve accessibility and recovery of CRMs. In addition, design for repair strategies from Dangal et al. (2022) and Faludi (2025) were incorporated to support product lifetime extension and improve component accessibility. Strategies were grouped into two categories relevant for CRM efficiency:

CRM reduction: Strategies that lower the amount of CRM used in products.

CRM recovery: Strategies that improve access to CRM-containing components to enable reuse, repair or recycling, thereby extending product lifetime and reducing the need for virgin raw materials .

An overview of the resulting guidelines divided into CRM demand reduction and CRM recovery is provided in Table 6.

Table 6. CRM guideline structure

CRM reduction	**CRM recovery**
Substitution	Surfacing
Standardisation	Clumping
Modularity	Standardisation
Pruning	Modularity
	Fastener types
	Mitigate embedded components
	Improve documentation

3.6 Vacuum cleaner case study specific method

3.6.1 CRM Component analysis

For the vacuum cleaner case study, 10 products were analysed to identify best practices and improvement opportunities for CRM efficiency. CRM-relevant components were compared across the models based on their integration within the product architecture.

The comparison focused on four aspects: Disassembly depth (defined as the number of steps required to access a component), ease of disassembly (e.g., required tools and accessibility), connection types (e.g., screws, clips, adhesives) and barriers to non-destructive disassembly.

For each CRM component, Snippets of disassembly maps were used to compare how the components were integrated across different products. An example of this analysis is shown in Figure 11, comparing the integration of the drive motor across two vacuum cleaner models.

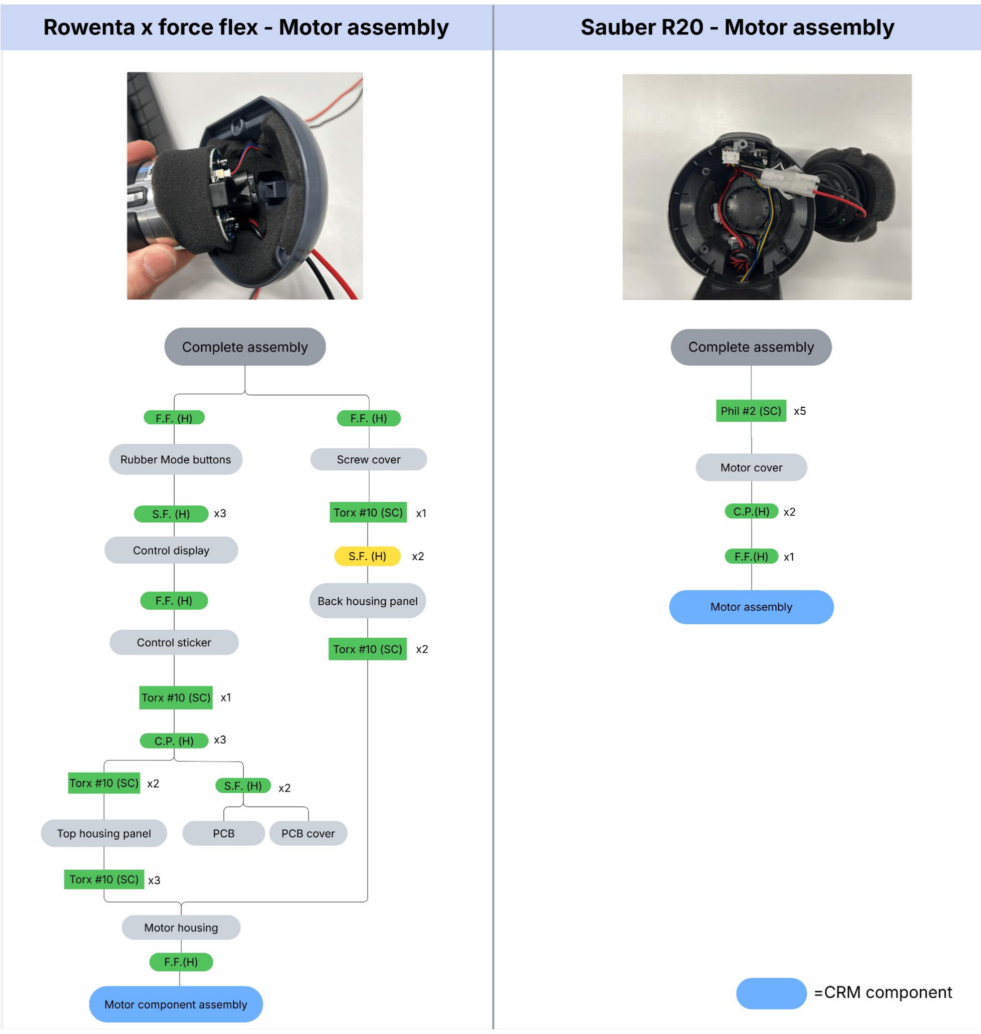


Figure 11 CRM component analysis example.

The analysis was conducted qualitatively by comparing component integration across the ten models to identify recurring patterns, best practices, and architectural constraints. These findings were then linked to the CRM efficiency guidelines to illustrate how specific design strategies can improve CRM efficiency in product design.

3.7 External validation

An external validation session was conducted to assess the relevance and applicability of the developed CRM efficiency guidelines. The session involved two experts from Invest-NL, a Dutch national financing and development institution that supports initiatives related to sustainability and the circular economy. The validation evaluated the CRM efficiency guidelines from three perspectives: desirability, feasibility, and viability. These criteria were used to assess whether the guidelines align with European policy objectives, whether they can be applied within product design processes and whether they could support regulatory developments such as the CRMA and the ESPR.

During the session, the CRM hotspot mapping method, the CRM efficiency guidelines and their associated trade-offs were presented. The guidelines from the vacuum cleaner case study were used as this case study forms the primary basis of the research. The session followed a semi-structured discussion format. After introducing the method and guidelines, the experts were asked to reflect on the desirability, feasibility, and viability of the proposed CRM efficiency strategies. Notes were taken during the discussion to capture expert feedback, which was later synthesised into key insights.

4. Results

4.1 Washing machine case study results

4.1.1 Product teardown & Disassembly map

For the washing machine use case a Hisense WDQR1014EVAJMT was used, see figure 12.

Figure 12. Hisense WDQR1014EVAJMT washing machine.

The teardown provided insights into component accessibility, connection types, required tools and the overall complexity of the product architecture. A complete teardown description is provided in Appendix A. The main findings are summarised below:

- Thirteen components were identified as potential CRM and SRM containing parts: the motor, main PCB, top PCB, power converter, touch sensor, heater element, heater fan, drain pump, soap inlet pump, cable assembly, power cable, inlet valve and electromagnetic Interference (EMI) filter.
- The washing machine has two main access points to reach the internal components, the top and back panel.
- The back panel opening is too small to allow removal of the motor.
- The main PCB is positioned at the bottom of the assembly, requiring extensive disassembly to access.
- Concrete counterweights are tightly friction-fitted, making them difficult to remove.
- Hex #7 screws are the primary fastener type used throughout the assembly.
- The disassembly requires screwdrivers, a spudger, pliers and a wrench.

The disassembly map seen in figure 13, illustrates the depth at which each of the 13 CRM-relevant components is embedded, the sequence of removal steps and the associated connection types.The map shows that the motor, main PCB and cable assembly are located deep within the product’s architecture, requiring multiple extraction steps. Their location significantly limits their accessibility for repair, reuse or recovery.

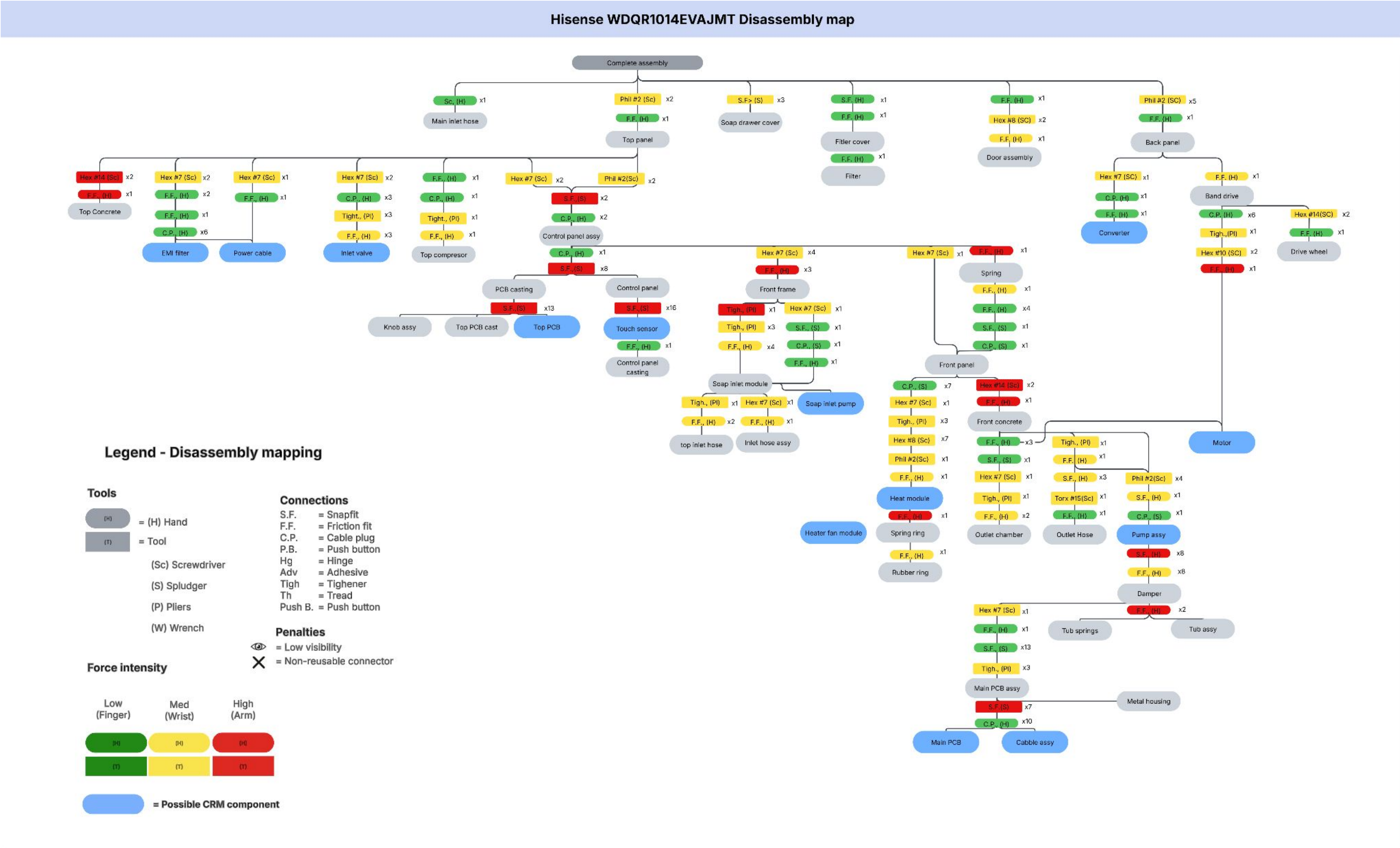


Figure 13. Hisense WDQR1014EVAJMT Disassembly map

4.1.2 CRM Hotspot mapping

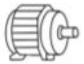
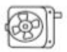
The CRM hotspot mapping method was applied to all relevant CRM-containing components to enable their prioritisation for the development of CRM efficiency guidelines. In this first iteration, the hotspot table included additional contextual columns describing component functionality, accessibility, connection types, price, and lifespan.

Within the first case study, component prioritisation was based on three criteria: material criticality of the CRM content, likelihood of CRM presence, and functional importance within the product. The results of this assessment are presented in Table 7.

The main motor, main PCB, and top PCB were classified as high-priority components, as they are likely to contain CRMs, align with high criticality indicators and are essential to product operation. Components such as the power converter, heater element, cable assembly and power cable were assigned medium priority, with lower CRM concentrations and a stronger association with strategic raw materials such as copper and nickel.

Auxiliary motors, including the fan motor, drain pump, and soap inlet pump, were classified as low priority. These motors typically rely on ferrite-based magnet technologies rather than rare-earth permanent magnets, resulting in lower CRM intensity (Tahanian, Aliahmadi, & Faiz, 2020). Similarly, the touch sensor, inlet valve, and EMI filter were assigned low scores due to limited CRM presence; for example, indium used in touch sensors is no longer classified as a Critical Raw Material (European Commission, 2023).

Table 7. CRM hotspot map of Hisense washing machine

Icon	Component	CRM content + (SRM)	Change of CRM in component	Functionality	CRM hotspot	Accessibility	Fasteners/ connections to liberate component	Price range	Component lifespan (years)
	Motor	Neodymium, Boron, Copper, (Dysprosium), (Praseodymium)	Medium	Critical	High	Difficult to access	Tool reversible connection	€200-€400	10-14
	Main PCB	Palladium, Tantalum,Nickel, Copper	High	Critical	High	Difficult to access	Permanent chemical connection	€100-€200	8-12
	Top PCB assembly	Palladium, Tantalum,Nickel, Copper	High	Critical	High	Moderately accessible	Reversible Connector	€100-€200	8-12
	Power converter module	Copper, Tantalum or Palladium	Medium	High importance	Medium	Accessible with effort	Reversible Connector	€80-€150	8-12
	Touch sensor	Indium, Copper	Low	Moderate importance	Low	Moderately accessible	Permanent chemical connection	€20-€60	6-10
	Heater element	Nickel, Copper	Medium	High importance	Medium	Accessible with effort	Tool reversible connection	€50-€120	8-12
	Heater fan motor	Neodymium, Boron, Copper, (Dysprosium), (Praseodymium)	Low	Moderate importance	Low	Accessible with effort	Reversible Connector	€30-100	8-12
	Drain pump	Neodymium, Boron, Copper, (Dysprosium), (Praseodymium)	Low	High importance	Low	Moderately accessible	Reversible Connector	€30-100	8-12
	Soap inlet pump	Neodymium, Boron, Copper, (Dysprosium), (Praseodymium)	Low	Moderate importance	Low	Moderately accessible	Reversible Connector	€20-€60	8-10
	Cable assembly	Copper, Nickel	Low	Critical	Medium	Difficult to access	Reversible Connector	€30-€80	10-15
	Power cable	Copper, Nickel	Low	Critical	Medium	Easily accessible	Reversible Connector	€10-€30	10-15
	Inlet valve	Copper	Low	High importance	Low	Easily accessible	Reversible Connector	€20-€80	8-12
	EMi filter	Copper	Low	Moderate importance	Low	Easily accessible	Reversible Connector	€15-€40	10-15

4.1.3 CRM efficiency guidelines

The CRM hotspot map presented in Section 4.1.2 identifies the main motor and PCB assemblies as the primary targets for CRM efficiency interventions. Applying the CRM efficiency strategies described in Section 3.5 to these components resulted in a set of product-level guidelines for the washing machine case study.

The guidelines are visualised through sketches to illustrate how each strategy affects the integration of CRM components within the product architecture. The sketches present a simplified view of the product with CRM components highlighted in blue to maintain focus on the identified hotspot components.

In addition, simplified disassembly maps are included where relevant to show the impact of the guidelines on accessibility, disassembly depth, and component hierarchy. These maps are intentionally reduced in complexity compared to the full disassembly map presented in 4.1.1. Connection types are removed to minimise visual clutter and to focus on the sequence of component removal. Within the simplified maps, CRM-containing components are colour-coded based on the CRM hotspot map to make clear where relevant CRM components are located within the product.

Figures 14 to 19 show the CRM efficiency guidelines created for the washing machine case study.

Clumping (Figure 14)

Grouping the main PCB and top PCB in one accessible location reduces disassembly depth and enables faster recovery or reuse of PCB modules, especially if future products adopt standardized formats.

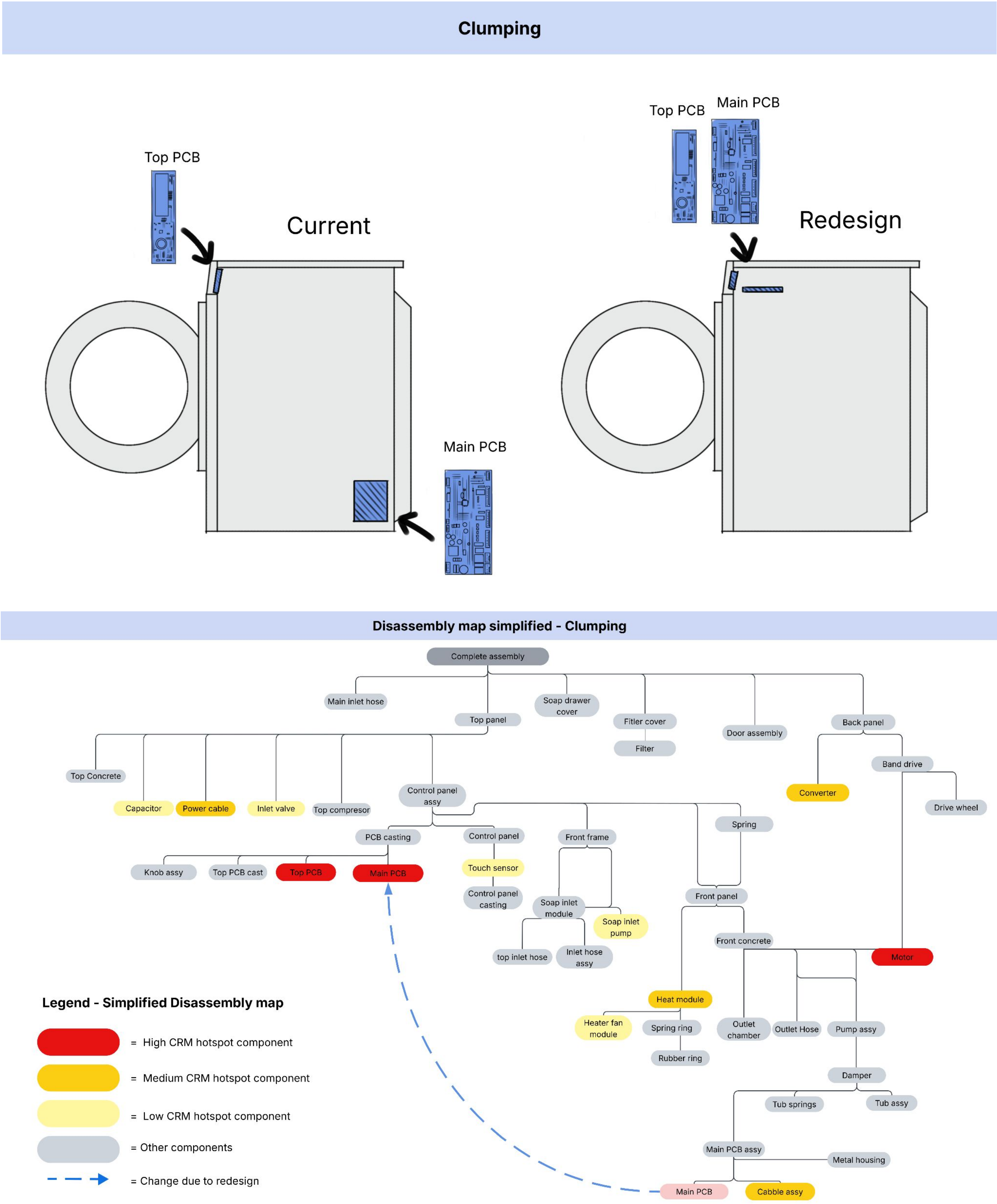


Figure 14. Clumping and simplified disassembly map illustrating the impact.

Accessing / Surfacing (Figure 15)

Enlarging the back opening and adding an additional access point improves reachability of CRM-intensive components such as the motor and main PCB, reducing labour time for repair and recovery.

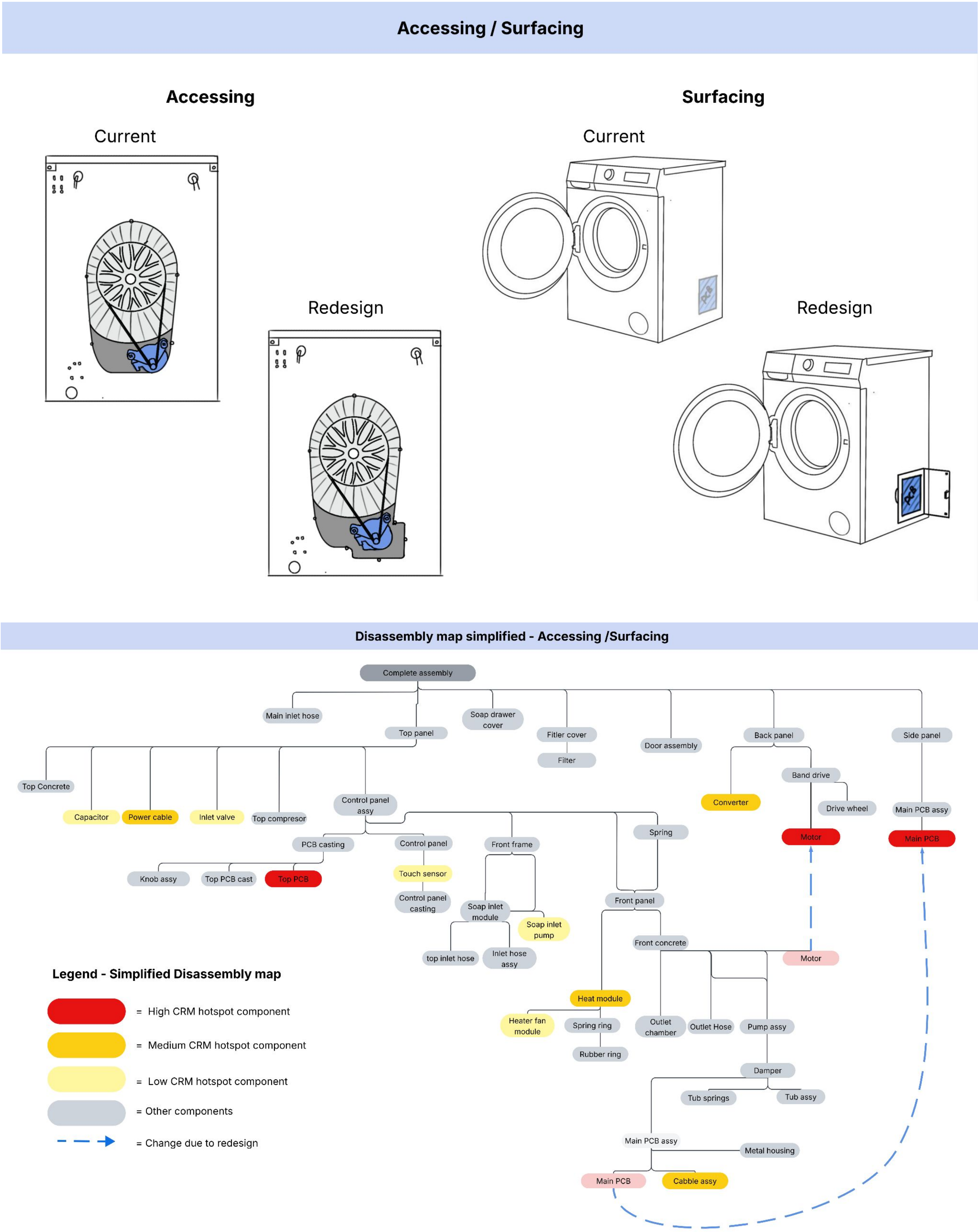
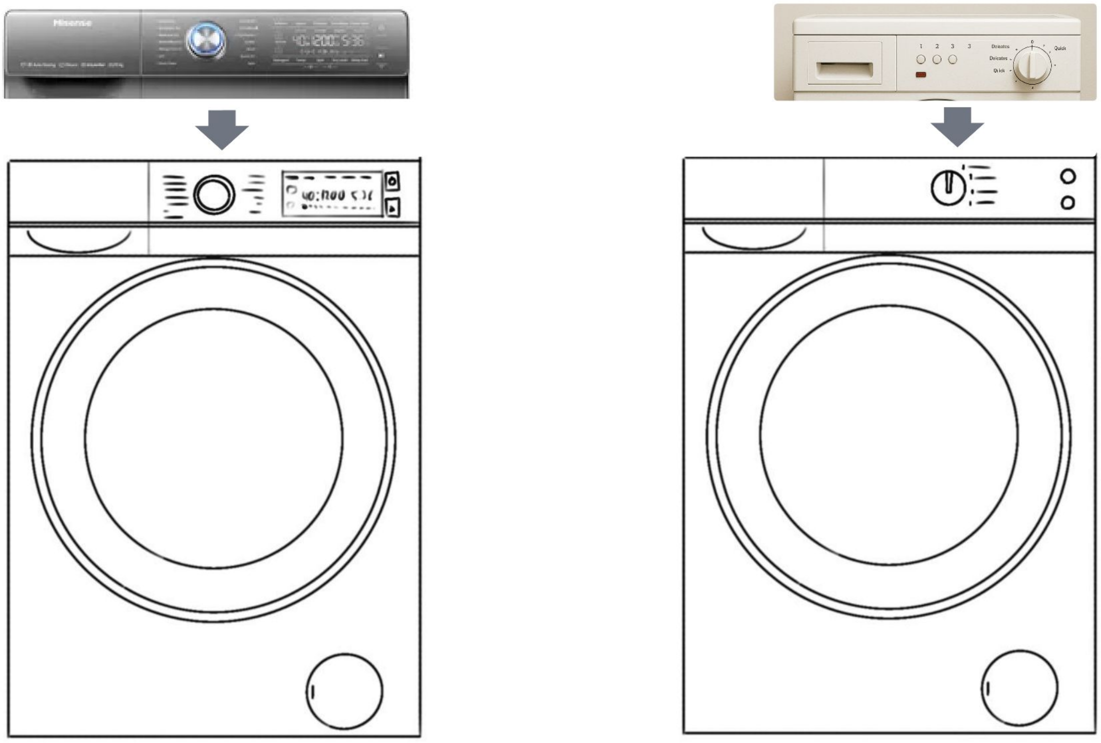


Figure 15. Accessing + surfacing and simplified disassembly map illustrating the impact.

Pruning (Figure 16)

Removing non-essential features, such as touchscreens or complex interface boards, lowers CRM demand by reducing the number and complexity of CRM-containing electronic components.

Pruning



Disassembly map simplified - Pruning

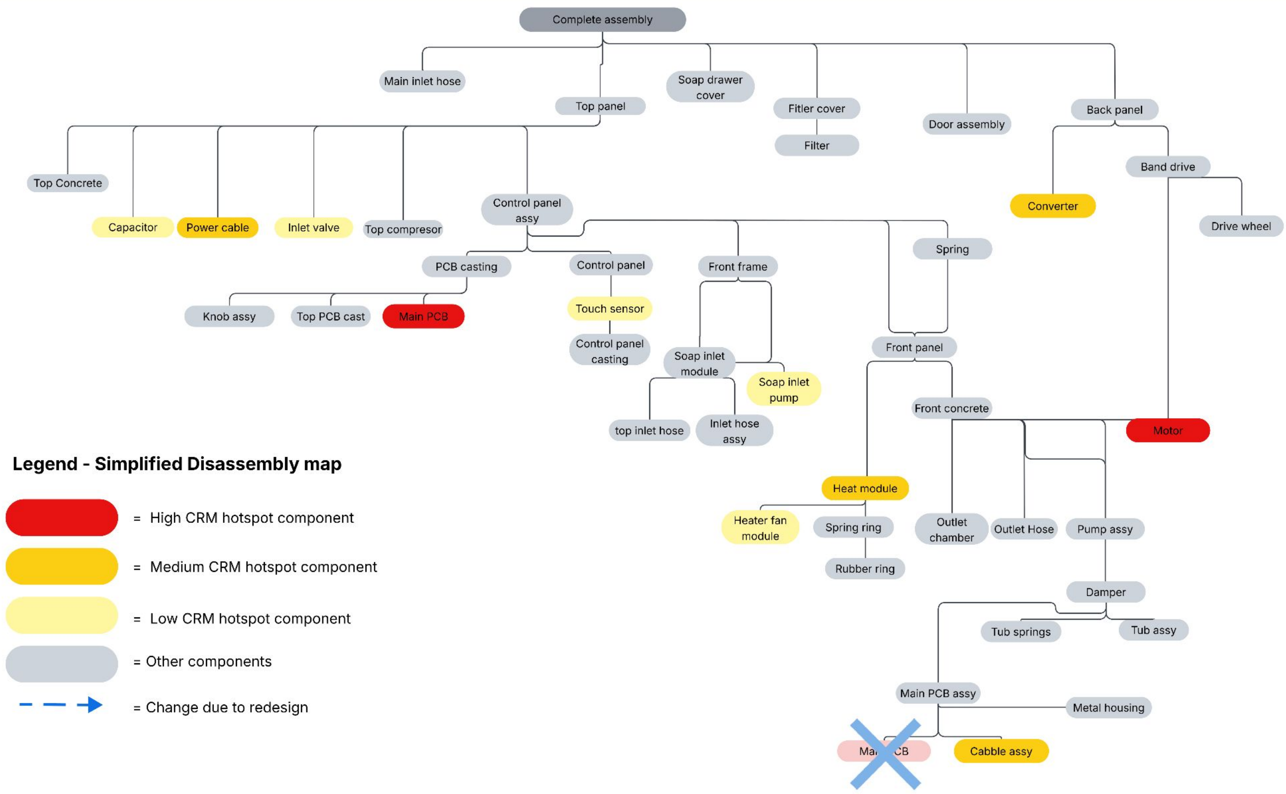


Figure 16. Pruning and simplified disassembly map illustrating the impact.

Substitution (Figure 17)

Replacing rare-earth permanent magnet motors with non-CRM alternatives (e.g., induction motors) or using lower-grade magnets directly reduces CRM content.

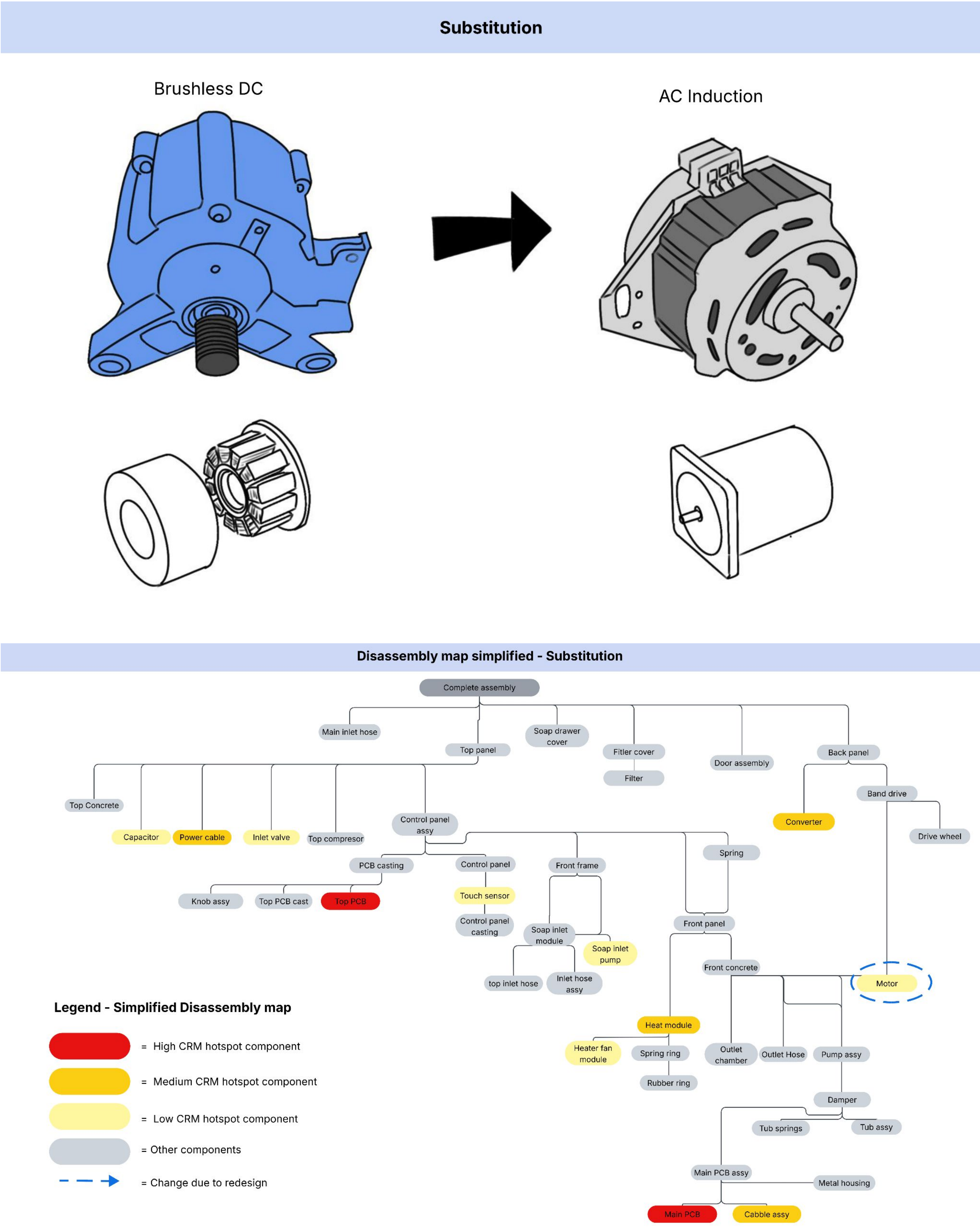


Figure 17. substitution and simplified disassembly map illustrating the impact.

Standardization (figure 18)

By regulating the maximum allowed performance in products, standardization can limit the overspecification of performance of magnets. potentially reducing the need for CRMs.

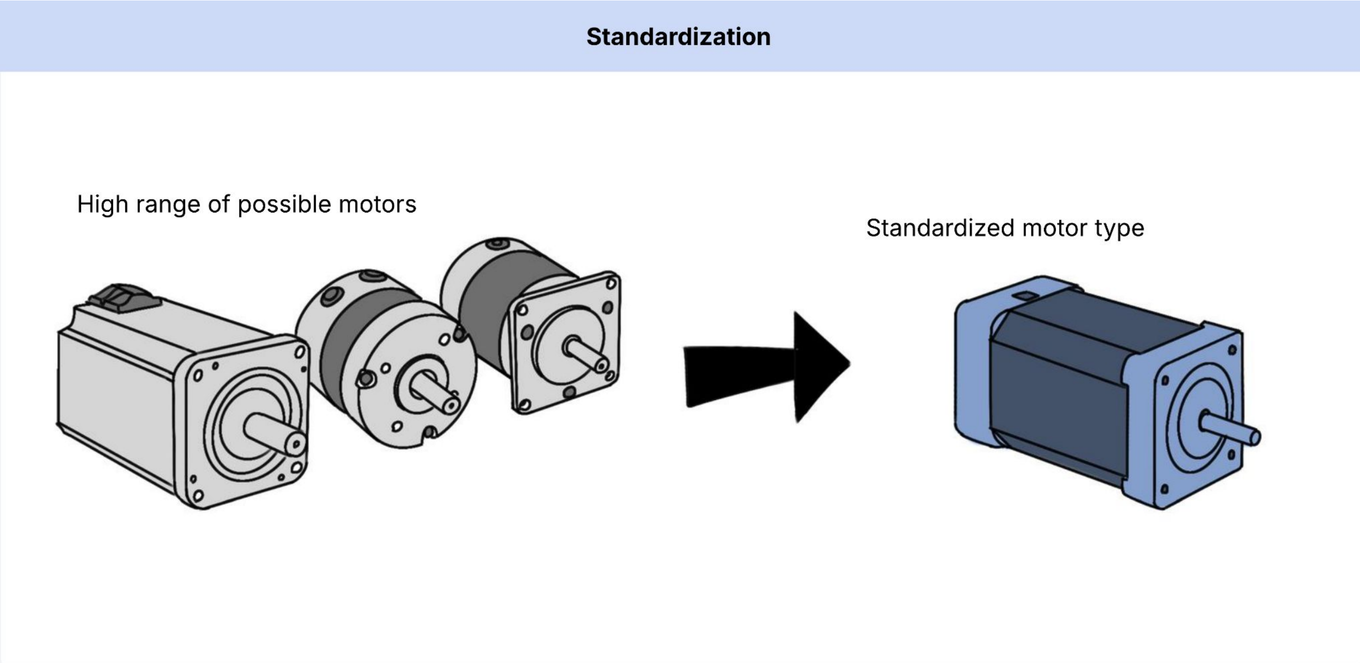


Figure 18. Standardization visualised

Modularity (figure 19)

Improving component modularity facilitates cross-product reuse, reducing the need for virgin materials for maintenance and repairs.

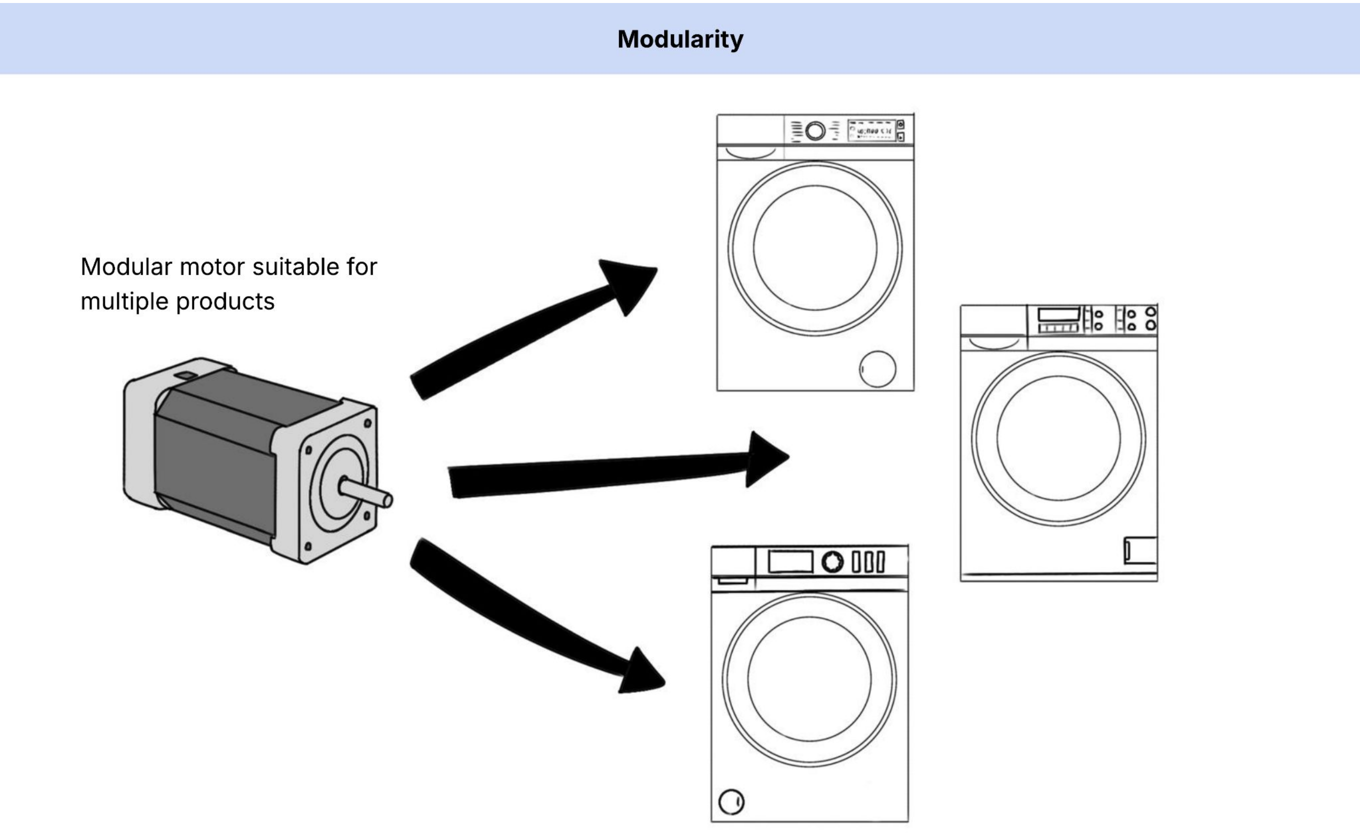


Figure 19. Modularity visualised

4.2 Cordless stick vacuum cleaner case study results

4.2.1 Product teardown and disassembly mapping

The dataset used in the second use case consists of ten cordless stick vacuum cleaners (see Figure 20), representing a diverse market segment within the product category. The products were primarily acquired through the Dutch second-hand platform “Marktplaats” to minimise the destruction of new products, particularly in cases where disassembly could not be performed non-destructively. Table 8 summarises the models housing configurations,what year they went into production, drive motor types and number of CRM components identified within the product. CRMs were primarily concentrated in the drive motor, battery assembly and printed circuit board assemblies (PCBAs).

Figure 20. Cordless stick vacuum cleaners used in this research

Table 8. Overview of cordless stick vacuum cleaners

Number	Brand	Model	Production year	Housing type	Drive motor type	Number of CRM components
1	Vytronix	NIBC22	2020	Split	DC Brushed	4
2	Turbotronic	TT-CF7	2022	Access point	DC Brushed	5
3	Turbotronic	TT-CF4	2020	Split	DC Brushed	5
4	Severin	S Special	2018	Access point	DC Brushed	6
5	Zedar	S600	2022	Access point	BLDC Brushless	7
6	AEG	QX8 Animal x power	2019	Access point	DC Brushed	4
7	Sauber	R20	2020	Access point	BLDC Brushless	6
8	Hoover	H-Free 500 Hydro plus	2021	Split	BLDC Brushless	6
9	Rowenta	X force flex 12.60	2021	Access point	BLDC Brushless	6
10	Dyson	V11 absolute	2019	Access point	BLDC Brushless	4

Within the ten products, two main housing types were identified: access point housings and split housings. Access point housings use dedicated covers to provide targeted access to specific components. For example, in some cases components such as PCB assemblies can be accessed by removing a cover at the back of the product. Multiple access points located at different positions on the product enable selective access to components without opening the entire housing.

In contrast, split housings divide the product housing into two main halves. Opening this type of housing generally requires more disassembly steps compared to access point designs. However, once opened, split housings provide simultaneous access to a large portion of the internal components. Figure 21 illustrates the difference between these housing types.

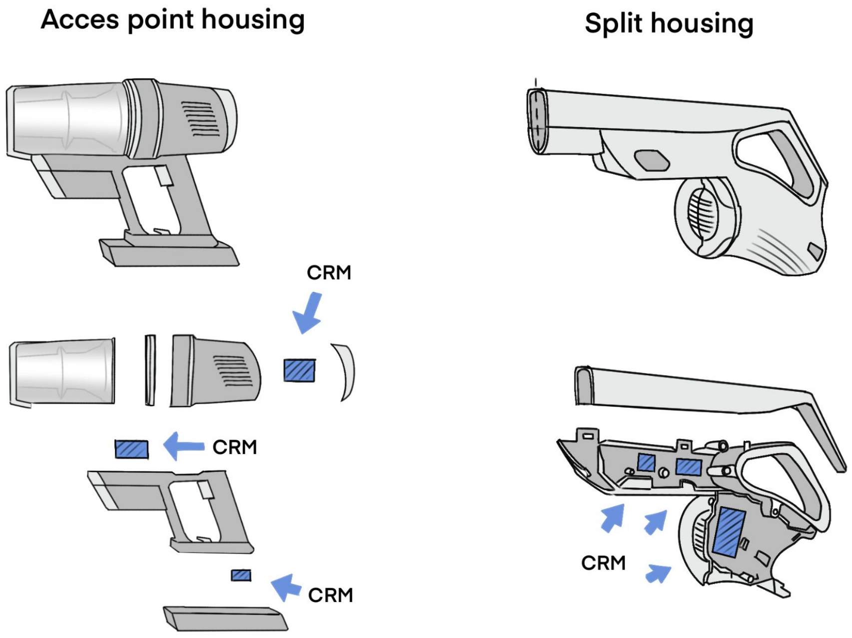


Figure 21. Access point housing vs Split housing

Insights from the teardown process of the vacuum cleaners are presented below. Indicating weak and strong points for each of the vacuum cleaners

Vytronix NIBC 22

The Vytronix model features a split housing architecture. Disassembly was straightforward, as all screws were externally visible and accessible. The exclusive use of screws instead of snap-fit connections enabled fully non-destructive disassembly. Although this approach may reduce perceived product quality due to visible fasteners, it significantly improves disassembly efficiency. Some screws were positioned deep within the housing, requiring extended tools. Figure 22 shows how the internal components are positioned in the housing.

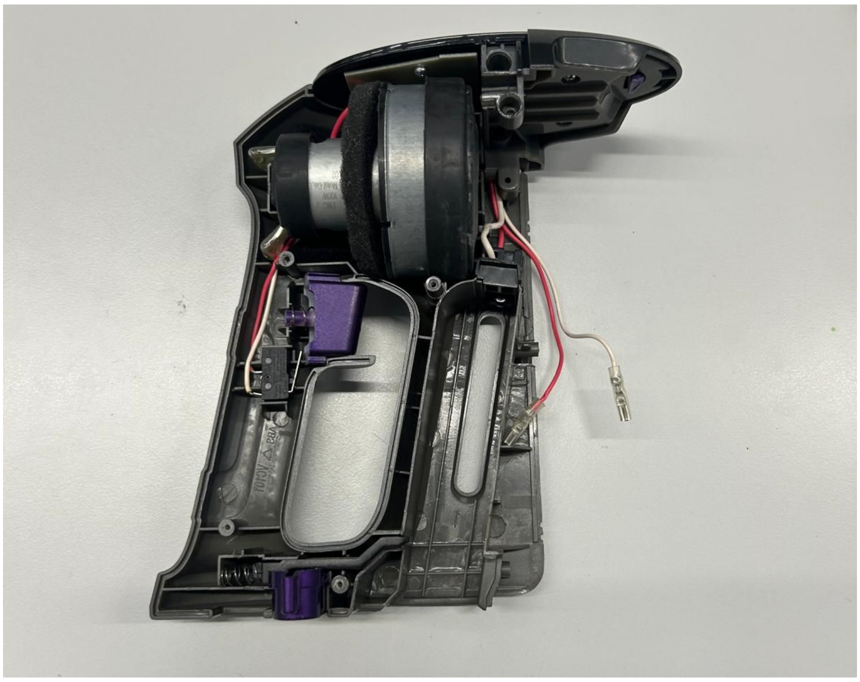


Figure 22. Split housing component integration

Turbotronic TT-CF7

This model uses an access point housing. Several access points were difficult to open due to the use of non-reversible snap-fit connections, some of which failed during disassembly. Once opened, internal components were relatively accessible. The head assembly of the brush module showed poor design for disassembly, with multiple obstructing plastic structures and a lack of clear access guidance, resulting in component damage during teardown. Figure 23 shows a hidden screw in the head assembly and easy to connect cables to the motor.

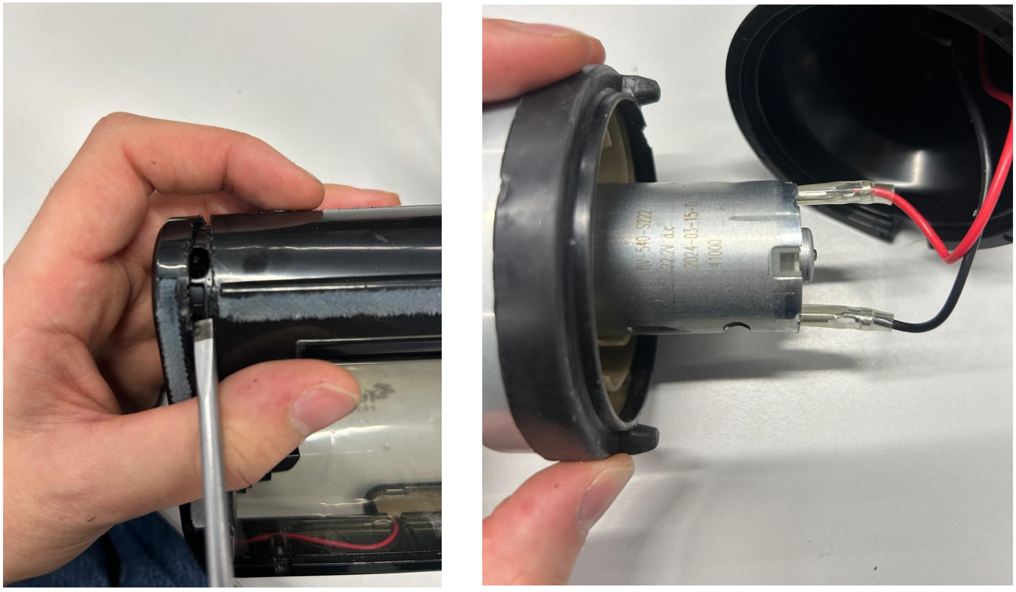


Figure 23. Hidden screw and easy to connect cable for the motor component

Turbotronic TT-CF4

The TT-CF4 had a split housing, which required full housing opening to access internal components. Screws were partially concealed by stickers, complicating disassembly. A combination of screws and snap-fits was used, with several snap-fits requiring force and breaking during disassembly. After opening, components were primarily secured using friction-based connections, enabling relatively easy removal. Figure 24 shows how stickers limit screw visibility and how components are positioned in the split housing.

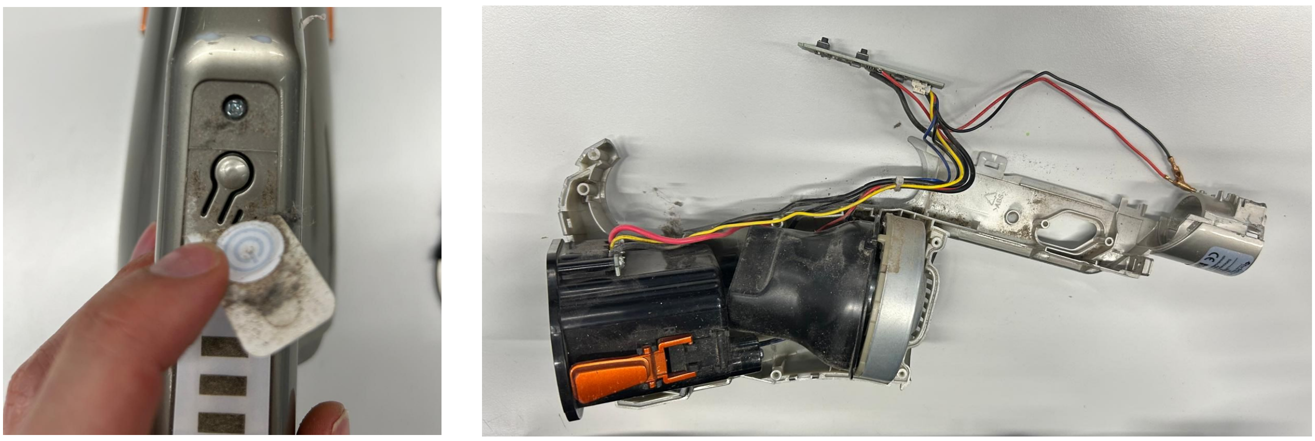


Figure 24. Sticker covers screw and split housing component integration

Severin S Special

This model uses access point housing and lacks a clear disassembly logic. A combination of screws and difficult-to-locate snap-fits increased disassembly complexity. Several snap-fit connections required force to open, leading to component damage. The absence of a clear disassembly sequence contributed to inefficiencies and errors during teardown. Figure 25 shows hard to access screws and snap-fit connections

Figure 25. Hard to access screws and snap-fits

Zedar S600

The Zedar S600 uses access points to reach internal components. Accessibility varied across components: key elements such as the motor were easily accessible via access covers, while other access points were obscured by stickers or relied on screws located in hard-to-reach positions, reducing overall ease of disassembly. Figure 26 shows the access point to the motor and deep hidden screws.

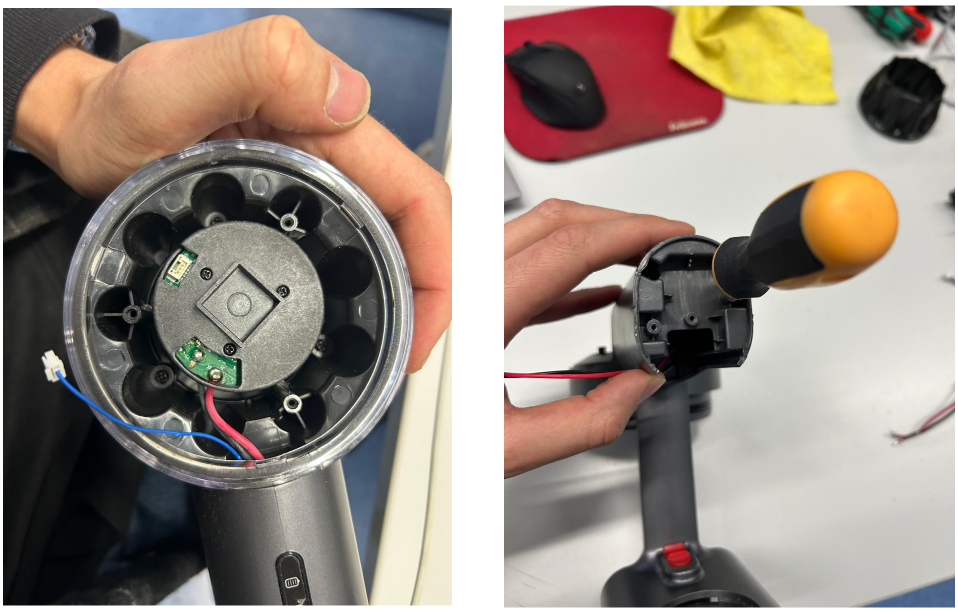


Figure 26. Access point to the motor and deep hidden screws.

AEG QX8 Animal x power

This model differs in architecture from the other 9 models, with the handheld unit integrated at the lower end of the product. It was the only model without an easily accessible battery assembly, limiting replacement and recovery potential. Figure 27 shows how the battery cells are integrated within the housing.

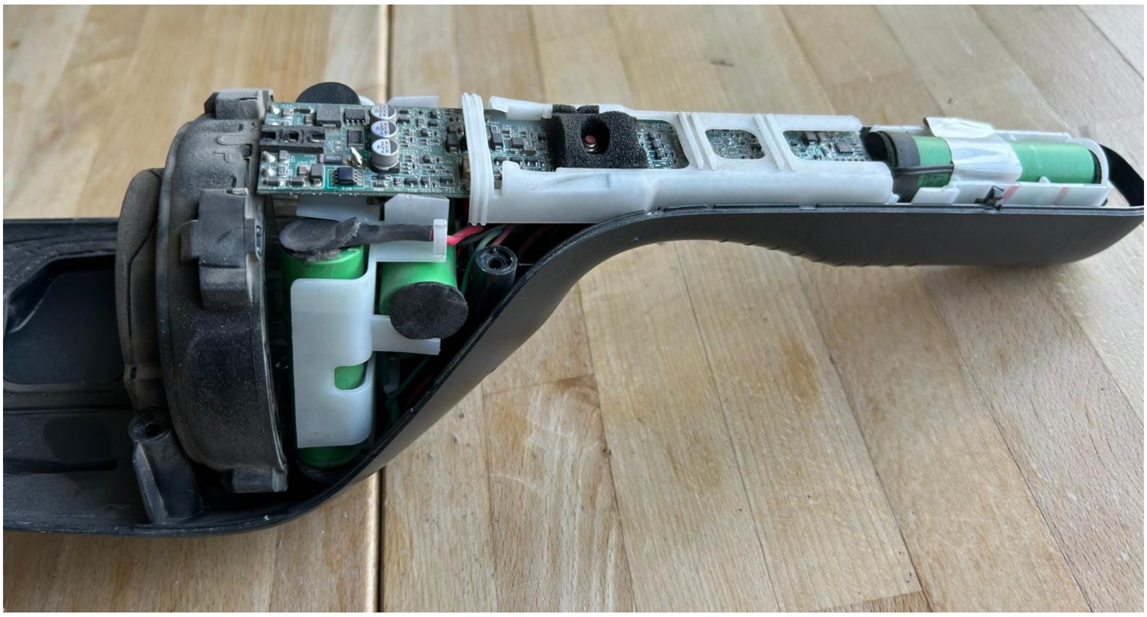


Figure 27. Battery integration within housing.

Sauber R20

The Sauber R20 uses an access point housing and demonstrates effective use of cable plug connections, improving component accessibility and reducing disassembly time. However, some snap-fit connections were difficult to access and failed during disassembly. Screws were partially hidden by stickers, increasing disassembly complexity. Figure 28 shows how the motor is connected with cable plugs and how screws are hidden behind stickers.

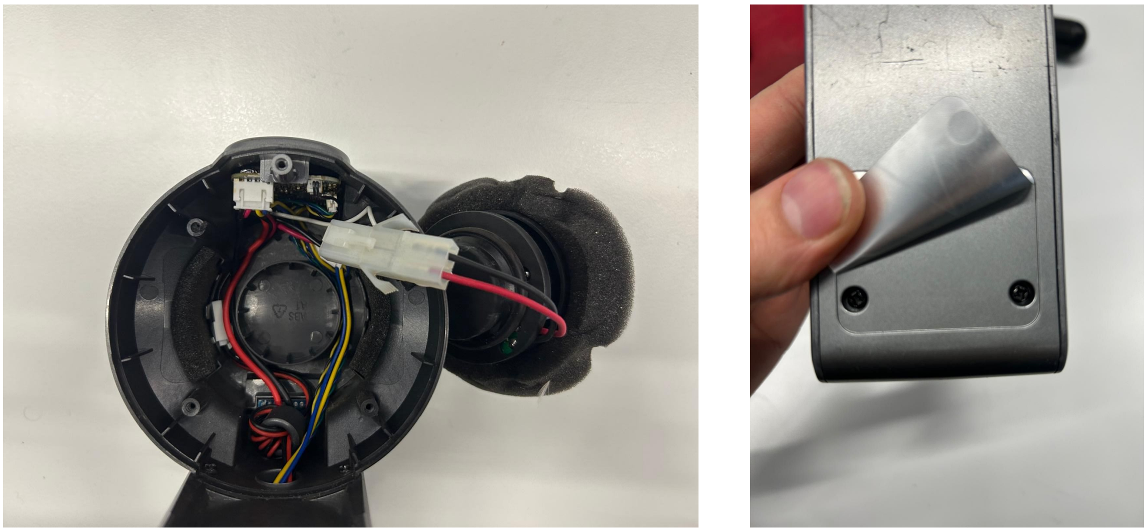


Figure 28. Cable plug usage and stickers that cover screws.

Hoover H-Free 500 Hydro plus

This model uses a split housing configuration. The housing is secured using both screws and snap-fit connections. While snap-fits were difficult to locate, they remained mostly intact during disassembly. Once opened, the architecture provided direct access to most internal components, see figure 29.

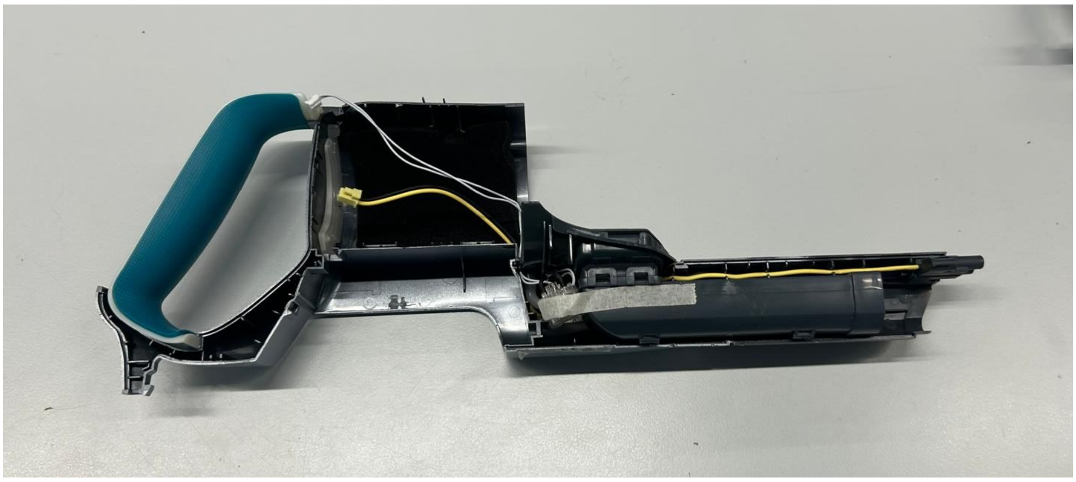


Figure 29. Split housing component access.

Rowenta X force flex 12.60

The Rowenta model uses multiple access points to reach internals, but these are not optimally integrated. Access to key components such as the motor required disassembly from multiple locations, reducing efficiency. Electrical components were soldered rather than connected via plugs, increasing the disassembly time. Figure 30 shows how soldering cables to components limit accessibility.

Figure 31. soldering cables to components limits accessibility

Dyson V11 Absolute

The Dyson V11 was the most difficult model to disassemble. Several subassemblies could not be accessed non-destructively due to hidden fasteners and non-reversible snap-fit connections. Screws were positioned deep within the assembly, requiring longer screwdrivers for disassembly. The motor was difficult to access due to connections that had to be squeezed through a small opening. Similarly, the battery assembly could not be opened without damage, limiting accessibility and recovery potential. Figure 32 shows deeply integrated screws and how the motor is disassembled from the housing.

Figure 32. Deeply integrated screws and motor integration.

Across the analysed products, reversible connections (e.g., screws, cable plugs, friction fit) and clearly defined access points consistently improved ease of disassembly, while hidden snap-fit connections and deeply embedded components limited accessibility.

Knolled pictures of disassembled vacuum cleaners were created to give an overview of components present in a vacuum cleaner and indicate roughly where they are located within the product. Two examples of knolled pictures are shown in figure 33 and 34, full documentation for all ten models is provided in appendix B.

The disassembly maps provided a structure for visualizing the product architecture and insights into the depth at which the CRM components are located within the assembly. Furthermore, they showcase the sequence of removal steps, the associated connection types and if the product can be disassembled non-destructively. The tube and container sub assemblies were not integrated in the disassembly maps as these do not contain CRMs Figure 35 and 36 show two examples of disassembly maps of different vacuum cleaner models, full documentation of all ten disassembly maps is provided in appendix C.

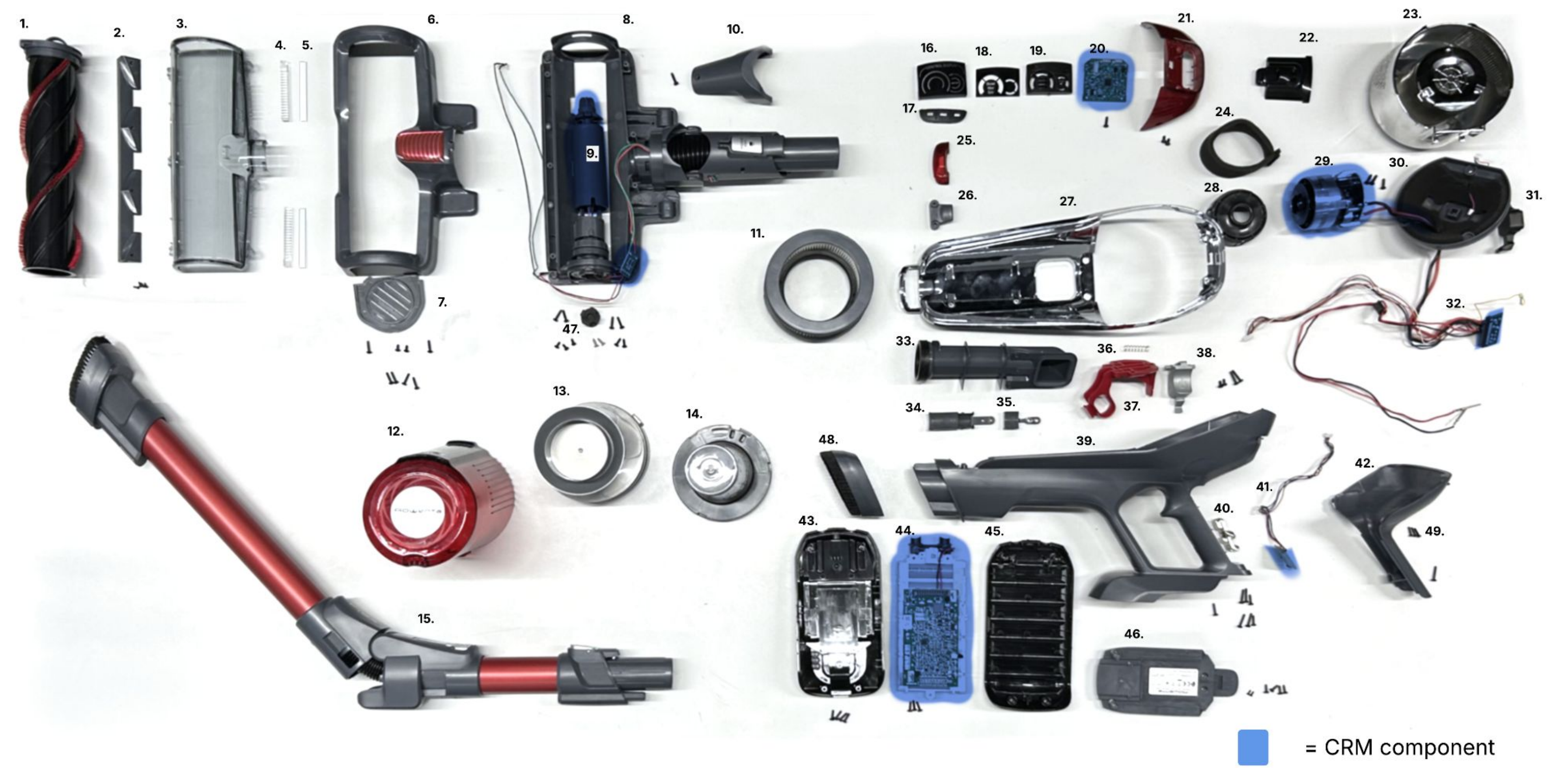


Figure 33. Knolled picture of Rowenta X force flex 12.60: 1. Brush; 2. Head real; 3. See through cover; 4. Light diffuser; 5. Light guide; 6. Top head cover; 7. End cap; 8. Bottom head cover assy; 9. Brush motor; 10. Tube connect cover; 11. Motorfilter; 12. Container; 13. Outer filter; 14. Inner filter; 15. Tube; 16. Control display; 17. Mode buttons; 18. Control sticker; 19. PCB cover; 20. PCB; 21. Top housing panel; 22. Container lock; 23. Motor housing; 24. Motor foam; 25. Front housing cover; 26. Container clip; 27. Chrome housing cover; 28. Motor cover; 29. Motor; 30. Motor back cover; 31. Rubber spacer; 32. Cable assy; 33. Dust guide; 34. Power cable connector; 35. Power cable connector cover; 36. Turbo trigger spring; 37. Turbo trigger; 38. Trigger; 39. Main housing; 40. Contact point?; 41. Trigger button component; 42. Back housing panel; 43. Battery housing; 44. Battery + PCB; 45. Batter housing cover; 46. Bottom housing cover; 47. Rubber spacer brush motor; 48. Brush attachment; 49. Screw cover.

Figure 34. Knolled picture of Vytronix NIBC22 *1. Head cover; 2. Wheel; 3. Brush; 4. See through cover; 5. Head side panel; 6. Foam cover; 7. Brush motor; 8. Bottom head assembly; 9. Cable cover; 10. Bottom tube connector; 11. Inner tube; 12. Top tube connector; 13. Outer tube; 14. Battery connector; 15. Front housing cover; 16. Motor; 17. Foam motor cover; 18. PCB assembly; 19. Trigger; 20. Battery release button; 21. Side housing R; 22. Side housing L; 23. Top housing cover; 24. Container release panel; 25. Top container assembly; 26. Filter; 27. Filter cover assembly; 28. Container housing; 29. Top battery cover; 30. Battery assembly; 31. Bottom battery assembly.*

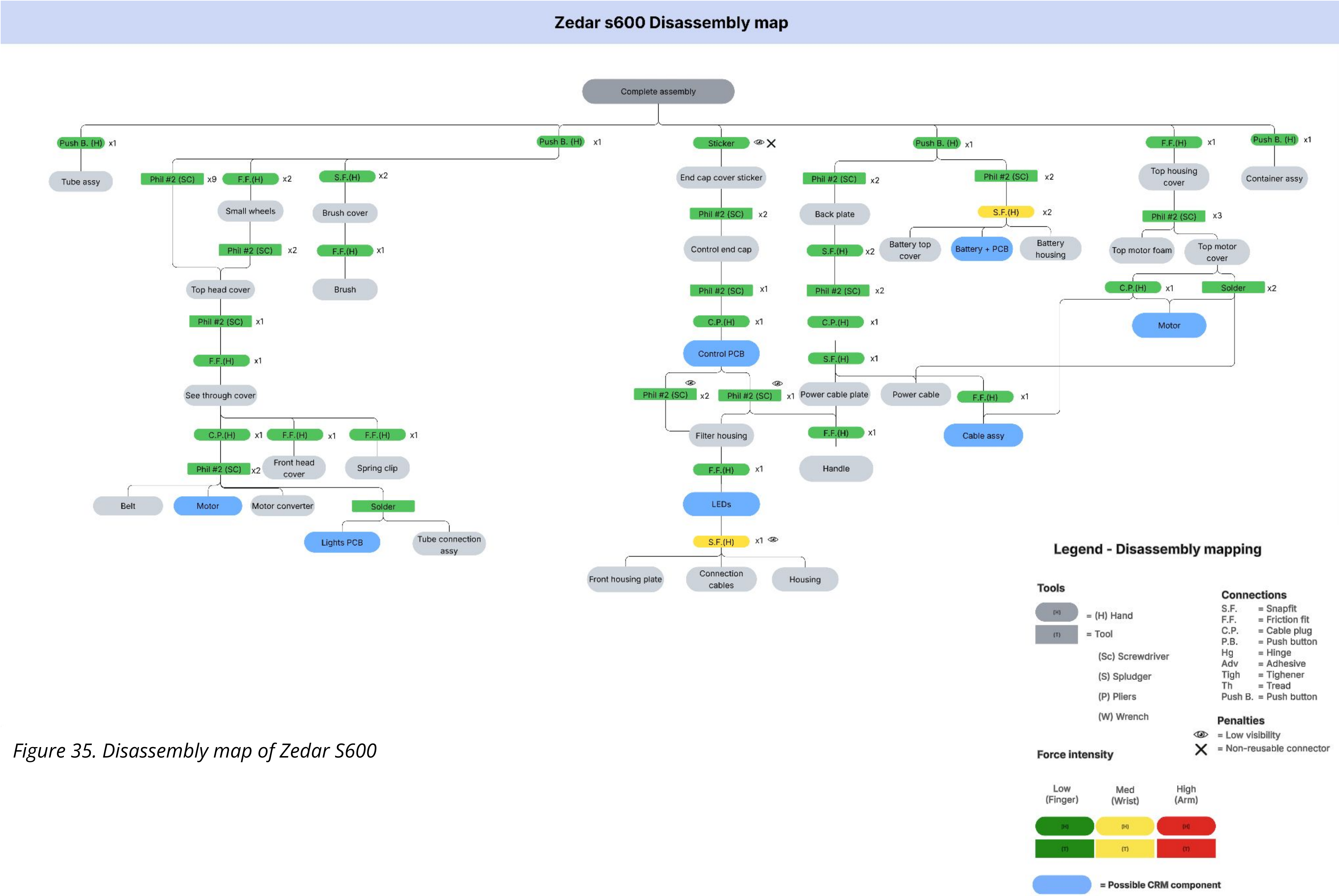


Figure 35. Disassembly map of Zedar S600

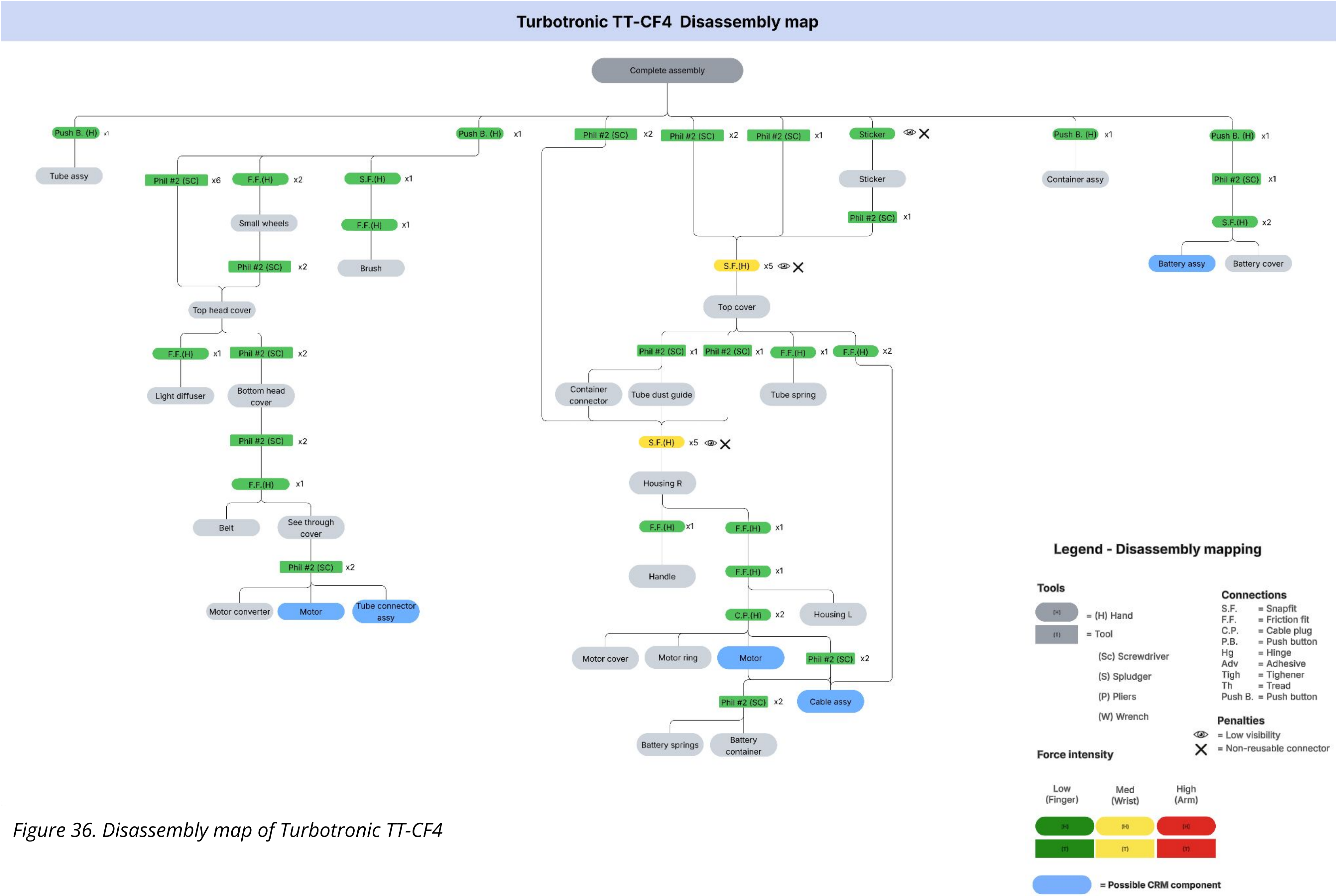


Figure 36. Disassembly map of Turbotronic TT-CF4

The disassembly maps showed that there is little communality within the product architectures. Only the head assemblies across the products showcase a similar approach to the disassembly: A top cover was fastened with screws and snapfits and upon removal access is granted to the internal components, like de brush motor and LED lights.

4.2.2 Bill of materials and CRM hotspot mapping

The CRM focussed bill of materials identified the components that might contain CRM and established their corresponding weight. Two examples of BoM are shown in table 9 and 10. Full documentation can be found in appendix D

Table 9. Bill of Materials of Zedar S600

Part numbe	Part name	Weight (g)	Material	Notes
1	Brush	98.2	Mixed	
2	See through cover	49.0	PC	
3	Top head cover	71.1	ABS	
4	front head cover	10.3	ABS	
5	Lights PCB	4.7	Electronics	CRM
6	Brush motor	164.5	Mixed	CRM
7	Belt	1.3	Rubber	
8	Motor converter	35.2	Mixed	
9	Tube connector assy	125.6	Mixed	
10	Bottom head cover	180.8	ABS	
11	Brush clip	4.4	ABS	
12	Spring clip	1.5	ABS	
13	See through motor cover	55.1	PC	
14	Plastic motor cover	32.6	ABS	
15	Filter housing	83.4	ABS	
16	Outer filter	44.8	Mixed	
17	Filter	36.6	Mixed	
18	Tube	277.5	Mixed	
19	Container	223.1	PC	
20	Top motor foam	0.1	Polyurethane	
21	Top motor cover	18.8	ABS	
22	Top housing cover	26.9	ABS	
23	Motor	153.7	Mixed	CRM
24	Motor rubber	15.3	Rubber	
25	Motor PCB cover	9.7	ABS	
26	Rubber support	5.9	Rubber	
27	Front housing plate	4.3	ABS	
28	connector cables	3.2	Electronics	
29	Housing	94.9	ABS	
30	LEDs	6.6	Electronics	CRM
31	Control PCB	3.5	Mixed	CRM
32	Control end cap	6.4	ABS	
33	End cap cover sticker	0.8	PC	
34	Handle	50.6	ABS	
35	Back plate	1.6	ABS	
36	Cable assy	4.6	Electronics	
37	Power cable	15.6	Electronics	CRM
38	Power cable plate	2.6	ABS	
39	Battery top cover	25.4	ABS	
40	Battery + PCB	305.3	Electronics	CRM
41	Battery housing	42.1	ABS	

Table 10. Bill of Materials of Sauber R20

Part number	Part name	Weight (g)	Material	CRM
1	Brush	36.4	Mixed	
2	See through cover	33.5	PC	
3	Top head cover	107.1	ABS	
4	Brush motor	105.6	Mixed	CRM
5	Motor converter	18.2	ABS	
6	Bottom head assy	93.5	ABS	
7	Wheels	1.9	Mixed	
8	Tube connector assy	108.8	Mixed	CRM
9	Cable cover	4.1	ABS	
10	Container	147.6	PC	
11	Filter	115.2	ABS	
12	Filter 2	0.7	Mixed	
13	Filter cover	27.5	ABs	
14	Tube	394.1	Mixed	
15	Motor cover	38.2	ABS	
16	Motor foam	1.5	PU	
17	Motor PCB cover	4.8	ABS	
18	Rubber support	13.1	Rubber	
19	Motor	166.5	Mixed	CRM
20	Motor rubber	31.4	Rubber	
21	Foam	0.1	PU	
22	PCB	22.1	Electronics	CRM
23	Motor housing	77.9	ABS	
24	Cable assy	1.9	Electronics	
25	Cable	3.5	Electronics	
26	Top housing	78.1	ABS	
27	Cable ring	5.5	High-carbon steel	
28	Bottom housing assy	126.4	ABS	
29	Charger cable	5.6	Electronics	
30	Buttom cover	33.1	ABS	
31	Trigger cable	1.7	Electronics	
32	Battery housing	53.7	ABS	
33	Battery housing cover	32.1	ABS	
34	Battery + PCB	215.6	Electronics	CRM
35	Trigger	3.8	ABs	
36	Spring	2.1	High-carbon steel	
37	Trigger pcb	1.5	Electronics	CRM
38	Trigger cover	10.8	ABS	

Based on insights from the washing machine case study, the CRM hotspotting method was refined to improve consistency and comparability across multiple products. An addition was the inclusion of component CMR mass relevance, which estimates the proportion of CRM within a component. This enables prioritisation of components where CRMs are present in substantial quantities, rather than in trace amounts with limited recovery potential.c

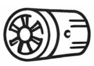
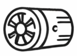
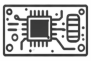
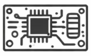
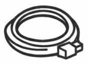
To further improve clarity, contextual component information such as accessibility, connection types, price, and lifespan was removed from the scoring criteria. This resulted in a more focused and consistent hotspot assessment across the ten vacuum cleaner models.

The refined CRM hotspotting method generates a hierarchy of components based on material criticality (derived from Economic Importance (EI) and Supply Risk (SR)) in combination with CRM mass relevance, as described in Section 3.4. Components are categorised into low, medium, and high hotspot scores, enabling prioritisation for CRM efficiency interventions.

To illustrate the scoring approach, the drive motor component is used as an example. Drive motors can contain materials such as neodymium, boron, copper and trace amounts of dysprosium and praseodymium. These materials are associated with high EI and SR values, resulting in a high material criticality classification. In addition, the CRM mass relevance of the drive motor is high (>1%), as NdFeB magnets typically contain 29–32% neodymium (Zhang et al., 2020). The combination of high material criticality and high mass relevance results in a high CRM hotspot score. The material-level EI and SR values, together with the assumptions used to determine CRM mass relevance and component scoring, are provided in Appendix E.

The CRM hotspot map identified the drive motor, brush motor and battery cells as the primary components to focus on for CRM efficiency guidelines. The results of the CRM Hotspotting can be seen in table 11.

Table 11. CRM hotspot map for cordless stick vacuum cleaners

Icon	Component	CRM content + (SRM)	Component CRM mass	Change of CRM in component	CRM hotspot
	Drive motor	Neodymium, Boron, Copper, (Dysprosium), (Praseodymium)	>1%	High	High
	Brush motor	Neodymium, Boron, Copper, (Dysprosium), (Praseodymium)	>1%	Medium	High
	Battery cells	Lithium, Cobalt, Natural graphite, Copper	>1%	High	High
	Battery PCBA	Palladium, (Tantalum), Nickel, Copper	0,01% - 1%	High	Low
	PCBA	Palladium, (Tantalum), Nickel, Copper	0,01% - 1%	High	Low
	Cables	Copper	-	Low	Low
	LEd lights	Gallium, Indium	< 0,01%	Medium	Low

By comparing the CRM components across the ten vacuum cleaner models a generalised visual overview was created to support the CRM hotspot table by showing where and what CRM components are located within cordless stick vacuum cleaners, see figure 37.

CRM components in cordless vacuum cleaners

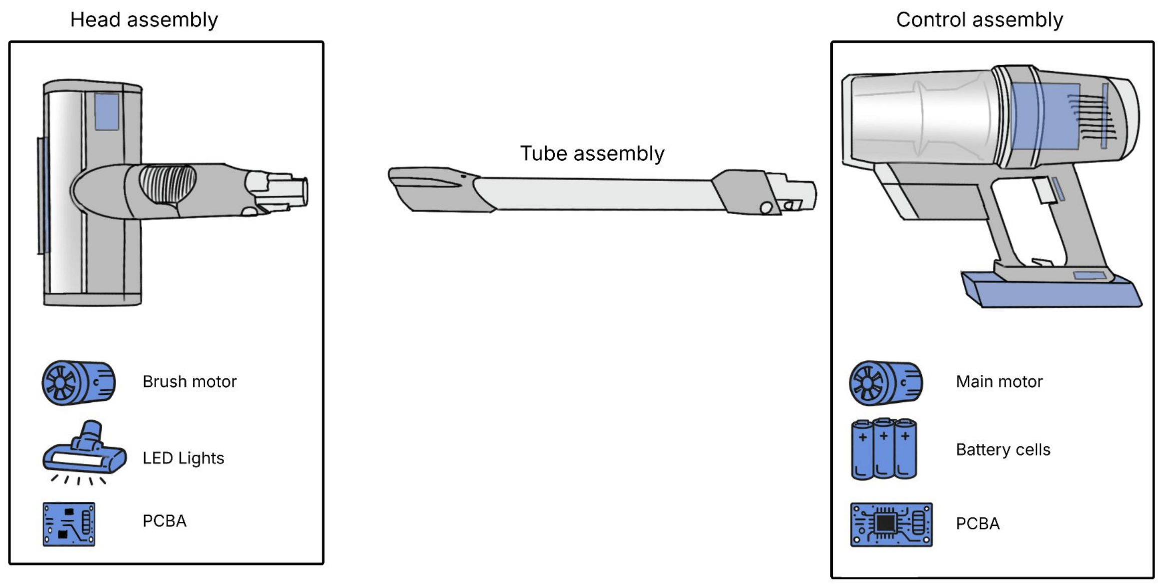


Figure 37. Visual overview of CRM content in cordless vacuum cleaners.

4.2.3 CRM component analysis

The component analysis showed how the identified CRM components are integrated into the architecture of the ten vacuum cleaners. The analysis focuses on barriers to facilitate ease of disassembly, best practices and points of improvement. The full analysis of CRM components can be found in appendix F.

The analysis illustrated the differences across models; no two models utilized the same motor or battery configuration. Key findings include:

- Drive motors are frequently hidden deep within the assembly, requiring more disassembly steps for liberation.
- PCBAs are often distributed in small modules throughout the device rather than centralized.
- Several models (e.g., Dyson, AEG, Rowenta) have components embedded within an assembly that require destructive force to access internal brush motors.

The comparison highlighted specific design choices affecting the accessibility of critical materials:

- Cable plugs and friction fits facilitate easier component removal than soldered wires or snapfits and screws.
- Standardized screws are preferred over hard-to-identify snap-fits, which frequently break during disassembly.
- Click-in battery packs enable easy component replacement, while internal battery cells remain difficult to access.
- A lack of visual disassembly cues on the products increases the risk of damage during disassembly.

4.2.4 CRM efficiency guidelines

The following guidelines are based on the CRM component analysis and describe strategies to improve CRM efficiency in cordless stick vacuum cleaners. The guidelines focus on components identified as CRM hotspots.

Sketches are used to show how each strategy changes the product at component level. Simplified disassembly maps are included where relevant to show how each guideline affects accessibility and disassembly depth. These maps only include the steps needed to access specific CRM-containing components to keep them clear and easy to read. Estimated disassembly times were added to the guidelines to make the impact of each guideline more tangible.

In cases where showing full disassembly sequences would reduce readability, more abstract representations are used. For example, in the clumping guideline, an abstracted disassembly map is used to communicate the principle without showing all disassembly steps.

Substitution (figure 38)

Substitution involves replacing high-risk materials, such as Rare Earth Elements (REEs), containing CRM in BLDC motors, with lower-risk alternatives like ferrite magnets in DC motors.

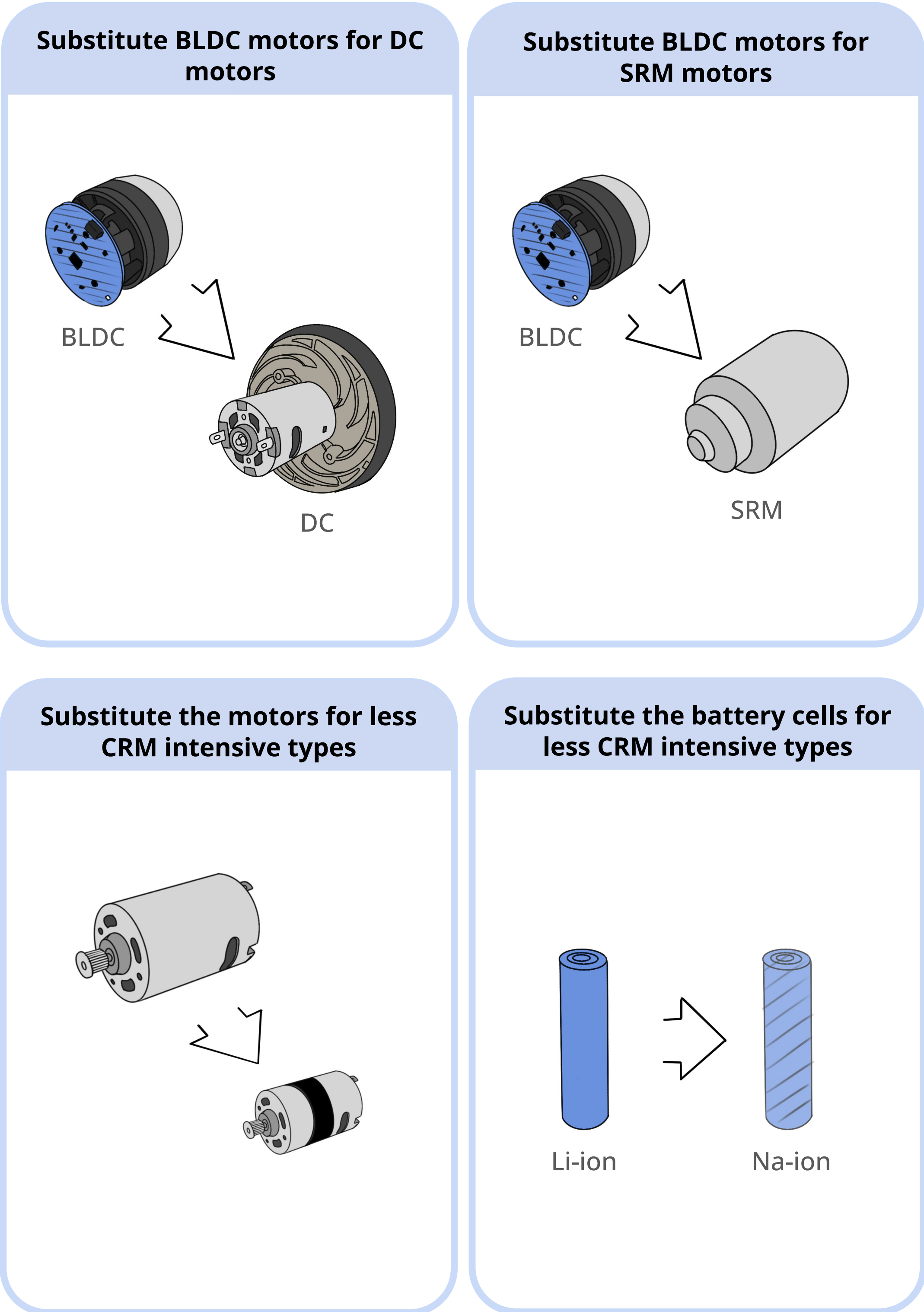


Figure 38. Substitution

Standardisation & Modularity (figure 39)

Standardising components such as motor types can help control the use of CRM-intensive designs and reduce variability in material flows. Standardisation also supports repairability by improving spare part availability and interchangeability.

Modular design further supports interchangeability, allowing for components to be switched between products, reducing the need for virgin materials and extending the products lifetime. This approach is strengthened by the standardisation of fastener types and cable connectors, enabling non-destructive disassembly and improved recovery potential of CRM components.

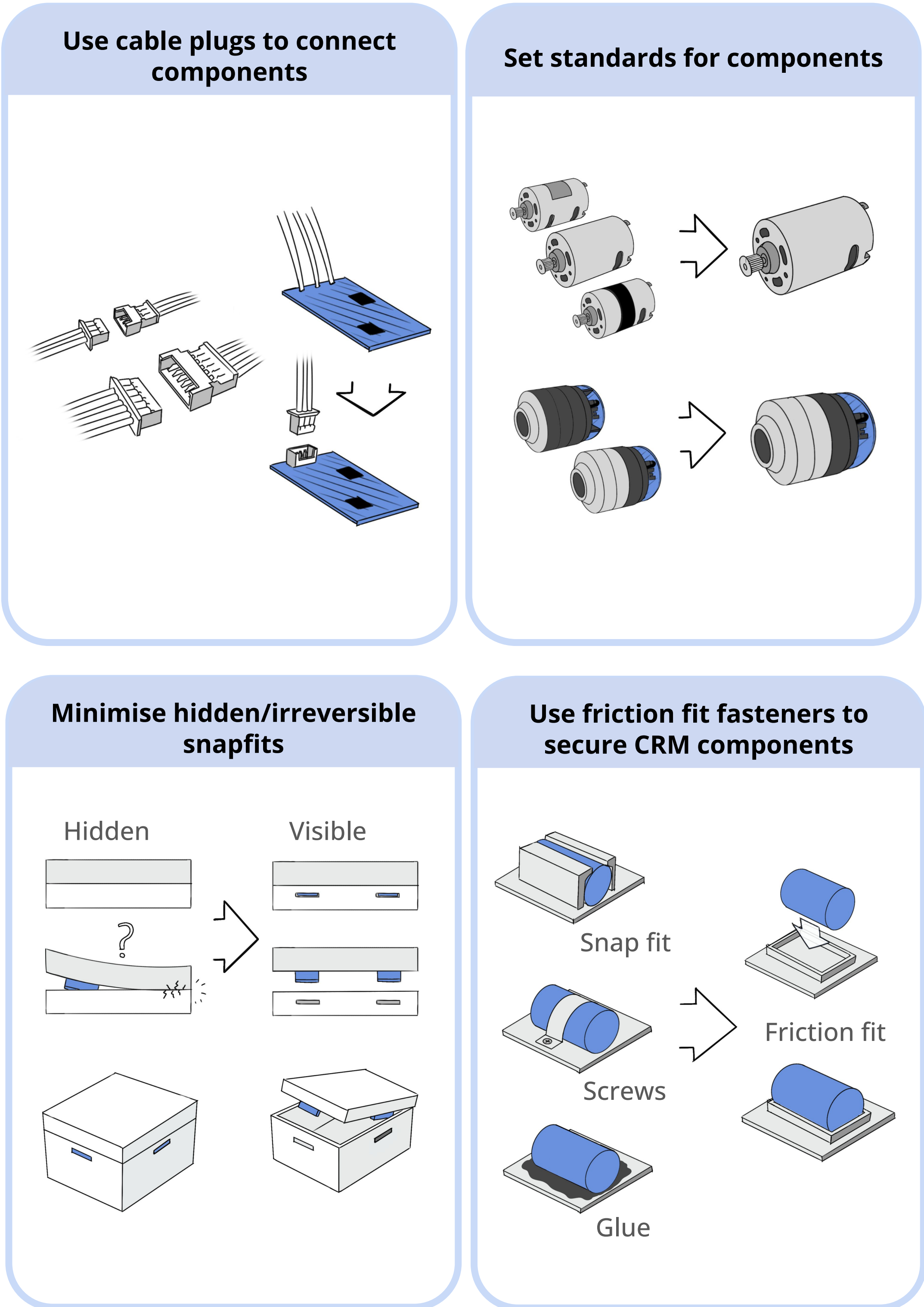


Figure 39. Standardisation & modularity

Pruning (figure 40)

Pruning aims to minimize the quantity of CRM components to the absolute functional necessity to limit the total CRM content within the product.

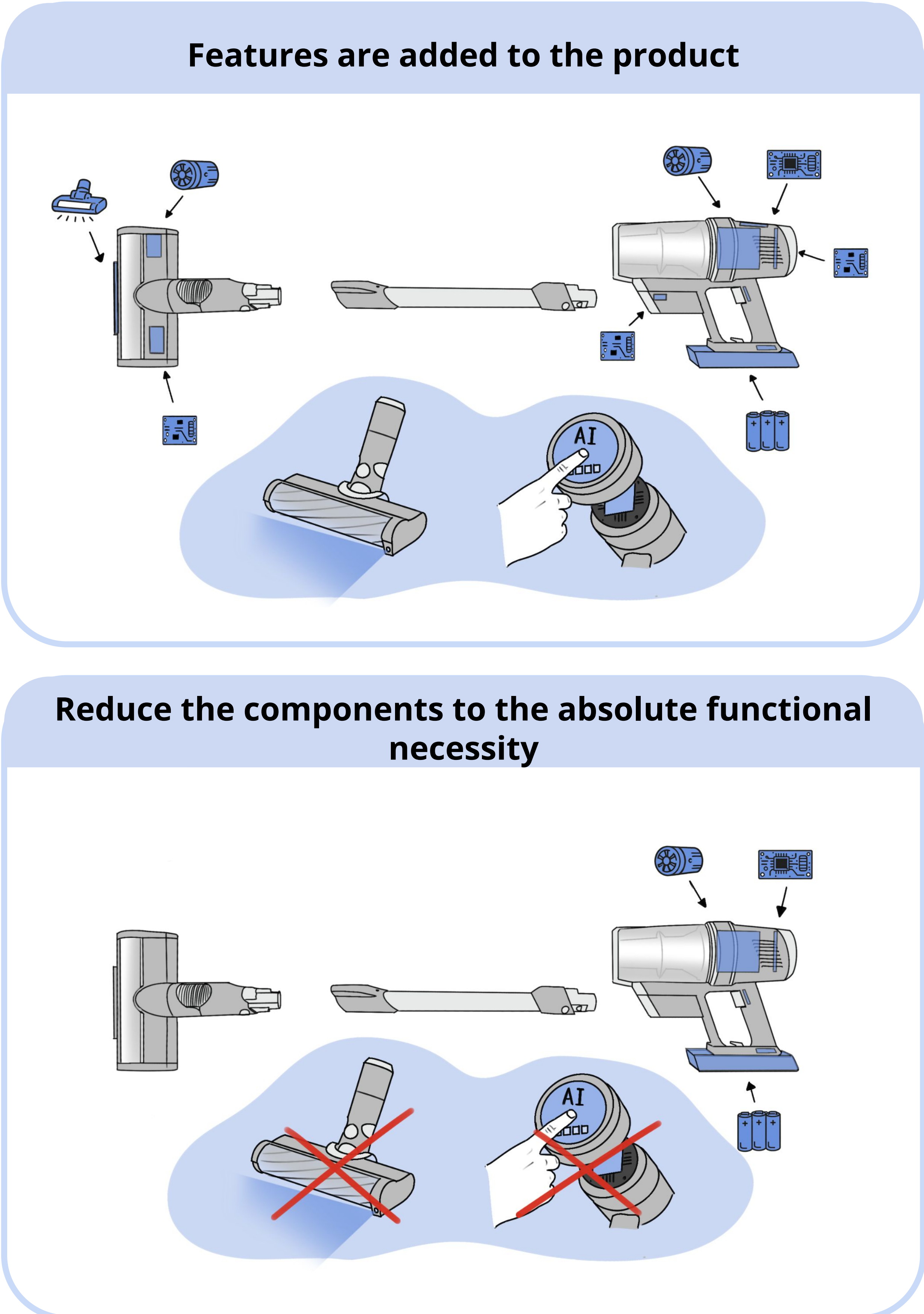


Figure 40. Pruning

Accessibility - Surfacing (figure 41-43)

Surfacing CRM components helps to reduce disassembly depth in order to facilitate easier component accessibility. Easier access to components improves repair and recovery and contributes to an extended product lifetime expectancy. Three examples are shown for improving component accessibility: The main motor, Battery cells and PCBA.

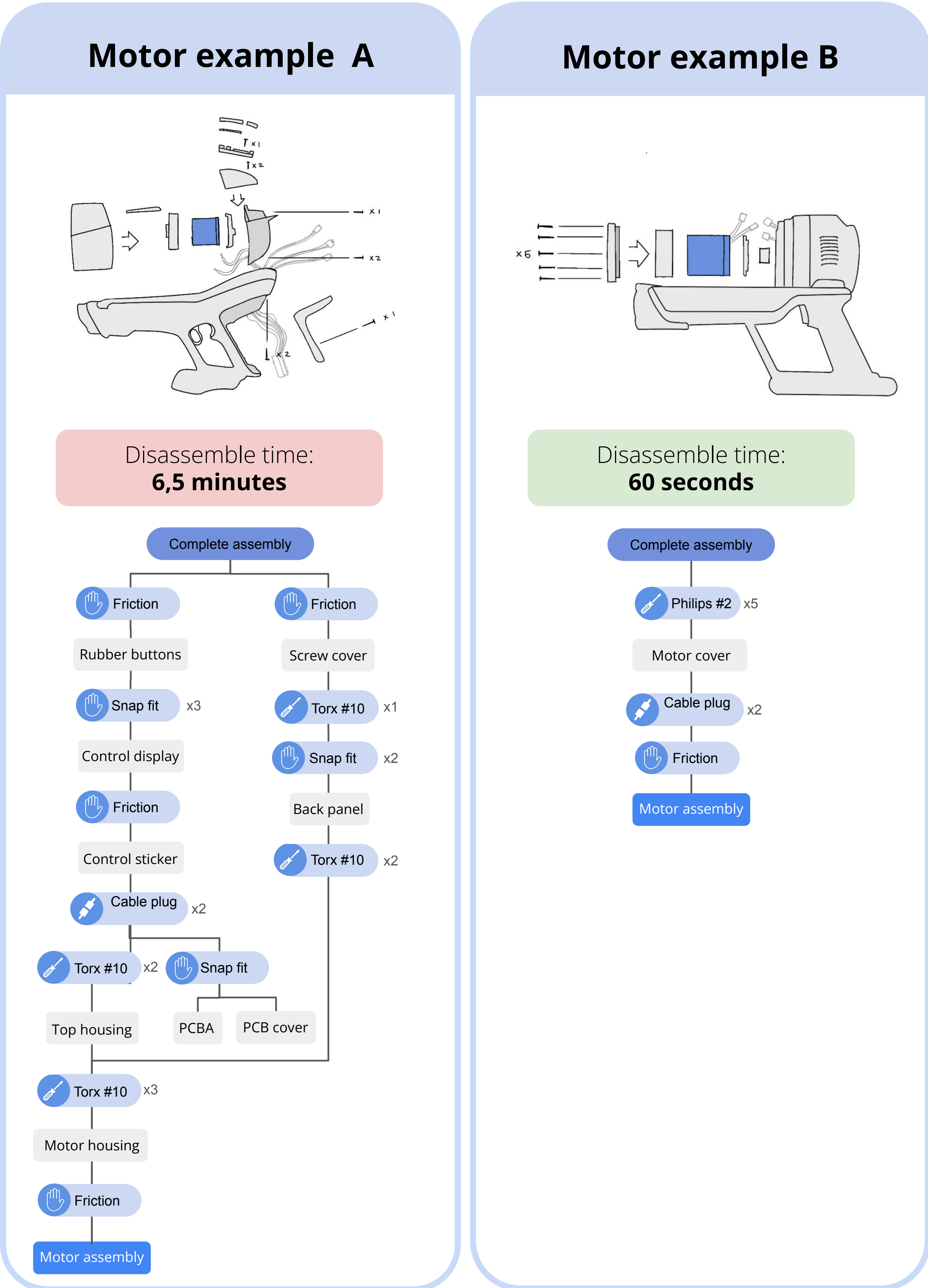


Figure 41. Surfacing the motor assembly.

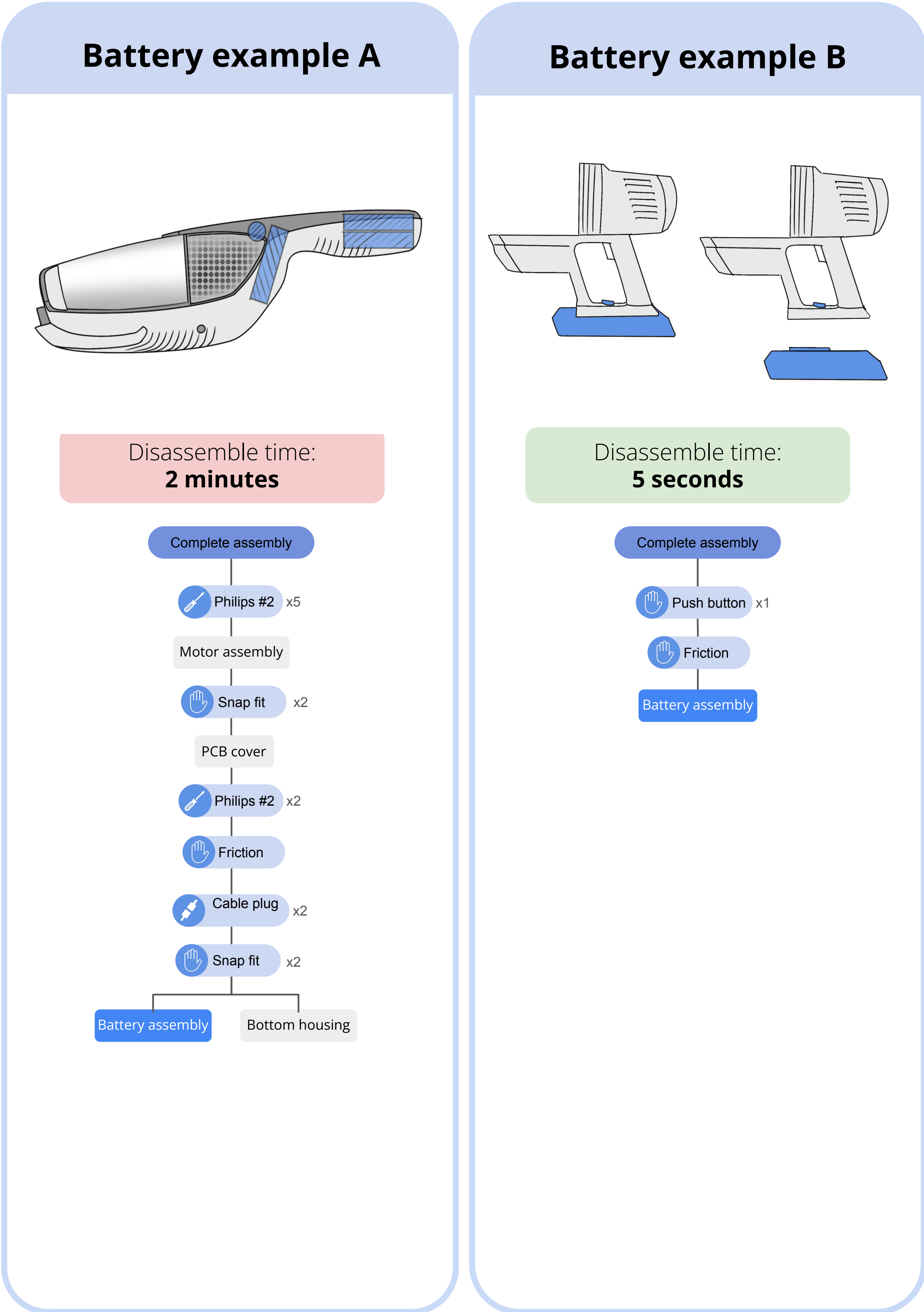


Figure 42. Surfacing Battery cells

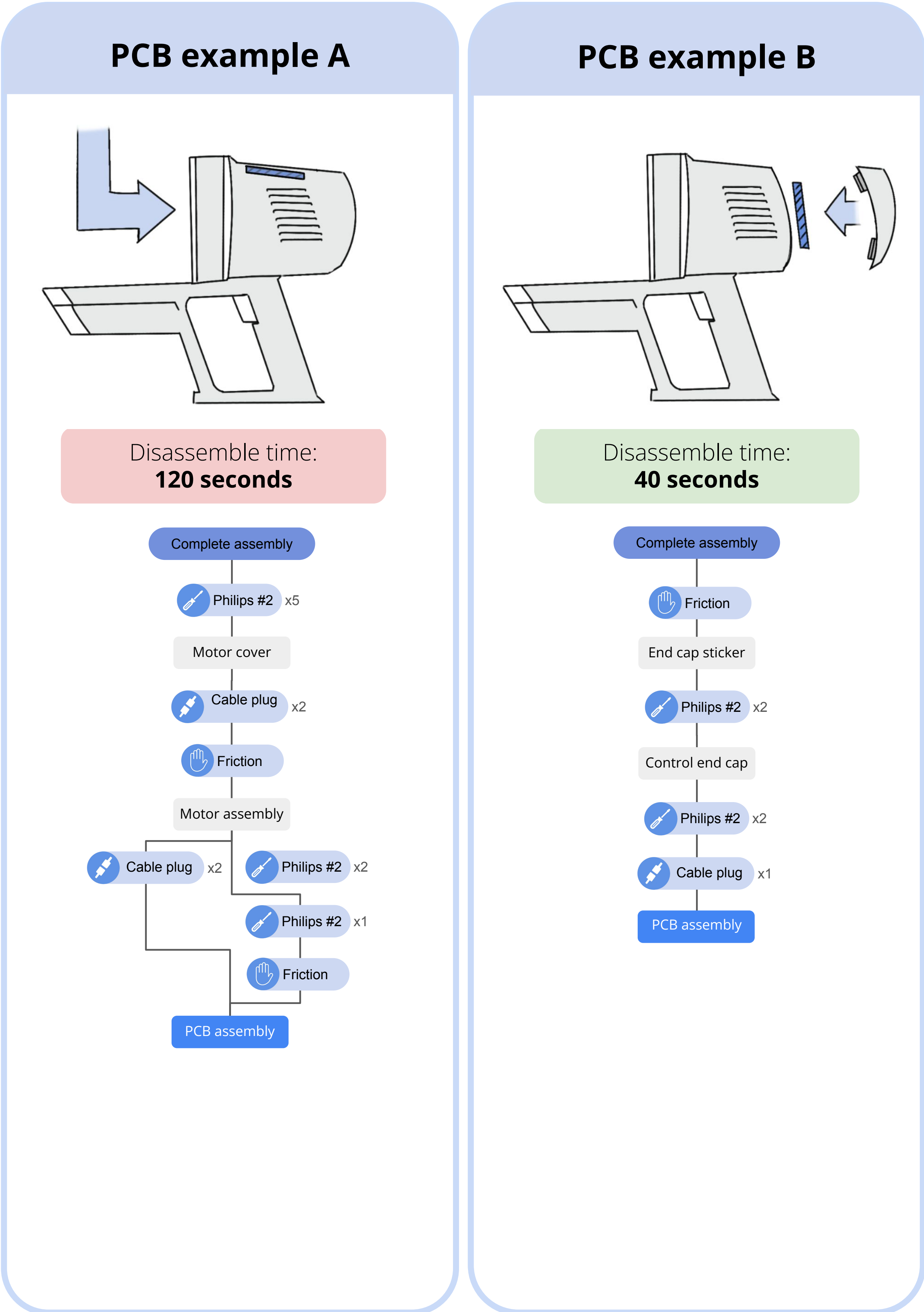


Figure 43. Surfacing the PCBA.

Accessibility - Clumping (figure 44)
Clumping involves grouping CRM components together to facilitate more efficient harvesting of components during disassembly.

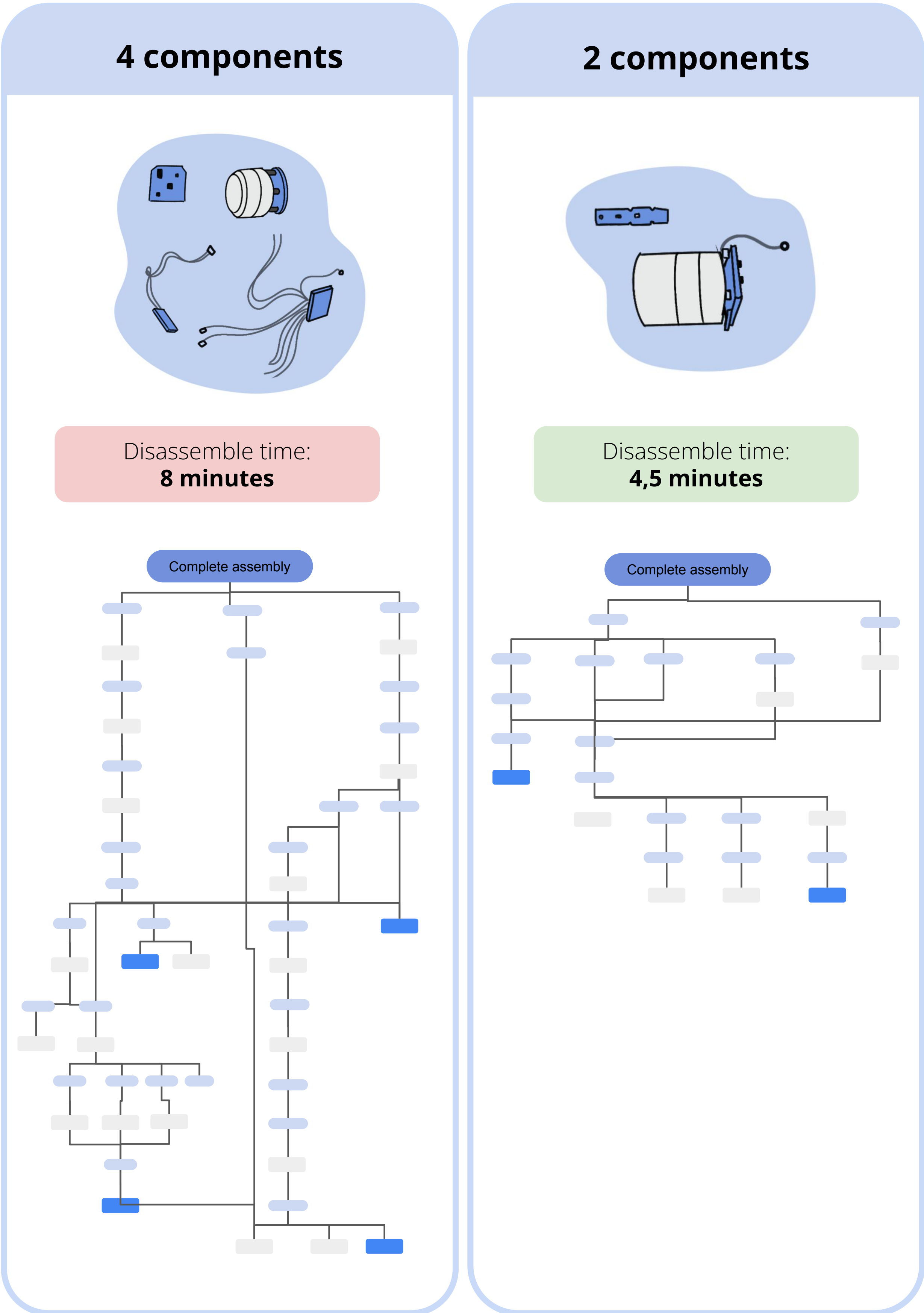


Figure 44. Clumping of CRM components.

Accessibility - Limit fastener usage (figure 45)
Limiting the usage of fasteners like screws allows for faster CRM component accessibility. reducing time needed for disassembly.

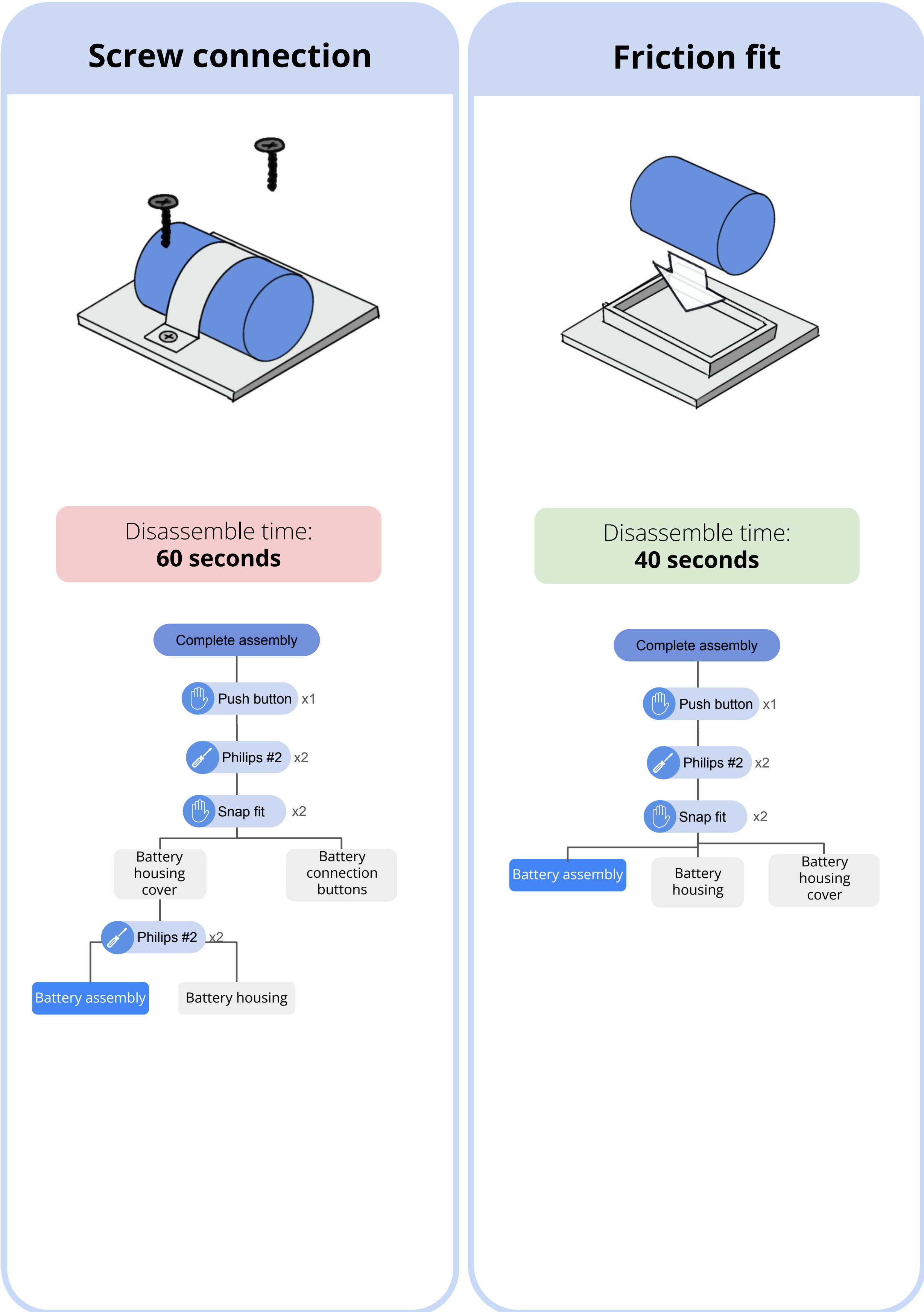


Figure 45. Limiting fasteners to reduce disassembly time.

Accessibility - Use cable plugs (figure 46)
By using cable plugs to connect PCB components to cable assemblies instead of solder, the disassembly time can be significantly shortened, resulting in better component access.

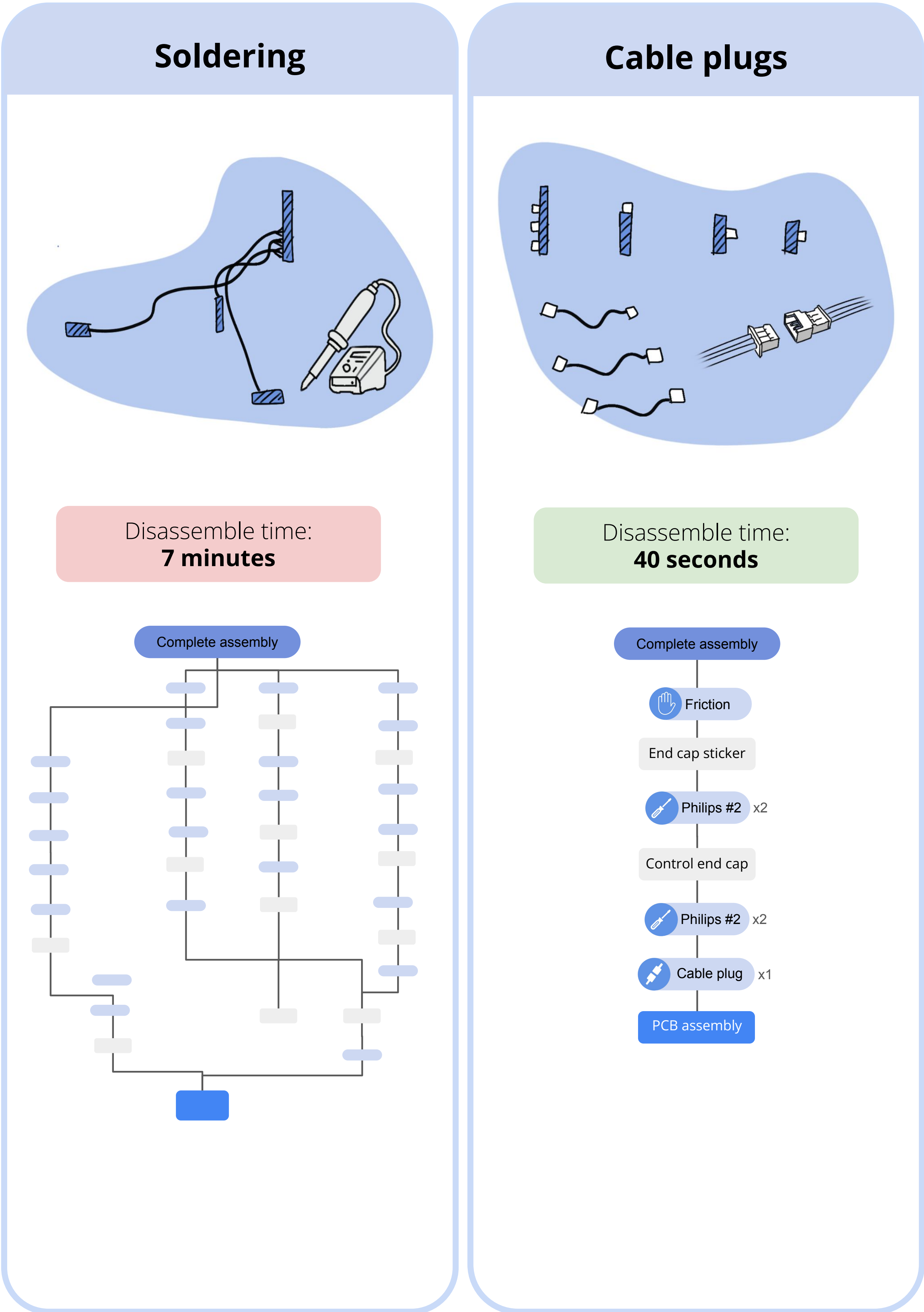


Figure 46. Cable plugs to improve accessibility.

Accessibility - Mitigate embedded components (figure 47)
In some cases CRM components were embedded within subassemblies that could not be disassembled non-destructively. These types of subassemblies need to be mitigated when designing products with CRM components in order to facilitate harvesting of components.

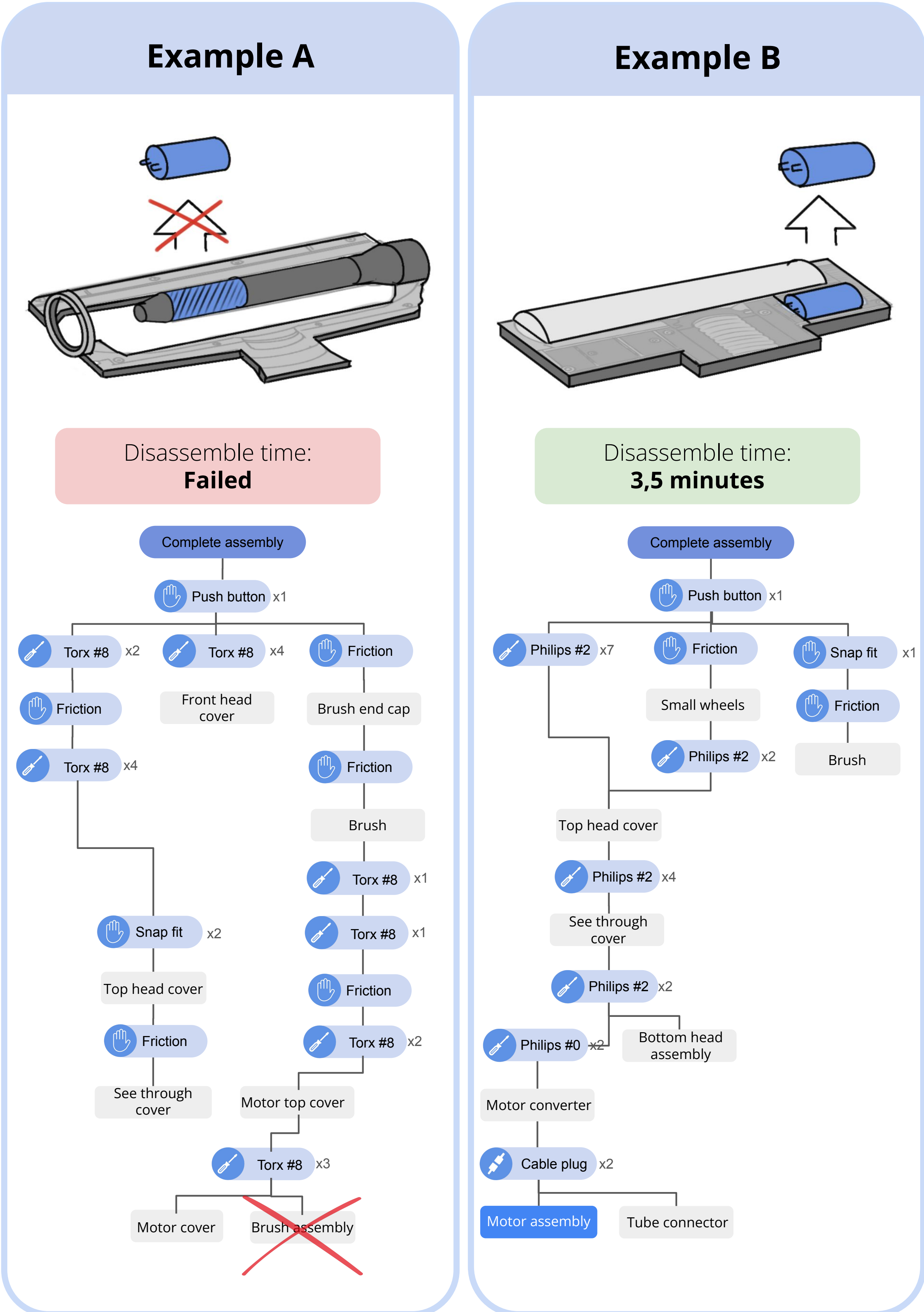


Figure 47. Mitigate embedding CRM components.

Improve Documentation (figure 48)

Improving product documentation through repair guides and Digital Product Passports (DPP) is essential for assessing CRM content in products and providing disassembly instructions that mitigate component breakage.

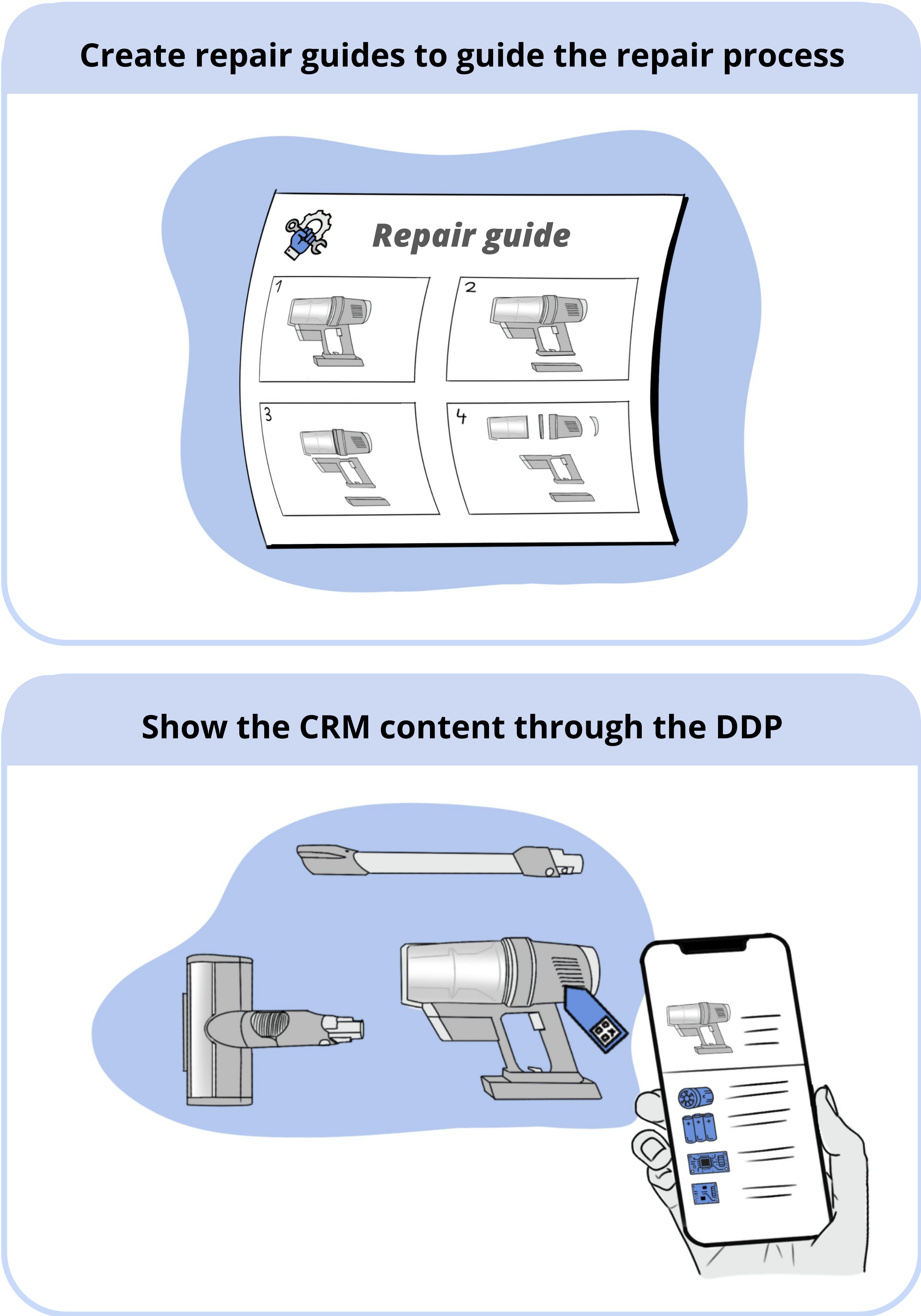


Figure 48. Improve documentation for CRM efficiency

These guidelines prioritize the CRM hotspotted components like the motors and battery cells, ensuring that design interventions are focused where they yield the maximum impact on resource efficiency.The 9R framework provided a structured hierarchy to the guidelines, prioritising higher value circular strategies as can seen in table 12.

Table 12. CRM guidelines aligned with R strategies.

R strategy	CRM efficiency guidelines	Principle
R2 Reduce	Substitution, Standardisation Pruning	Limit unnecessary CRM use in the product.
R3-R7 Reuse, Repair, Refurbish, Remanufacture and Repurpose	Standardisation Modularity Surfacing Clumping Limit fastener usage Mitigate embedded components use cable plugs	Extend the product's lifetime and support harvesting of CRM components for reuse in other products.
R8 Recycle	Standardisation Accessibility	Improve CRM recovery, but higher-order strategies that promote longer product lifetime are preferred for CRM efficiency

4.3 External validation

An external validation session was conducted with two experts from Invest-NL to assess the relevance and applicability of the developed CRM efficiency guidelines. The guidelines derived from the vacuum cleaner case study were used as the primary example during the session. The discussion evaluated the desirability, feasibility, and viability of the proposed CRM efficiency strategies. Expert feedback from the session was synthesised into the findings presented in the following sections.

4.3.1 Desirability

The experts indicated that the guidelines align with current European objectives to reduce dependency on critical raw materials and strengthen circular resource use. The focus on design interventions for CRM efficiency was considered relevant, as existing policy measures provide no guidance for product-level design interventions.

The visual presentation of the guidelines through sketches and simplified disassembly maps was considered clear and effective. According to the experts, these visuals help illustrate how design decisions influence component accessibility and recovery potential. The addition of disassembly time to reach certain components proved valuable to make guidelines even more tangible.

4.3.2 Feasibility

The proposed guidelines for CRM efficiency build on existing design-for-disassembly and repairability principles that are already applied in product development. As a result, the strategies were considered technically feasible.
However, the expert noted that the applicability of the guidelines depends on the design philosophy and value proposition of the product. Products designed for durability and repairability may integrate CRM efficiency strategies more easily than products that prioritise performance, compactness or low production cost. In these cases, product requirements like performance targets, compact product architecture or cost constraints may limit the implementation of CRM efficiency strategies.

During the discussion, the experts emphasised that extending product lifetime should generally be prioritised over CRM efficiency, as longer product lifetimes reduce overall material demand. Implementing CRM efficiency strategies therefore depend on the specific product use case.

4.3.3 Viability

The experts indicated that the largest potential impact on CRM efficiency may occur in products that are integrated into product-service systems, such as leasing or service-based ownership models. In these systems, incentives exist to extend product lifetimes, improve maintenance and enable controlled product return at end-of-life. The experts indicated that this alignment between product design and business model could facilitate the recovery of CRM components and reduce the demand for virgin materials.

4.3.4 Key insights from the external validation

In addition to evaluating the desirability, feasibility and viability of the guidelines, the experts also pointed out methodological improvements. In particular, the current CRM hotspotting approach relies on qualitative estimates of component material composition, which may limit its transferability to other product categories. The experts also suggested that quantitative tools, such as Material Flow Analysis (MFA) and Life Cycle Assessment (CLA), could support future evaluation of CRM efficiency strategies and support evaluation of trade-offs. The main insights from the external validation session are summarised in Table 13.

Table 13. Main insights from external validation session.

Validation aspect	Key insights
Desirability	Visual guidelines and simplified disassembly maps effectively communicate CRM efficiency strategies.
Feasibility	Applicability of CRM guidelines depends on a product's design philosophy and value proposition.
Viability	Product-service systems may provide the largest impact for CRM efficiency
Method improvement	The CRM hotspotting method relies on qualitative material estimates. Applying the method to other product categories may require improved component material transparency.
Method improvement	Tools such as Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) could support the evaluation of CRM efficiency strategies and help quantify trade-offs.

5. CRM efficiency guideline booklet

This chapter describes the booklet created to support the CRM efficiency guidelines. It translates the findings of this research into a format that is accessible and applicable for design practice. The booklet is intended for product designers who want to integrate CRM efficiency into their design process. It describes guidelines that illustrate how to implement CRM efficiency within a product's architecture, identifies the relevant trade-offs and additional tools that help evaluate these trade-offs and quantify CRM reduction.

5.1 Booklet structure

The booklet begins with a short introduction to CRMs, the intended user group, and the relevance of product design for CRM efficiency. It includes an overview of where CRMs are typically found in products, allowing designers to quickly assess whether CRM efficiency is relevant for their product. This is followed by a section explaining how the booklet is structured and how it should be used, clarifying that the guidelines are linked to trade-offs and supporting tools see figure 49

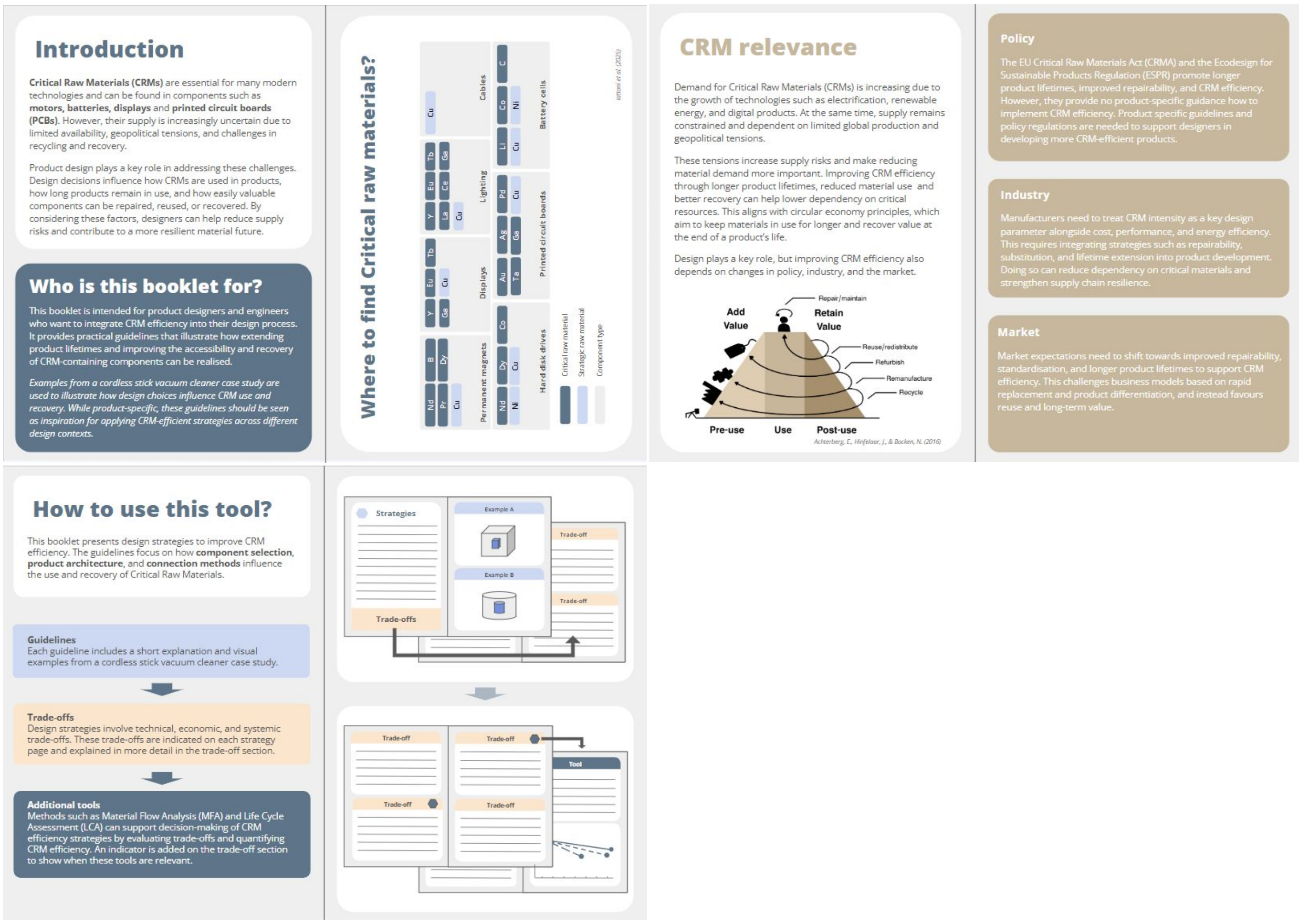


Figure 49. Introduction, CRM relevance and how to use this tool pages

The CRM hotspot mapping method is then introduced through the example from the cordless stick vacuum cleaner case study, showing how designers can identify and prioritise CRM-containing components for implementing CRM efficient strategies. The main part of the booklet consists of the CRM efficiency guidelines, presented as strategies with explanations in text and visual examples from the vacuum cleaner case study. Relevant trade-offs are indicated within this section and linked to the following chapter see figure 50.

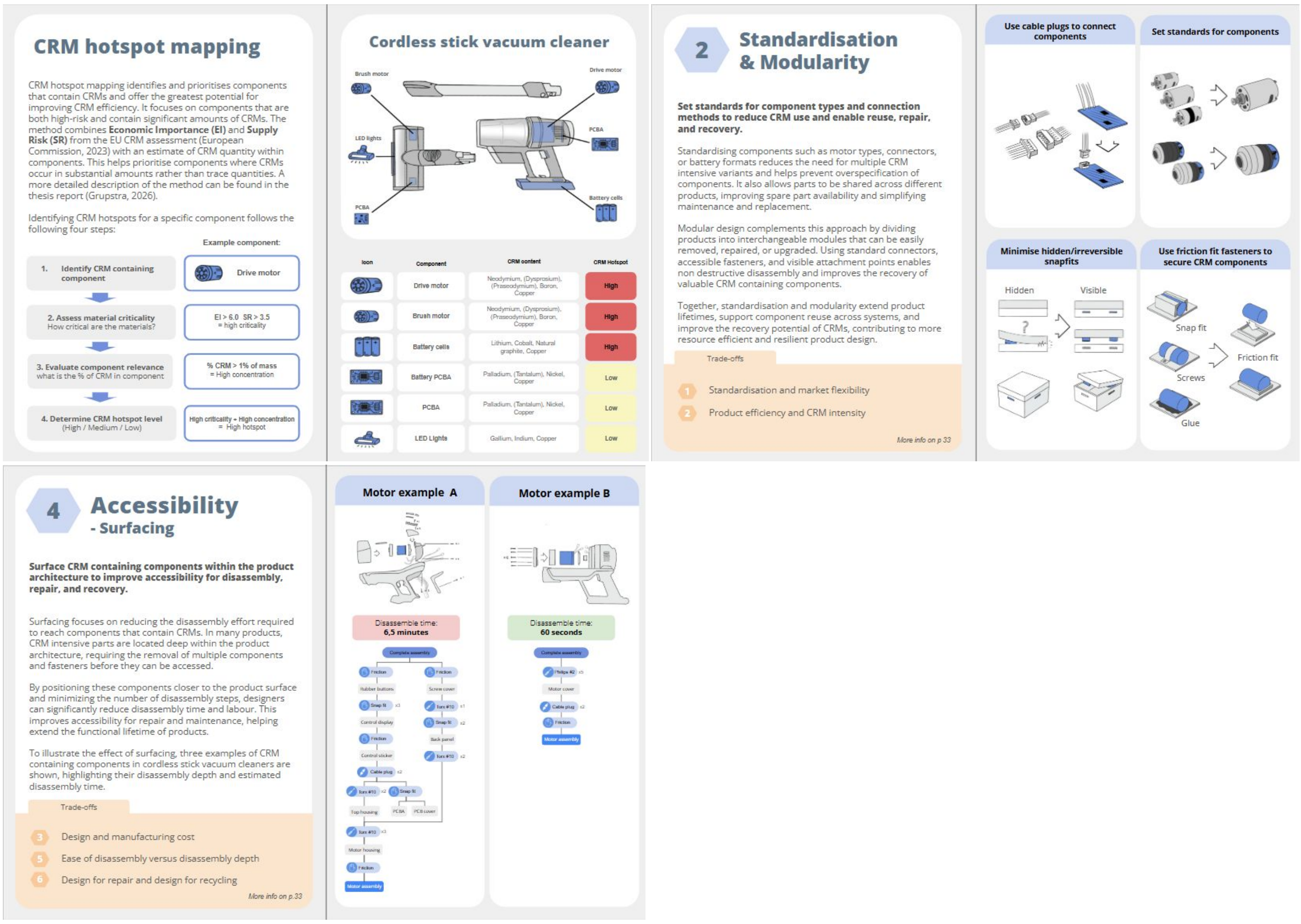


Figure 50. CRM hotspot and guideline example pages

The next chapter describes the trade-offs associated with applying the strategies, including their effects on product performance, cost, manufacturability, and component accessibility and recovery. A hexagonal icon is used to indicate when additional tools can support designers with the evaluation of these trade-offs and help quantify CRM reduction. These icons refer to the final chapter, where the additional tools, MFA and LCA, are presented by giving an example from Sprecher et al. (2026). The inclusion of these tools is based on insights from the external validation session. This section describes when these tools can be used and briefly explains how they can be applied, see figure 51.

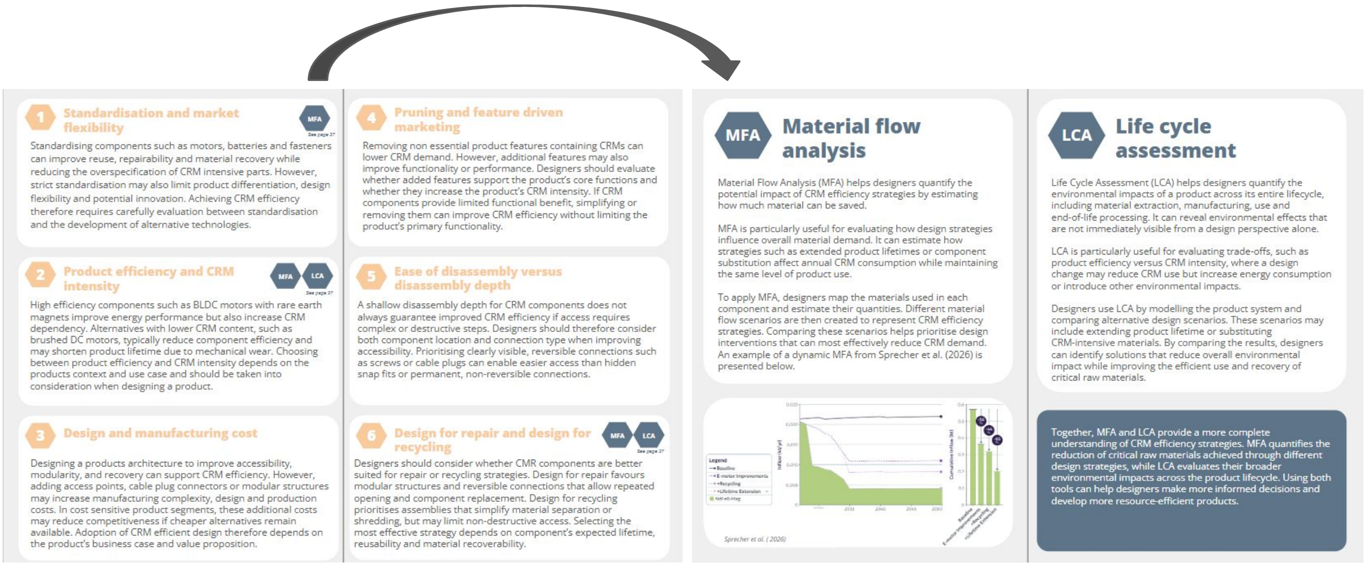


Figure 51. Trade-offs and additional tool pages.

5.2 Visual structure of the guideline section

The guideline section of the booklet uses a consistent layout to present each strategy. Each guideline includes a title, a short explanation, visual examples, and the associated trade-offs. The title indicates the strategy, while the explanation describes its principle and relevance for CRM efficiency. Visuals show how the strategy affects product architecture through comparisons between different design approaches. These highlight changes in component position, disassembly steps and connection types. Trade-offs are indicated within each guideline and linked to the trade-off section.

The visuals use simplified representations of product architecture and disassembly. They focus on CRM component accessibility and disassembly depth. Only the steps relevant to the strategy are shown, making the effect of design decisions on CRM efficiency easier to see.

Figure 52 shows the structure of a guideline page and the elements used to present each strategy.

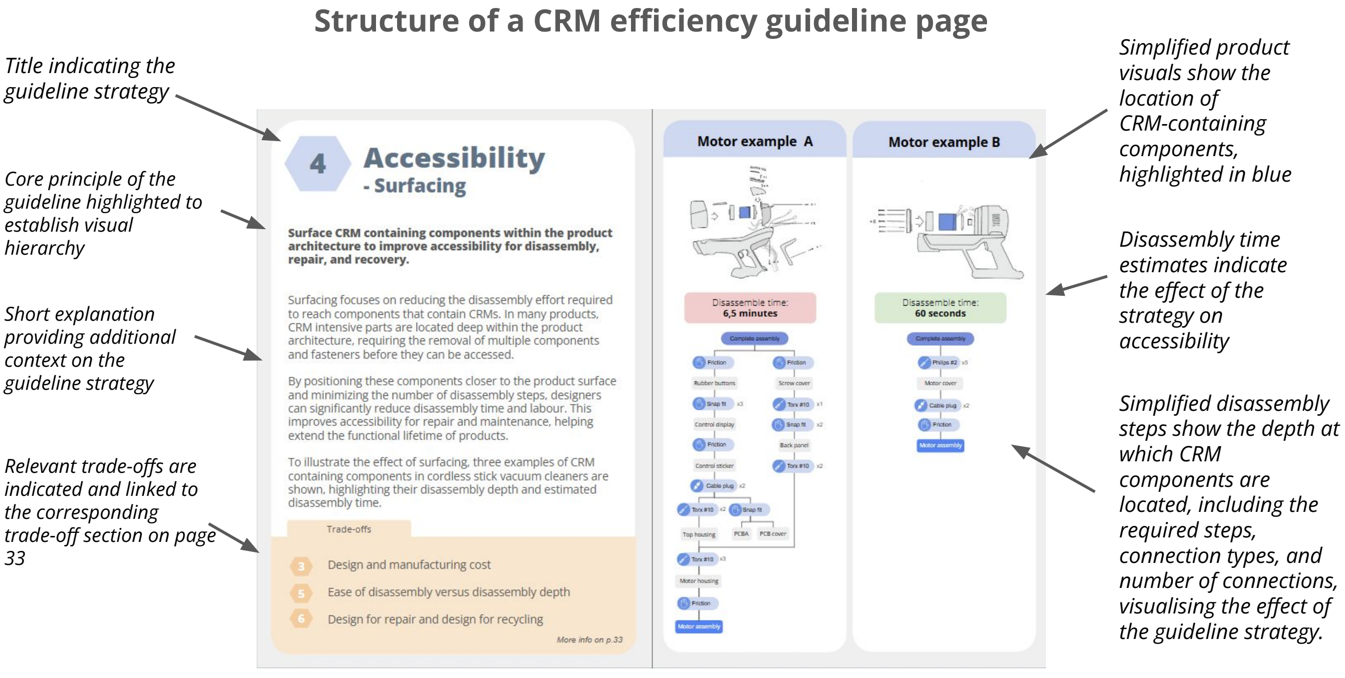


Figure 52. Structure of CRM efficiency guideline page

6. Discussion

6.1 Interpretation and evaluation of case study findings

6.1.1 Washing machine case study

The washing machine case study functioned as an exploratory use case for creating guidelines for CRM efficiency. The methods described were less refined and relied on a single product, limiting robustness and applicability.

The CRM hotspot mapping method in the case study was based on material criticality, likelihood of CRM presence and functional importance. In practice, functional importance did not meaningfully differentiate between components, since most CRM containing parts were necessary for product operation. Prioritisation therefore relied mainly on material criticality and estimated CRM presence. The absence of component mass relevance as a metric was also a limitation. Without accounting for component CRM mass, the assessment did not distinguish between components with significant CRM content and those containing only trace amounts with low recovery potential.

In the case study, the CRM hotspot table included additional contextual information on accessibility, connection types, price and lifespan. This reduced clarity of the table overview by combining ranking criteria with descriptive data. This added information was therefore removed in the second case study. The CRM hotspot table identified the main motor and printed circuit board assemblies as the primary CRM hotspots for guideline creation. Both components were deeply embedded within the product architecture, requiring multiple disassembly steps to access. This limits recovery potential and highlights the influence of product architecture on CRM efficiency. CRM efficiency is therefore shaped not only by material content, but also by component integration in the product.

CRM content within components had to be estimated from literature and component type, due to limited available data. The method therefore operates on uncertainty rather than measured material composition. The CRM hotspot mapping method helped with identifying priority components, but its precision is limited by the lack of transparent component level material data.

The Simplified disassembly maps, supporting the CRM efficiency guidelines where possible, visualised the impact of the guidelines on product architecture but could be further refined in the second use case for more clarity. Instead of showing the entire product architecture, focussing on the relevant steps for CRM component accessibility would be preferred.

Overall, the washing machine case established the structure of identifying CRM efficiency guidelines through product teardown and CRM hotspot mapping.The case study revealed a need for method simplification, clearer hotspot criteria and improved data reliability.

6.1.2 Vacuum cleaner case study

The vacuum cleaner case functioned as the primary case study within this thesis, expanding the dataset to ten products to allow for evaluation across a broader range of product architectures.

The teardown of ten vacuum cleaners showed how cordless stick vacuums are typically designed. Many products relied on non-reversible or hard to identify snap-fit connections, which often broke during disassembly, limiting the repairability potential of the models.
Higher-priced models, including the Hoover, Dyson and Rowenta, were not easier to disassemble than cheaper alternatives due to added product complexity and reliance on hidden snap-fit connections to give the product a more refined appearance. This is a missed opportunity, as the higher price point would create more incentives to repair and can prolong the products lifespan to reduce the need for CRMs. The Dyson model was particularly difficult to disassemble, even requiring improvised tools to reach certain components.

More expensive models also included additional features, such as automatic power modes and head assembly lighting. These functionalities improve user comfort, but also increase product complexity and require more components to be integrated within the product, which can increase the CRM material use and makes disassembly more difficult. Together, these design choices limit access to CRM components and reduce recovery potential and need to be improved to facilitate CRM efficiency.

In comparison to the washing machine case study, the CRM hotspot table was simplified by removing the columns with contextual information on accessibility, connection types, price and lifespan. These columns reduced clarity the overview of the table with too specific information for all of the ten vacuum cleaner models. In order to create a single CRM hotspot table the CRM components from all models were combined and generalised in a single list.

The criteria for CRM hotspot prioritisation was refined to material criticality (EI + SR) and component CMR mass relevance. Incorporating component CRM mass relevance allowed for distinguishing between components with significant CRM content and those containing only trace amounts with low recovery potential.

CRM content within components had to be estimated using literature and general knowledge of component types, as detailed material composition data was not publicly available. To reduce uncertainty, the estimated CRM content in the hotspot table was reviewed together with a professor of Circular Product Design at TU Delft. During this review, the assumptions about component material composition were discussed and adjusted where needed. Although the material estimates remain indicative, this review helped confirm that the CRM allocations used for the hotspot analysis were reasonable.

Besides the material uncertainty, extra uncertainty was present as not all components were of the same type. Higher priced models more frequently used Brushless DC motors which are more likely to contain REE magnets, meaning that across the models CRM content could vary.

The “chance of CRM in the component” column within the hotspot table aims at reducing some of this uncertainty, but its precision remains limited. The CRM hotspot method identified the motors and battery cells as primarily hotspots for guideline creation in cordless stick vacuum cleaners. Although the other components received a “low” hotspot rating, this does not imply that they should be excluded from CRM efficiency strategies.

The CRM component analysis method used in this case study helped to identify both effective design choices and limitations for CRM efficiency. Differences in component types and product architectures made it difficult to define uniform technical guidelines for the category. However, some patterns were consistent across products. Reversible connections, such as screws and cable plugs, improved access to CRM components, while deeply embedded components and concealed snap-fit connections reduced accessibility.

The proposed guideline strategies were aligned with the 9R framework to indicate their contribution to narrowing, slowing, and closing material loops (Table 13). This alignment however does not imply that higher-order R-strategies should be prioritised over others, as all guidelines contribute to CRM efficiency and should be considered in combination, to maximise CRM efficiency in product design.

The vacuum cleaner case showed that CRM hotspotting can be applied across a product category and used to support guideline development. Comparing how CRM components are integrated across different products helped identify both effective design choices and recurring limitations affecting CRM efficiency. The case study pointed out that variation in product architecture and uncertainty in material data remain key constraints when developing product specific CRM-efficient guidelines.

6.1.3 Cross case comparison

The cross case comparison identified overlap and differences between the case studies.

The two case study product categories differ in both lifespan and architecture. Washing machines are larger, longer-lasting products with more available internal space, which can support repair and component access. In contrast, cordless vacuum cleaners are more compact and integrated. Vacuum cleaners also show greater variation in form factor across models, which makes it more difficult to define product-specific guidelines.

The CRM hotspot method was simplified in the vacuum cleaner case. In the washing machine case, additional contextual columns reduced clarity without directly improving component prioritisation. Removing the contextual columns enabled the use of a single CRM hotspot table across multiple products. The hotspot assessment criteria were also refined to material criticality (EI + SR) and component mass relevance. This refinement allowed for a clearer distinction between components containing significant CRM content and those containing only trace amounts with limited recovery potential.

Across both cases, motor components consistently ranked as primary hotspots. Battery cells also scored highly where present. PCB assemblies showed greater variation between cases. In the washing machine case, PCB assemblies emerged as clear hotspots due to their functional importance and CRM presence. In the vacuum cleaner case, however, it became apparent that PCB assemblies often contained only small CRM fractions, which do not justify high prioritisation for CRM efficiency guidelines because of the limited recovery potential of the CRMs.

There was clear overlap in guideline directions. In both cases, accessibility of CRM components played a central role for improving CRM efficiency. Strategies such as surfacing, clumping and standardised connection types directly affected component recovery potential. Substitution, pruning, standardisation and modularity emerged as recurring design principles. The guidelines presented in the vacuum cleaner case were formulated in a more focused manner by showing only part of a disassembly map to visualise guideline influence on product architecture instead of the whole disassembly map.

The CRM hotspot mapping method was effective in identifying priority components across both cases. However, the guidelines cannot be applied directly to specific products and need to be adapted to each product architecture. They should therefore be seen as a starting point rather than fixed rules for improving CRM efficiency.

6.2. Tradeoffs for CRM efficiency guidelines

While the developed guidelines provide a clear framework for CRM efficiency, their implementation within product architecture introduces several technical, economic and systemic trade offs that need to be discussed.

Standardisation versus market flexibility

Standardising components such as motors, batteries and fastener types improves reuse potential and recovery feasibility. It may also reduce overspecification of CRM intensive components.

However, strict standardisation can limit product differentiation and reduce design flexibility. Prescribed formats or performance ceilings may restrict innovation, including the development of alternative technologies that could potentially reduce CRM dependency. The balance between setting standards and innovation therefore requires careful consideration.

Product efficiency versus CRM intensity

High efficiency components, such as BLDC motors using rare earth permanent magnets, improve product energy performance but increase CRM content. Alternatives with lower CRM use, such as brushed DC motors, typically reduce efficiency and may shorten product lifetime due to mechanical wear.

Current ecodesign regulations prioritise energy efficiency but do not account explicitly for CRM intensity. As a result, improving product performance may increase reliance on CRMs. Energy efficiency and material criticality can therefore lead to conflicting optimisation outcomes. Choosing between product efficiency and CRM intensity depends on the use case of the product. For products with longer lifespans, higher energy efficiency may justify the use of CRM-intensive components due to reduced energy consumption over time. Life cycle assessments and material flow analysis can support this decision by comparing the impacts of energy use from different CRM component types and quantify the CRM reduction.

Redesign versus manufacturing cost
Changing a product's architecture can improve accessibility and recovery, by adding access points and modular connections. This can however increase manufacturing complexity and production cost. In cost sensitive product segments, such as lower priced vacuum cleaners, these additional costs may reduce competitiveness if non compliant alternatives remain available. Adoption of CRM efficient design therefore depends on the product's business case and value proposition.

Pruning versus feature driven marketing
Reducing non-essential product features can lower CRM demand by decreasing component complexity and material use. However, product development is often driven by the addition of features and performance improvements as a means of market differentiation. This creates a tension between pruning and feature-driven design.

Designers should therefore assess whether added features contribute to the product's core function or disproportionately increase CRM intensity. When CRM-containing components provide limited functional benefit, simplifying or removing them can improve CRM efficiency without significantly affecting product performance. However, applying such strategies may be constrained by market expectations, where added functionality is often prioritised.

Design for repair versus resign for recycling
Design for repair favours reversible connections and modular structures that allow repeated opening and component replacement (Dangal et al., 2022). Design for recycling prioritises snap-fit assemblies or simplified material separation that facilitate shredding and homogenous material recovery, but limit non-destructive access (Faludi, 2025).

This trade off is important for CRM intensive components. In the case studies, motors and battery components contain concentrated CRMs and benefit from repair or component harvesting strategies to keep the materials in the loop. In contrast, PCB assemblies typically contain CRMs in low concentrations distributed across complex product specific structures, making component level reuse less feasible. The appropriate strategy for CRM efficiency therefore depends on the concentration and recovery potential of CRM within the component.

Ease of Disassembly versus Disassembly Depth
A shallow disassembly depth does not automatically result in easy removal if the required steps are complex or destructive. In contrast, deeper integration combined with simple, reversible connections may allow for easier disassembly. CRM accessibility therefore depends on both component position and connection type.

Specifically in the vacuum cleaner use case housing configuration strongly influences accessibility. Split housing types provide broad internal access and are effective when multiple CRM components are distributed throughout the product. Access point housings allow targeted removal of single components with minimal steps, but when several CRM components are located in different positions, multiple access points can increase disassembly time. The housing architecture of the product should therefore reflect the number and distribution of CRM intensive components.

6.3. CMR efficiency guidelines booklet evaluation

This section evaluates the CRM efficiency guidelines booklet based on designer feedback, focusing on its usefulness, strengths, limitations, and applicability as a design tool.

Perceived usefulness and applicability

The CRM efficiency guidelines booklet was evaluated in a semi-structured session with a circularity expert. The booklet was considered useful for identifying and comparing CRM efficiency strategies in product design. The overview of where CRMs are typically found in components allows designers to quickly assess the relevance of the guidelines for a given product. The inclusion of background context on CRM relevance helps to underline the importance of design guidelines for CRM efficiency.

The visualisations of the guidelines make the impact of the guidelines on product architecture explicit by showing how design changes affect component accessibility. However, it remained unclear when and how specific guidelines should be applied within the design process. While the overall structure of the booklet links guidelines to trade-offs and supporting tools, clearer guidance on the timing and application of strategies would improve usability.

Strengths of the booklet

The key strength of the booklet is the use of visuals to support the guidelines. The simplified disassembly maps clearly show how design decisions affect product architecture and the accessibility of CRM-containing components. The sketches are easy to understand and indicate how CRM efficiency can be improved. The consistent layout of the guideline pages further improves readability and supports comparison between strategies.

Limitations of the booklet

The CRM efficiency guidelines cannot be applied directly and depend on the product, its architecture, the context of use and the evaluation of trade-offs. As a result, they require interpretation rather than providing fixed solutions. In addition, the CRM hotspot mapping method remains too vague for application to other product categories and requires further clarification on how it should be applied.

The evaluation also indicated that the booklet is relatively text-heavy, which may limit usability in practice. Furthermore, the presence of multiple guidelines within the design field, addressing aspects such as repair and recycling, creates overlap and can make it difficult for designers to navigate between tools. As a standalone resource, the booklet may therefore be challenging to integrate into existing design workflows.

Trade-offs and decision support

The booklet helps identify relevant trade-offs for CRM efficiency and proposes additional tools for decision making. Applying the guidelines depends on the product context, use case, and value proposition, and therefore requires additional analysis. The linking of guidelines to trade-offs and supporting tools helps structure decision-making. The additional tools, Material Flow Analysis (MFA) and Life Cycle Assessment (LCA), can support designers with quantification of CRM reduction and the evaluation of trade-offs.

Role of the booklet as a design tool

The booklet functions as a decision-support tool rather than a set of fixed rules. It helps identify and showcase CRM efficiency strategies, but requires interpretation and adaptation in practice. Further development into a more integrated or interactive tool could improve usability and support its use alongside other circular design strategies.

6.4. Limitations

This study demonstrates that CRM efficiency guidelines can be developed through product teardown analysis and CRM hotspot prioritisation. However, several methodological and conceptual limitations must be acknowledged.

The hotspot assessment is based on estimated CRM content at component level due to limited material transparency. These estimates were derived from literature and component type and supported by expert input, but remain qualitative. As a result, the hotspot method supports relative prioritisation of components rather than precise quantification of CRM content.More reliable component level data, for example through digital product passports, would strengthen future analyses. In addition, CRM criticality is dynamic. Changes in economic importance and supply risk may alter prioritisation outcomes over time, requiring the method to be updated to remain relevant.

The case studies focused on specific product categories and although the vacuum cleaner study included ten products, the sample does not fully represent the whole market diversity. Therefore product specific bias cannot be excluded for the thesis. While the guidelines can be applied to other product categories, the feasibility of design interventions, the level of standardisation and the applicability of pruning strategies remain product-dependent. In high performance or high safety standard products, such as electric vehicles, reducing CRM content may compromise functionality, whereas less critical products, like vacuum cleaners can allow more extensive CRM reduction strategies.

A key limitation of the study is that the impact of the proposed guidelines on CRM content has not been quantified. The analysis is based on qualitative assessment rather than measurable reductions in CRM use. Methods such as Material Flow Analysis (MFA) could be used to quantify the effect of design strategies on CRM content at product level. In addition, no Life Cycle Assessment (LCA) was conducted to evaluate trade-offs between CRM use and other environmental impacts, such as energy efficiency. As a result, the environmental implications of applying the guidelines remain uncertain and their effectiveness in reducing CRM demand cannot be fully assessed.

The guidelines, supported by simplified disassembly maps, illustrate structural principles for improving CRM efficiency, but do not provide detailed engineering specifications. They function as decision-support tools rather than technical prescriptions, limiting their applicability when precise product specific rules are required.

Furthermore, the guidelines focus on improving access to CRM-containing components for reuse and recovery. However, the actual recovery of CRMs remains technically challenging due to low material concentrations and component complexity. The study does not address how component-level design changes are needed to improve repairability and material recovery. As a result, improved accessibility currently does not necessarily lead to effective CRM recovery, which limits the overall impact of the proposed guidelines.

Finally, the validation of the CRM efficiency guidelines was limited to two external experts. This small sample size restricts the strength of the evaluation, meaning the findings are indicative rather than representative of broader design practice. Further validation with a larger and more diverse group of designers is needed to assess the robustness and applicability of the guideline booklet.

6.5. Recommendations & Future research

This research presents a method for prioritising CRM-intensive components and translating material criticality into product design guidelines. To improve its robustness and practical applicability, several areas for further research are identified.

Further development of the methods described requires more reliable component-level material data. The current hotspotting approach relies on qualitative estimation due to limited material transparency, which introduces uncertainty. Improved data availability, for example through digital product passports or enhanced CRM disclosure requirements, would enable more precise assessment of CRM content. In addition, applying the methods across a wider range of product categories would help evaluate its robustness and refine its applicability to different product architectures.

A key area for future research is the quantitative evaluation of the proposed guidelines. Methods such as Material Flow Analysis (MFA) can quantify changes in CRM content at product level, while Life Cycle Assessment (LCA) can evaluate trade-offs between CRM use and other environmental impacts, such as energy consumption. Without such analyses, the effectiveness of the guidelines remains difficult to assess. Developing prototypes or demonstrator products could further support validation of the guidelines by testing structural feasibility and disassembly performance under real conditions.

To improve the practical application of the guidelines, future research should focus on improvements of the guideline booklet. Transitioning from a static booklet to a digital platform could improve navigation and provide more structured guidance throughout the design process. Integrating the guidelines with existing circular design tools would support a more holistic approach and reduce fragmentation across multiple guideline sets.

Further research is needed to support the implementation of CRM efficiency strategies. Policy analysis should assess how existing regulations, such as the CRMA and ESPR, can incorporate product-level CRM strategies and where changes are required. In addition, extending product analysis with recyclability maps alongside disassembly maps could strengthen CRM efficiency assessment by linking component accessibility to actual material recovery potential.

Finally, future research could explore the role of automated disassembly in CRM recovery. The guidelines in this study focus on manual disassembly, while large-scale recovery is likely to depend on automated processes. Identifying design principles that support automated disassembly would improve the scalability of CRM efficiency strategies.

6.6. Personal reflection & Project evaluation

Before starting on my thesis project, I knew I wanted to work on a topic that could have a meaningful impact. Critical raw materials caught my interest due to the increasing attention they receive in both policy and media. During my education at the faculty of Industrial Design Engineering at TU Delft, I developed a strong interest in sustainable product design, particularly through courses on how to design for repair and recycling. This led me to explore how product design could contribute to more efficient use of critical raw materials and support material resilience.

During the project, I realised that the topic of critical raw materials is highly complex and spans the entire product lifecycle. Focusing on specific product case studies helped to make this complexity somewhat more manageable and allowed me to explore the role of design in a more concentrated way.

This thesis shows that product design can positively influence CRM efficiency through material reducing strategies such as substitution, standardisation and pruning and through Improving the accessibility of CRM-containing components. By supporting product repair, reuse and recovery, product lifetimes can be prolonged, causing the need for new material extraction to be reduced.

At the same time, the project made clear that product design is only one part of a much larger system. The effectiveness of the proposed guidelines depends on factors such as material recovery technologies, policy frameworks and market conditions.

The outcome of this thesis should therefore be seen as a starting point rather than a complete solution. It highlights the role product design can play in improving CRM efficiency, while also pointing to the need for further development and integration with other domains. I hope this work encourages others to explore how product design can contribute to addressing complex critical raw material challenges.

7. Conclusion

This thesis answers the research question: how can product specific design guidelines contribute to enhancing Critical Raw Material (CRM) efficiency? The findings show that CRM efficiency can be addressed at product level by combining systematic identification of CRM relevant components with product architecture design decisions. This can be achieved by reducing material demand through substitution, standardisation and pruning, and by integrating CRM components in ways that support repair, reuse, and recovery. These approaches extend product lifetimes and reduce the need for new material extraction.

CRM containing components can be identified and prioritised through product teardown analysis, Bills of Materials and literature based estimations. Combining Economic Importance, Supply Risk, and component CRM mass relevance provides a workable basis for distinguishing between components with trace amounts of CRM and those with concentrated and strategically significant CRM content. Across both case studies, motors and battery cells consistently emerged as primary hotspots. However, the method relies on estimations of material composition and does not capture exact CRM quantities, which limits its precision.

CRM efficiency can be described in terms of reduction and recovery. Reduction strategies such as substitution, pruning, and standardisation lower CRM demand. Recovery strategies enable reuse, repair and recycling, extending product lifetime and reducing the need for virgin raw materials. In practice, these strategies introduce several trade offs, meaning that CRM efficiency cannot be optimised in isolation.

The implementation of design guidelines remained strongly product dependent. Differences in product architecture, functional requirements, and value proposition limit direct transfer of specific guidelines. The guidelines therefore function more as decision support tools than as fixed design prescriptions.

Overall, the study provides a structured way of linking CRM hotspot identification to product level design decisions. It shows that CRM efficiency can be achieved through product design strategies, while also highlighting the limits of generalisation and the need for context specific adaptation. Further work is needed to validate and quantify these strategies using more detailed material data across a wider range of products.

8. Disclaimer

This thesis was conducted and written independently by the author. All research design decisions, methodology development, product teardowns, data collection, analysis, and formulation of CRM efficiency guidelines were carried out by the author.

Artificial intelligence (AI) tools, specifically the large language models ChatGPT and Google Gemini, were used during the writing process for language refinement and structural suggestions. This included improving grammar and sentence clarity, strengthening academic tone and restructuring paragraphs for clarity and coherence.

AI outputs were treated as suggestions rather than final content. All suggestions were critically reviewed, adapted, or rejected based on the author’s own judgment and domain knowledge. Responsibility for the final content of this thesis rests entirely with the author.

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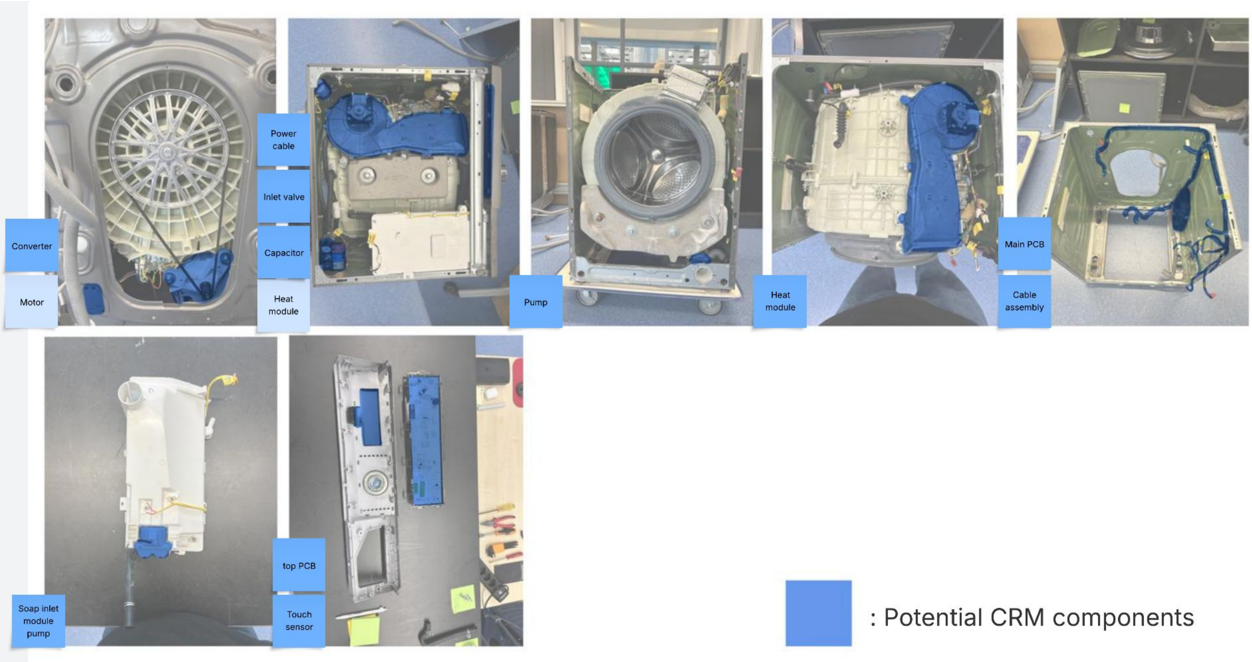
10. Appendix

Appendix A - Hisense WDQR1014EVAJMT product teardown



After opening the top panel, 4 components can be emidiately liberated

The washing machine has to main acces points: the top and the back

The washing machine uses the mostly the same type of screws

Removing the tub is hard, due to the weight and size

Removing the dampers is hard because of restricted access to the connections.

Tools needed for opening the machine are: screwdriver, wrench, pliers, Spudger

Front concrete is hard to remove

The open bottom design makes it easier to reach the engine and the

PCB and Cable are hard to reach/ deep in the assembly

Motor is hard to liberate through the back panel

Without the proper tool it is impossible to remove the drive wheel

Appendix B - Vacuum cleaner Knolled pictures

Vytronix

Knolled picture of Vytronix NIBC22 1. Head cover; 2. Wheel; 3. Brush; 4. See through cover; 5. Head side panel; 6. Foam cover; 7. Brush motor; 8. Bottom head assembly; 9. Cable cover; 10. Bottom tube connector; 11. Inner tube; 12. Top tube connector; 13. Outer tube; 14. Battery connector; 15. Front housing cover; 16. Motor; 17. Foam motor cover; 18. PCB assembly; 19. Trigger; 20. Battery release button; 21. Side housing R; 22. Side housing L; 23. Top housing cover; 24. Container release panel; 25. Top container assembly; 26. Filter; 27. Filter cover assembly; 28. Container housing; 29. Top battery cover; 30. Battery assembly; 31. Bottom battery assembly.

Turbotronic TT-CF7

Knolled picture of Turbotronic TT-CF7 1. LED cover; 2. See through cover; 3. Brush motor; 4. Side panel L; 5. Motor belt; 6. Brush; 7. Top head cover; 8. Inner dust guide; 9. Bottom head cover; 10. wheels; 11. Head to tube assembly; 12. Bottom connector cover; 13. Bottom connector; 14. Tube; 15. Top connector cover; 16. Top connector; 17. Motor front cover; 18. Motor; 19. Motor housing; 20. Outing housing; 21. PCB; 22. Interface cap; 23. Container connector; 24. dust guide; 25. silicon ring; 26. Cable connector; 27. Trigger; 28. Controller handle; 29. cable assembly; 30. Battery release button; 31. Bottom housing cover; 32. Container; 33. Filter assembly; 34. Filter; 35. Battery cover; 36. Battery assembly.

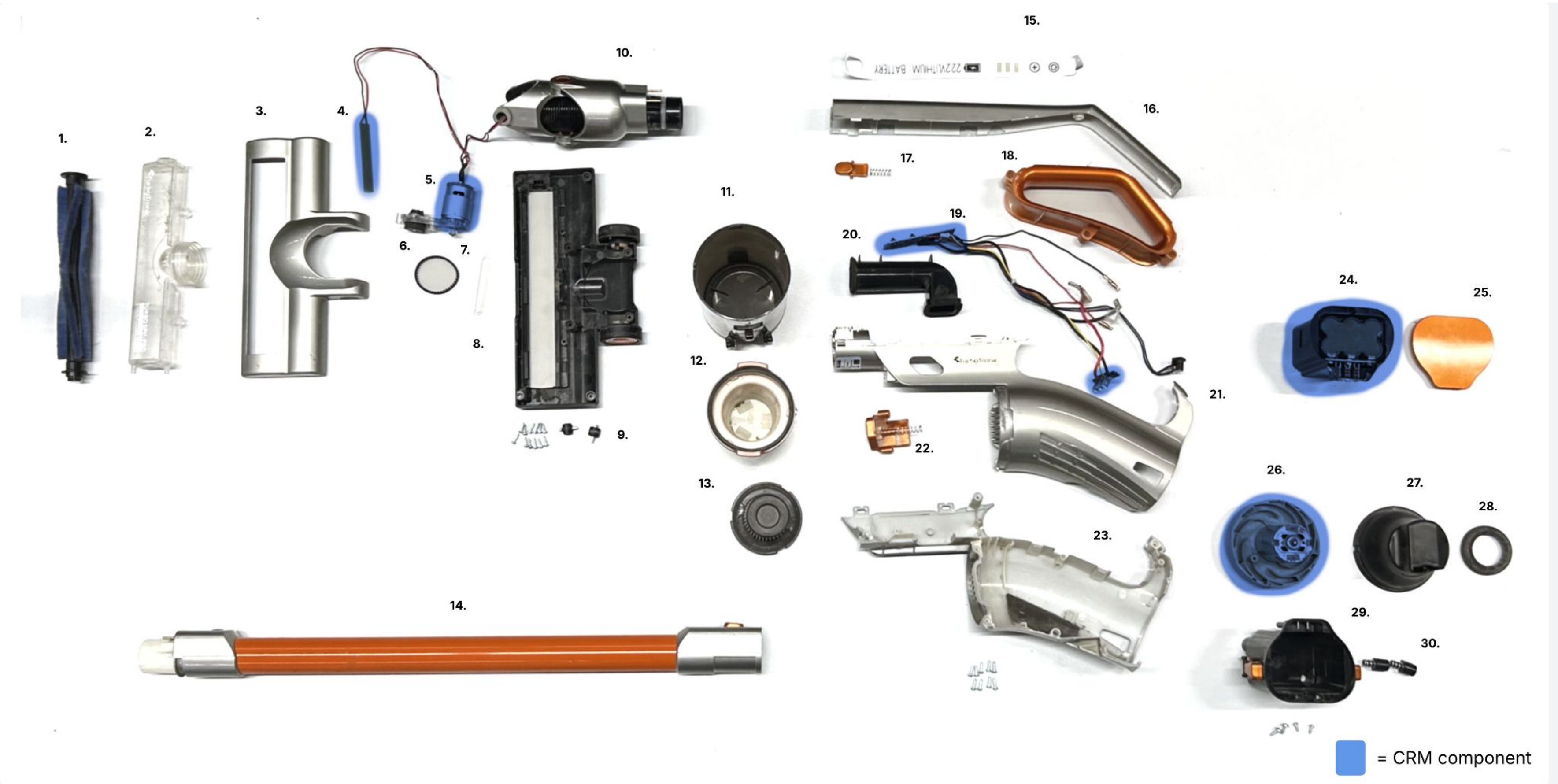
AEG QX8 animal X power

Knolled picture of AEG QX8 animal X power 1. Head cover; 2. See through cover; 3. Brush motor assembly; 4. Bottom head cover; 5. Tube connector; 6. Wheel assembly; 7. Side panel; 8. Brush connection ring; 9. Top stick cover; 10. Bottom stick cover; 11. Cable assembly; 12. Container; 13. Filter cover; 14. Filter; 15. Top controller housing; 16. PCB cover; 17. Electronics assembly; 18. Bottom controller housing; 19. Main housing top; 20. Main housing bottom.

Dyson V11 absolute

Knolled picture of Dyson V11 absolute 1. Front head cover; 2. Outer brush; 3. Brush end cap; 4. Motor top cover; 5. Motor side cover; 6. Inner brush assembly; 7. Head to tube assembly; 8. Outer head body; 9. See through cover; 10. top head cover; 11. Container; 12. Container rail; 13. Filter assembly top; 14. Filter assembly middle; 15. Filter assembly inside component; 16. Filter assembly bottom; 17. Cable cover; 18. Cable rings; 19. Filter assembly bottom cover; 20. Tube assembly; 21. Power cable cover; 22. PCB cover; 23. Handle; 24. Filter; 25. Motor + PCB assembly; 26. Trigger assembly; 27. Battery assembly.

Turbotronic TT-CF4



Knolled picture of Turbotronic TT-CF41.Brush; 2. See through cover; 3. Top head cover; 4. Light PCB; 5. Motor; 6. Belt; 7. Light diffuser; 8. Button head cover; 9. Wheels; 10. Tube connector; 11. Container; 12. Outer filter; 13. Filter; 14. Tube; 15. Sticker; 16. Top cover; 17. Tube spring; 18. Handle; 19. Cable assy; 20. Tube guide; 21. Housing L; 22. Container connector; 23. Housing R; 24. Battery; 25. Battery cover; 26. Motor; 27. Motor cover; 28. Motor ring; 29. Battery container; 30. Battery springs.

Sauber R20

Knolled picture of Sauber R20 1. Brush; 2. See through cover; 3. Top head cover; 4. Brush motor; 5. Motor converter; 6. Bottom head assy; 7. Wheels; 8. Tube connector assy; 9. Cable cover; 10. Container; 11. Filter; 12. Filter 2; 13. Filter cover; 14. Tube; 15. Motor cover; 16. Motor foam; 17. Motor PCB cover; 18. Rubber support; 19. Motor; 20. Motor rubber; 21. Foam; 22. PCB; 23. Motor housing; 24. Cable assy; 25. Cable; 26. Top housing; 27. Cable ring; 28. Bottom housing assy; 29. Charger cable; 30. Bottom cover; 31. Trigger cable; 32. Battery housing; 33. Battery housing cover; 34. Battery + PCB; 35. Trigger; 36. Spring; 37. Trigger pcb; 38. Trigger cover.

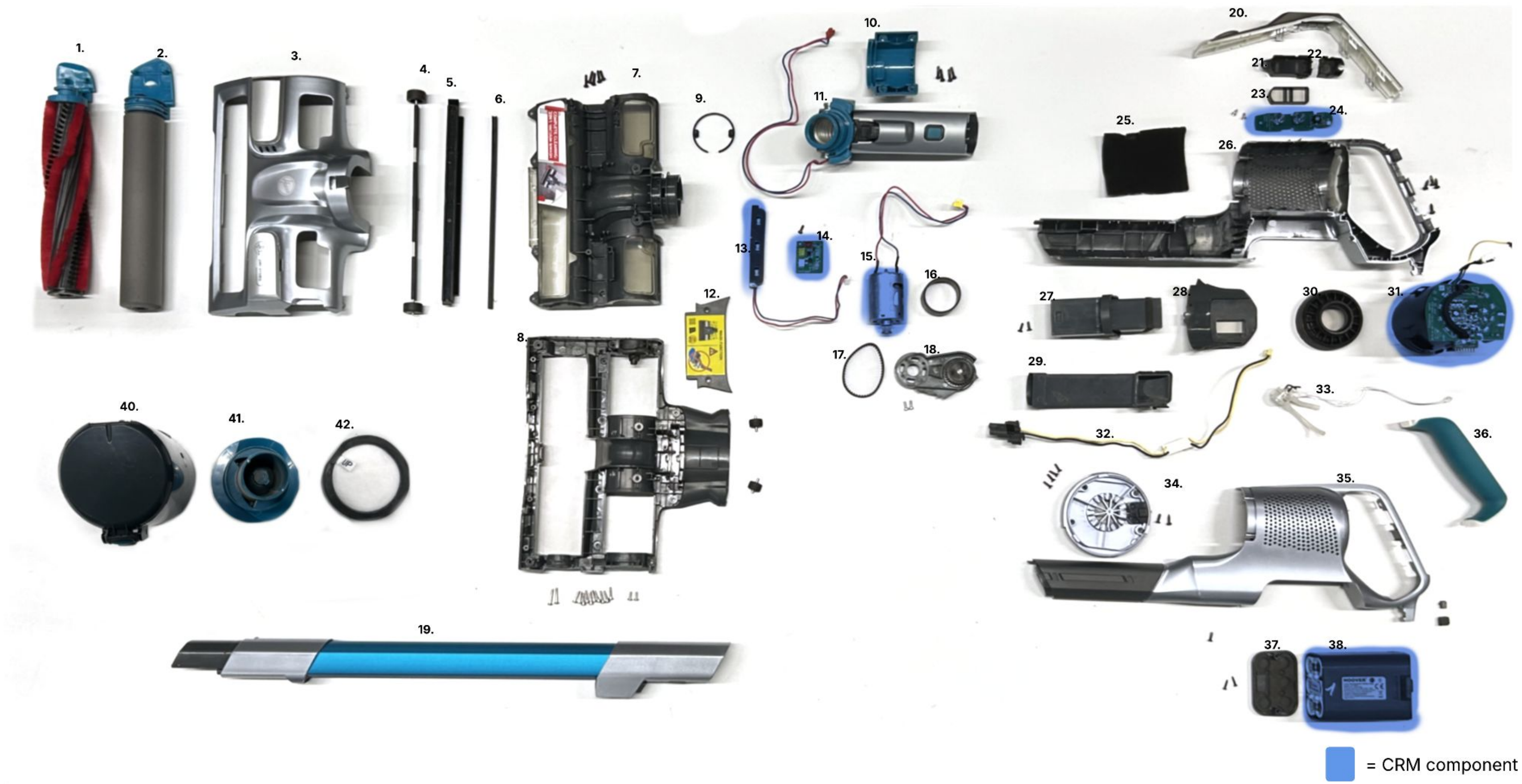
Severin S Special

Knolled picture of Severin S Special 1. Brush; 2. Brush clip; 3. See through cover; 4. Top head cover; 5. LED; 6. Brush motor; 7. Motor converter; 8. Belt; 9. Bottom head cover; 10. Tube connector; 11. Tube connector cover; 12. Container; 13. Lid botton; 14. Lid; 15. Light panel; 16. Light diffuser; 17. Top housing; 18. Rails; 19. Main housing; 20. Filter cover; 21. Filter; 22. Tube; 23. Foam; 24. Motor; 25. Motor front cover; 26. Motor foam; 27. Motor cover front; 28. PCB Cable; 29. Power button; 30. Charger cable; 31. Battery cable assy; 32. Back panel; 33. Bottom panel; 34. Battery housing cover; 35. Battery + PCB; 36. Battery housing; 37. Battery connection buttons.

Zedar S600

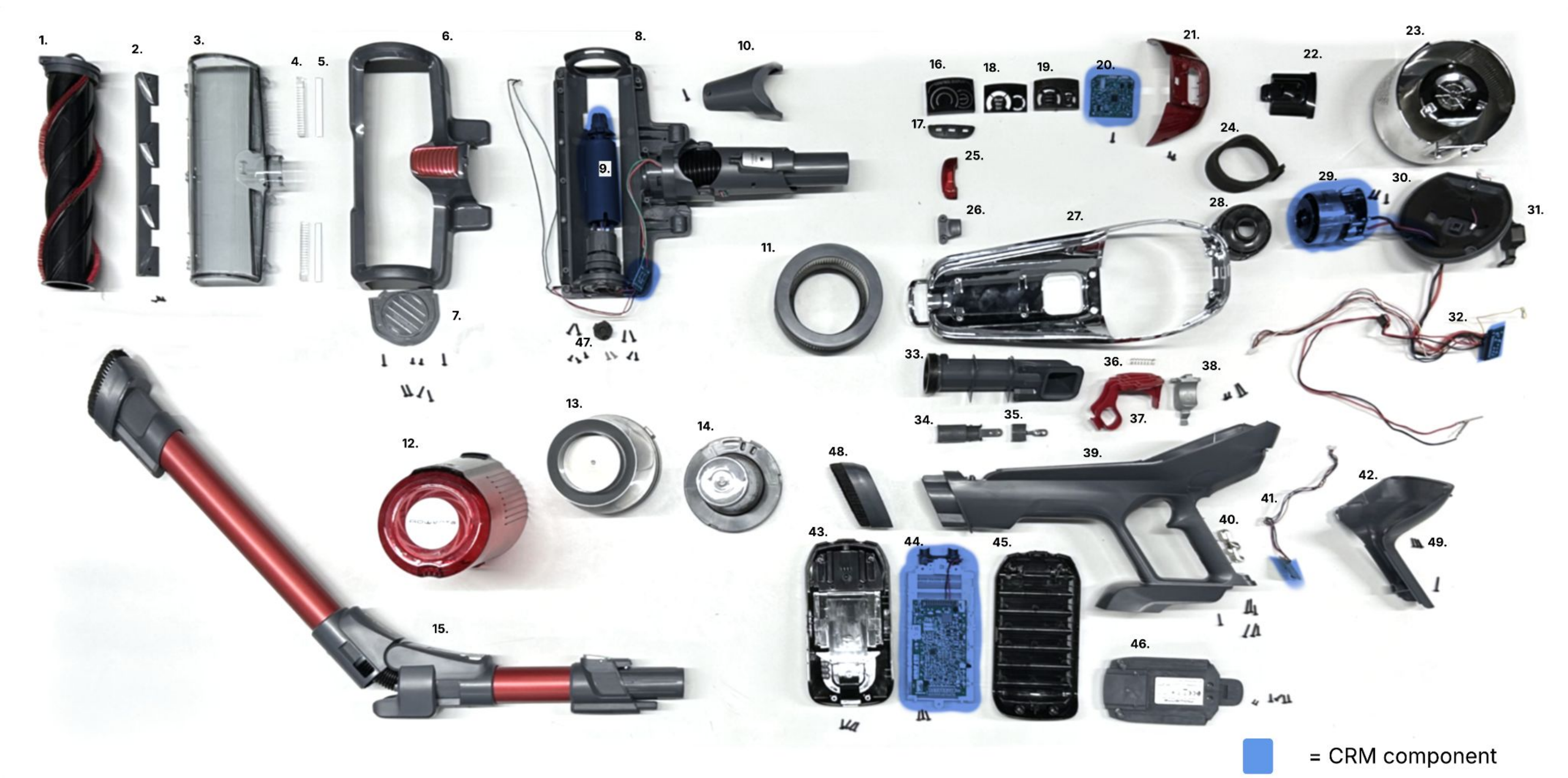
Knolled picture of Zedar S600 1. Brush; 2. See through cover; 3. Top head cover; 4. front head cover; 5. Lights PCB; 6. Brush motor; 7. Belt; 8. Motor converter; 9. Tube connector assy; 10. Bottom head cover; 11. Brush clip; 12. Spring clip; 13. See through motor cover; 14. Plastic motor cover; 15. Filter housing; 16. Outer filter; 17. Filter; 18. Tube; 19. Container; 20. Top motor foam; 21. Top motor cover; 22. Top housing cover; 23. Motor; 24. Motor rubber; 25. Motor PCB cover; 26. Rubber support; 27. Front housing plate; 28. connector cables; 29. Housing; 30. LEDs; 31. Control PCB; 32. Control end cap; 33. End cap cover sticker; 34. Handle; 35. Back plate; 36. Cable assy; 37. Power cable; 38. Power cable plate; 39. Battery top cover; 40. Battery + PCB; 41. Battery housing.

Hoover H-Free 500 Hydro plus



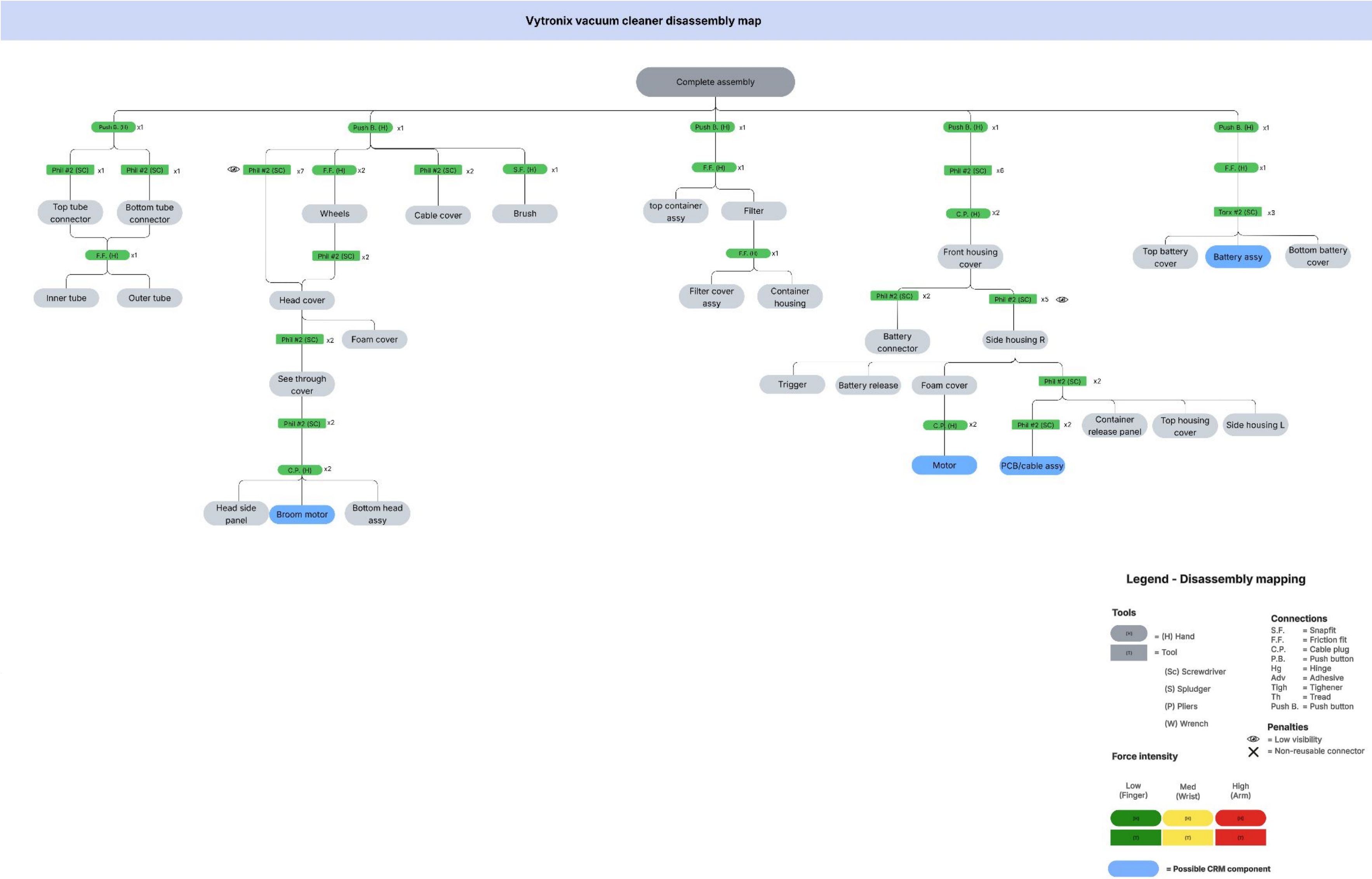
Knolled picture of Hoover H-Free 500 Hydro plus 1. Brush; 2. Roller; 3. Top head cover; 4. Front wheel assy; 5. Rubber guide; 6. Rubber guide guide; 7. See through cover; 8. Bottom head cover; 9. Connection ring; 10. Tube connector cover; 11. Tube connector; 12. Bottom head plate; 13. LED; 14. PCB; 15. Brush motor; 16. Motor rubber ring; 17. Belt; 18. Motor converter; 19. Tube; 20. Top housing cover; 21. Mode button; 22. Power button; 23. Button insert; 24. Button PCB; 25. Foam; 26. Housing L; 27. Tube connection; 28. Tube connection 2; 29. Tube connection 3; 30. Motor rubber cover; 31. Motor; 32. Power cable; 33. Cable assy; 34. Motor cover; 35. Housing R; 36. Handle; 37. Battery cover; 38. Battery housing + Battery; 39. Rubber; 40. Container; 41. Filter; 42. Filter top.

Rowenta X force flex 12.60

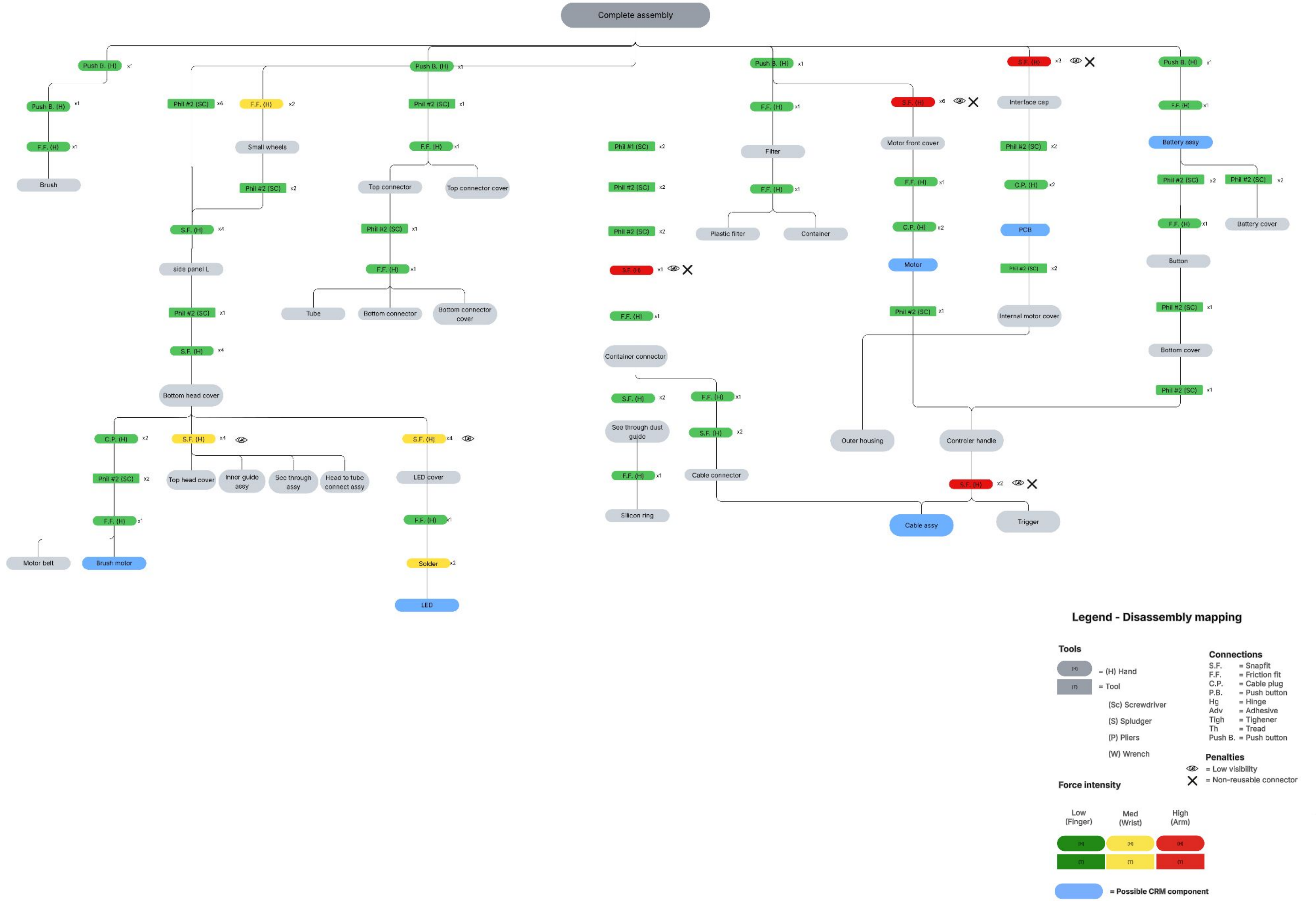


Knolled picture of Rowenta X force flex 12.60: 1. Brush; 2. Head real; 3. See through cover; 4. Light diffuser; 5. Light guide; 6. Top head cover; 7. End cap; 8. Bottom head cover assy; 9. Brush motor; 10. Tube connect cover; 11. Motorfilter; 12. Container; 13. Outer filter; 14. Inner filter; 15. Tube; 16. Control display; 17. Mode buttons; 18. Control sticker; 19. PCB cover; 20. PCB; 21. Top housing panel; 22. Container lock; 23. Motor housing; 24. Motor foam; 25. Front housing cover; 26. Container clip; 27. Chrome housing cover; 28. Motor cover; 29. Motor; 30. Motor back cover; 31. Rubber spacer; 32. Cable assy; 33. Dust guide; 34. Power cable connector; 35. Power cable connector cover; 36. Turbo trigger spring; 37. Turbo trigger; 38. Trigger; 39. Main housing; 40. Contact point?; 41. Trigger button component; 42. Back housing panel; 43. Battery housing; 44. Battery + PCB; 45. Batter housing cover; 46. Bottom housing cover; 47. Rubber spacer brush motor; 48. Brush attachment; 49. Screw cover.

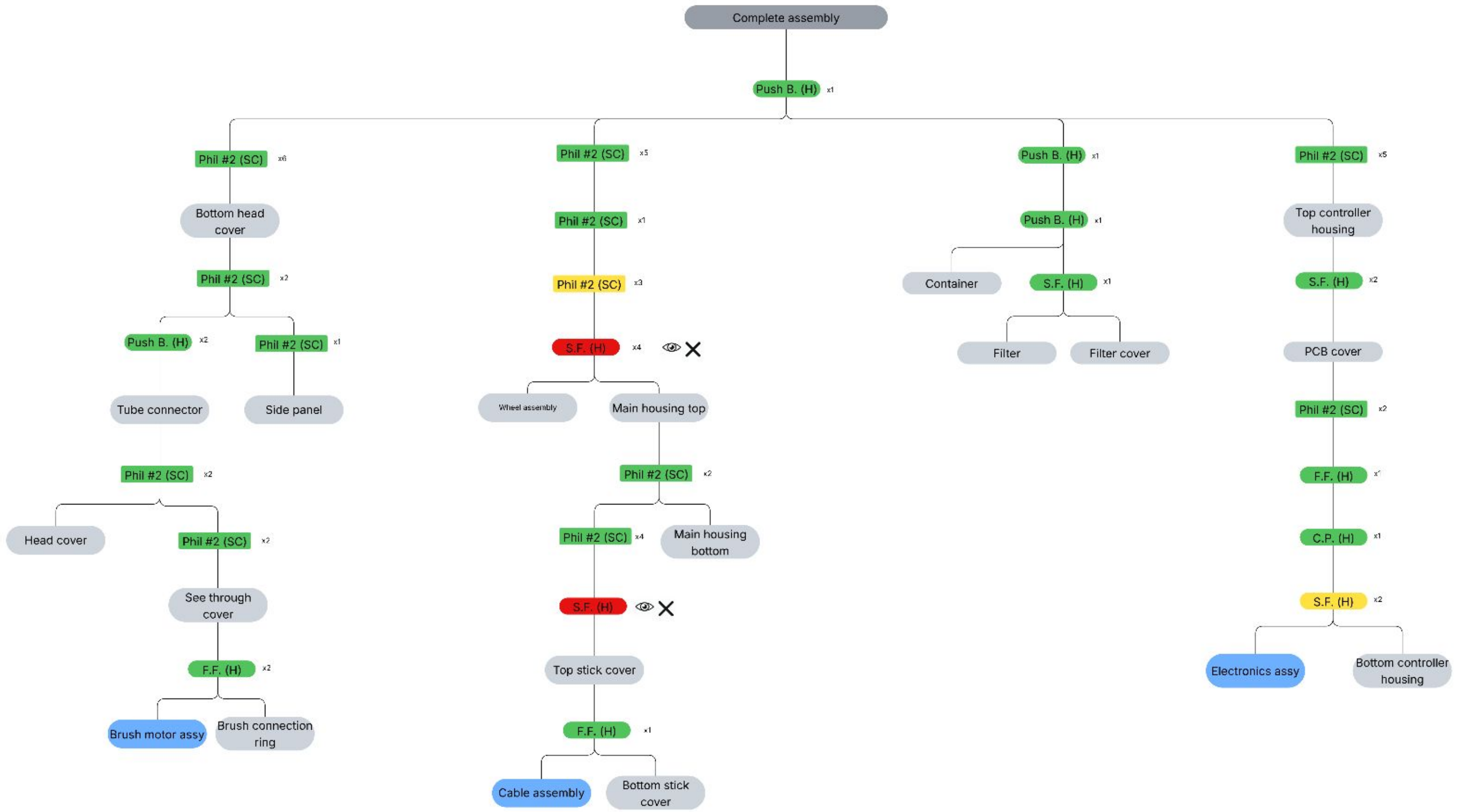
Appendix C - Vacuum cleaner disassembly maps



Turbotronic TT-CF7 Disassembly map



AEG QX8 animal x power Disassembly map



Legend - Disassembly mapping

Tools

- (H) = (H) Hand
- (T) = Tool
  - (Sc) Screwdriver
  - (S) Spludger
  - (P) Pliers
  - (W) Wrench

Connections

S.F. = Snapfit
F.F. = Friction fit
C.P. = Cable plug
P.B. = Push button
Hg = Hinge
Adv = Adhesive
Tigh = Tighener
Th = Tread
Push B. = Push button

Penalties

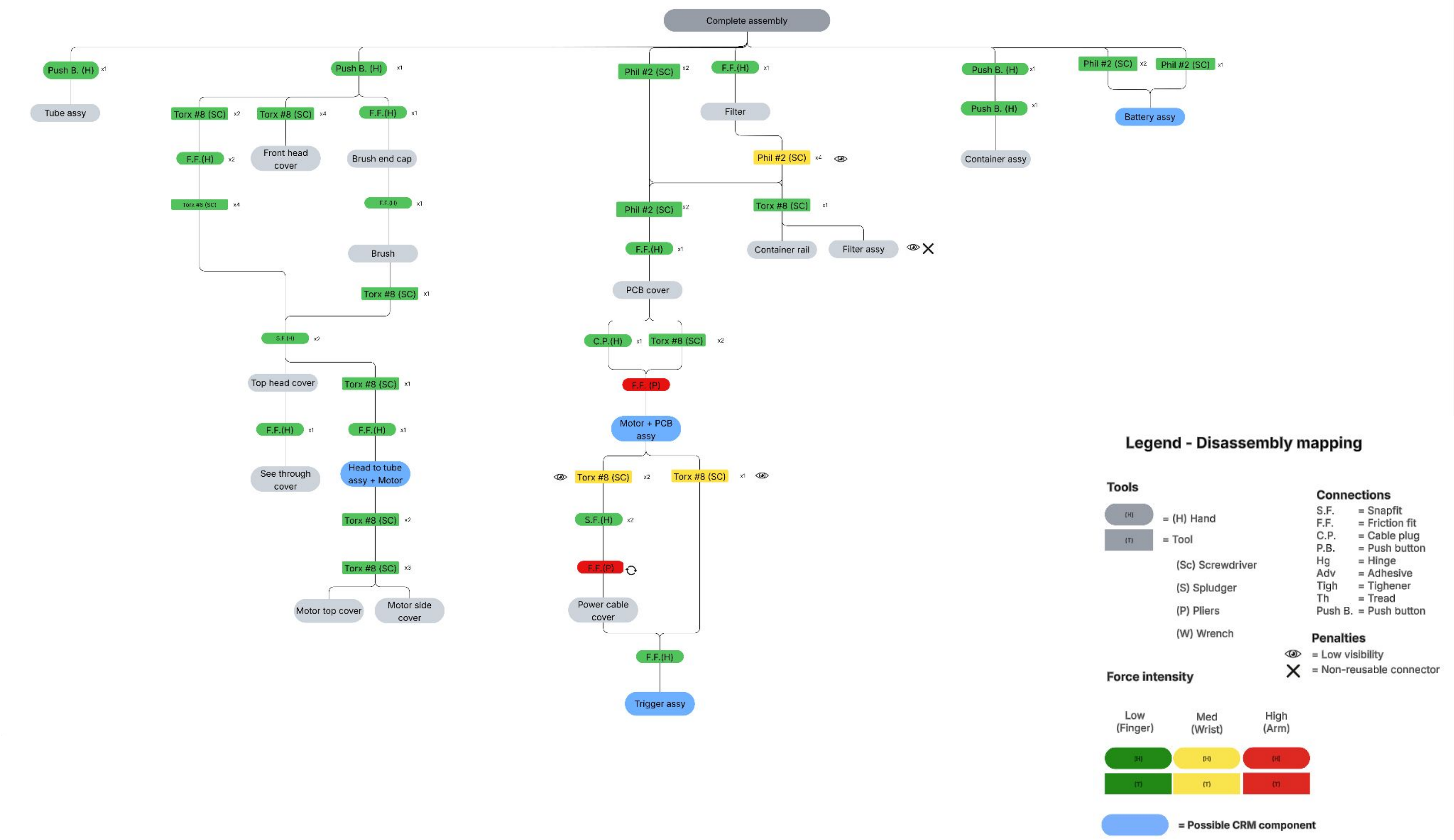
👁 = Low visibility
✕ = Non-reusable connector

Force intensity

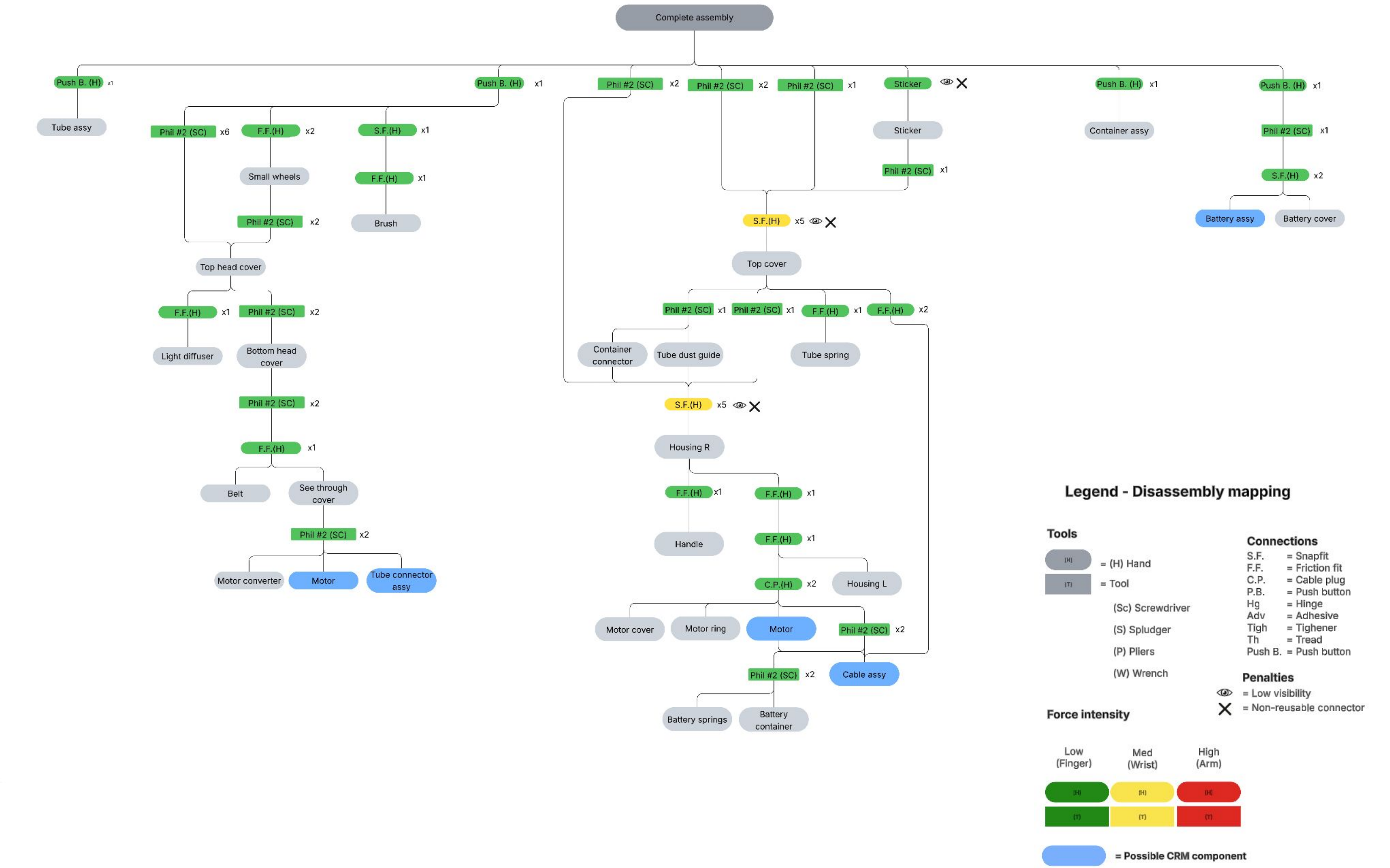
Low (Finger)	Med (Wrist)	High (Arm)
(H)	(H)	(H)
(T)	(T)	(T)

= Possible CRM component

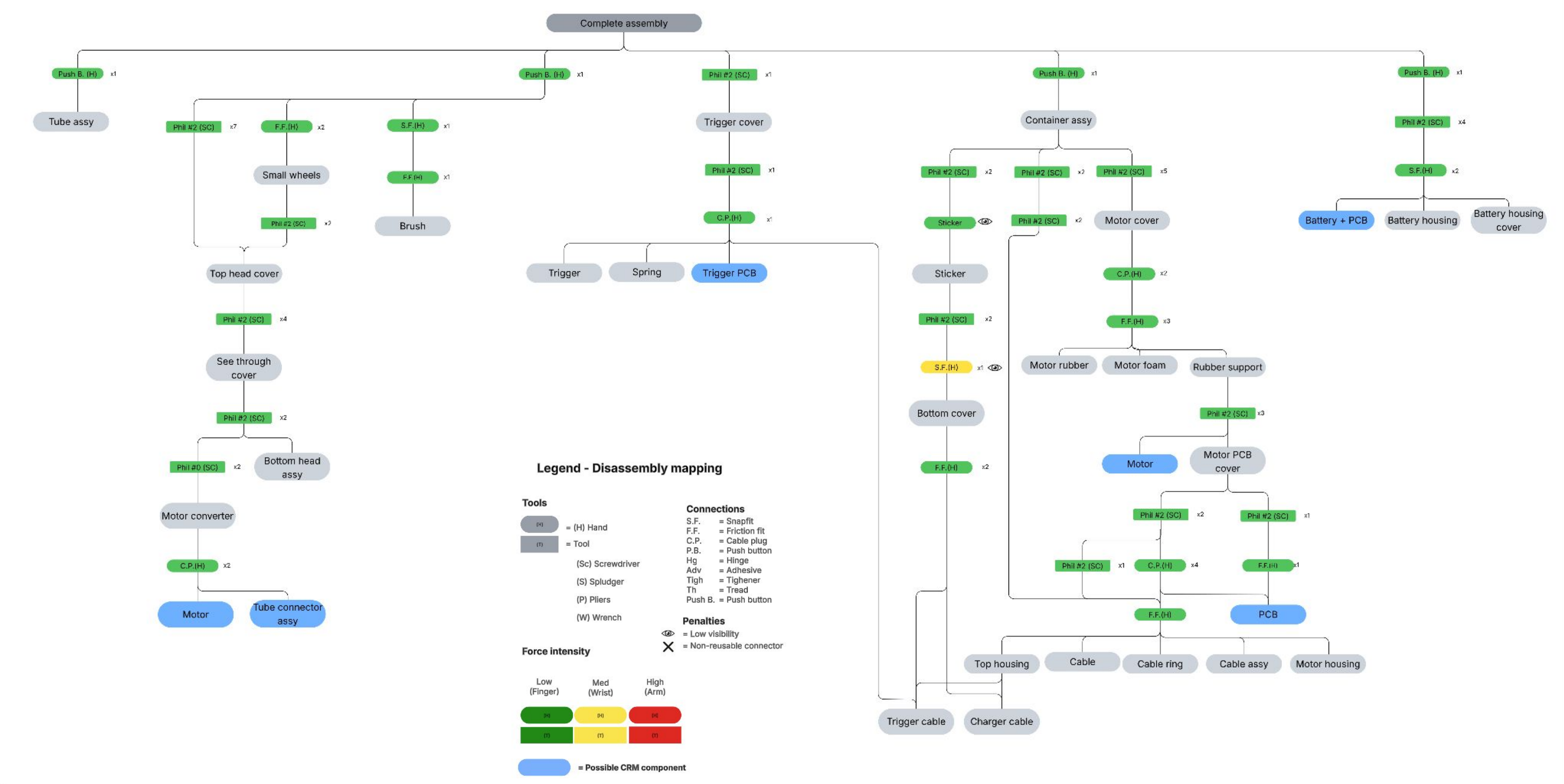
Dyson v11 absolute Disassembly map



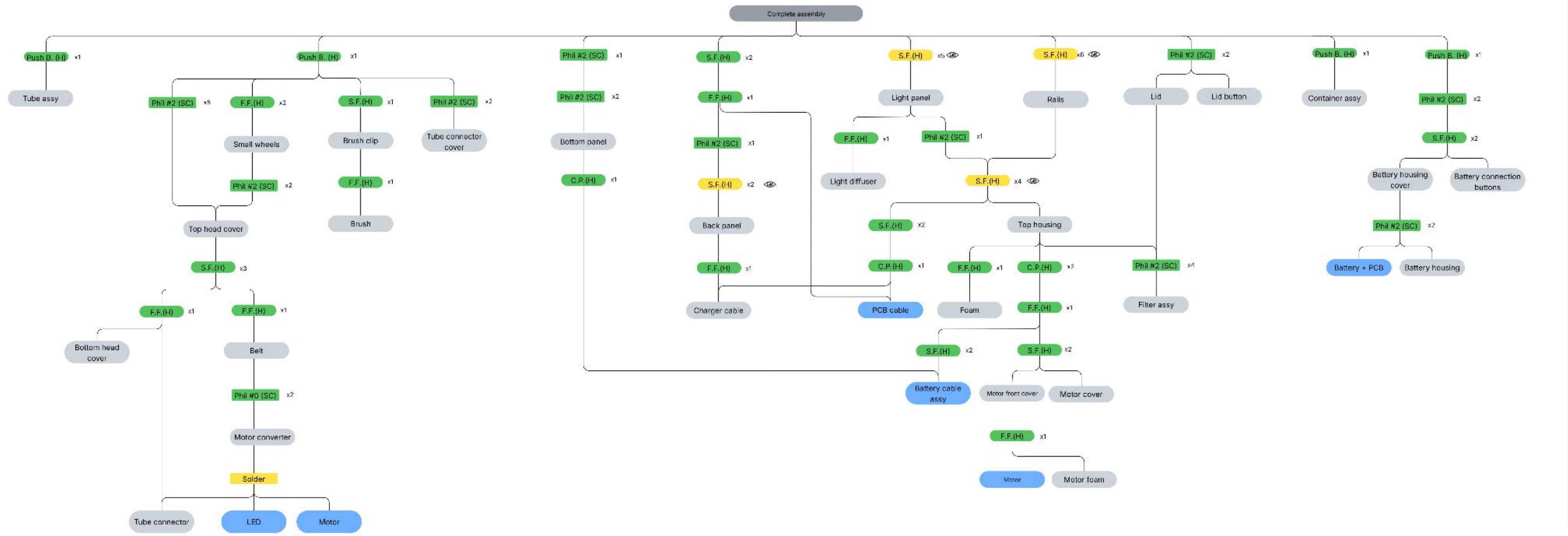
Turbotronic TT-CF4 Disassembly map



Sauber R20 Disassembly map



Severin S Special Disassembly map



Legend - Disassembly mapping

Tools

(H) = (H) Hand

(T) = Tool

(Sc) Screwdriver

(S) Spludger

(P) Pliers

(W) Wrench

Connections

S.F. = Snapfit
F.F. = Friction fit
C.P. = Cable plug
P.B. = Push button
Hg = Hinge
Adv = Adhesive
Tigh = Tighener
Th = Tread
Push B. = Push button

Penalties

= Low visibility

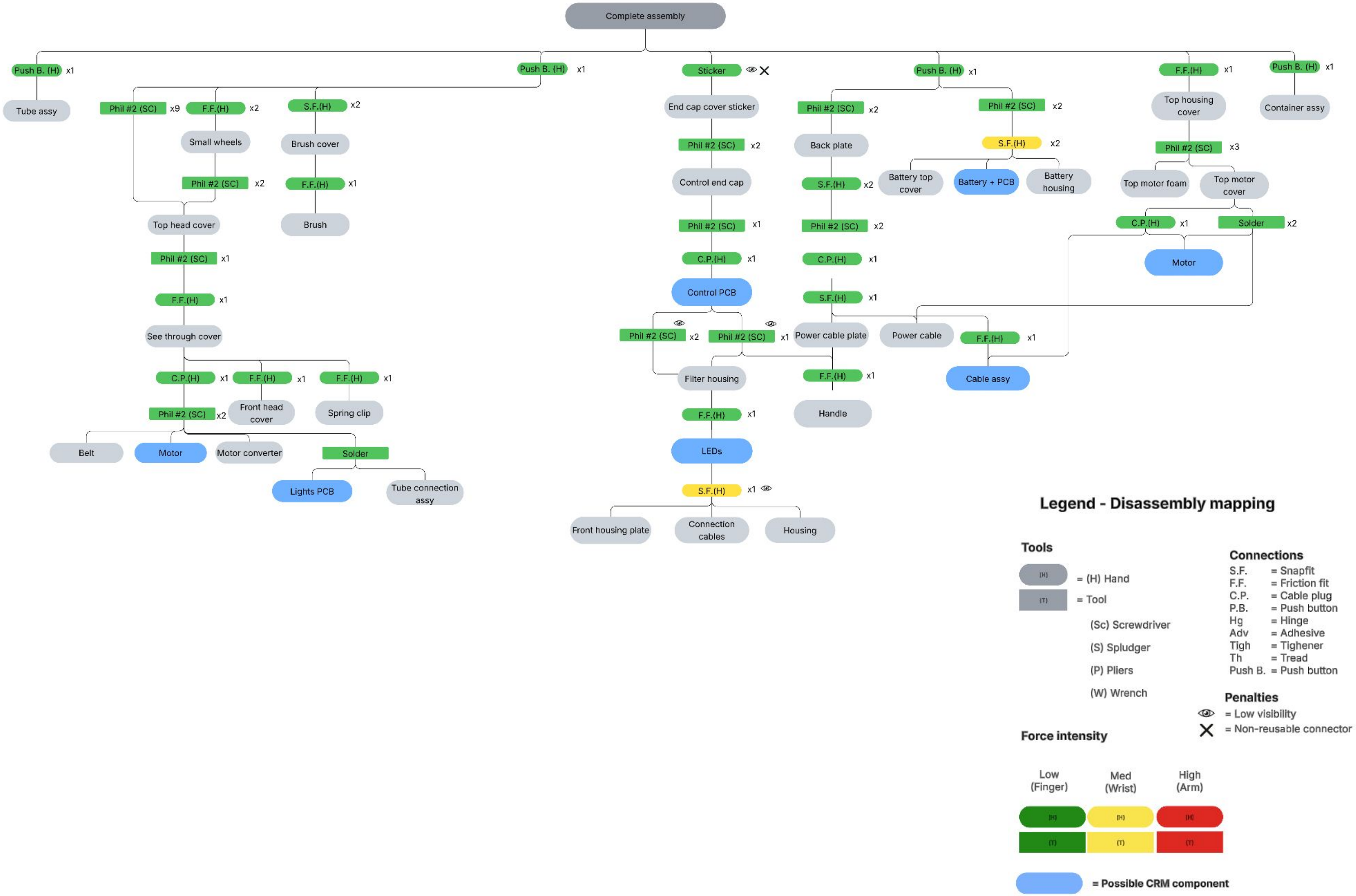
= Non-reusable connector

Force intensity

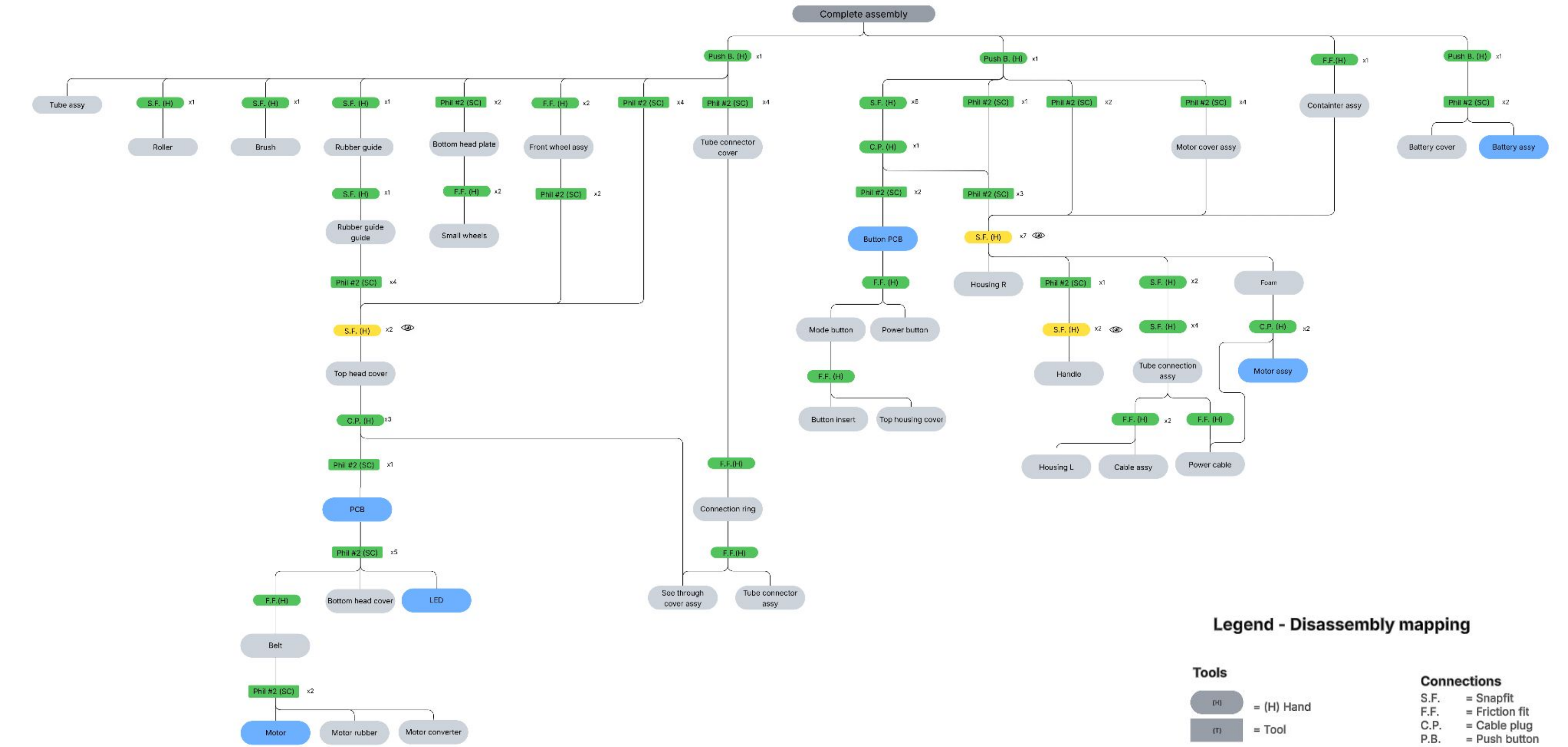
Low (Finger)	Med (Wrist)	High (Arm)
(H)	(H)	(H)
(T)	(T)	(T)

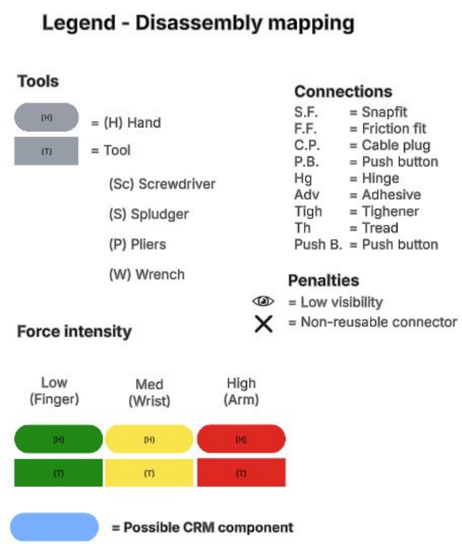
= Possible CRM component

Zedar s600 Disassembly map

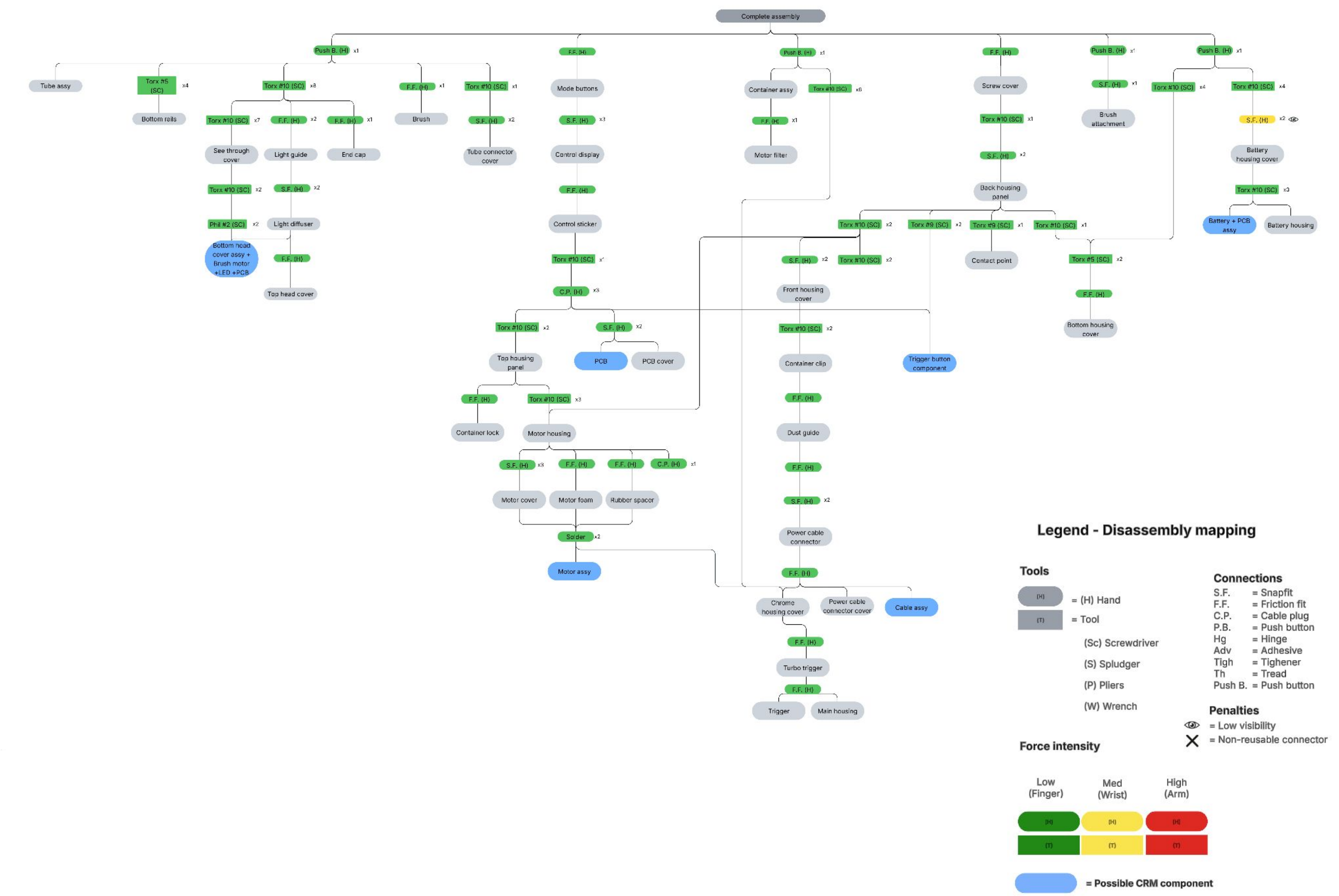


Hoover H-Free 500 HYDRO plus Disassembly map





Rowenta x force flex Disassembly map



Appendix D - Vacuum cleaner Bill of Materials

Vytronix

Part number	Part name	Weight (g)	Material	CRM
1	Head cover	105.3	ABS	
2	Wheel	2.4	Rubber	
3	Brush	35.0	Mixed	
4	See through cover	34.8	PC	
5	Motor converter	12.5	Mixed	
6	Foam cover	0.1	PU	
7	Brush motor	97.5	Mixed	CRM
8	Bottom head assembly	188.6	ABS	
9	Cable cover	42.0	ABS	
10	Bottom tube connector	35.3	ABS	
11	Inner tube	25.8	ABS	
12	Top tube connector	36.0	ABS	
13	Outer tube	176.4	ABS	
14	Battery connector	10.2	Electronics	
15	Front housing cover	50.4	ABS	
16	Motor	249.2	Mixed	CRM
17	Foam motor cover	0.1	PU	
18	PCB assembly	28.5	Electronics	CRM
19	Trigger	4.0	ABS	
20	Battery release button	8.2	ABS	
21	Side housinig R	119.5	ABS	
22	Side housing L	119.5	ABS	
23	Top housing cover	24.0	ABS	
24	Container release panel	22.6	ABS	
25	Top container assembly	105.9	ABS	
26	Filter	27.9	Mixed	
27	Filter cover assembly	119.4	ABS	
28	Container housing	242.4	PC	
29	Top battery cover	32.5	ABS	
30	Battery assembly	304.8	Electronics	CRM
31	Bottom battery assembly	39.7	ABS	

Turbotronic TT-CF7

Part number	Part name	Weight (g)	Material	CRM
1	LED cover	16.4	Mixed	
2	See through cover	138.8	PC	
3	Brush motor	155.6	Mixed	CRM
4	Side panel L	19.3	ABS	
5	Motor belt	1.5	Rubber	
6	Brush	56.1	Mixed	
7	Top head cover	41.0	ABS	
8	Inner dust guide	29.0	ABS	
9	Bottom head cover	62.5	ABS	
10	wheels	3.4	Mixed	
11	Head to tube assembly	138.8	ABS	
12	Bottom connector cover	27.3	ABS	
13	Bottom connector	31.1	ABS	
14	Tube	138.6	Mixed	
15	Top connector cover	21.2	ABS	
16	Top connector	29.5	ABS	
17	Motor front cover	70.2	ABS	
18	Motor	137.3	Mixed	CRM
19	Motor housing	37.2	ABS	
20	Outing housing	89.4	ABS	
21	PCB	13.6	Electronics	CRM
22	Interace cap	21.5	ABS	
23	Container connector	22.8	ABS	
24	dust guide	15.5	ABS	
25	silicon ring	3.7	Silicon	
26	Cable connector	2.5	ABS	
27	Tirgger	2.6	ABS	
28	Controller handle	99.0	ABS	
29	calbe assembly	18.4	Electronics	CRM
30	Battery relese button	1.6	ABS	
31	Bottom housing cover	4.5	ABS	
32	Container	160.2`	PC	
33	Filter assembly	147.3	Mixed	
34	Filter	31.6	Mixed	
35	Battery cover	4.5	ABS	
36	Battery assembly	392.9	Electronics	CRM

AEG QX8 animal X power

Part num	Part name	Weight (g)	Material	CRM
1	Head cover	70.8	ABS	
2	See through cover	96.4	PC	
3	Brush motor assembly	311.9	Mixed	CRM
4	Bottom head cover	50.0	ABS	
5	Tube connector	22.1	Mixed	
6	Wheel assembly	76.8	Rubber	
7	Side panel	3.7	ABS	
8	Brush connection ring	0.9	Rubber	
9	Top stick cover	120.1	ABS	
10	Bottom stick cover	135.8	ABS	
11	Cable assembly	36.1	Electronics	CRM
12	Container	104.8	ABS	
13	Filter cover	21.9	mixed	
14	Filter	62.7	Mixed	
15	Top controller housing	88.5	ABS	
16	PCB cover	4.9	ABS	
17	Electronics assembly	309.4	Mixed	CRM
18	Bottom controller housing	195.2	ABS	
19	Main housing top	233.8	ABS	
20	Main housing bottom	290.1	ABS	

Dyson V11 absolute

Part number	Part name	Weight (g)	Material	CRM
1	Front head cover	25.6	ABS	
2	Outer brush	92.8	Mixed	
3	Brush end cap	13.1	ABS	
4	Motor top cover	7.4	ABS	
5	Motor side cover	10.8	ABS	
6	Inner brush assembly	246.2	Mixed	CRM
7	Head to tube assembly	117.7	Mixed	
8	Outer head body	111.9	ABS	
9	See through cover	74.9	ABS	
10	top head cover	20.1	ABS	
11	Container	262.7	Mixed	
12	Container rail	27.7	ABS	
13	Filter assembly top	122.8	Mixed	
14	Filter assembly middle	31.4	Mixed	
15	Filter assembly inside component	71.7	Mixed	
16	Filter assembly bottom	87.5	Mixed	
17	Cable cover	0.6	High-carbon steel	
18	Cable rings	4.8	High-carbon steel	
19	Filter assembly bottom cover	64.3	Mixed	
20	Tube assembly	254.0	Mixed	
21	Power calbe cover	6.4	ABS	
22	PCB cover	14.4	ABS	
23	Handle	108.8	ABS	
24	Filter	113.6	Mixed	
25	Motor + PCB assembly	267.2	Mixed	CRM
26	Trigger assembly	39.7	Mixed	CRM
27	Battery assembly	490.3	Mixed	CRM

Turbotronic TT-CF4

Part number	Part name	Weight (g)	Material	CRM
1	Brush	30.9	Mixed	
2	See through cover	42.9	PC	
3	Top head cover	58.7	ABS	
4	Light PCB	4.5	Electronics	CRM
5	Motor	87.0	Mixed	CRM
6	Belt	1.2	Rubber	
7	Light defuser	1.1	PC	
8	Buttom head cover	96.5	ABS	
9	Wheels	4.0	Rubber	
10	Tube connector	141.5	Mixed	
11	Container	122.8	PC	
12	Outer filter	42.3	ABS	
13	Filter	24.0	Mixed	
14	Tube	235.6	Mixed	
15	Sticker	1.6	PC	
16	Top cover	57.1	ABS	
17	Tube spring	1.5	Mixed	
18	Handle	47.4	ABS	
19	Cable assy	21.1	Electronics	CRM
20	Tube guide	18.7	ABS	
21	Housing L	102.2	ABS	
22	Container connector	6.5	ABS	
23	Housing R	85.4	ABS	
24	Battery	337.4	Electronics	CRM
25	Battery cover	13.6	ABS	
26	Motor	228.0	Mixed	CRM
27	Motor cover	25.6	ABS	
28	Motor ring	8.3	Rubber	
29	Battery container	46.1	ABS	
30	Battery springs	4.2	High carbon steel	

Sauber R20

Part number	Part name	Weight (g)	Material	CRM
1	Brush	36.4	Mixed	
2	See through cover	33.5	PC	
3	Top head cover	107.1	ABS	
4	Brush motor	105.6	Mixed	CRM
5	Motor converter	18.2	ABS	
6	Bottom head assy	93.5	ABS	
7	Wheels	1.9	Mixed	
8	Tube connector assy	108.8	Mixed	CRM
9	Cable cover	4.1	ABS	
10	Container	147.6	PC	
11	Filter	115.2	ABS	
12	Filter 2	0.7	Mixed	
13	Filter cover	27.5	ABs	
14	Tube	394.1	Mixed	
15	Motor cover	38.2	ABS	
16	Motor foam	1.5	PU	
17	Motor PCB cover	4.8	ABS	
18	Rubber support	13.1	Rubber	
19	Motor	166.5	Mixed	CRM
20	Motor rubber	31.4	Rubber	
21	Foam	0.1	PU	
22	PCB	22.1	Electronics	CRM
23	Motor housing	77.9	ABS	
24	Cable assy	1.9	Electronics	
25	Cable	3.5	Electronics	
26	Top housing	78.1	ABS	
27	Cable ring	5.5	High-carbon steel	
28	Bottom housing assy	126.4	ABS	
29	Charger cable	5.6	Electronics	
30	Buttom cover	33.1	ABS	
31	Trigger cable	1.7	Electronics	
32	Battery housing	53.7	ABS	
33	Battery housing cover	32.1	ABS	
34	Battery + PCB	215.6	Electronics	CRM
35	Trigger	3.8	ABs	
36	Spring	2.1	High-carbon steel	
37	Trigger pcb	1.5	Electronics	CRM
38	Trigger cover	10.8	ABS	

Severin S Special

Part number	Part name	Weight (g)	Material	CRM
1	Brush	38.7	Mixed	
2	Brush clip	3.0	ABS	
3	See through cover	48.1	PC	
4	Top head cover	80.6	ABS	
5	LED	9.4	Electronics	CRM
6	Brush motor	76.4	Mixed	CRM
7	Motor converter	17.5	Mixed	
8	Belt	1.4	Rubber	
9	Bottom head cover	142.1	ABS	
10	Tube connector	89.1	ABS	
11	Tube connector cover	8.5	ABS	
12	Container	251.2	PC	
13	Lid button	6.3	ABS	
14	Lid	30.4	ABS	
15	Light panel	16.7	ABS/PC	
16	Light defuser	8.4	Rubber	
17	Top housing	77.2	ABS	
18	Rails	11.9	ABS	
19	Main housing	243.9	ABS	
20	Filter cover	86.8	Mixed	
21	Filter	120.3	Mixed	
22	Tube	314.5	Mixed	
23	Foam	2.0	PU	
24	Motor	197.3	Mixed	CRM
25	Motor front cover	16.0	Mixed	
26	Motor foam	1.6	PU	
27	Motor cover front	31.6	Mixed	
28	PCB Cable	8.6	Electronics	CRM
29	Power button	3.1	ABS	
30	Charger cable	2.6	Electronics	
31	Battery cable assy	12.3	Electronics	CRM
32	Back panel	18.6	ABS	
33	Bottom panel	13.5	ABS	
34	Battery housing cover	20.2	ABS	
35	Battery + PCB	317.8	Electronics	CRM
36	Battery housing	68.9	ABS	
37	Battery connection buttons	5.2	ABS	

Zedar S600

Part number	Part name	Weight (g)	Material	CRM
1	Brush	98.2	Mixed	
2	See through cover	49.0	PC	
3	Top head cover	71.1	ABS	
4	front head cover	10.3	ABS	
5	Lights PCB	4.7	Electronics	CRM
6	Brush motor	164.5	Mixed	CRM
7	Belt	1.3	Rubber	
8	Motor converter	35.2	Mixed	
9	Tube connector assy	125.6	Mixed	
10	Bottom head cover	180.8	ABS	
11	Brush clip	4.4	ABS	
12	Spring clip	1.5	ABS	
13	See through motor cover	55.1	PC	
14	Plastic motor cover	32.6	ABS	
15	Filter housing	83.4	ABS	
16	Outer filter	44.8	Mixed	
17	Filter	36.6	Mixed	
18	Tube	277.5	Mixed	
19	Container	223.1	PC	
20	Top motor foam	0.1	Polyurethane	
21	Top motor cover	18.8	ABS	
22	Top housing cover	26.9	ABS	
23	Motor	153.7	Mixed	CRM
24	Motor rubber	15.3	Rubber	
25	Motor PCB cover	9.7	ABS	
26	Rubber support	5.9	Rubber	
27	Front housing plate	4.3	ABS	
28	connector cables	3.2	Electronics	
29	Housing	94.9	ABS	
30	LEDs	6.6	Electronics	CRM
31	Control PCB	3.5	Mixed	CRM
32	Control end cap	6.4	ABS	
33	End cap cover sticker	0.8	PC	
34	Handle	50.6	ABS	
35	Back plate	1.6	ABS	
36	Cable assy	4.6	Electronics	
37	Power cable	15.6	Electronics	CRM
38	Power cable plate	2.6	ABS	
39	Battery top cover	25.4	ABS	
40	Battery + PCB	305.3	Electronics	CRM
41	Battery housing	42.1	ABS	

Hoover H-Free 500 Hydro plus

Part number	Part name	Weight (g)	Material	CRM
1	Brush	105.1	Mixed	
2	Roller	94.4	Mixed	
3	Top head cover	150.0	ABS	
4	Front wheel assy	26.5	Mixed	
5	Rubber guide	16.2	Rubber	
6	Rubber guide guide	4.7	Rubber	
7	See through cover	150.0	ABS	
8	Bottom head cover	178.4	ABS	
9	Connection ring	0.9	ABS	
10	Tube connector cover	19.1	ABS	
11	Tube connector	150.0	Mixed	
12	Bottom head plate	9.6	ABS	
13	LED	5.2	Electronics	CRM
14	PCB	4.6	Electronics	CRM
15	Brush motor	160.4	Mixed	CRM
16	Motor rubber ring	5.2	Rubber	
17	Belt	2.3	Rubber	
18	Motor converter	29.0	ABS	
19	Tube	265.2	Mixed	
20	Top housing cover	23.3	ABS	
21	Mode button	3.7	ABS	
22	Power button	1.7	ABS	
23	Button insert	1.4	ABS	
24	Button PCB	5.5	Electronics	CRM
25	Foam	0.8	PU	
26	Housing L	105.0	ABS	
27	Tube connection	26.2	ABS	
28	Tube connection 2	16.8	ABS	
29	Tube connection 3	23.9	ABS	
30	Motor rubber cover	22.2	Rubber	
31	Motor	219.3	Mixed	CRM
32	Power cable	16.2	Electronics	
33	Cable assy	6.1	Electronics	
34	Motor cover	32.8	ABS	
35	Housing R	101.0	ABS	
36	Handle	27.8	TPE	
37	Battery cover	9.5	ABS	
38	Battery housing + Battery	347.2	Electronics	CRM
39	Rubber	0.8	Rubber	
40	Container	143.5	Mixed	
41	Filter	85.0	ABS	
42	Filter top	19.0	Mixed	

Rowenta X force flex 12.60

Part number	Part name	Weight (g)	Material	CRM
1	Brush	143.7	Mixed	
2	Head real	14.1	ABS	
3	See through cover	92.0	PC	
4	Light defuser	6.0	PC	
5	Light guide	0.9	PC	
6	Top head cover	48.3	ABS	
7	End cap	7.3	ABS	
8	Bottom head cover assy	231.1	Mixed	
9	Brush motor	182.6	Mixed	CRM
10	Tube connect cover	11.7	ABS	
11	Motor filter	68.1	Mixed	
12	Container	188.8	Mixed	
13	Outer filter	87.8	Mixed	
14	Inner filter	58.6	Mixed	
15	Tube	624.5	Mixed	
16	Control display	4.2	ABS	
17	Mode buttons	2.7	ABs	
18	Control sticker	0.5	ABS	
19	PCB cover	2.9	ABS	
20	PCB	8.2	Electronics	CRM
21	Top housing panel	17.7	ABS	
22	Container lock	8.9	ABS	
23	Motor housing	114.9	ABS	
24	Motor foam	0.01	PU	
25	Front housing cover	2.0	ABS	
26	Container clip	2.2	ABS	
27	Chrome housing cover	69.9	ABS	
28	motor cover	13.5	ABS	
29	Motor	188.6	Mixed	CRM
30	Motor back cover	37.7	ABS	
31	Rubber spacer	7.8	Rubber	
32	Cable assy	20.2	Electronics	CRM
33	Dust guide	31.1	ABS	
34	Power cable connector	3.4	ABS	
35	Power cable connector cover	1.2	ABS	
36	Turbo trigger spring	0.01	High-carbon steel	
37	Turbo trigger	13.2	ABS	
38	Trigger	4.6	ABS	
39	Main housing	206.5	ABS	
40	Contact point (grounding point)	14.5	Zinc alloy	
41	Trigger button component	4.2	Electronics	CRM
42	Back housing panel	25.9	ABS	
43	Battery housing	30.7	ABS	
44	Battery + PCB	378.3	Electronics	CRM
45	Batter housing cover	55.7	ABS	
46	Bottom housing cover	20.5	ABS	
47	Rubber spacer brush motor	4.3	Rubber	
48	Brush attachment	12.2	Mixed	
49	Screw cover	2.8	Rubber	

Appendix E - CRM hotspot mapping inputs and component scoring

This appendix presents the material-level Economic Importance (EI) and Supply Risk (SR) values used in the CRM hotspot mapping method described in Section 3.4. These values are derived from the European Commission Critical Raw Materials assessment (European Commission, 2023) and form the basis for evaluating material criticality.

For each CRM-containing component, relevant CRMs were identified based on literature and typical component compositions. This approach provides an indicative measure of component-level criticality, to support prioritisation for CRM components. CRM mass relevance was assessed separately. Component weights were measured during disassembly and the average weight for each component type was calculated across the ten analysed vacuum cleaner models. The percentage of CRM content within components was estimated based on literature and used to categorise components into low, medium, and high CRM mass relevance.

The following tables present the material-level EI and SR values, the criteria used for cutoff points, the method for combining EI and SR into material criticality, the resulting component-level criticality and CRM mass relevance assessments and the final hotspot scores as presented in section 4.2.2.

Material level EI and SR values from European Commission. (2023)

Material	Supply risk	Economic importance
Neodymium	4.5	7.2
Dysprosium	5.6	7.8
Praseodymium	3.2	7.0
Boron	3.6	3.9
Lithium	1.9	3.9
Cobalt	2.8	6.8
Natural graphite	1.8	3.4
Palladium	1.5	8.1
Tantalum	1.3	4.8
Gallium	3.9	3.7
Indium	0.6	2.6
Copper	0.1	4.0
Nickel	0.5	5.7

Criteria cutoff points

Criteria	Low	Medium	High
Supply risk	< 2.0	2.0 - 3.5	> 3.5
Economic importance	< 4.0	4.0 - 6.0	> 6.0
CRM mass relevance	< 0.01%	0,01% - 1%	> 1 %

Combining SR and EI into CRM criticality

	Low SR	Medium SR	High SR
Low EI	Low criticality	Low criticality	Medium criticality
Medium EI	Low criticality	Medium criticality	High criticality
High EI	Medium criticality	High criticality	High criticality

Component-level CRM criticality results

Component	Material	SR average	EI average	Criticality
Drive motor	Neodymium, (Dysprosium), (Praseodymium), Boron, Copper	4.2	6.5	High
Brush motor	Neodymium, (Dysprosium), (Praseodymium), Boron, Copper	4.2	6.5	High
Battery cells	Lithium, Cobalt, Natural graphite, Copper	2.1	4.7	High
PCBA	Palladium, (Tantalum), Nickel, Copper	1.4	6.4	Medium
Cables	Copper	0.1	4.0	Low
LED lights	Gallium, Indium	2.2	3.1	Low

Component-level CRM mass relevance assessment

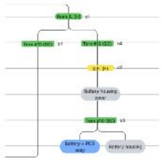
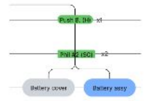
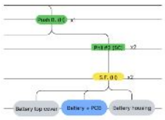
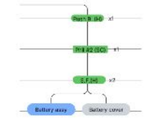
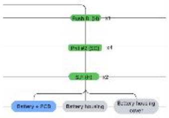
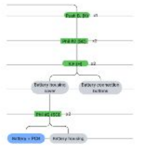
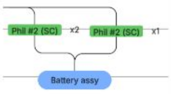
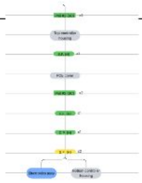
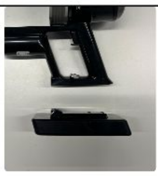
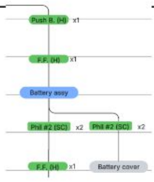
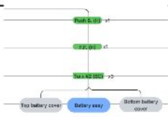
Component	Material	Component weight average (g)	CRM content	CRM mass relevance	Source
Drive motor	Neodymium, (Dysprosium), (Praseodymium), Boron, Copper	209	>1%	High	(Zhang et al., 2020)
Brush motor	Neodymium, (Dysprosium), (Praseodymium), Boron, Copper	128,7	>1%	High	(Zhang et al., 2020)
Battery cells	Lithium, Cobalt, Natural graphite, Copper	334,9	>1%	High	(Ghatak et al., 2018)
PCBA	Palladium, (Tantalum), Nickel, Copper	14.3	0,01% - 1%	Medium	(European Commission.2019)
Cables	Copper	-	*>1% (only SRM)*	-	(Li et al., 2017)
LED lights	Gallium, Indium	7.6	< 0,01%	Low	Professor of Circular Product Design at TU Delft

CRM hotspot scores

Component	Material	Criticality	CRM mass relevance	Hotspot score
Drive motor	Neodymium, (Dysprosium), (Praseodymium), Boron, Copper	High	High	High
Brush motor	Neodymium, (Dysprosium), (Praseodymium), Boron, Copper	High	High	High
Battery cells	Lithium, Cobalt, Natural graphite, Copper	High	High	High
PCBA	Palladium, (Tantalum), Nickel, Copper	Medium	Medium	Low
Cables	Copper	Low	-	Low
LED lights	Gallium, Indium	Low	Low	Low

Appendix F -Vacuum cleaner CRM Component

Battery + Battery PCB assembly

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex			-Removable battery	-Hard to open the battery assembly due to snapfits -Battery and PCB are soldered togehter	Use less hard snapfits for opening the assembly
Hoover H-Free 500 HYDRO plus			-Removable battery	-Hard to open the battery assembly	Use less hard snapfits for opening the assembly
Zedar s600			-Removable battery	-Hard to open the battery assembly due to snapfits -Battery and PCB are soldered togehter	Use less hard snapfits for opening the assembly
Turbotronix TT-CF4			-Removable battery	-Hard to open the battery assembly	Use less hard snapfits for opening the assembly
Sauber R3			-Removable battery -Easy to open battery assembly	-Battery and PCB are soldered togehter	
Severin S Special			-Removable battery -Easy to open battery assembly	-Battery and PCB are soldered togehter	Use less hard snapfits
Dyson v1			-Removable battery	-Battery assembly is secured in by screws -Difficult to open the battery assembly	Make it easier to open battery assembly
AEG QX8 animal x power			-CRM components are close together	-Non removable battery -Hard to reach the battery components	Make battery removable
Turbotronix TT-CF			-Removable battery	-Screws under the battery assembly -Hard to open the battery assembly	Make it easier to open battery assembly
Vytroni			-Removable battery -Easy to open battery assembly	-Akward release button position -Battery and PCB are soldered togehter	

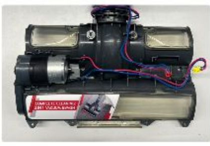
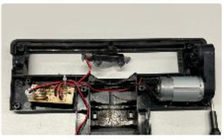
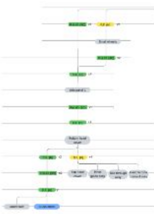
Battery assembly general findings

General findings

- Battery is most often removable
- The battery and PCB are soldered together almost every time
- Battery assembly is often located at the bottom of the housing

Method/Findings	CRM efficient
Have an easily removable battery assembly. eg. Pushbutton release	This enables you to quickly liberate or swap CRM components from the assembly. If the battery is hard to remove it is less likely to be relaced, causing product disposel. whereas if you can replace the battery easily you can extent the products lifetime.
Enable the opening of the battery assembly to liberate the battery cells and the PCB.	Allowing the battery assembly to be openend helps the liberation of components and reprocessing of CRMs
Standardisation of battery cells Standardisation of battery components is less realistic --> limits product shape ect.	Allows swapping off battery cells, similar connection methods, improve recovery rate and reuse.

Brush motor

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex			-Relatively straightforeward disassembly	-Hard to saperate the motor from the housing -Hidden screws beneeth the small wheels	Make motor accessible for liberation
Hoover H-Free 500 HYDRO plus			-The motor is connected with a cable plug that can easily be unplugged	-Hard snapfits make it difficult to open the head assembly	Use less light snapfits to secure housing
Zedar s600			-The motor can be easiliy removed through cable plugs	-Hidden screws beneeth the small wheels	
Turbotronix TT-CF4			-Relatively straightforeward disassembly	-The motor is soldered to the cables	Use cable plugs to connect motor
Sauber R20			-The motor can be easiliy removed through cable plugs -Relatively straightforeward disassembly	-Hidden screws beneeth the small wheels	
Severin S Special			-Relatively straightforeward disassembly	-Hidden screws beneeth the small wheels -The motor is soldered to the cables	Use cable plugs to connect motor
Dyson v11				-Hard to saperate the motor from the housing -Different types of screws used	Make motor accessible for liberation
AEG QX8 animal x power				-Hard to saperate the motor from the housing -Hard to figure out how to disassemble	Make motor accessible for liberation
Turbotronix TT-CF			-Motor can be disassembled from the cables with cable plugs	-Hard to figure out how to disassemble -Many staps to reach motor -Hidden screws beneeth the small wheels -Excessive use of snapfits and covers make it hard to disassemble	Use less steps and snapfits to reach motor. Usecues to guide through disassembly
Vytronix			-Relatively straightforeward disassembly	-Hidden screws beneeth the small wheels -The motor is soldered to the cables	Use cable plugs to connect motor

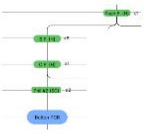
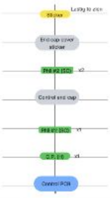
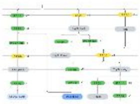
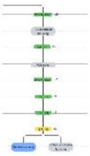
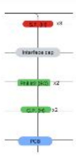
Brush motor general findings

General findings

- Similar disassembly steps across different models.
- Hidden screws underneeth wheels
- Friction fit components
- Components hidden within the brush axle
- Similar type of brushed motors are used (different models)

Method/Findings	CRM efficient
Use friction fit to secure the motor to the housing	This makes it easy to liberate the component, helping in repair and recycling, by not fastening with screws or irreversable snapfits. If the component can be easily replaced --> less new CRM is needed.
Using similar disassembly steps in the head assembly helps to easy the disassembly.	An easier disassembly means more successful repairs --> longer product lifetime --> less new CRM needed.
Use cable plugs to connect the brush motor to wires helps to make liberation easier	Without the need of soldering It becomes easier to liberate the CRM from the motor. Using cable pugs in compination with friction fit connections can surface the brush motor component
Standardization of motor type	Setting standards for motors can limit the overstandsardization of certain motors, that use more CRMs then necessary to power motors. Setting a limit can control the amount of CRM that can enter the product. Standards will need to be updated, as innovations can improve CRM effiency over time by creating more magnet efficient motors for example. Using similar motor types can help with repair of the product by making it easier to get spare parts.
Mitigate the use of snapfits that hold the head assembly together	Snapfits are a less intuative connection method to disassemble, they tend to get damaged when trying to open the product and make it difficult to see how to open the product. By using less snapfits --> easier repair --> longer product lifetime.
Add usecues on how to disassemble the product	Helps with understanding how to open the product, so that you don't accidentally damage the product during repair, shortening its lifespan.

Control PCBA

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex			-Removable PCB by usage of cable plugs -Relatively easy to reach component (straightforward) -Can reach the component from the exterior of the housing -Only one screw is used to secure the PCB together with snapfits	-Lack of usecues how to disassemble	-Usecues showing how to disassemble
Hoover H-Free 500 HYDRO plus			-Removable PCB by usage of cable plugs -Can reach the component from the exterior of the housing	-Lack of usecues -Difficult to see how to reach the component -Two screws used to secure PCB	-Usecues showing how to disassemble
Zedar s600			-Removable component due to cable plug -Only one screw used to secure component -Can reach the component from the exterior of the housing	-Hard to access component due to lack of usecues (sticker on top to hide screws)	-Usecues showing how to disassemble
Turoctronix TT-CF4			-PCB is located on underneath a top cover on the outside of the main housing	-Component is hard to liberate due to soldering cables instead of cable plugs	-Add cable plugs to connect to PCB
Sauber R20			-Component can be liberated due to cable plug connections -Only one screw is used to connect PCB	-PCB is located on the inside of the housing and is hard to reach. -Screw to fasten components are hard to reach	Make PCB easier to reach (less deep in assembly)
Severin S Special			-Component can be liberated through the usage of snapfits -Only snapfits are used to secure component -Can reach the component from the exterior of the housing	Panel that covers the PCB component is not easy to liberate due to somewhat hidden snapfits	-Usecues showing how to disassemble
Dyson v11			-Only one PCB is used throughout the product. -The motor/PCB assembly can be liberated without soldering (cable plugs)	-Liberating the component is hard to due to the power calbe connection pieces that need to fit through a cutout. -Motor and PCB cannot easily be liberated. -PCB is located on the inside of the housing and is hard to reach.	Make PCB and motor removable from eachother
AEG QX8 animal x power			-All CRM components are located close together and can be liberated as one	-The components are soldered together and are hard to liberate from eachother -PCB is located on the inside of the housing and is hard to reach. -Screws and snapfits are used to fasten the component	Make the PCB easier to reach and use snapfits and cable plugs to fasten the component
Turoctronix TT-CF			-The component can be liberated by use of cable plugs. The component is not deep in the assembly -Can reach the component from the exterior of the housing	-Figuring out how to reach the component is hard, the snapfits are to strong and irreversable	Usecues to indicate how to open assembly and no irreverable snapfits
Vytronix			-Disassembly is relatively straigthforward, No hidden screws or irreversable snapfits. easy to figure out how to reach component.	-PCB is located on the inside of the housing and is hard to reach. -PCB is soldered to components making it difficult to liberate	Use cable plugs to connect to cables Make PCB accessible from the exteriour.

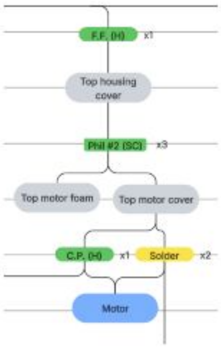
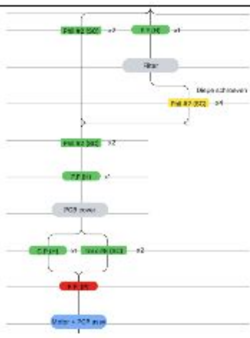
Control PCB general findings

General findings

• Reachable underneeth snapfits, that are not always easy to spot
• Sometimes hidden deep within the assembly
• All PCBS have different chapes and sizes
• There is a need for some sort of indicator how to access the component

Method/Findings	CRM efficient
Use friction fit to secure the component to the housing	This makes it easy to liberate the component, helping in repair and recycling, by not fastening with screws or irreversable snapfits. If the component can be easily replaced --> less new CRM is needed.
Surfacing the PCB by making it accesible from the exterior of the housing	This makes it easier to liberate the CRM component allowing it to be replaced or collected.
Mitigate the use of snapfits that hold the head assembly together	Snapfits are a less intuative connection method to disassemble, they tend to get damaged when trying to open the product and make it difficult to see how to open the product. By using less snapfits --> easier repair --> longer product lifetime.
Use cable plugs to connect the PCB to wires helps to make liberation easier	Without the need of soldering It becomes easier to liberate the component Using cable pugs in compination with friction fit connections can surface the component
Add usecues on how to disassemble the product	Helps with understanding how to open the product, so that you don't accidentally damage the product during repair, shortening its lifespan.
Clumping PCB modules together	Clumping the PCB modules together creates a PCB hotspot within the product disassembly --> making it easier to liberate the PCBs

Motor + PCB

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex				-The components is soldered to the power cables -The PCB is potted in ressin -It takes a lot of steps to reach the component, its hidden deep within the assembly	Use Cable plugs to connect the motor PCB assembly surface the motor assembly
Hoover H-Free 500 HYDRO plus			-The motor assembly can be liberated by cable plugs -Once the housing is opened, the motor is only fastened with friction fit and cable plugs to the housing. so no screws are used.	-It takes quite a lot of steps to figure out how to open the housing assembly to reach the motor.	Usecues to help with opening the main housing
Zedar s600			The motor assembly is easy to reach by staightforeward steps and the motor is only friction fitted on the housing. The Motor and PCB can be seperated by unplugging cable plugs and screws	-The moter is soldered to the power cables	*Use only cable plugs to reach the motor PCB assembly*
Sauber R20			-The motor can be liberated by cable plugs -The motor is straightforward to reach --> open motor covel, pull out the assembly and disconnect the cable plugs. The motor component is frictionfit to the housing, so no screws or snapfits are used. The Motor and PCB can be seperated by unplugging cable plugs and screws		
Dyson v11			-The assembly can be removed without soldering so with cable plugs and screws	-The PCB and motor are hard to liberate from eachother due to soldering. -Liberating the component is hard to due to the power calbe connection pieces that need to fit through a cutout. -The assembly is hard to take apart	

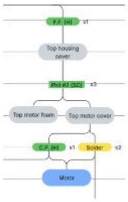
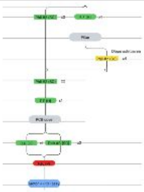
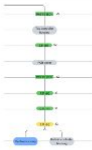
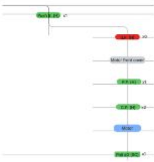
Motor + PCB general findings

General findings

- 5 models of vacuumcleaners use motors that imcorperate PCBs and are likely more powerfull BLDC motors.
- These motors and PCBs are soldered together

Method/Findings	CRM efficient
Do not use resin the pot the PCB	This makes it harder to liberate the component, making it harder to recycle the PCB
Standardization of motor type	Setting standards for motors can limit the overstandsardization of certain motors, that use more CRMs then necessary to power motors. Setting a limit can control the amount of CRM that can enter the product. Standards will need to be updated, as innovations can improve CRM effiency over time by creating more magnet efficient motors for example. Using similar motor types can help with repair of the product by making it easier to get spare parts.
Use cable plugs to connect the motor to wires helps to make liberation easier	Without the need of soldering It becomes easier to liberate the CRM from the motor. Using cable pugs in compination with friction fit connections can surface the motor component
Essentialization can limit the functionality requirements of the motor	This can push for a simpler motor desgin that uses less permanent magnets for instance.

Motor

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex			-The motor is not screwed or snapfitted to the housing	-It takes a lot of steps to reach the component, its hidden deep within the assembly -The motor is soldered to the power cables and therfore more difficult to liberate	Surfacing the motor assembly
Hoover H-Free 500 HYDRO plus			-The motor assembly can be liberated by cable plugs -Once the housing is opened, the motor is only fastened with friction fit and cable plugs to the housing. so no screws are used.	-It takes quite a lot of steps to figure out how to open the housing assembly to reach the motor. -Hard snapfits	Usecues to help with opening the main housing Surfacing
Zedar s600			-The motor assembly is easy to reach by staightforeward steps and the motor is only friction fitted on the housing.	-The moter is soldered to the power cables -The PCB and motor are hard to liberate from eachother due to soldering.	Use only cable plugs to reach the motor PCB assembly
Turbotronix TT-CF4			-The motor assembly can be liberated by cable plugs -Once the housing is opened, the motor is only fastened with friction fit and cable plugs to the housing. so no screws are used.	-It takes quite a lot of steps to figure out how to open the housing assembly to reach the motor. -Hard snapfits	Usecues to help with opening the main housing Surfacing
Sauber R20			-The motor assembly can be liberated by cable plugs -The motor assembly is easy to reach by staightforeward steps and the motor is only friction fitted on the housing.	The motor housing is quite tight and makes it more difficult with all the calbles to connect them.	Usecues
Severin S Special			The motor is frictionfitted in the housing -The motor assembly can be liberated by cable plugs	A lot of steps to open the top housing, making it harder to reach the motor assembly	Surfacing
Dyson v11			-The assembly can be removed without soldering so with cable plugs and screws	-The PCB and motor are hard to liberate from eachother due to soldering. -Liberating the component is hard to due to the power calbe connection pieces that need to fit through a cutout. -The assembly is hard to take apart	Different connection types. Surfacing -->although it is already quite good
AEG QX8 animal x power			The motor is frictionfitted in the housing All CRM heavy components are clumped toghether	-The PCB and motor are hard to liberate from eachother due to soldering. -Hard snapfits are used to secure the housing what makes it hard to open	Other connections to hold the housing Cable plug connections
Turbotronix TT-CF			-Cable plugs allow the motor to be liberated easily -Besides the hard snapfits, a easy and straightforeward disassembly	-Hard snapfits are used to secure the motor front cover what makes it hard to open	Usecues to show that snapfits are used, Other fastening method to fasten motor front cover
Vytronix			-Once the housing is opened, the motor is only fastened with friction fit and cable plugs to the housing. so no screws are used.	It takes a lot of steps to open the housing. with deep screws.	Less screws to open the assembly

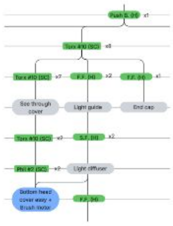
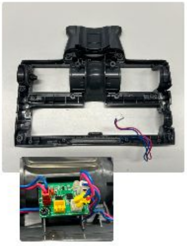
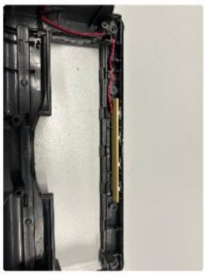
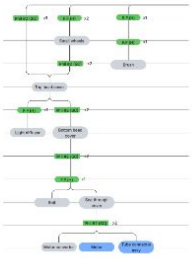
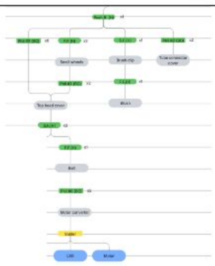
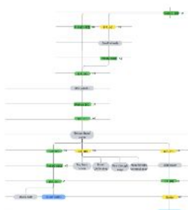
Main Motor general findings

General findings

• 5 models of vacuumcleaners use motors that imcorperate PCBs and are likely more powerfull BLDC motors.
• These motors and PCBs are sometimes together
• The other 5 motors are more "traditional" brushed motors, similar to the brush motors in the head assembly
• All motors are friction fitted into the housing and supported with rubber supports to be kept in place.
• There are 2 types of housings --> split housings that open up creating two halves and housing that has access points that open. The split housings need to be fully opened to reveal the motor whereass the other housings have acces points revealing the motor.
• The brushed motors have a spiral cover piece to create the suction for the vacuum cleaner.

Method/Findings	CRM efficient
Using friction fit to fasten the motor component	improves the ease fo disassemlby of the product and allows for easier liberation of CRM component.
Standardization of motor type	Setting standards for motors can limit the overstandsardization of certain motors, that use more CRMs then necessary to power motors. Setting a limit can control the amount of CRM that can enter the product. Standards will need to be updated, as innovations can improve CRM effiency over time by creating more magnet efficient motors for example. Using similar motor types can help with repair of the product by making it easier to get spare parts.
Use cable plugs to connect the motor to wires helps to make liberation easier	Without the need of soldering It becomes easier to liberate the CRM from the motor. Using cable pugs in compination with friction fit connections can surface the motor component
Essentialization can limit the functionality requirements of the motor	This can push for a simpler motor desgin that uses less permanent magnets for instance.
Surfacing the motor allows for faster motor liberation, by limiting the amount of disassembly steps	Easier CRM recovery

Sensing / feedback (Head LED lights + PCB Components)

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex			-Relatively straightforeward disassembly to reach component -No screws are used to fasten the components (friction fit)	The components are hard to liberate from the sub assembly. -The PCB is soldered to the power cable	Allow for the lights to be disconnected from the subassembly
Hoover H-Free 500 HYDRO plus			-The LED component can be liberated through a cable plug. -No screws are used to fasten the LED (friction fit) -The PCB component used cable plugs to connect to electronics	-The LED component is hidden deep within the assembly. -The PCB component is fastend with a screw -An additional PCB is used in the head assembly	Surface the LED component Use friction fit to fasten PCB
Zedar s600			-No screws are used to fasten the component (friction fit) -Relatively straightforeward disassembly to reach component	-The componend is soldered to the tube connection assembly.	Use a cable plug to connect component
Turbotronix TT-CF4			-No screws are used to fasten the component (friction fit) -Relatively straightforeward disassembly to reach component	-The component is soldered to the tube connection assembly.	Use a cable plug to connect component
Sauber R20			-Relatively straightforeward disassembly to reach component	-Screws are used to secure the component -The componend is soldered to the tube connection assembly. -A extra, small, PCB is used in the head assembly	Use a friction fit to secure the component Use cable plugs to connect the component
Severin S Special			-Relatively straightforeward disassembly to reach component	-The componend is soldered to the tube connection assembly.	Use cable plugs to connect the component
Turbotronix TT-CF				-The componend is soldered to the tube connection assembly. -The component is hard to reach in the assembly through a lot of snapfits and difficult to spot the disassembly steps	-Disassemly usecues -Less snapfits and parts -Cable plugs to connect the component -Surfacing

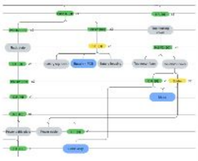
Sensing + feedback general findings

General findings

• Most LED PCBs are friction fit into the assembly
• Not all products have LED lights
• The LED lights help provide the user with feedback --> seeing the dust that is picked up.
• The tube connector connects to wires that power the motor and LED lights and in some cases a small PCB is connected.

Method/Findings	CRM efficient
Using friction fit to fasten component	improves the ease fo disassemlby of the product and allows for easier liberation of CRM component.
Standardization of light	Improve modularity, better repair, less net CRM
Use cable plugs to connect the componet to wires helps to make liberation easier	Without the need of soldering It becomes easier to liberate the CRM from the componet. Using cable pugs in compination with friction fit connections can surface the component
Essentialization can limit the functionality requirements of the motor	This can push for a simpler motor desgin that uses less permanent magnets for instance.
Surfacing the componet for faster liberation, by limiting the amount of disassembly steps	Easier CRM recovery
Mitigate the use of snapfits that hold the head assembly together	Snapfits are a less intuative connection method to disassemble, they tend to get damaged when trying to open the product and make it difficult to see how to open the product. By using less snapfits --> easier repair --> longer product lifetime.

Power cable connector PCB

Model	How integrated	Disassembly map	Good	Bad	Improvements
Rowenta x force flex				-Component is hidden deep within the assembly -Cables are fastened to different parts of the assembly, making it difficult to liberate the PCB component -Component is soldered to cables	Cable plugs on the PCB component to improve liberation
Hoover H-Free 500 HYDRO plus			-The Power connector is connected to the PCB of the motor clumping PCB components together. -The component is held in place with friction fit	-The component is still deep in the assembly	
Zecar s600			-The PCB component is accessible from the outside housing	-A combination of cable plugs and soldering make it hard to liberate the PCB component -The component needs to be disconnected in multiple parts of the assembly	-Cable plugs to improve liberation
Turbotronix TT-CF4				-Component is hidden deep within the assembly -Cables are fastened to different parts of the assembly, making it difficult to liberate the PCB component -Component is soldered to cables	-Cable plugs to improve liberation
Sauber R20			-The Power connector is connected to the PCB of the motor clumping PCB components together.	-The PCB is soldered to the main PCB instead of cable plugs. -The PCB is hidden withing the motor housing assembly	Surfacing, cable plugs
Severin S Special			-The PCB component is accessible from the outside housing	-Cables are fastened to different parts of the assembly, making it difficult to liberate the PCB component -Component is soldered to cables	
Dyson v11				-Component is hidden deep within the assembly -Component is hard to remove	
AEG QX8 animal x power				-Component is hidden deep within the assembly -Cables are fastened to different parts of the assembly, making it difficult to liberate the PCB component -Component is soldered to cables -The component is hidden underneeth irreversable snapfits	
Turbotronix TT-CF			-The PCB component is accessible from the outside housing	-Cables are fastened to different parts of the assembly, making it difficult to liberate the PCB component -Component is soldered to cables	
Vytronix			-The component is only connected with friction fit to the housing.	-Component is soldered to cables -Component is hidden in the assembly	

Power cable connector PCB general findings

General findings

• The power connection PCB module is hard to liberate since it is connected to a lot of cables that are integrated thoughout the product.
• Adding a cable plug would make liberating the power connection PCB easier.
• Some products provide a seperate access point to liberate the power connection PCB

Method/Findings	CRM efficient
Using friction fit to fasten component	improves the ease fo disassemlby of the product and allows for easier liberation of CRM component.
Standardization of light	Improve modularity, better repair, less net CRM
Use cable plugs to connect the componet to wires helps to make liberation easier	Without the need of soldering It becomes easier to liberate the CRM from the componet. Using cable pugs in compination with friction fit connections can surface the component
Essentialization can limit the functionality requirements of the motor	This can push for a simpler motor desgin that uses less permanent magnets for instance.
Surfacing the componet for faster liberation, by limiting the amount of disassembly steps	Easier CRM recovery
Mitigate the use of snapfits that hold the head assembly together	Snapfits are a less intuative connection method to disassemble, they tend to get damaged when trying to open the product and make it difficult to see how to open the product. By using less snapfits --> easier repair --> longer product lifetime.
Improve accessiblity to component	Currently, the component is in some ways connected to different parts of the assembly, making it difficult to liberate the component and recover the CRM or repairing the component.

Appendix G -Project brief

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	Grupstra	IDE master(s)	IPD ✔ Dfl ☐ SPD ☐
Initials	I.H.	2nd non-IDE master	
Given name	Ids	Individual programme (*date of approval*)	
Student number	4820215	Medisign	☐
		HPM	☐

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Benjamin Sprecher	dept./section	Design for Sustainability
mentor	Conny Bakker	dept./section	Circular Product Design
2nd mentor			
client:			
city:		country:	
optional comments			

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Personal Project Brief – IDE Master Graduation Project

Name student Ids Grupstra **Student number** 4,820,215

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

Project title Guidelines for critical raw material efficiency in product design.

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)

Critical Raw Materials (CRMs) like Lithium, Neodymium and Iridium (see image 1) are essential for renewable energy, digital infrastructure, and high-tech applications.Their unique material properties make them difficult to substitute and create strong dependencies for the EU, which relies heavily on CRM imports (Vafeas et al., 2024). Demand for CRMs is growing rapidly, while geopolitical instability, limited availability, and their high environmental impact increase supply chain risks and make reduction urgent. Securing access to CRMs has therefore become a priority on both national and European policy agendas.

In 2024, the EU introduced new ecodesign legislation aimed at doubling material circularity by strengthening sustainability requirements of products. These requirements are put in place in aspects such as recyclability, repairability and resource efficiency and will be tailored to every product group. By reducing dependencies on CRM imports and increasing the reuse of materials, the EU seeks to improve resource security and progress toward climate and energy goals.

This thesis project, commissioned by the Ministry of Infrastructure and Water Management (I&W), investigates whether less material intensive products can help reduce CRM demand. While CRMs are often used in small quantities, their extraction and processing carry a high environmental impact (Hofmann et al., 2018). Limiting CRM usage at the design stage could therefore lower this impact. However, reducing material content may also negatively affect durability and shorten product lifespans, creating a need for tradeoffs between material efficiency and performance.

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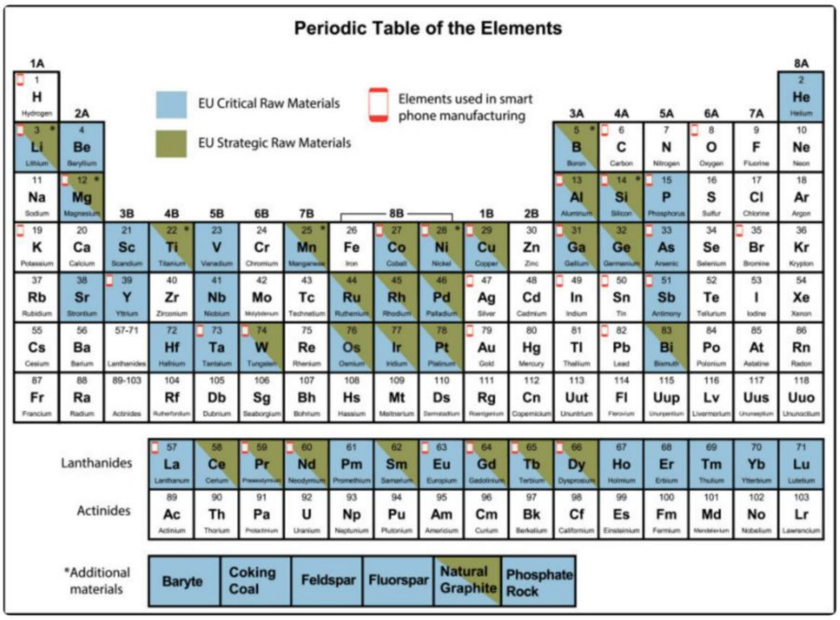
introduction (continued): space for images



(Vafeas et al., 2024)

image / figure 1 Image showing Critical Raw Materials and Strategic Raw Materials on the Periodic Table of elements.

image / figure 2

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)

In this thesis, I aim to develop guidelines for reducing the CRM content in products, using the 9R framework for circular design as a starting point. Within this framework, I will focus on strategies that support the reduction of CRM content.

By applying R-strategies to reduce CRM content, other aspects of the products, like durability, performance and lifespan could be compromised. Therefore, tradeoffs between resource efficient strategies and product durability need to be explored and translated into guidelines. These guidelines should provide value to the Ministry of I&W by supporting the development of legislation that promote material efficient products within specific product categories.

Currently, ecodesign regulations such as the Ecodesign for Sustainable Products Regulation (ESPR) set important sustainability requirements, but do not provide guidance for making concrete design decisions on CRM usage at the product level. Furthermore, methods that evaluate environmental and material efficiency such as Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) often require specialized expertise and complex tools, which limits their usability in practice. Therefore, the design guidelines developed in this project need to be both usable and actionable, supporting the Ministry of I&W as well as product designers in reducing CRM usage.

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:

Design and validate guidelines to reduce the use of Critical Raw Materials through circular R-strategies, ensuring they improve material efficiency without compromising product lifetime and assess their usability for policy development and design manuals.

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

The project begins with an explorative case study on washing machines to examine composition, design choices, and material content. Together with a literature review on CRMs and circular R-strategies, the first iteration of a guideline framework for CRM reduction will be created. The framework will be tested by analysing vacuum cleaners, with robot vacuum cleaners in particular through a redesign, comparing CRM efficiency with the original. Insights will refine the framework into recommendations for the Ministry of I&W and integration into design manuals.
To guide my thesis, I formulated the following research questions:

What role do CRMs play in product design and how do design choices affect dependency?
Which R-strategies best reduce CRM use while maintaining product lifetime?
How can a framework guide tradeoffs between CRM reduction and other design factors?
How applicable is the framework across different product categories?
How can the guidelines be translated into recommendations for policy and design manuals?

Project planning and key moments

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

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

Kick off meeting 26 sept 2025

Mid-term evaluation 21 nov 2025

Green light meeting 23 jan 2026

Graduation ceremony 20 feb 2026

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

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

Comments:

Motivation and personal ambitions

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

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

I chose this thesis to make a positive impact on rethinking how we design for the future. The issue of critical raw materials is urgent, and design changes are needed now. Through this work, I want to explore whether I see myself in the field of Ecodesign while gaining hands-on experience in creating practical design guidelines and redesigning products. My goal is to develop guidelines that are both usable and implementable, ensuring my efforts have lasting value. Understanding what makes guidelines effective is not only an important part of my education but also a skill I can carry into my career.

References

Hofmann, M., Hofmann, H., Hagelüken, C., & Hool, A. (2018). Critical raw materials: A perspective from the materials science community. Sustainable Materials and Technologies,17.
https://www.sciencedirect.com/science/article/pii/S2214993717300969?via%3Dihub

Vafeas, N. A., Slezak, P., & Hitzman, M. W. (2024). Analysis of critical raw materials policy for electrical and electronic equipment: Planning for a truly circular economy. Resources Policy,99.
https://www.sciencedirect.com/science/article/pii/S0301420724007475?via%3Dihub