PROMPT

Premature Obsolescence Multi-Stakeholder Product Testing Program

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D.4.3: Design for physical durability, diagnosis, maintenance, and repair

Table of Contents

1 EXECUTIVE SUMMARY

This report presents the research conducted on physical design aspects influencing diagnosis, maintenance, repair, and physical durability of electrical and electronic household products. This is done through analysing repair data, expert interviews, observational user tests and design analysis of products. Based on the key insights obtained, this report presents design principles and design guidelines affecting the diagnosis, maintenance, repair, and physical durability of electrical and electronic household products. The guidelines are intended for designers, manufacturers, and product engineers to design and develop electrical and electronic household appliances that resist and postpone premature obsolescence.

The diagnosis framework and features influencing the diagnosis process are presented. Nine principles and four design guidelines were identified for diagnosis. In general, the diagnosis process could be facilitated by: minimizing disassembly, facilitating disassembly when needed, and providing timely and understandable feedback and instructions.

General design principles for reparability are presented based on literature research, tear-down experiments, and a user survey. 13 design principles were identified. Several of these principles are similar to principles for diagnosis. From the identified principles; ease of disassembly/reassembly, standardization, information accessibility and safety are discussed in more detail. The main design recommendations are as follows:

- Designing products with features facilitating ease of diagnosis and enabling disassembly with basic tools could remove some of the major barriers towards repair by users, and stimulate more users to repair their products.
- Avoid using fasteners that require proprietary tools, bundling of priority parts, and using non-reusable fasteners (eg. glueing, one-way snap-fits), as these hamper the reparability of the product.
- Safety during and after repair could be facilitated by having smaller and fewer risk zones (eg. by insulating high voltage surface) , facilitating diagnosis without disassembly, and facilitating correct reassembly of especially wiring and hoses.
- Regarding Information accessibility, clear information to maintain, diagnose, repair, are important to facilitate reparability.

Insights on maintenance are presented based on the analysed products during reparability analysis. The general principles for maintenance are largely similar to repair. Maintenance could further be facilitated by providing visual and auditory indicators, minimizing the number of steps and tools required for maintenance, and providing clear maintenance instructions.

Physical durability/robustness of household electrical and electronic products relates to 15 design principles. These principles could be categorized into five main strategies; decouple, shield, distribute, dissipate, and endure. The robustness of a design can be achieved by different balanced combinations of design principles. As a result, it is difficult to reliably assess the robustness of the product by assessing specific features related to the product architecture. Therefore, for durability, experimental testing on the ease of inducing failure (as covered in WP3) is a more effective method for assessment.

Finally, aspects related to software updates and part pairing is discussed. To prevent software-related obsolescence, software updates should be transparent, reversible, and should not hamper the functional performance or the reparability of the product in any way. Additionally, digitally pairing spare parts to the product should not hamper the functional performance of the device.

The design features that conform with the guidelines presented in the report will be considered for the testing program for premature obsolescence of products and will be presented in D4.4.

2 INTRODUCTION

This report presents the research conducted on physical design aspects influencing diagnosis, maintenance, repair, and physical durability of electrical and electronic household products. This is done through analysing repair data, expert interviews, observational user tests and design analysis of products. Based on the key insights obtained, this report presents design guidelines affecting the diagnosis, maintenance, repair, and physical durability for electrical and electronic household products. This guideline is intended for designers, manufacturers, and product engineers to design and develop electrical and electronic household appliances that resist and postpone premature obsolescence.

This report is structured as follows:

- Section 2 presents the design aspects influencing diagnosis. This section presents the diagnosis framework and features influencing the diagnosis process.
- In section 3, design aspects influencing reparability are discussed. Here, firstly the general design principles for reparability are presented based on the literature and activities conducted in PROMPT. This section further presents insights on ease of disassembly based on product teardown analysis. This is followed by a discussion of aspects related to standardization, information accessibility and safety.
- Section 4 discusses aspects influencing maintenance. Here, insights on maintenance are presented based on the analysed products during reparability analysis.
- In section 5, design aspects influencing the physical durability of products are discussed. This section presents the design principles and overview framework for the robustness of household electrical and electronic products.
- Section 6 presents the software and upgradability. This section mainly focuses on smartphones and Smart TV and discusses aspects related to software updates and part pairing.

Reparability and parts of durability analysis were conducted based on the priority parts of the four chosen products. These priority parts, as discussed in D6.1, were identified based on failure likelihood and functional relevance of the parts; parts that have a medium or high functional relevance, and high failure likelihood (see Table 1).

Table 1: Priority parts in the PROMPT product categories

Product	Component	Functional Relevance	Failure Likelihood
Television	Mainboard (including soundboard and ethernet port)	high	high
	Display assembly (failure rate including related lighting technology)	high	high
	TCon board (attached to display)	high	high
	LED board / backlighting	high	high
	Internal power supply/power board (including inverter board)	high	high
Smart phone	Display assembly	high	high
	Battery	high	high
Vacuum Cleaner	Cord Reel	medium	high
	Battery	high	high
	Motor	medium	high
	Filter (Dust Bag, Exhaust Filter, Motor Filter, etc.)	high	high
	Floor nozzle	high	high
	Suction hose	medium	high
	Handle	medium	high
	Casing (Dust compartment cover, etc.)	medium	high
Washing machines	Door Seal	high	high
	Door Lock	medium	high
	Drum Bearings	medium	high
	Shock Absorbers	high	high
	Pumps	high	high
	Electronics	medium	high
	Heater	high	high
	Hoses	medium	high
	Tub Assembly	medium	high
	Door	medium	high

3 DESIGN ASPECTS INFLUENCING DIAGNOSIS

Diagnosis is the first step of the repair process. Surprisingly, this step has hardly been investigated from a design perspective and not at all for household appliances. We explored this topic in depth in Deliverable 4.1. The main results are presented here for the completeness of this report.

3.1 Design features and diagnosis framework

A user observational study was conducted to understand the diagnostic process and the design features influencing this process. The results show that users go through three diagnosis stages of fault detection, fault location, and isolation. The sequence of the stages has shown to be iterative rather than linear as previous literature suggested (see Figure 1). Designs should guide the symptom-to-cause deduction to reduce the number of iterations between location and isolation. The repair occurs when the user is certain and has found a defective component that needs to be repaired. In consequence, functional testing is an operation that should occur to verify that the repair has been successfully executed and to identify other potential faults if the appliance had failed due to multiple faults.

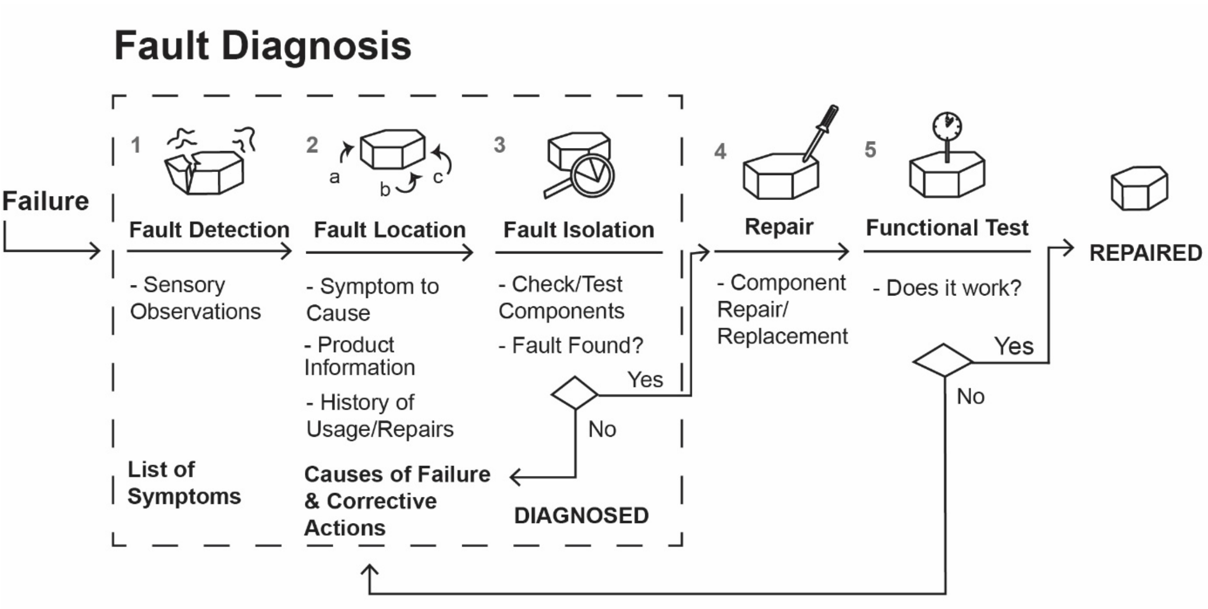

Figure 1: Framework of the Process of Fault Diagnosis by End-users. [1]

The analysis shows that there is no significant difference in the choice of diagnostic strategy based on the participant's repair skills. However, it was observed that repair experience was useful during disassembly because participants with more repair experience required significantly less help than less experienced participants. This indicates that repair experience is a valuable skill to facilitate the diagnosis if the process of diagnosis requires disassembly. In addition to this, disassembly is also observed as one of the main bottlenecks during the diagnostic process if the component requires disassembly.

Design was found to be the most influential factor for the diagnosis strategy a user follows during the process. Table 2 presents the design features that were observed to influence the diagnostic process, their respective design principle, and their relevance for different stages of diagnosis. The design is shown to influence the user’s decision on whether to proceed with the diagnosis and consequently whether to repair or replace the appliance.

Table 2: Design Features influencing the diagnostic process and their relevance at each diagnostic stage. Features that have a positive effect are marked by +, and features that have a negative effect are marked by – and have a grey background

<table>
<tr><th rowspan="2">Design Principles</th><th rowspan="2">Design Features</th><th colspan="3">Diagnosis Step</th><th rowspan="2">Explanation</th></tr>
<tr><th>Detection</th><th>Location</th><th>Isolation</th></tr>
<tr><td rowspan="7">ACCESSIBILITY</td><td>Geometries wide enough to allow manual inspection by finger or hand</td><td rowspan="5"></td><td rowspan="5">+</td><td rowspan="5">+</td><td rowspan="5">Allows quick inspection of components without disassembly</td></tr>
<tr><td>Section-able component (example: section-able hose of a vacuum cleaner)</td></tr>
<tr><td>Long cables</td></tr>
<tr><td>Lid</td></tr>
<tr><td>opening in the casing,</td></tr>
<tr><td>non removable encapsulation</td><td></td><td></td><td>-</td><td>Components cannot be checked</td></tr>
<tr><td>Non-ergonomic geometry</td><td></td><td></td><td>-</td><td>Difficult inspection of components, could require further disassembly</td></tr>
<tr><td rowspan="8">INFORMATION TO USER</td><td>Blinking lights</td><td>+</td><td>+</td><td></td><td>Directs the participants to potentially defective components, however, the study shows that interpreting their meaning required previous experience with using similar appliances.</td></tr>
<tr><td>Display with text</td><td>+</td><td>+</td><td>+</td><td>Communicates user the process the appliance is performing or executing.</td></tr>
<tr><td>colour contrasting with grime</td><td></td><td></td><td>+</td><td>Quickly check the condition (cleanness) of component</td></tr>
<tr><td>Light when powered</td><td rowspan="2">+</td><td rowspan="2">+</td><td rowspan="2">+</td><td rowspan="2">Confirms the user that components are working</td></tr>
<tr><td>click sound during attachment/ detachment</td></tr>
<tr><td>Engraved labels and marking in the appliance</td><td>+</td><td></td><td>+</td><td>Guidance on correct usage of appliance</td></tr>
<tr><td rowspan="2">User manual</td><td></td><td>+</td><td>+</td><td>Guidance on maintenance operations</td></tr>
<tr><td></td><td>-</td><td>-</td><td>Lack of disassembly information</td></tr>
<tr><td>INTERCHANGEABILITY</td><td>easily replaceable standard components</td><td></td><td></td><td>+</td><td>Able to quickly isolate the faulty component by replacing with a working one (If spare parts are readily available)</td></tr>
</table>

ROBUSTNESS	materials and construction are unlikely to fail, even if the product is treated roughly			+	allows inspection and disassembly without fear of damaging the device or components
MODULARITY	the device is built from individually distinct functional units.		+	+	Allows condition inspection of individually distinct functional units.
REDUNDANCY	More than one way of delivering a function		+		Certainty for fault location
ENABLE TESTING	non-isolated electrical measuring points			+	Facilitate the measurements with multi-meter
VISIBILITY	Material transparency,	+	+	+	Quick Inspection without disassembly
	Full view of components				
	Coloured wires		+		Understand working mechanism of the appliance.
	Full view of components,				
	visible relationship between components				
	Symmetric positioning of components			+	Inspection by comparison
	Non-contrasting colour between components		-	-	Identify different components
DISASSEMBLY	Seams (of housing),			+	Understand product's construction
	visible fastener head,				
	Easy-to-detach (Detachment within 2 actions, low force and without any tools)			+	Component Release
	Large number (5+) of screws at different surfaces for one component (housing)			-	Understand product's construction + Component Release
	Hidden high force snap fits				
	Screw location (of housing) away from component needed to be checked				
	Deeply recessed fasteners				
	Hidden high force snap fits			-	Provokes fear of breaking the product
	Components of same functional subsystems at different disassembly levels (>2 level)		-		Understand working mechanism of the appliance.

The findings of this study largely agree with the design features proposed in Pozo Arcos et al. [2]. The difficulty of the disassembly of products, especially removing the outer housing of the appliance, appears to be a major hindrance to the diagnostic process. It was commonly related to expressions of frustration and intentions to give up on the diagnosis. These results also coincide with the findings of Brusselaers et al. [3]: out of frustration, participants would be willing to give up the repair and simply replace the products. This frustration can be provoked by the appliance's design. For instance, in the study, if diagnosis required disassembly, participants were more tempted to give up; however, if disassembly was not required participants would be less likely to give up. This indicates that diagnostic abilities that don't require disassembly, have a higher likelihood of enabling repair and thus prolonging the product's lifetime.

3.2 Design recommendations for diagnosis

Based on the study conducted and literature, the following design guideline is presented for the diagnosis of household appliances.

- Facilitate fault detection and symptom-to-cause deduction, giving timely and understandable feedback that does not require product specific knowledge. E.g.,
    - Sound or text signals that communicate the correct appliance usage and the process executed in the product.
    - Sound or text signals that communicate component failure.
- Minimize the need to disassemble the product for inspection. E.g.,
    - Include lids or doors to access the components.
    - Include testing ports.
    - Include Transparent casing to see conditions of encased components
- If product disassembly is needed, facilitate it. E.g.,
    - Provide, instructions for disassembly.
    - Design for disassembly in as few steps as possible, and with few (common) tools as possible.
- Provide Diagnosis instruction. E.g.,
    - Provide troubleshooting instructions in the user manual or attached to the product

3.3 Translation towards a scoring system

The design features that conform with the guidelines presented above are relevant for the testing program to determine the ease of diagnosis of a product. Products might be tested for the presence of design features that lead the user towards diagnosing the product without disassembly, as disassembly was observed as one of the main bottlenecks for diagnosis for conventional users. The testing procedure for ease of disassembly is already part of testing for repairability (see Chapter 3).

4 DESIGN ASPECTS INFLUENCING REPARABILITY

This chapter presents the design aspects influencing the reparability of the four PROMPT product categories. Firstly, design principles influencing reparability are presented. Then, a product teardown analysis is presented to establish the disassembly time required to reach priority components. In this way disassembly determining design principles are related to specific design features. This section then presents a discussion on aspects related to standardization, information accessibility and safety. Finally, an overview of factors influencing consumers barriers to repair is presented.

4.1 General framework

Literature research was conducted on design features and principles influencing the reparability of the products (See Appendix 1 for the complete literature review paper). 18 different design principles were identified that are considered important for reparability of EEE. These design principles were then further verified and updated through a product teardown analysis. Table 3 presents the overview of design aspects shown to influence reparability.

Table 3: Overview of design aspects empirically shown to influence reparability, and their descriptions.

Design principles	Definition and how it relates to repair
Disassembly	The product is taken apart such that it could subsequently be reassembled and made operational [4]. Required to access components for most repairs [5]
Reassembly	Assembling a product after disassembly, to its original configuration [6]. Required to return a product to operation.
Modularity	Modularity refers to the way in which a product design is decomposed into different modules. A module can consist of one or more components. Modules can be separated from the rest of the product; they can be isolated as self-contained, semi-autonomous chunks; and they can be recombined with other components [7]. The degree of modularity needs to be balanced for product reparability; big modules (bundling) could decrease disassembly time, however would make spare parts expensive and vice versa.
Ease of Handling	Features such as small size, low centre of gravity, & handle promote handling of the product [8,9]. Facilitates disassembly process during product manipulation.
Interchangeability	Assuring components can be replaced in the field with no physical rework required for achieving a physical fit. Allows for component testing [1,2] & facilitates component replacement. Interchangeability of components (from hardware and software) is required for the replacement of the component.
Robustness	Selecting designs that are robust. Assures products do not break during repair [10], increases confidence during disassembly [1].
Redundancy	Providing an excess of functionality and/or material in products or parts. Allows removal of material as part of a recovery intervention [11]. Functional redundancy assists fault location and isolation [1,2].
Keying	Providing "keyed" slots so that parts could only fit in one direction. Assists in correct reassembly of the product. Increases reassembly time and decreases post-repair safety hazards [12].
Firmware Reset	Software and the electronics-related issue could be fixed via reset [13]. Reset functions facilitate cause-oriented diagnosis [1,2].
Standard parts and interface	Enforcing "the conformance of commonly used parts and assemblies to generally accepted design standards for configuration, dimensional tolerances, performance ratings and other functional design attributes" [14]. Standardization reduces spare part costs, tooling, component identification complexity, and skill level required, and increases interchangeability of components during maintenance and repair. [15]

Accessibility of Information	Accessibility of Information to the user and repairers. Whilst this is not directly a design element, manuals and labels are provided with the product. Guides repair process [1,2,16–18].
Health and Safety	Health and Safety risk to the user during and after repair. Features minimizing safety risks also increases confidence in product disassembly and reassembly [19].
Adaptability/Upgradability/ Updatability	Adaptability allows performing the designed functions in a changing environment. Upgradability and Updatability enhances the functionality of a product [9]. Software related issues in the product sometimes could be repaired through updates.

Disassembly and reassembly are critical steps in the repair process. In general, disassembly of the product is observed to be influenced by the following design principles: design simplicity, redundancy, keying, modularity, and ease of handling [5,6,9,10,20]. Therefore, features that influence the disassembly and reassembly of the product are considered in more depth in Section 3.2 through product teardown analysis.

In addition, “Standard parts and interface”, “Information accessibility” and “Health and safety” are also regarded as important and are discussed further. Finally, software aspects are also considered important, and the related principles regarding software aspects of 'Interchangeability’, and ‘Adaptability/ Upgradability/ Updatability’ are discussed in Chapter 6.

4.2 Teardown analysis on aspects that influence product reparability.

In this analysis, 10 washing machine, 10 vacuum cleaners, 12 Smart TVs and 20 smartphones were disassembled and analysed to determine the aspects that influenced the reparability of the products. Specific attention was given to the design features mentioned above and especially the design features listed in Table 4. The products were disassembled until all priority parts were removed. Here, the disassembly time to reach each priority part is recorded. The samples were chosen to represent manufacturers by market share and provided a diverse range of designs and characteristics within the product group (see Table 5).

Table 4: Overview of design features of specific interest to disassembly

Design Features	Definition and how it relates to repair
Fastener Visibility	Whether more than 0.5 mm2 of the fasteners surface area is visible when looking at fastening direction [5] and visual cues [10]. Facilitates product disassembly.
Fastener type	Facilitation on removability of fasteners while ensuring that there is no impairment of the parts [or product] due to the process. Required for disassembly and ease of reassembly.
Tools Required	Number and type of tools necessary for repair of the product [21]

Table 5: List of analysed products

Vacuum Cleaners			
Simens VSZRK212	AEG SH360L25	Dyson SV12	Grundig VCC5850
Simens VSQ8MSA332	Inventum STS725RC	Bosch BBS1U224	Rowenta RO7230EA
AEG VX9	Vorwerk VK200		
Washing Machines			
Samsun g WW7X M642O	LG FH4J3TDN0	LG 910PWAWL2808	Siemens WM6HXF90NL
Gorenje W2A744T	AEG L6FB64470	Siemen s WM14N270	BEKO WQY9736XSWBT
Miele WDB330 WPS	Bauknecht care 8418		
Smart TV			
Samsung UE55NU7179	Loewe Connect 48	LG OLED55B8LLA	Metz Fineo 49
Samsung GQ55Q80	HiSense H55B7100	Sony Bravia XG70	Philips US7393
Sony Bravia XG90	LG 49UM71	Samsung QE55	Philips S7502
Smartphones			
Apple iPhone 6s	Huawei Nexus 6P	Samsung Galaxy A5	HTC One M8
Apple iPhone 7	Huawei P9 Lite	Samsung Galaxy S7	HTC One M9
Apple iPhone 8+	Huawei P10	Samsung Galaxy J3 Duos	Nokia 6.1
Fairphone 2	Huawei Mate 20	Samsung Galaxy S8	Oppo R9s
Google Pixel 2	LG G5	Samsung Galaxy XCover Pro	Shift 6m

The different product categories show distinct design architecture and were analysed by different parties (RUSZ worked on washing machine and vacuum cleaners, iFixit worked on smartphones and tablets). Therefore the structure of the analysis varies between the product categories. Whist the focus was on insights related to disassembly and reassembly, other relevant insights on maintenance, diagnosis and physical durability are also recorded.

4.2.1 **Vacuum Cleaner (VC)**

Table 6 presents the disassembly time of priority parts in different vacuum cleaners. The total time to disassemble all the parts from the vacuum cleaners ranged from 126 seconds (Dyson SV12) to 993 seconds (AEG SH3360L25). Figure 2 shows a box plot of the distribution of disassembly time for the priority parts of vacuum cleaners. The disassembly time of the following parts showed a large variation; handle, cord reel/battery, motor, and On/Off switch. For this, Table 7 lists the most prominent design features that influence the disassembly and reassembly. Occasionally, a feature promoting disassembly/reassembly may reversely influence other aspects (such as physical durability, diagnosis and safety). Such tensions between different aspects are also presented in the table. A more detailed overview is presented in Appendix 2.

Table 6: Disassembly time of priority parts in different vacuum cleaners. X = not removable. N/A = part not present.

Model	Disassembly time (s)							
	Floor Nozzle	**Suction Hose**	**Dust compartment cover**	**Handle**	**Cord Reel/Battery**	**Motor**	**On/Off Switch**	**Wheels**
Simens VSZRK212	5	6	13	9	145	124	128	21
Simens VSQ8MSA332	5	9	42	31	265	261	282	28
AEG VX9	6	13	69	24	280	429	256	485
Dyson SV12	54	N/A	12	6	52	64	X	51
Bosch BBS1U224	46	N/A	14	296	5	6	362	26
AEG SH360L25	97	N/A	22	168	306	568	83	29
Inventum STS725RC	21	N/A	15	51	3	354	82	4
Vorwerk VK200	240	N/A	5	375	12	427	X	X
Grundig VCC5850	5	12	17	22	437	520	238	22
Rowenta RO7230EA	3	50	5	207	387	350	276	30

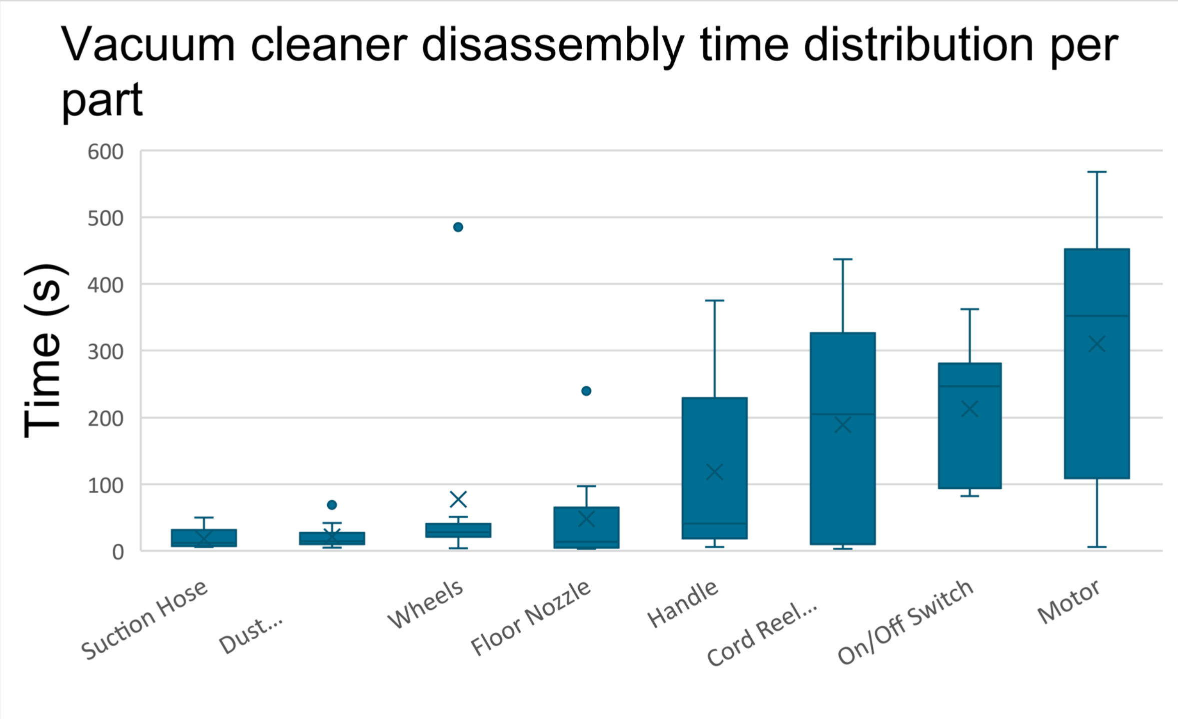

Figure 2: Vacuum cleaner disassembly time box plot distribution per part

Table 7: Observed design features and their influence on diagnosis, reparability, maintenance, and durability, from the product teardown analysis of vacuum cleaner. "+" = promotes the aspect, "- = hinders the aspect, "- - " = severely hinders the aspect

Diagnosis	Maintenance	Disassembly	Reassembly	Repair safety	Durability	Other Functionality	Observed features	Influence
+	+				+		Dust compartment and motor filter accessible by one cover	Allows easy access to maintenance points
		+	+				Screwed in carbon brushes instead of non removable brushes.	Allows disassembly and replacement of brush, instead of the whole motor
					+		Lid can only close if dust bag is present	Assists in proper use of product
+	+						VC with clog indicator	Assists diagnosis and maintenance
		+	+				motor attached with friction fit instead of screw	Easy to disassemble and Reassemble
			--				Precise cable positioning required for reassembly	Cables reassembly becomes difficult if low tolerance fit is required
		-	--				Interconnection between multiple parts	Difficult to keep track reassembly sequence.
		-					Hidden Screws	Slows disassembly process in the case no disassembly documentation is provided
		--	-	-			Hidden Snap fits	Unclear on how to unsnap, increasing disassembly time and chance of breakage
		-	-				Suction hose deep within disassembly tree	Increases disassembly time
			--				loaded springs (on handles and buttons)	Difficult to align and reassemble
			-				slot available for dust bags to fit properly	Assists in correct reassembly. Allows for
+					-		Transparent floor nozzle	allows for diagnosis of nozzle, however prone to visible scratches.
+		-			-	+	Several pressure monitoring sensors present in the machine.	Increases number of parts for disassembly, however assists in diagnosis and energy efficiency.
		+	+		+	-	One power setting	Fewer parts for disassembly and failure. However limits functionality.

4.2.2 **Washing Machine**

Table 8 presents the disassembly time of priority parts in different washing machines. The total time to disassemble all the parts from washing machines ranged from 1135 seconds to 2031 seconds. However, the bearings of 6 out of 10 washing machines could not be removed from the tub, decreasing total disassembly time, but rendering the bearings unrepairable. This permanent connection between bearing and tub is currently not considered in the disassembly time and should be considered carefully in the testing program.

Figure 3 shows a box plot of the distribution of the disassembly time for the priority parts of the washing machines. In general, the removability of drum bearings takes significantly longer time than other priority components of the washing machine, this is in part because almost all other components have to be removed before the bearing can be removed (high disassembly depth). The disassembly time of other priority parts (except the door lock and heater) shows a large variation.

Similar to the vacuum cleaners, Table 9 presents the insights from the teardown study on design features that influence the disassembly and reassembly of the washing machine. This table presents observed design features, their influence, and the tensions between the aspect of diagnosis, maintenance, disassembly, reassembly, safety and durability. A more detailed overview is presented in Appendix 2.

Table 8: Disassembly time of priority parts in different washing machines. X = not removable.

Model	**Disassembly time (s)**									
	Door	**Door Lock**	**Door Seal**	**Drum Bearing**	**Electronics**	**Heater**	**Hoses**	**Pumps**	**Shock Absorbers**	**Tub Assembly**
Samsung WW7X M642O	152	67	190	1310	346	139	238	207	206	1370
Gorenje W2A744T	55	77	235	X	308	68	491	152	227	1195
Miele WDB330 WPS	270	252	245	1680	370	286	363	332	326	1018
LG 910PWAWL2808	215	75	366	1750	525	83	797	402	423	1393
Siemen s WM14N270	150	40	321	X	213	343	367	378	447	862
LG FH4J3TDN0	139	63	357	1412	198	111	561	406	468	1158
AEG L6FB64470	130	44	292	X	269	84	587	529	489	997
Bauknecht care 8418	182	82	252	X	247	93	393	417	512	675
Siemens WM6HXF90NL	1841	51	361	X	489	92	359	372	539	1132
BEKO WQY9736XSWBT	189	80	375	X	295	94	628	528	624	1068

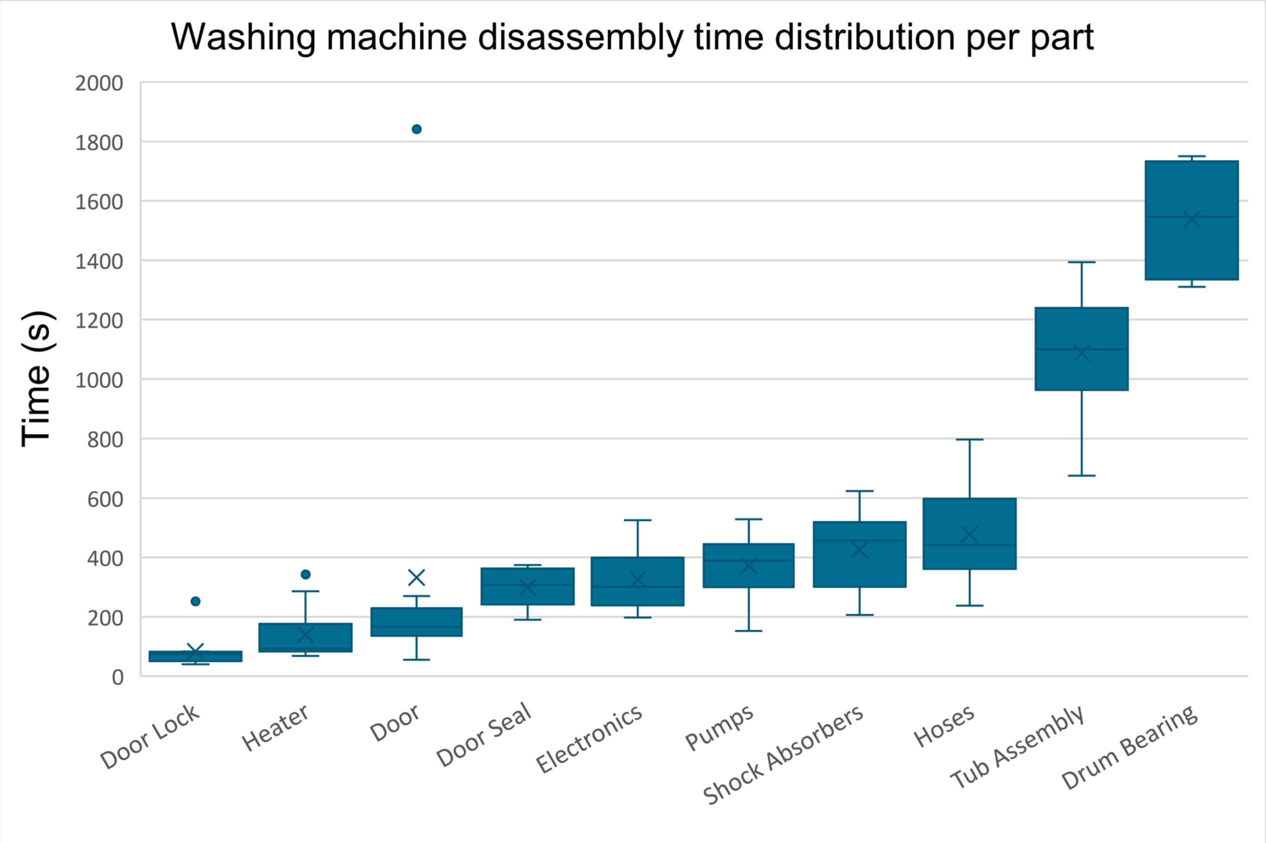

Figure 3: Washing machine disassembly time box plot distribution per part

Table 9: Observed design features and their influence on diagnosis, reparability, maintenance, safety, and durability, from the product teardown analysis of the washing machine. "+" = promotes the aspect, "- = hinders the aspect, "- - " = severely hinders the aspect.

Diagnosis	Maintenance	Disassembly	Reassembly	Repair safety	Durability	Other Functionality	Observed features	Influence
				+	+		Opening service door automatically drains the water.	Minimizing electrical safety hazards and component damage
+	+				+		Visible access to lint filter	Allows users to see when filter needs to be cleaned
		+	+				Reusable cable/hose ties fixed to housing	Doesn't require new fastener during reassembly process. Decreases reassembly time
		+					Shock absorber only removable from back of the machine	Machine should be moved, increasing disassembly time
	+				+		Visual highlights on maintenance area	Promotes maintenance by providing information
	+				+		Drum cleaning Cycle	Automated maintenance activity eases maintenance
		+	+				Door seals removable without removal of other parts	Decreases disassembly and reassembly time
		--	-	-			Hidden Snap fits	Unclear on how to unsnap, increasing disassembly time & chance of breakage
		+	+			-	Different functional PCB boards bundled in a single boards	Decreases the disassembly time but significantly increases the spare part price
		-	-				Electronics only reachable after removal of the motor	Increases disassembly and reassembly time
		-	-				Shock absorbers only replaceable after lifting tub	Increases disassembly and reassembly time
		--	--	-			Shock absorbers needs drilling with special tools	Hampers disassembly and reassembly
		-	--				Non reusable Cable tie	Hampers disassembly and reassembly
					-		Tension springs without protection	Damages tub suspension overtime
		--					Non removable drum lifters	Hampers reparability
		--					Non removable drum bearings	Hampers reparability
					-		circulation-hose close to power electronics	chance of abrasive wear
			-	-			Loaded springs on tub assembly	Difficult to align properly during reassembly. Chance of leakage
		-			+		Resin encased electronics	Hinders board level repair, however provides protection against water damage
		-	-		+		Screws covered with stickers	Slows disassembly in the case no disassembly documentation is provided, but could reduce corrosion damage to screws

4.2.3 **Smartphones**

Table 10 lists the disassembly time of priority parts in the analysed smartphones. Figure 4 shows a box plot of the distribution of the disassembly time for these priority parts. In all devices, both battery and display assembly could be removed without damaging the device. However, the disassembly time for both batteries and displays varied from about 10 seconds to over 1000 seconds. This large variation in disassembly time is due to different design architecture and types of connection used in the analysed models.

In terms of design architecture, most of the components are attached to the back cover, to a frame, or even to the display. In all architectures, intricate layering of components can be observed. A common example is the display cable passing underneath the battery, requiring the removal of the battery to replace the display assembly. As a result, disassembly depth could be relatively high in smartphones as several components may need to be removed before the defective part can be accessed and replaced.

Table 10: Disassembly time of priority parts in different smartphones.

Model	**Disassembly Time (s)**	
	Battery	**Display assembly**
Apple iPhone 6s	378	284
Apple iPhone 7	410	337
Apple iPhone 8+	813	364
Fairphone 2	19	29
Google Pixel 2	1014	494
HTC One M8	978	1645
HTC One M9	527	1956
Huawei Nexus 6P	562	1111
Huawei P9 Lite	678	1505
Huawei P10	301	537
Huawei Mate 20	1113	724
LG G5	10	196
Nokia 6.1	625	420
Oppo R9s	168	478
Samsung Galaxy A5	1103	1977
Samsung Galaxy S7	548	934
Samsung Galaxy J3 Duos	987	760
Samsung Galaxy S8	552	1841
Samsung Galaxy XCover Pro	8	232
Shift Shift 6m	20	209

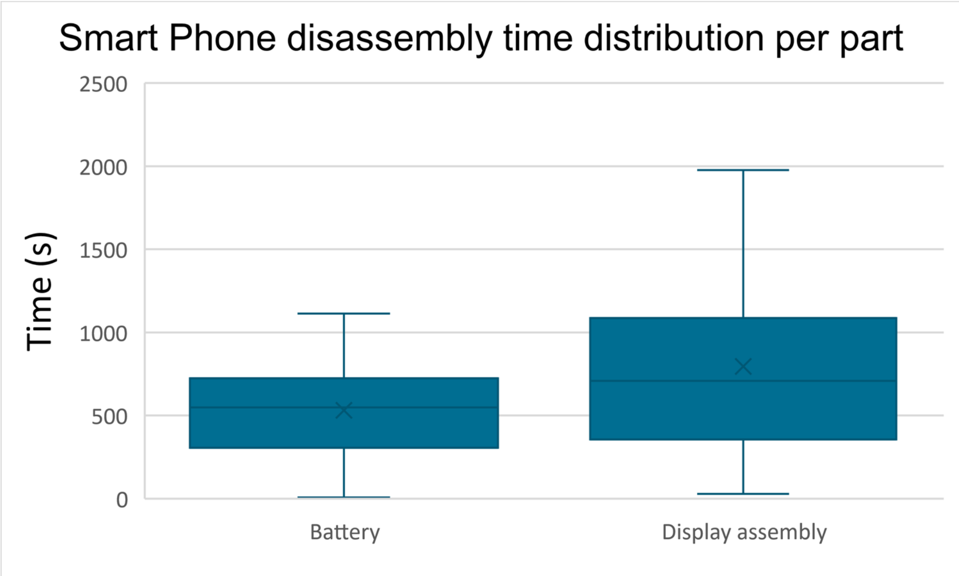

Figure 4: Smartphone disassembly time box plot distribution per part

In smartphones, it is common practice to join different components using adhesive. Display assemblies, batteries, and back covers fixed with adhesive impede the disassembly process. This is because removing the components generally requires a tedious and elaborate application of force through prying, potentially in combination with heat to soften the adhesive. The process can easily cause damage to delicate components like the display assembly. Smaller components may be fixed with adhesive as well but as these cover a smaller area removal is generally feasible using leverage force.

The display assembly is joined with adhesive in the majority of the analysed devices. The only exceptions were brands that focus on repairability such as Fairphone and Shift. These brands were significantly faster to disassemble than brands using adhesives.

Batteries are predominantly attached using adhesive. Although the simple adhesive is most observed in our dataset, easier to remove forms of adhesive such as stretch release adhesive and pull-tab adhesive are becoming more common. These techniques are shown in Figure 5.

Figure 5: A smartphone battery joined with stretch release adhesive (left) and pull-tab adhesive (right).

In general, the adhesive is used in smartphones to provide water ingress protection (IP). However, there are designs that provide a similar level of IP rating without the use of adhesives. The Samsung Galaxy XCover Pro obtains an IP rating of IP68 while having a back cover that is joined with snap fits and a battery that can be removed without tools. In this model, the back cover contains a seal to protect the device from ingress of dust and moisture (see Figure 6).

Figure 6: Galaxy XCover Pro back cover with water tight seal

Design of multi-functional modules consisting of multiple parts permanently attached together (bundling) was also seen during the analysis (for example, in Fairphone 2 the aux port, speaker and camera are placed in the same module, Figure 7). This design choice of having large modules combining multiple functionalities generally decreases the disassembly time to remove the module (and the parts underneath the module). However, if a component (e.g. aux port) fails within the module, the whole module needs to be replaced; and this significantly increases the spare part price. Therefore, the degree of modularity needs to be balanced for product reparability.

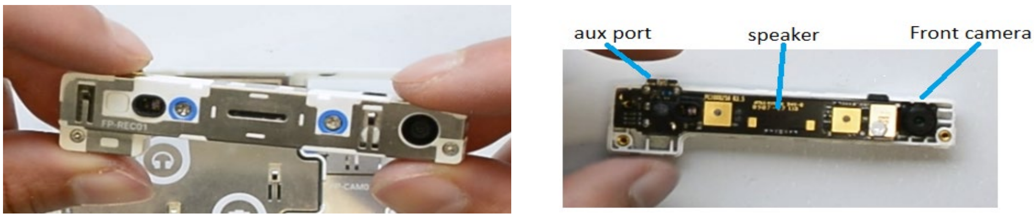

Figure 7:Fair phone module (left) consisting of aux port, speaker, and front camera. Further disassembly of the module shows all these components are permanently attached to a single chip (bottom)

Screws are common in smartphones to position shields and PCBs. While Philips screws are most common, Torx, Tri-point, Pentalobe and standoff screw heads are also encountered. In some smartphones, three different types of screw heads can be found. Having a variety of screws increases the disassembly and reassembly time due to tool change, as well as for keeping track of screw placement.

Nearly all devices require general-purpose tools and product category-specific tools [21] to remove priority parts, however, the best reparable devices don’t need any tools or only general-purpose tools. A lot of devices, however, do require heat to remove adhesive connections, which can cause injury and damage.

Overall, the devices that were easier to disassemble did not use any adhesives. This allowed for faster disassembly as well as the use of basic class A tools. For brands that were glued, having stretch release adhesives or pull tabs eased the deluging process.

4.2.4 **Smart TV**

Table 12 lists the disassembly time of priority parts in different smart TVs. Figure 8 shows a box plot for the distribution of disassembly time for each priority part of smart TVs. In general, the design architecture of smart TVs was similar in all products. In all devices, the back cover needs to be removed before any priority parts could be reached. The variation in time was mainly determined by the time required for the removal of this back cover (ranging from 96 to 326 seconds).

The type of fastener used for the back cover is critical to the ease of its disassembly (from snap-fit being the most difficult, followed by screws and a slide-lock mechanism being most favourable). These fasteners were frequently used together and the procedure of opening the back cover was often not straightforward. For example, one brand (Samsung) required a specific opening tool with a certain depth, long enough to release the snap-fit clips but not long enough to cause significant damage to the components. Care had to be still taken during the prying process to not damage the components, this slowed down the disassembly process.

Table 11: Disassembly time of priority parts in a different smart TV.

Model	**Disassembly Time (s)**				
	Back-cover	**Mainboard**	**Power board**	**T-con board**	**Inverter board**
Samsung UE55NU7179	108	165	130	Integrated	Integrated
Samsung GQ55Q80	120	200	137	Integrated	147
Sony Bravia XG90	96	180	141	253	138
LG OLED55B8LLA	107	196	178	206	Integrated
Sony Bravia XG70	187	276	216	301	Integrated
Samsung QE55Q80	189	257	289	Integrated	Integrated
Loewe Connect 48	233	358	311	333	Integrated
HiSense H55B7100	221	351	Integrated	Integrated	Integrated
LG 49UM71	304	358	351	358	Integrated
Metz Fineo 49	268	396	324	356	356
Philips US7393	393	399	370	398	Integrated
Philips S7502	316	470	365	391	Integrated

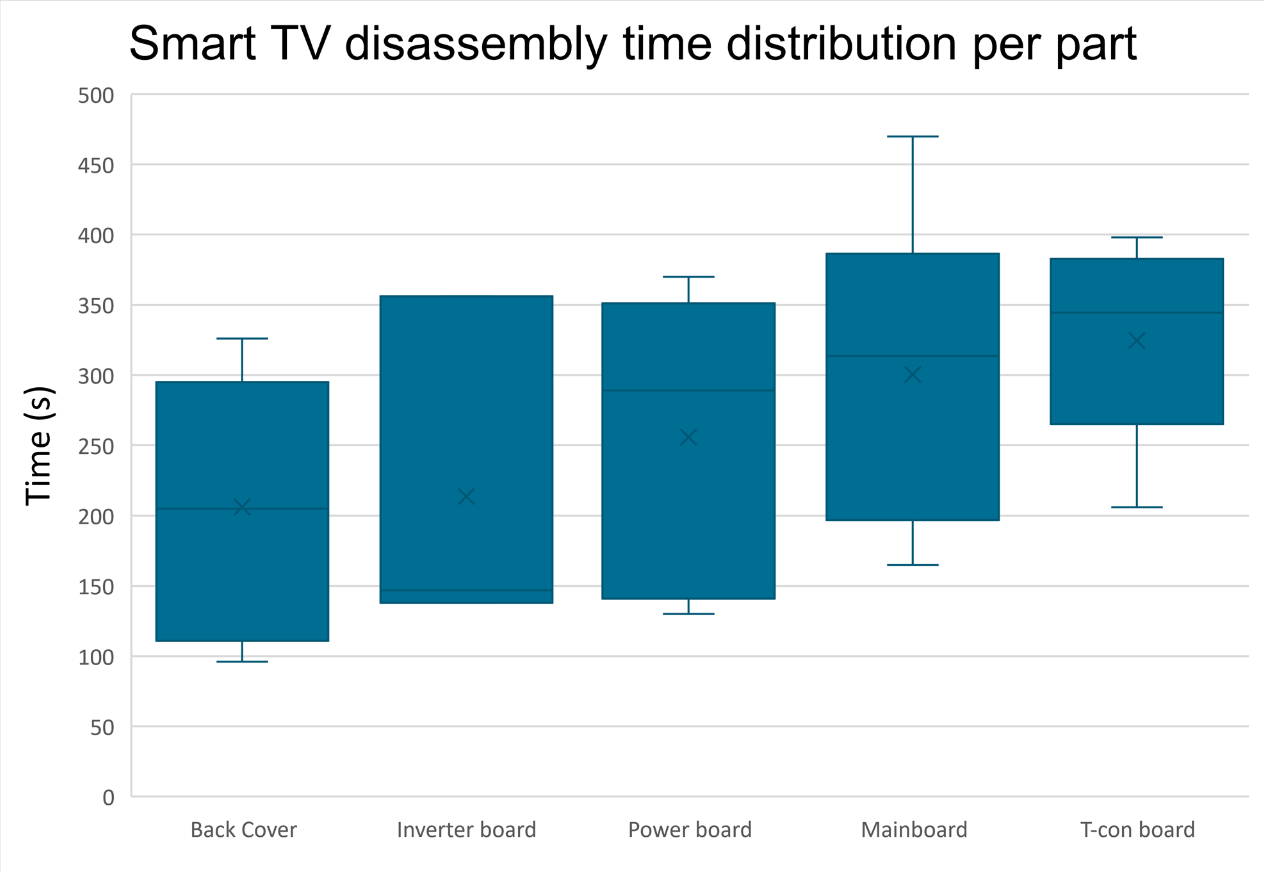

Figure 8: Smart TV disassembly time box plot distribution per part

Once the back cover is removed, the different components of the TV unit become accessible. Figure 9 shows the typical positioning of the different components encountered in the devices in this study. Often, the T-con board is hidden by a shield.

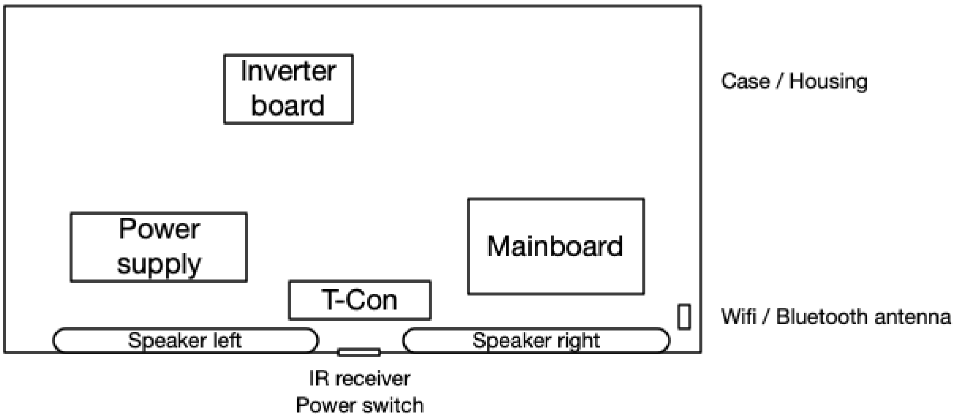

Figure 9: Typical layout of the different components on the backside of a TV screen

The layout indicates the characteristically low disassembly depth. Once the back cover is removed, the different PCBs and other components are directly accessible. This is illustrated visually in the disassembly trees of the Philips 49PUS49PUS7502 TV set in Figure 10.

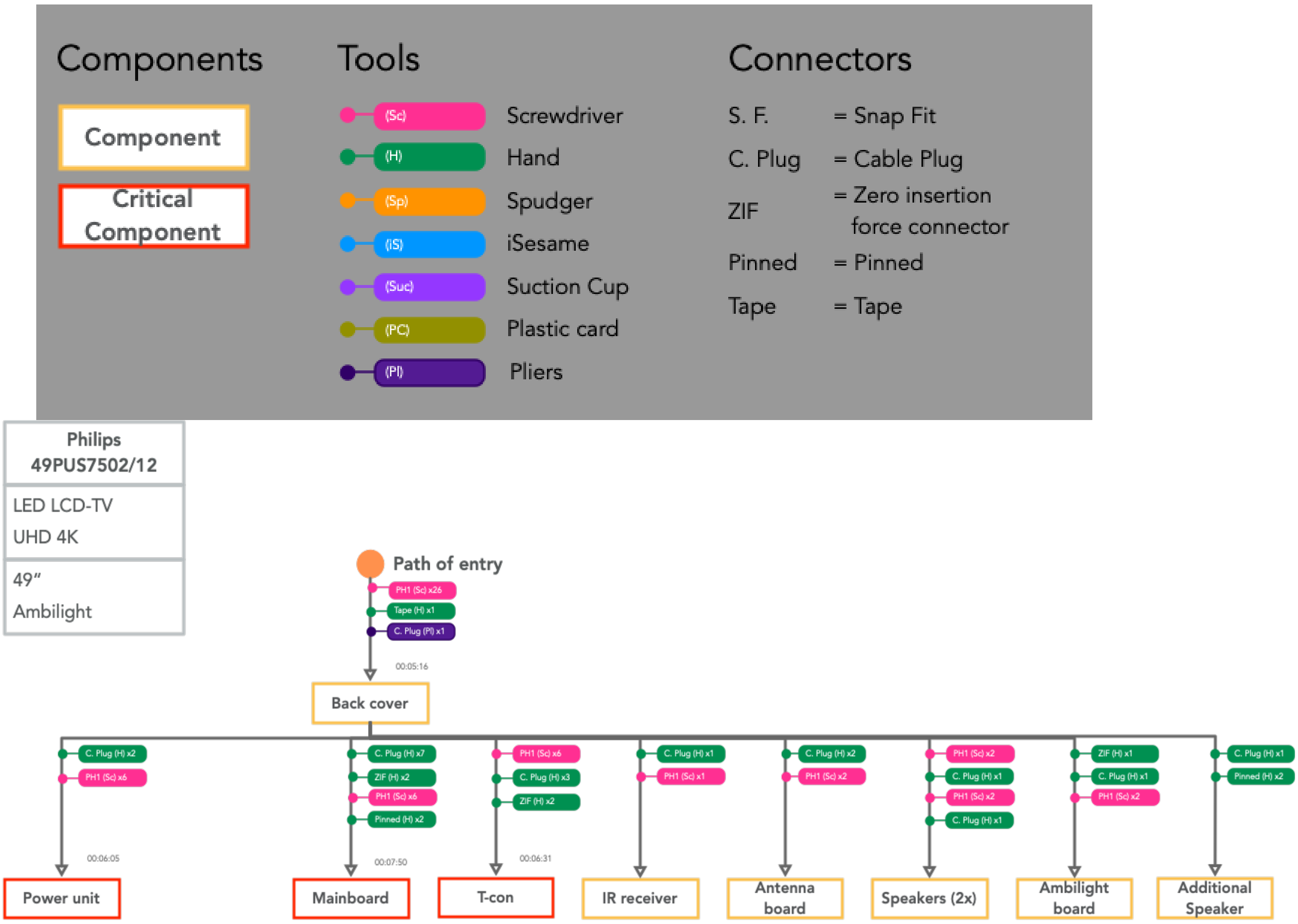

Figure 10: Disassembly tree of Philips 49PUS49PUS7502 TV set, with legend. All components are accessible once the back cover is removed.

Replacing the priority parts leads to two practical difficulties. One is the difficulty in replacing the screen; the other is the level of integration of the PCBs.

It is deemed not feasible to disassemble and replace the display in the selected devices in a non-professional repair scenario. The sheer size, the pliability, and the fragility of the display units sum up to a highly complex and risky operation. In addition, special care needs to be taken to avoid dust particles on-screen components.

We consider the display unit not replaceable if all of these conditions are met:

1. The display size is larger than 40 inches
2. The display unit is a multi-layer assembly
3. The display unit is not mounted to a frame other than the device's chassis.

All selected devices meet these conditions. Currently, it is not straightforward to assess the ease of disassembly of the Smart TV screen in current models. Therefore, the display is excluded from thorough ease of disassembly assessment. Instead, we evaluated whether the conditions that would facilitate screen repair are met in a device. This would entail higher scores for repairable screens to encourage manufacturers to develop this.

The degree of integration of the four remaining priority parts varies widely. Two devices have four separate boards, one device only has a single main board with all functionalities integrated. The remaining devices all have a power board separate from the main board, but different configurations of integration of T-con and inverter boards (see Table 11). Figure 9 shows the disassembly tree of the HiSense H55B7100 TV set that has a single board. In contrast, Figure 10 shows the disassembly tree of the Metz Fineo 49TY8254 TV set, containing 4 different PCBs.

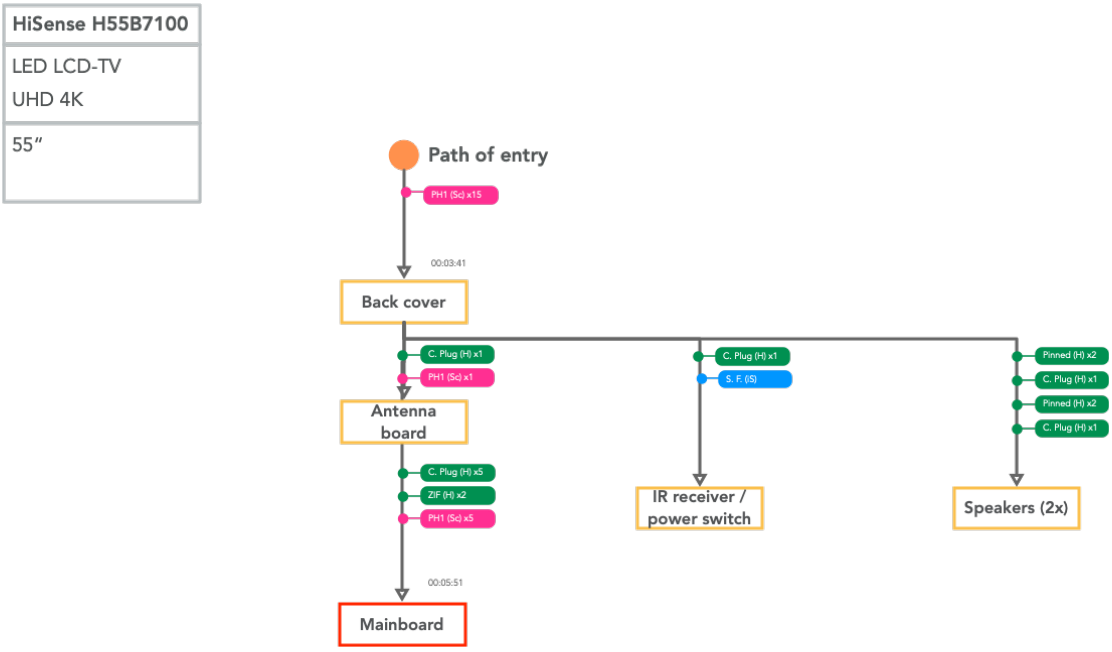

Figure 11: Disassembly tree of HiSense H55B7100 TV set. The device contains a single, fully integrated PCB (red box).

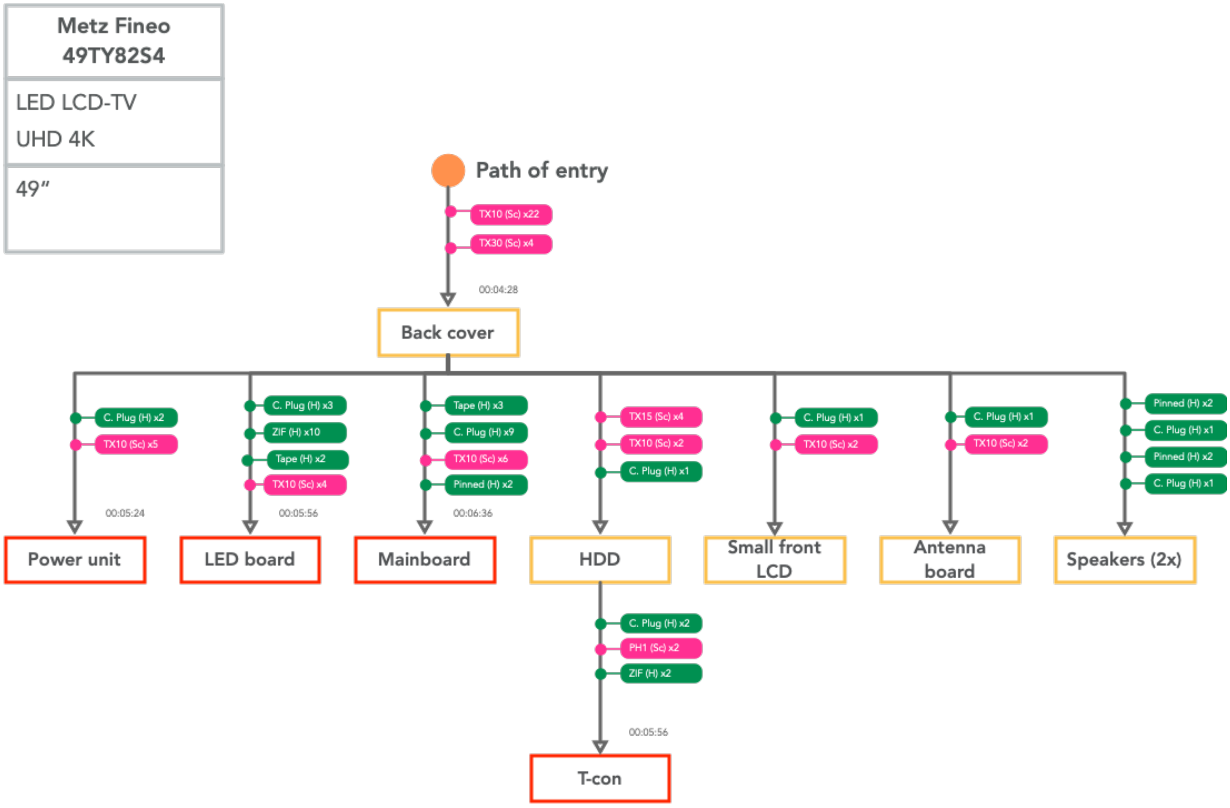

Figure 12: Disassembly tree of Metz Fineo 49TY8254 TV set. The device contains 4 different PCBs (red boxes).

The level of integration affects the ease of disassembly. Fewer components make them more accessible and require fewer fasteners, fewer tools, and fewer interconnection cables to be disconnected. However, it does not necessarily facilitate repair since the price of the replacement board is expected to be higher. These trade-offs should be carefully accounted for in a scoring system.

4.2.5 Design Recommendations for ease of disassembly and reassembly

Based on these insights gathered through the study of four product groups, the following design recommendations for ease of disassembly and reassembly of products are proposed

- Avoid bundling priority parts with other parts (i.e., priority parts should be individually removable).
  - Whist Bundling components together at the surface could help reduce the number of components that need to be removed before the priority part could be removed, bundling components in the priority part could increase the price of the priority part, rendering the reduction in disassembly time futile.

- Minimize the number of components needed to be removed before priority parts are removed.
  - This decreases the disassembly time required to reach the priority part.

- Minimize the diversity of fasteners along a disassembly pathway of a priority part.
  - Using a low variation of fasteners minimizes the tool change and decreases the disassembly time. Additionally, minimizing the diversity of fasteners will help keep track of

fasteners for reassembly.

- For different types of fasteners ordered consecutively to be removed, design the disassembly pathway such that fasteners that required the same tools are clustered together
  - Having the same type of fastener along the disassembly pathway minimizes tool change and therefore reduces the disassembly time

- Use fasteners that require no tools or basic tools to disassemble
  - If the product is designed to be disassembled by common users, ideally no tools should be required to disassemble the product. If tools are required, they should preferably be basic tools. We can distinguish the following order in tool preference: No tools > Basic tools (e.g., screwdriver, Allen key, Wrench, Plier) > Advanced tools (e.g., soldering iron, heat gun) > Proprietary tools. (Note, this order deviates in details from EN45554 [21] which considers e.g. a soldering iron a basic tool; further research may be required to align the standard to PROMPT findings)

- Provide disassembly instructions
  - E.g., Provide a disassembly guide in the manual
  - E.g., indicate fasteners need to be removed in the product.

- Provide correct assembly indication *(promotes ease of reassembly)*
  - E.g., by keying, marking connections or providing auditory verification (click-connection) on correct assembly.

- Avoid Non-reusable fasteners or fasteners prone to breaking
  - E.g., glued components, one-way snap fits, and hidden high force snap-fits.

- If glueing is required, provide features facilitating its removal
  - E.g., by adding pull tabs or stretch tabs.

4.3 Accessibility of information

Accessibility of information concerns the ability of the public and repairers to access repair information. Analysis of literature and already existing scoring systems (See Appendix 1) shows that transparent information regarding repair is considered important. Table 12 gives an overview of the types of information that are desired.

Table 12: Information considered important for diagnosis and repair.

Information Availability	Explanation
repair Instructions/manual/bulletin	Guides repair process
Product identification	Assists in acquiring repair instruction and spare parts
Component identification	Assists in acquiring repair instruction and spare parts
Exploded view	Guides disassembly and diagnosis process and identification of spare parts
Diagnosis information/ Troubleshooting chart	Guides diagnosis
Repair service offered by the manufacturer	Promotes users to give for repair
Safety measures	Promotes safe repair
List of available updates	Guides update

Update method	Guides update
Disassembly sequences	Guides disassembly and diagnosis process
Reassembly sequence	Guides reassembly
Fault detection software	Guides Diagnosis process
PCB/Electronic board diagram	Guides Diagnosis process and identification of spare parts and board level repair
Error codes	Guides Diagnosis process
3D printing of spare parts	Assists in acquiring spare parts
Procedure to reset to working condition	Assists in diagnosis
Service centre accessibility	Promotes users to give for repair
Transportation instructions	guides proper transportation of products for repair
Circuit/Wiring diagram	Guides Diagnosis process and board level repair
Replacement supplier/supply information	Assists in acquiring spare parts
Tools required during the repair	Assists disassembly and diagnosis
Access to training available to all technicians	Enables 3rd party repairers to repair products
Recommended torque for fasteners	Guides proper disassembly and reassembly
Compatibility of parts with other products	Enables use of 3rd party spare parts
Functional specification of parts (eg. Resistor values)	Guides Diagnosis, repair
Reference values for measurements	Guides Diagnosis process

In practice, for fault diagnosis, A study analysis of 150 manuals of 4 different household appliances [22] found that the manuals insufficiently facilitate the diagnosis of common faults. Most of these manuals only address overdue maintenance and faults related to the internal state of electronics. Hardware failure due to other causes is rarely addressed.

For reparability, in the analysis of 20 mobile phones. the guide to replace the priority parts was given by the manufacturer for only 3 mobile phones. Similarly, for television, only one manufacturer, out of 10 provided the disassembly instructions to end-users (indicating how to remove the back cover, mainboard, power board, hard disk, and foot support plate).

For information attached to the products, visual cues can lower the barriers to successfully conducting repair operations, even for laypeople. However, the only visual help that was encountered are small arrows or circles marking screws that need to be removed to open the shell or release a component. In terms of washing machines, only one out of 10 washing machines had visual information attached on how to loosen a specific type of fastener.

These insights portray a severe lack of information available to the users for diagnosis and reparability of the products currently. Manufacturers (allegedly) do this because of safety concerns. However, this impedes the reparability of products, especially in DIY scenarios. Based on the analysis, at the least, Information should be available from manufacturers on “Repair instruction”, “Diagnosis information”, and “Safety measures”. For the testing program, these aspects should be considered.

Based on these insights, the Design recommendation for information accessibility is as follows

- Provide clear information to diagnose, repair, and the safety measures to do so, for consumers and independent repair shops.
- If possible, this information should be provided attached/engraved in relevant areas of the product. *(Indicating disassembly pathway, screws to remove, and safety indication on hazardous areas.)*

4.4 Standardisation

Standardization is the process of developing and implementing technical standards. The process establishes specification of e.g. engineering criteria, terms, practices, materials, items, processes, dimensions, interfaces. This could either occur within a brand level (e.g., lighting port used by various apple products), across multiple (two or more) brands (eg., use of USB c connector), or even within a brand (proprietory standardization). In this report, a part and/or its interfaces is considered a standard if it is used by multiple brands.

Standardisation of parts and/or their interfaces might improve the access to spare parts and thus enhance reparability. Also, when a part is standardized, the costs per part are likely to decrease through economies of scale. In general, it is recommended to standardize parts which have the same function across all manufacturers, however, don't have a significant distinguishing performance and don't have an aesthetic need. In the following section, the potential for standardisation of parts (especially their interfaces, dimensions and performance) and interfaces is discussed for the PROMPT product categories. This part on standardisation gives general recommendations to designers and manufacturers regarding parts that could potentially be standardised to promote the product's reparability. The focus is exclusively on aspects related to repairability and this discussion, therefore, neglects other arguments related to standardization, like competitive position, proprietary knowledge and performance optimisation.

4.4.1 **Vacuum cleaners and washing machine**

Table 13 provides insights on aspects relevant to the standardization of priority parts for vacuum cleaners and washing machines.

Table 13: potential for standard parts to be used in washing machines and vacuum cleaners

Vacuum Cleaners	**Power cord/Cord reel**	The majority of the analysed vacuum cleaners used brand and product line specific cord and cord reels. The function of the cord and cord reel is observed to be similar across vacuum cleaners yet a different interface exists. Use of standard cord reel (like in AEG VX9 vacuum cleaner) is preferred.
	Battery	The battery of vacuum cleaner Bosch BBS1U224 could be used in a variety of other cordless electronics (within Bosch). This indicates an opportunity to standardise batteries for cordless electronics more in general.
	Suction hose	The diameter at the ends of a suction hose is observed to vary between vacuum cleaners, having a similar hose diameter and interface on each end of the suction hose would promote its interchangeability without compromising its functionality.
Washing machine	**Pumps**	The majority of the analysed washing machine used brand specific and/or product line specific pumps. However, all the analysed pumps performed similar functions and had similar form factors, the difference occurred only at its connecting interface to the washing machine. Here, the use of standard pumps (like in Gorenje W2A744T) are preferred.
	Brushless Motors	Simar to pumps, the majority of the analysed washing machine used brand specific and/or product line specific brushless motors. However, all the analysed brushless motors performed a similar function, and a clear reason is not found for producing such a variety of different motors. Here, the use of a standard brushless motor (like in Gorenje AEG L6FB64470) is preferred.
	Drum lifters	Drum lifters move the laundry up and drop it into the washing fleet when the drum is moved during the washing process. Whist the design of the drum lifters

		could be changed/improved, there is an opportunity to standardise the interface that attaches drum lifters to the drum.
	TUBS	5 of the 10 tubs had non-removable bearings, leading to the replacement of the whole tub in case of failure. This renders the tubs economically unrepairable. Here tubs with a standard -removable- interface for ball bearings are preferred,

4.4.2 Smartphones

An external power supply or charger can be used across devices and brands provided it has the correct connector. Currently, most smartphone chargers have USB-C connectors on Android devices and Lightning connectors on iOS devices. The European Commission has proposed the common charger initiative that would harmonise charging ports to USB-C for electronic devices, a much wider scope than only smartphones.

A standardised component in most low-end phones is the slot for microSD cards to extend the device memory. In high-end phones, several brands sell phone models with varying amounts of onboard memory capacity, which cannot easily be upgraded.

In general, the rapid pace of technological development and integration impedes the standardisation of components. A few instances have been reported where certain sub-assemblies are cross-compatible with another model, for example, the display assembly, cameras and Taptic Engine of the iPhone SE are swappable with iPhone 8 parts. The Fairphone 3+ is the upgraded version of the FairPhone 3 that allows updating the cameras and the speaker module, while other modules are interchangeable.

4.4.3 Smart TV's

TV display technology is under continuous development, with new technologies being released every couple of years. Mini LED screens started being shipped in 2020, Quantum Dot (QD) displays are released in TV units in 2022, and rollable units are expected to be rolled out in 2025. In such a market, where screen technology is a significant selling point and advances quickly, it is not feasible (and possibly detrimental to the advancement of technology and associated performance improvement) to standardise the displays.

Even within technologies, there is a lack of standardisation. "LCD screens with identical specifications often have different connectors and operate with different signals (number of leads, signal frequency, voltage). Even screens with identical dimensions, mounting means, and connectors may not be interchangeable. The same model of TV may be equipped with a different type of LCD, and the firmware may or may not be adaptable to another type."[1]

The T-con and backlighting boards that perform image processing need to be specifically designed to control the specific screen. As such, standardising these is not feasible as long as screens are not standardised. In the analysed devices, two examples were seen that indicate a potential to use certain components across devices within a brand. The Sony XG70 has an external power supply, instead of simply a cable connecting the TV to the mains. This adapter could be reused across devices, as is the case in some other product categories.

The Samsung QE55Q7FGM comes with the Samsung One Connect Box. It is marketed as a device to simplify cable management, with entry ports for a variety of connectors, and a single transparent cable connecting the One Connect Box to the screen. The functionality related to processing the different input channels that are usually on the mainboard is now performed in the board located in the One Connect Box. As such, the board that processes the input channels can be used across Samsung devices that support the

One Connect Box functionality. Yet, today, different and non-compatible versions of the One Connect Box have already been introduced.

The potential for standardisation of power and mainboards is lost if these are integrated with the T-con or inverter boards. In the HiSense H55B7100, the mainboard, power board, T-con board, and inverter board are integrated into a single board. While a single board may have a smaller ecological footprint and be more robust than multiple boards connected with cables, it removes the potential for standardisation and is a barrier to repair if one of the functionalities breaks down. Integration of components leads to reduced modularity and influences the potential for standardisation.

With the current rate of technological development in displays, and the need for other priority parts to be adapted to the display, it is currently not straightforward to standardise priority parts across brands.

Overall

In general, parts of the vacuum cleaner and washing machine here have more potential to be standardized than those of Smart TVs and phones. Since the technological progress of vacuum cleaners and washing machines is much slower than that of TV and phones. From a design perspective, it is recommended to use standardised parts whenever possible. However, adding testing criteria for the use of standardised parts may not be an appropriate solution toward increased reparability as this could potentially impede innovation.

4.5 Safety

Certain physical characteristics of a product (such as sharp edges or voltage carrying components that could be touched during repair) can increase repair-related safety risks, whereas others (such as keyed wire connections) decrease it. This chapter provides an overview of general design guidelines related to repair & post repair safety.

Ingemarsdotter et. al., [12] established a risk assessment framework for the repair of household appliances, taking into account risks during as well as after repair. This framework supports documentation of risks by specifying risk type, injury type, the probability of injury through injury scenarios, the severity of the injury, the cause of the risk, and design recommendations that could reduce or eliminate the risk. In this report, the framework was applied to 14 products from five product categories (coffee maker, blender/mixer, CD player/radio, washing machine, vacuum cleaner). While the report presents a risk assessment framework related to repair, it still is to an extent subjective, especially in defining the probability of risks in repair. The PROMPT repair safety assessment further expands on the risk assessment framework by providing a more objective guideline for the likelihood of incidents occurring and the severity of the consequences if an incident occurs. This safety assessment will be presented in D4.4.

Based on the report and the framework, the following design guidelines are presented for design for safe repair.

- Aim for few and small risk zones
  - Encase high-voltage components and their connections
  - Ensure that the repairer must break the electric circuit by performing a disassembly operation prior to reaching the high-voltage components.
  - Making often-failing components accessible from outside risk zones.
  - Place target components at a large enough distance from the source(s) of danger, if the target components cannot be accessed from outside the risk zones.
  - Place potentially dangerous non-priority parts deep in the disassembly tree

- Facilitate Diagnosis without disassembly
  - Enable the product to self-diagnose.

- Facilitate correct reassembly of wiring and hoses
  - Provide correct reassembly indicators

- Provide click connections

4.6 Design factors affecting users' ability to DIY repair

Understanding the extent of common users' capabilities to repair products themselves, and the barriers during the repair could help legislators and manufacturers to improve the design of products. A user survey was conducted that investigated the following three aspects: their capacity for using various common repair tools, their experience in repairing different household appliances, and the degree to which greater repair experience enables them to overcome related barriers to repair. (See Appendix 3 for the full paper). The key takeaways from this study are as follows:

- Most respondents said they were able to use basic mechanical tools, but less than half stated proficiency in using soldering irons or multi-meters for repair Figure 13). This indicates that more users may be able to perform diagnosis and repair of mechanical problems than electrical problems.

- 74% state they have repaired an electronic household appliance at least once in their lifetime (Figure 14). This suggests that repair could be a widespread activity.

- Users with no repair experience listed significantly more design-related barriers to repair than users with repair experience. These design-related barriers mostly concerned diagnosis and disassembly (Figure 15). Thus, designing products with features facilitating ease of diagnosis and enabling disassembly with basic tools could remove some of the major barriers towards repair by users, and stimulate more users to repair their products.

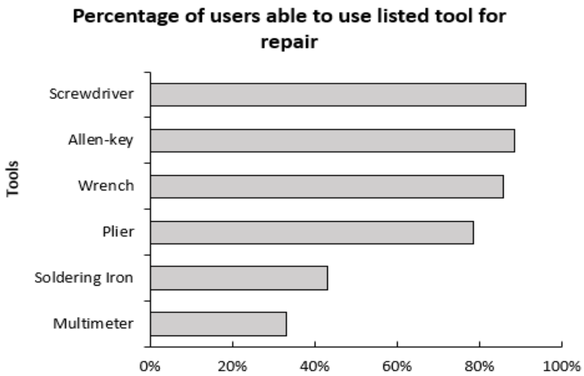

Figure 13: Percentage of users able to use listed tool for repair

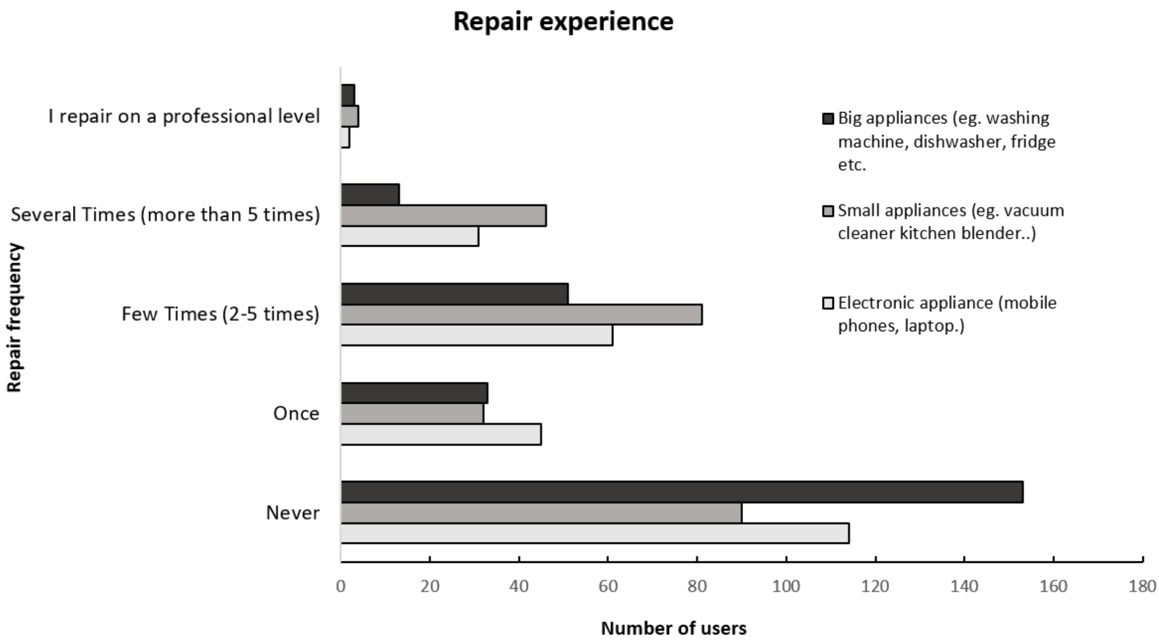

Figure 15: Repair frequency from number of users who have reported to self-repaired the listed category of appliances in the past

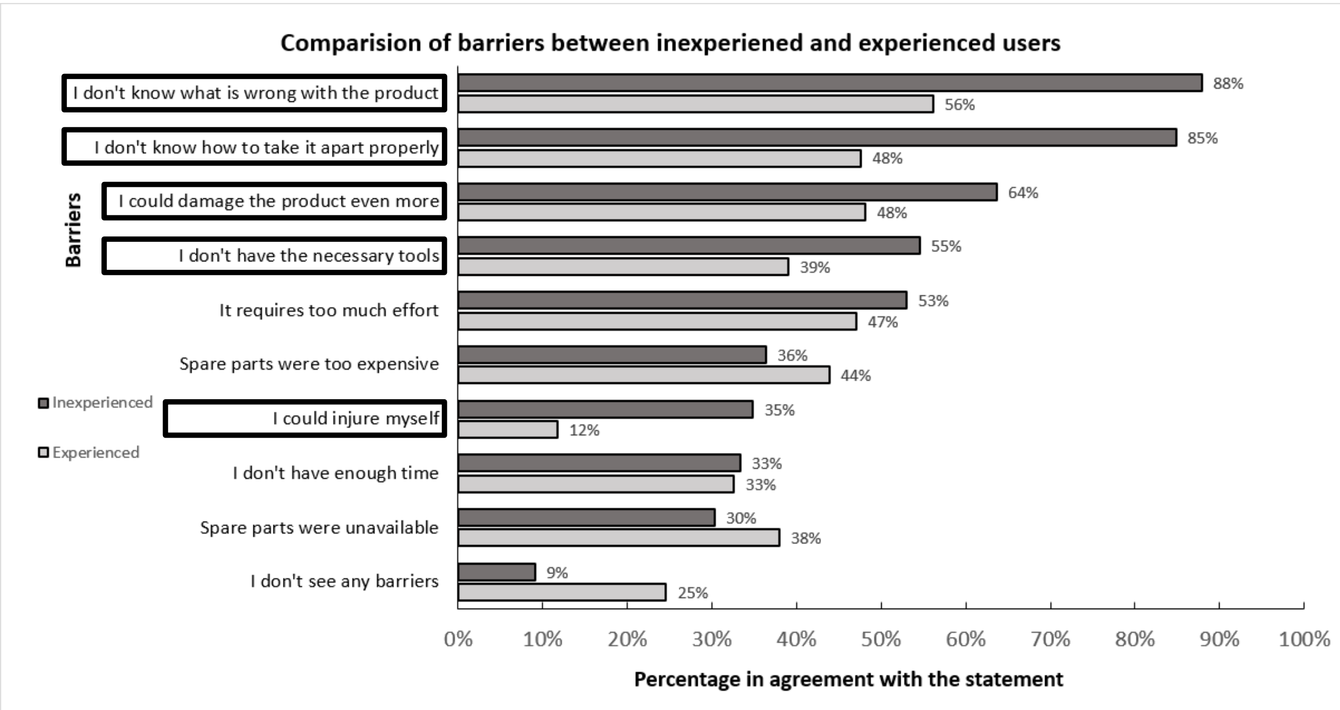

Figure 14: Percentage of respondents listing barriers to repair, in order of agreement. Barriers listed significantly more often by inexperienced users are outlined in boxes.

4.7 Translation towards a scoring system

Based on the insights regarding reparability from this chapter, the following key aspects should be considered for the testing program. Deliverable 4.4 will provide the details of the scoring system.

- Ease of disassembly metrics constitute a significant indicator of the complexity of the device and should be assessed for the priority parts. Quantifying the disassembly complexity in an operator-independent manner is particularly challenging for smartphones, due to the common use of adhesive to join display assembly, back cover and battery.

- Spare part availability and affordability are vital for repair and should be an integrated part of the scoring system. Here, features that render products economically unrepairable (eg. non-removable bearing in the washing machine leading to uneconomic replacement of the full tub) should be heavily penalized. A methodology to identify “economically unrepairable” cases should be developed.

- Trade-offs resulting from modularity need careful consideration in a scoring system, as bundling might pose advantages as well as disadvantages.

- Repair information should be part of the scoring system. Points should only be awarded for going beyond the mandatory eco-design requirements. Repair information should include spare part availability and price, diagnosis, and safety measures.

- Standardization of components might increase spare part availability and decrease its costs. However, a separate criterion assessing standardisation separately is not desirable since it may impede the development of technology.

- The PROMPT repair safety assessment framework should be part of the scoring system to underpin the importance of safety.

5 DESIGN ASPECTS INFLUENCING MAINTENANCE

Maintenance is the performance of inspection and/or servicing tasks at regular intervals, to retain a product's functional capabilities and/or cosmetic condition [9]. This action prolongs durability/robustness without the need for repair. The general principles for maintenance and repair are largely similar as repair can be considered "corrective maintenance" [9]. Therefore, the design principles presented in Table 3 are to a large extent also relevant for design for maintenance. Additionally, since maintenance of household appliance is an activity generally done by the user; features that influence ease of maintenance, and feature that triggers users to maintain the products are discussed.

5.1 Vacuum Cleaner

Insights related to the maintenance of vacuum cleaner is as follows.

- One vacuum cleaner had a clog indication: This assists in the diagnosis and de-clogging of brushes and air pathways. Pressure indicators indicating clog/full dust container were present in the majority of the vacuum cleaner, however, for an uninformed user, this indicator without additional information may not be helpful. Additionally, users could be triggered to maintain the product by providing clear auditory and visual cues.

- In one of the analysed vacuum cleaners, the dust compartment and motor filter could be accessed by one cover. This design feature of having all the maintenance points within the same area decreases the steps required for maintenance and might promote regular maintenance of all necessary parts.

- Designs, where a product stops working until maintenance is conducted could be a strong stimulation for users to maintain their products.

- User manuals provide instructions for the maintenance and overdue maintenance of product.

5.2 Washing Machine

For washing machines, insights on maintenance are as follows:

- For all the analysed washing machines, detergent drawers of all washing machines can be easily taken out within two steps and cleaned for maintenance. They consist of two to five parts which need to be taken apart for proper cleaning. This maintenance is crucial to ensure that the laundry soap reaches the laundry and that the washing machine stays odour free.

- All tested WMs have visible access to the lint filter, which needs to be cleaned regularly by the user to ensure a proper function of the pump. There are also WMs on the market which have a base cover in front of the lint filter, which makes the lint filter and its needed maintenance invisible.

- Further promotion for maintenance of washing machines could be specific graphical highlights on the housing of the washing machine to indicate the area with a maintenance need. The analysed washing machines did not have such indication for maintenance.

- Visual or auditory indicator for regular maintenance activities (e.g., Running 90* wash cycle was every 1-2 months), stimulates users to maintain the products.

- User manuals provide instructions for the maintenance and overdue maintenance of product..

5.3 Smartphones

Smartphone and TV set user manuals do not instruct users to perform maintenance. In the manuals, the phrase "maintenance" is generally associated with professionals in the service network as the counterpart of repair. Software updates can be considered a form of maintenance since they retain a product in a condition to be able to function as required, but since it is such a specific topic it is discussed in the dedicated software section.
Some manuals provide instructions on how to clean the screen without damaging it. Although smudges and dust impact the viewing experience, it does not affect the technical performance of the device. Therefore, cleaning is considered care for the product rather than maintenance.

Some smartphone user manuals mention resetting the phone, resetting connections such as WiFi or Bluetooth, or improving memory performance. While important, these actions are generally performed when the functionality of the device is reduced and can be considered troubleshooting.

As a mobile device, the care for a smartphone also includes avoiding dropping or hitting it, keeping it dry, and perhaps using a phone case or screen protector that may be provided with the device.

5.4 Smart TV's

User manuals warn users to avoid displaying still images or image elements for longer periods. This can cause image burn-in and the discolouration of parts of the screen. The underlying mechanism differs between technologies, and some technologies are more sensitive to image burn-in than others (eg. OLED screens are more susceptible to burn-ins than typical LED TVs). In general, bright spots in still images cause those parts of the screen to age faster than other parts.

Manufacturers of TV sets have mitigated image burn-in by improving and adapting the hardware to be less susceptible to it and developing software strategies to reduce image retention. Software strategies include screensavers periodically shifting the image slightly, periodically inverting the colour of system elements such as the navigation bar, recalibrating the screen, and more.

Avoiding still images is not a maintenance task but a usage condition. Running the appropriate software tool that recalibrates the screen when image burn-in is noticed, can be considered troubleshooting. Manufacturers do not consider image burn-in as a device malfunction and generally do not cover it by warranty.

5.5 Design recommendations for maintenance

Based on the literature and the insights from the product analysis, the following design recommendation for promoting maintenance is proposed.

- Whenever possible, cluster points that require maintenance together.
  - E.g., for a vacuum cleaner, opening a single cover allows access to both the motor filter and dust compartment

- Provide visual or auditory indicators to facilitate maintenance
  - E.g., the colour of the dust filter changes if the dust filter needs cleaning
  - E.g., an Auditory signal when descaling is required

- Minimize the number of steps and tools required to reach the maintenance point.

- Provide maintenance instructions and a maintenance schedule. This should ideally be attached to the product, near the maintenance point.

5.6 Translation towards a scoring system

For washing machines and vacuum cleaners, the following insights are proposed to be translated into a scoring system.

- The operation of the device should be as simple as possible (e.g., self-explanatory) and the instructions easy to read and understand.

- Instruction for maintenance should at least be available in the user manual, but preferably accessible from the product.

- Given the limited relevance of maintenance for smart TVs and Smartphones, it is not deemed necessary to include it in those in the scoring system.

6 DESIGN ASPECTS INFLUENCING PHYSICAL DURABILITY/ROBUSTNESS OF PRODUCTS.

Reliability and physical durability (or robustness) are considered the key aspects of the ability of a product to resist obsolescence, i.e. to keep functioning over time [11,23,24]. Reliability is defined as the probability that the product does not fail under normal conditions during a defined period of time [25], while robustness is defined as the ability of the product to withstand variations that are beyond normal conditions [26]. However, design-related aspects of reliability and robustness are often inseparable. Anyhow, products that have a high level of robustness by design by definition do exhibit a high level of reliability since these products are designed with higher specifications than needed to operate under normal conditions. The aspect of reliability is investigated in Work Package 3, which focuses on experimental testing of reliability. Here, we will discuss how different design principles affect the robustness of products. General design guidelines will be provided for design for robustness during the product's operating lifetime and beyond in the case of reused/refurbished. The results focus on the four product categories studied in PROMPT.

The investigation of design for the physical robustness of products was done in three parts.

- In the first phase, literature research was conducted by using the search terms “design” followed by “robustness”, “physical durability”, and “reliability” in Scopus and Google Scholar. Wildcards were used to ensure wide coverage. The search was conducted within title, abstract, and keywords. Additionally, the search was focused on the following subject areas: engineering, material science, environmental science, industrial design, and design. Additional papers were identified via snowballing [27]. Relevant articles were filtered by first reading the abstracts, followed by reading the entire paper. Additionally, books and reports on reliability and failure analysis [28–31] were also considered during the research.

- In the second phase, product analysis of mobile phones, washing machines, vacuum cleaners, and smart TV is conducted through data from repaired products, teardowns, workshops, and interviews with repair experts. The failure cause, design opportunities facilitating robustness and design principles addressing the opportunities are identified through repair video and data (to understand the reason for failure, and relevant features where no repair was needed), interviews with repair experts and workshops with consortium partners. This is presented in Appendix 4.

- In the third phase, the data from the literature and the product analysis is used to establish a framework relating robustness to five different common failure types (mechanical, electrical, thermal, chemical, and sunlight). This framework presents design principles and associated features facilitating robustness against different types of failure. Finally, in the third phase, based on the activities conducted on previous points, design strategies and guidelines for robustness are presented.

6.1 Design principles related to robustness/physical durability

Based on the product analysis of failure causes presented in Appendix 4, and with the support of additional literature, Table 14 presents the list of failures, design opportunities facilitating robustness and the design principle that addresses the opportunity. The common failures were categorized into 5 categories: Mechanical, Thermal, Electrical, Liquid and UV (Sunlight). For each failure cause, the table presents the main source of cause and its principal effects on the product. The table then presents the design improvement opportunities to address the failure. Afterwards, design principles that address the opportunities are presented. in total 15 principles could be applied that provided robustness to the product.

From Table 14, we can observe that each failure cause could be addressed through multiple design principles. For instance, a failure caused by overheating could be prevented by different design features, like using components that are less sensitive to heat, using components that produce less heat, or using features that facilitate cooling. In practice, a balanced approach between different design solutions is likely. The robustness of a design can be achieved by different combinations of design principles and can result in quite different use of various design features.

Based on this analysis and the literature The design principles for the robustness of products are presented in Table 15. Design principles are not always independent of each other (and they are not intended to be); these interdependencies are mentioned in the table.

Table 14: Overview of failures and design opportunities facilitating robustness/physical durability of products

	Failure Cause	Main Source	Principal Effects	Design improvement opportunities (abbreviation in the parenthesis {} refer to principle that addresses the design opportunity)	Current Testing procedure
MECHANICAL	**Mechanical stress and strain (includes impact, cyclic loading and overloads)**	1. Drops and bumps 2. Excessive/improper loading 3. Excessive/improper cyclic loading 4. fluid build-up due to clogs	1. Cracking (rapid, fatigue, ruptures) 2. Plastic deformation (rapid, fatigue) 3.Loosening & Disjointing of components	1. Provide mechanical Flexibility {Flexibility} 2. Select Adequate specification and materials withstanding stress and strain {Overspecifying, Material Selection} 3. Provide use instructions {Use and Maintenance encouragement} 4. Provide ergonomic design for handling {Handling} 5. Implement sensors able to detect and throttle build up pressure at critical areas {Condition Maintenance} 6. Provide cleaning instructions {Use and Maintenance encouragement} 7. Implement sensors to detect and throttle pressure overloads {Condition Maintenance} 8. Implement designs that minimize dirt accumulation {Condition Maintenance} 9. Implement designs that provide self cleaning function {Condition Maintenance} 10. Follow the lines of force/Avoid stress concentrations {Overspecifying}	• Monotonic bending test (e.g.. IPC-JEDEC-9702) • Cyclic bending test (e.g.. JESD 2bb113) • FEM mechanical simulation
	Vibration (possibly cyclic load)	1. Failure of shock absorbers 2. Drops and bumps 3. Vibration due to internal moving components	1. Cracking (rapid, fatigue) 2. Plastic deformation 3.Loosening & Disjointing of components	1. Provide adequate vibration dampening system. {Flexibility} 2. Select Adequate dimensions and materials against vibration by stiffening, reducing moment of inertia & controlling resonant frequencies) {Overspecifying, Material Selection} 3. Provide use instructions {Use and Maintenance encouragement} 4. Provide ergonomic design for handling {Design to avoid dropping} 5. Reduce moving parts where possible {Design Simplicity} 6. Provide tight tolerances to reduce impact during vibration {Controlled Tolerances}	• Seismic testing (e.g.. IEC 60068-3-3) • FEM mechanical simulation
	Mechanical shock	1. Drops and bumps	1. Cracking (rapid, fatigue) 2. Plastic deformation 3.Loosening & Disjointing of components	1. Provide adequate shock dampening system. {Flexibility} 2. Select Adequate dimensions and materials against vibration and bending. {Overspecifying, Material Selection} 3. Provide use instructions {Use and Maintenance encouragement} 4. Provide ergonomic design for handling {Design to avoid dropping} 5. Follow the lines of force/Avoid stress concentrations {Overspecifying}	• Tumbling test (e.g.. IEC 60068-2-31) • Drop tests (e.g.. ASTM D5276) • FEM mechanical simulation
	Wear (Abrasive, Scuffing)	1. Inadequate lubrication due to leaks, dissolution or evaporation. 2. Presence of abrasive 3. Unintended Contact between moving surfaces	1. Rapid degradation of nearby electronics due to overheating (aspects of overheating applies) 2. Rapid degradation of material (via microplowing, micro cutting, microcracking) 3. Excessive vibration 4. Product appearance detrition	1. Seal against dust for internal moving components {Shielding} 2. Provide instructions for maintenance and use (for lubrication and cleaning) {Use and Maintenance encouragement} 3. Select materials less prone to wear {Material Selection} 4. Minimize moving parts {Design Simplicity} 5. Select self reinforced seal {Self Reinforcement} 6 Design tight tolerances to provide seal as well as to reduce vibration {Controlled Tolerances}	• Accelerated Lifetime test (e.g.. HAL, HAST) • Erosion and Abrasion test (e.g.. ASTM G65, ASTM G105). [6] • Dust Ingress Protection test (e.g.. IEC 60529)

	Failure Cause	Main Source	Principal Effects	Design improvement opportunities (abbreviation in the parenthesis {} refer to principle that addresses the design opportunity)	Current Testing procedure
THERMAL	**Overheating**	1. Cooling system failure due to undermentioned cooling system or inadequate cleaning. 2. Electronics near heat source 3. Electronics or Nearby electronics dissipating excessive heat 4. Electrical overload 5. Inadequate cooling system 6. Mechanical overload due to clogs and wear	1. Deformation of low grade plastics leading to structural degradation/failure and degradation of aesthetics. 2. Rapid degradation or total failure of temperature sensitive components (capacitors, transistors and motor coils) 3. Thermal runaway leading to circuit-board damage 4. Deterioration of insulation 5. Viscosity of lubricants reduces 6. Electrical parameter drift leading to components not functioning adequately	1. Provide features that facilitate cooling (heat sink, ventilation etc.) {Condition Maintenance} 2. Implement temperature sensors and controlled power down function {Condition Maintenance} 3. Provide temperature sensitive circuit breakers 4. Insulate temperature sensitive components from components dissipating heat. (via proximity or through insulating materials) {Decoupling}{Shielding} 5. Select materials and components that can withstand high temperatures and temperature cycles. {Material Selection} 6. Implement sensors able to detect and throttle thermal overloads. {Condition Maintenance} 7. Provide maintenance instructions {Use and Maintenance encouragement} 8. Select components that produces less heat {Material Selection} 9. Provide heat conduction path {Condition Maintenance}	• Heat storage test (e.g.. ASTM C1784-20) • Accelerated Lifetime test (e.g. .HALT, HAST) • CFD Thermal simulation
	Low Temperatures	1. Storage and use of products in cold environments	1. Material embrittlement and fracture 2. Viscosity of lubricants decreases 3. Electrical parameter drift leading to components not functioning adequately	1. Provide thermal insulation on sensitive temperatures {Shielding} 5. Select materials and components that doesn't embrittle in low temperatures {Material Selection} 6. Provide active heating element {Condition Maintenance}	• Heat storage test (e.g.. ASTM C1784-20) • Accelerated Lifetime test (e.g. .HALT, HAST) • CFD Thermal simulation
	Thermal shock (hot shock)	1. Cold starts 2. Equipment's that remain operational under extreme conditions (e.g. Kettle)	1. Local deformation due to thermal expansion leading to component failure 2. Cracking through mechanical stress 3. Rapid degradation or total failure of temperature sensitive components 4. Thermal runaway leading to circuit-board damage 5. Dislodgement of soldered components 6. Thermomechanical fatigue cracks 7. Seal failures	1. Provide thermal insulation on components subject to thermal shocks {Shielding} 2. Provide features that facilitate cooling (heat sink, ventilation etc.) {Condition Maintenance} 3. Provide temperature sensitive circuit breaks {Condition Maintenance}{Shielding} 4. Select plastics that can withstand high temperatures {Material Selection} 5. Select components that can withstand high temperatures {Material Selection} 6. Increase proximity for temperature sensitive components from components dissipating heat {Decoupling} 7. Provide thermal conduction path {Condition Maintenance} 8. Add thermal mass (e.g. use bigger heatsinks) {Overspecifying}	• Thermal shock test (MIL-STD-202) [7] • CFD thermal simulation • Accelerated Lifetime test (e.g. .HALT, HAST)
	Thermal shock (cold shock)	1. Sudden liquid contact (e.g. Hot heating rod in sudden contact with water) 2. Brought to very cold temps. (e.g. taking product outside in cold winter)	1. Joint failure due to thermal mismatch 2. Cracking through mechanical stress 3 Detachment of adhesives due to embrittlement 4. Local deformation and failure due to bending in component interconnections. 5. Material embrittlement and fracture 6. Thermomechanical fatigue cracks 7. Condensation see "Water (ionic)" failure 8. Seal failures	1. Provide thermal insulation on components subject to thermal shocks {Shielding} 2. Provide thermal conduction path {Condition Maintenance} 3. Add thermal mass (e.g., use thicker thermally conductive materials) {Controlled Tolerances} 4. Select plastics which doesn't embrittlement in thermal shock{Material Selection} 5. Select components that don't embrittlement in thermal shock{Material Selection} 6. Provide active heating element {Condition Maintenance}	• Temperature shock MIL-STD-810 • CFD thermal simulation • Accelerated Lifetime test (e.g. .HALT, HAST)
	Thermal cycles	1. Self heating and cooling during On/Off 2. Day/Night cycle 3. Indoor/Outdoor cycle 4. Frequent water submersion	1. Thermomechanical fatigue cracks	1. Choose CTE (coefficient of thermal expansion) matched materials {Material Selection} 2. Provide adequate cooling solution. {Condition Maintenance} 3. Select components that do not generate too much heat. {Material Selection} 4. Provide Flexibility (provide Flexibility parts in between different materials) {Material Selection}{Controlled Tolerances}	• Accelerated Lifetime test (e.g. .HALT, HAST)

	Failure Cause	Main Source	Principal Effects	Design improvement opportunities (abbreviation in the parenthesis {} refer to principle that addresses the design opportunity)	Current Testing procedure
Liquid	**Water (ionic) (POWER on)**	1. Spills 2. Submersion 3. Moisture condensing 4. leakage	1. Electronic failure due to short circuiting 2. If no direct short circuiting, malfunction due to increased leakage current.	1. Provide water detection that triggers (part of) electronics shut down. {Shielding}{Condition Maintenance} 2. Provide circuit breakers to handle short circuiting {Shielding, Condition Maintenance} 3. Provide water ingress protection. {Shielding} 4. Provide use and maintenance instruction. {Use and Maintenance encouragement} 5. Provide drains to eliminate condensed moisture. {Condition Maintenance}	• Water Ingress test (e.g.. IEC 60529) • Condensation test (e.g.. IEC 60068-2-30)
	Water (ionic) (POWER OFF)	1. Spills 2. Submersion 3. Moisture condensing 4. leakage	1. Galvanic corrosion to metals resulting in permanent damage to electronics and components 2. Formation of short circuit pathways from galvanic corrosion leading to failures during power On 3. Absorption by polymers of electronics resulting to (a) change in electrical properties which may have an effect on electronic performance or failure (b) Swelling and degradation of materials impacting mechanical robustness. 4. Corrosion leading to degradation of appearance 5. Fungus growth leading to short-circuit and degradation of appearance	1. Provide water detection that triggers (part of) electronics shut down. {Shielding}{Condition Maintenance} 2. Provide circuit breakers to handle short circuiting {Shielding}{Condition Maintenance} 3. Provide water protection as per IEC 60529. {Shielding} 4. Use same materials in all contacted area of an electrical contact to prevent galvanic corrosion {Material Selection} 5. Minimize electric fields and exposed metal surfaces, maximize the distance between unsoldered exposed conductive areas. {Decoupling} 6. Apply conformal coating on critical water sensitive electronics {Surface Treatment} 7. Select materials resistant to corrosion {Material Selection} 8. Provide corrosion resistant outer surface finishing {Surface Treatment} 9. Provide use and maintenance instruction {Use and Maintenance encouragement} 10. Provide drains to eliminate condensed moisture {Condition Maintenance}	• Water Ingress test (e.g.. IEC 60529) • Condensation test (e.g.. IEC 60068-2-30)
	Acid and Bases	1. Electrolyte leakage from capacitors 2. Leaked battery cells 3. Leakage of chemicals used by the product (e.g. washing liquid)	Acceleration of Liquid water related failures.	1. Provide water detection that triggers (part of) electronics shut down. {Shielding}{Condition Maintenance} 2. Provide circuit breakers to handle short circuiting {Shielding}{Condition Maintenance} 3. Provide water protection as per IEC 60529. {Shielding} 4. Use same materials in all contacted area of an electrical contact to prevent galvanic corrosion {Material Selection} 5. Minimize electric fields and exposed metal surfaces, maximize the distance between unsoldered exposed conductive areas. {Decoupling} 6. Apply conformal coating on critical water sensitive electronics {Surface Treatment} 7. Select materials resistant to corrosion {Material Selection} 8. Provide corrosion resistant outer surface finishing {Surface Treatment} 9. Provide use and maintenance instruction {Use and Maintenance encouragement}	• Ingress test (e.g.. IEC 60529) with acid and bases instead of water
	Other types of liquid (Grease oil and cleaning agent)	1. Leakage from components (e.g., lubricant leakage from shock absorbers) 2. Leakage of chemicals used by the product (e.g. washing liquid) 3. Spills	1. Absorption by PCB laminate / polymers, leading to weakening and cracks. 2. Damage of internal structure of capacitors 3. Degradation of product appearance 4. Dissolution of polymer altering the mechanical properties	1. Provide conformal coating in sensitive elements {Surface Treatment} 2. Provide ingress protection as per IEC 60529 {Shielding} 3. Provide corrosion resistant outer surface finishing {Surface Treatment} 4. Select materials resistant to corrosion {Material Selection}	• Ingress test (e.g.. IEC 60529) • Damp heat storage test (e.g.. IEC 60068-2-2-78) with solvents and oils.
	Humidity	1. Placement in High relative humidity area (>60%)	1. Corrosion weakens structural integrity and function. 2. Corrosion leading to leakage current, contact resistance and short circuit 3. Corrosion leading to degradation of appearance	1. Provide water detection that triggers (part of) electronics shut down. {Shielding}{Condition Maintenance} 2. Provide circuit breakers to handle short circuiting {Shielding}{Condition Maintenance} 3. Provide water protection as per IEC 60529. {Shielding} 4. Use same materials in all contacted area of an electrical contact to prevent galvanic corrosion {Material Selection} 5. Minimize electric fields and exposed metal surfaces, maximize the distance between unsoldered exposed conductive areas. {Decoupling} 6. Apply conformal coating on critical water sensitive electronics {Surface Treatment} 7. Select materials resistant to corrosion {Material Selection} 8. Provide corrosion resistant outer surface finishing {Surface Treatment}	•Damp heat storage test (e.g.. IEC 60068-2-2-78)

	Failure Cause	Main Source	Principal Effects	Design improvement opportunities (abbreviation in the parenthesis {} refer to principle that addresses the design opportunity)	Current Testing procedure
ELECTRICAL	**ESD (Electrostatic discharge)**	1. Maintenance activities 2. (unlikely in use cases): products are normally is designed to withstand ESD.	1. Burnout of sensitive components (transistors)	1. Protect electronics by providing conductive and grounded enclosures {Shielding} 2. Provide maintenance instructions. {Use and Maintenance encouragement} 3. Provide ESD protection circuitry {Shielding} {Decoupling}	• ESD robustness test (e.g.. IEC-61000-4-2)
	(EOS) Electrical Overstress (voltage	1. lightning strikes 2. Failing power supplies 3. Failing of nearby connecting equipment's 4. Interconnection errors 5. Accidental Short Circuiting 6. (Inadequate mains supply)	1. Failure of sensitive components (transistors, capacitors) 2. Di-electric breakdown (capacitors) 3. Acceleration of Electromigration effect	1. Provide proper grounding {Condition Maintenance} 2. Provide EOS protection circuitry {Shielding} 3. Provide adequate fuses on all connection lines to the outside world {Shielding, Decoupling} 4. Provide use and maintenance instructions {Use and Maintenance encouragement} 5. Provide adequate insulation or isolation for cables as according voltage standard. {Material Selection}	• EOS robustness test (e.g.. IEC-61000-4-5) • standards for isolation of power supply
	Component Degradation (capacitors and transistors)	1. Ageing 2. Electromigration , 3. Electrochemical migration (humidity)	1. Failure of the capacitor	1. Component selection {Material Selection} 2. Adequate, cryosection of copper in PCB {Over Specifying}	• Accelerated Lifetime test (e.g. .HALT, HAST)
Radiation (Sun)	**Ultraviolet light**	1. Prolonged exposure to sunlight	1. Degradation of mechanical properties (strength and ductility) of polymers [1,2] 2. Degradation of product appearance [1,2]	1. Placement/Use instruction {Use and Maintenance encouragement} 2. Use materials that are UV resistant {Material Selection} 3. Provide UV resistant surface coating {Surface Treatment}	• UV exposure test (e.g.. ASTM D4329)

Table 15: Design principles for robustness and its inference

DESIGN PRINCIPLE	EXPLANATION
Design Simplicity	Selecting a basic conceptual operating principle for performing a specific function that reduces the number of (moving) parts required for performing that particular function, thereby maximizing the simplicity and the robustness of the operating principle [11,23,24,32].
Material and Component Selection (interdependent with over-specifying)	Careful matching of type and grade of components and materials with functional requirements and use environment can prevent degradation (of chemical, mechanical, radiation and/or thermal nature) during the performance of a particular function [11,23,24].
Over-specifying (interdependent material selection)	Over-specifying parts so that the load (e.g., mechanical, thermal load) on the part during use will under normal conditions never exceed the load that the material can handle. This helps withstand stress during use [24,32]. Furthermore, dimensioning interfaces of moving parts to provide smooth running without excess wear could also be considered.
Shielding (protection from outside conditions). (Interdependent with surface treatment)	This strategy reduces variation in the component by shielding the product/component from the cause of the environmental variation. (e.g,, protecting sensitive electronics from water by using a watertight cover, shielding against electric overcurrent by providing a circuit breaker, or surface treating the material to shield from UV).
Surface treatment (Interdependent with shielding)	Selection of the type of surface treatment to prevent degradation (of chemical, mechanical, radiation and/or thermal nature) during the performance of a particular function [24,32]. It is also possible to choose a treatment where wear would be acceptable or even beneficial (e.g., patina on the copper roof, leather shoes fitting better by stretching, etc.).
Redundancy (Interdependent with Expendable parts)	Redundancy is typically used where the functional variation can become so extensive that it turns into a failure with serious consequences [33]. (e.g., coaxial pipe system that only becomes active when the inner pipe fails)
Use of Expendable parts (Interdependent with redundancy)	Design of the weakest link; An inexpensive part that is designed to wear out during use, thereby protecting parts that are more expensive and difficult to replace [32] (Eg. Brake pads in the disc brakes of a car wears out much faster than disc brakes, thereby protecting disc brakes).
Component lifespan match	Choosing components to match components with the longest lifespan in the product prevents the "weakest link" in the design and assures a component doesn't fail until the rest of the product fails [8].
Uncoupling/Decoupling	Components designed with parameters independent from each other could reduce performance variation since individual optimum design parameters could be specified [34,35]. (E.g., positioning capacitors away from hot transistors ensures they do not need the same thermal resistance.)
Self-reinforcement	Functional performance improves certain design parameters deviating from nominal conditions. [33,36] (E.g., Rubber lip ring sealing which becomes tighter as the pressure increases.)
Flexibility (Interdependent with loose tolerances)	Flexible parts can absorb parameter variation and therefore reduce the performance variation. It is worth noting that flexibility is a function of both material properties and geometry [32].
Controlled tolerances	Controlling tolerances based on the requirement reduces variation in the product. For instance, introducing looser tolerances essentially 'delays' how the variation of a design parameter influences the functional performance. If loose tolerances exist between two functional surfaces, variation of one surface can occur to some extent without affecting the interfacing surface [33,37]. In contrast, Tightening the allowable parameter variation will inherently reduce the performance variation as it reduces wear. [37,38].

Proper Use and Maintenance Encouragement	Whist this principle also falls under repair and maintenance, encouraging product maintenance and proper use has shown to induce fewer failures over its lifetime (Eg. Indicator light in coffee maker when descaling is required).
Condition maintenance feature	Features that maintain the condition of the product actively or passively assure that any variation does not exceed the tolerances of a component and therefore reduce the failure chance. (e.g., cooling, and throttling system for IC chips to prevent overheating, automatic load balancing system in a washing machine).
Design to avoid dropping:	For products that can be easily moved by the user (under 10kg), having ergonomic handling features (e.g., Handles for a vacuum cleaner, grips for phones), assure that the product is less likely to be dropped when transported during its use phase.

6.2 Design recommendations for physical durability of products

The design principles for physical durability could be categorized into five main guidelines/strategies: Prevent, Block, Distribute, Dissipate, and Endure.

- Prevent (De-couple): Design products so that environmental variation could be avoided. Examples are:
    - indicate proper use and maintenance of the product: Indicate proper use and maintenance of the product make sure the product does not get exposed to extreme situations.
    - Provide breakers: Have breakers (such as circuit breakers, throttle valves and overheat shutdowns) to make sure the variation does not reach high enough for potential failure.
    - Use components that produce little variations (e.g. More efficient chips).
    - Separating sensitive components from components that produce variations.
    - Provide ergonomic design to avoid drops.

- Block (shielding): Design products so that their environmental variation is shielded. Examples are:
    - Provide Surface coating to materials to resist UV.
    - Provide Thermal insulation to temperature-sensitive materials.
    - Shield against water through watertight seals.

- Distribute: Design products so that any variation is evenly distributed within the product so that stress (thermal or mechanical) concentrations are minimized. Examples are:
    - Follow the line of stress.
    - Add thermal mass.

- Dissipate: Design products so that any variation is dissipated to the environment. Examples are:
    - Provide active/passive cooling to products that produce heat.
    - Provide Dampening against vibration and shock.

- Endure (Resist): Design products to endure the variation. Examples are:
    - Selecting proper materials and components .
    - Specifying/over-specifying dimensions.

Table 16 presents the strategies and the failure causes that can be addressed by a particular strategy (based on table 16). The table shows that majority of strategies could be applied to address most failure causes. These strategies may need to be carefully balanced and implemented to provide an optimal design for a durable product.

Table 16: Strategies and failure cause it addresses

Strategy	**Failure Cause**				
	Mechanical	**Thermal**	**Electrical**	**Liquid**	**UV (Sun)**
Decouple	*	*	*	*	*
Shield	*	*	*	*	*
Distribute	*	*			
Dissipate	*	*	*	*	
Endure	*	*	*	*	*

Design principles of robustness, if applied in isolation, might on the one hand lead to products with high manufacturing and material costs, that are not viable for the market. On the other hand, their effect might be counterbalanced by neglecting other design principles, resulting in a product that is robust in some respect, but weak in other. Finding the appropriate balance between different design principles for robustness will be required.

6.3 Translation towards a scoring system

As discussed previously, the robustness of a design can be achieved by different combinations of design principles and can result in quite different use of various design features. Therefore, it is difficult to reliably assess the robustness of the product by features related to assessing the product architecture. This means that it is almost impossible to establish robustness/reliability based on the product's architecture.

This is also observed in practice. As assessment through analysis of the product design is usually not fruitful, testing that induces a failure cause (e.g., through accelerated lifetime tests, and mechanical and thermal stress tests) is the most prominent testing procedure (See Table 14). Such experimental testing on the ease of inducing failure is covered in WP3.

An alternative to experimental testing could be simulations; The occurrence of a failure cause can be simulated through finite element analysis or computational fluid dynamics thermal simulation. However, these types of simulations are very resource heavy and put tight requirements on data completeness and quality, these are normally only applied for specific parts. Therefore, this is not considered feasible for testing products within the scope of PROMPT.

7 SOFTWARE AND UPGRADABILITY

Software related aspects are a cause of increasing importance for premature obsolescence in a growing number of product categories. The impact of software on product obsolescence is expected to further grow with increasing Internet of Things and network connectivity of ever more devices (Figure 16).

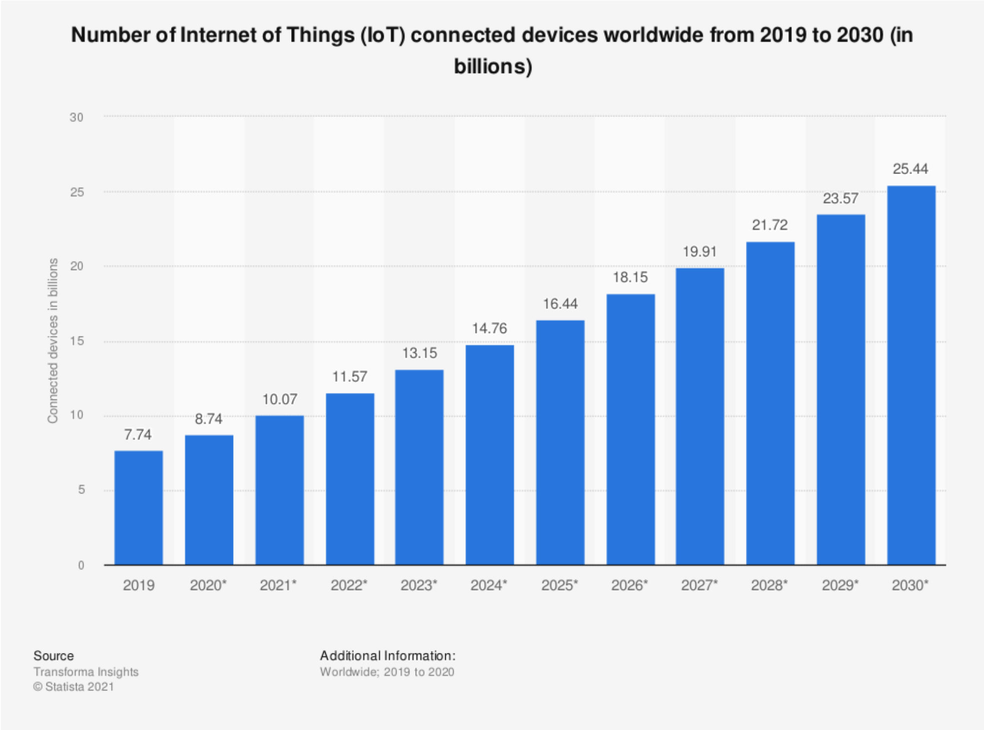

Figure 16: Forecast of IoT connected devices worldwide from 2019 to 2030, in billions (source: Transformation Insights)

Software obsolescence can be traced in the context of a broad range of topics, including diagnostics, updates, relations between hardware, firmware and software, green coding, code accessibility, and software pairing. While it is not feasible to investigate all these aspects within the scope of PROMPT, it is valuable to further investigate selected aspects.

In the analyses presented here, the scope will be limited to aspects of software obsolescence related to the functional state of the product, preventive maintenance, and repair. In particular, security updates will be looked into as an aspect of preventive maintenance, while part pairing will be discussed as a potential barrier to repair.

7.1 Software updates

Software updates, in general, are used to address issues (bug fixing), patch security vulnerabilities, optimize and adapt to newer applications, or to add new features. Therefore, ICT devices relying on software are susceptible to obsolescence if the appropriate software is unavailable, since this would lead to crashing and deterioration of performance of the product, as well as increased venerability to attacks.

A 2020 Eurobarometer survey found that 19 percent of Europeans replaced their last digital device (smartphone, tablet, or laptop) because the performance of the old device had significantly deteriorated, and another 19 percent replaced it because certain software stopped working on the old device [39].

Similarly, regarding security updates, few appliance manufacturers are willing to commit to a period during which they will provide security updates [40]. However, security updates are regarded as very important by appliance owners [41,42].

Some smart TV manufacturers commit to a period during which they will provide software updates. For smartphones, several smartphone manufacturers release information on the duration of the availability of software updates. Apple provides software updates for a minimum of five years after launch [43]. Samsung's support duration depends on the device, where select devices launched in 2019 will receive four or five years of security updates [44]. However, this in practice might result in the sale of older devices that are only supported for a couple of months. Therefore, manufacturers should commit the number of years to the availability of software updates from the time production and sales of the product are ended, not from the launch date. However, this may be a complicated criterion to test as the self-time in the store is unknown.

Software updates are essential to ensure the continued interoperability of products and address new security and privacy risks. In contrast, they can also be used to reduce the performance of devices, remove functionality, or prevent third-party repair of the product. For example;

- In 2017, Apple released software updates that reduced the peak voltage drawn from older batteries. This slowed down the operation of these devices considerably. However; on the other hand, this prolongs the lifetime of the devices. The owners of the devices had not been informed about this potential effect on their devices, and could not revert their devices to the previous operating system state. Here users should be transparently communicated on what the updates provide so that users can make an informed decision for updating. Additionally, update reversibility should be provided.

- In 2015, an iOS 9 upgrade disabled all iPhones with a Touch ID sensor that had their home button replaced by an unauthorised repair provider – a part that is often replaced by default together with a broken screen [45]. As a result, these users could no longer operate their devices. As the update made their phones as useful as a brick, inoperable devices have since been referred to as 'bricked'. In this case, a software update made devices effectively unusable, while all of its components were entirely functional.

These insights indicate that transparent information regarding what the update does, should be provided to the user before the update. In addition, reversing the software updates should be possible for the user. Furthermore, any update should not hamper the functional performance or the reparability of the product in any way.

7.2 Part Pairing

This section discusses the specific ways in which software and firmware issues can affect product life spans by restricting repair activities. The phenomenon of part pairing or serialisation can be observed in various products, ranging from electronics, to household appliances, to gardening tools.

There is an increasing trend in electronic products towards part serialisation. Serial numbers encoded in the firmware of spare parts provide manufacturers with specific information about the spare part. Some devices are being designed so that replacement parts will not be accepted into the device without their serial numbers being paired anew to the motherboard or controller component.

Security is often quoted as a rationale for the pairing approach; however, pairing is not technically necessary to achieve adequate security. Alternative design approaches include:

- Central storage of authentication data: whether authentication data is stored within the authentication part or within, for example, the CPU is a design choice, with central storage representing a more secure design with no need for pairing.

- Multi-step authentication for informed consent to accept new parts: when parts are replaced, multi-step authentication can be used via non-hardware means (e.g., pin, password etc) before the functionality of a new part, such as touch or face ID, is activated.

In certain cases, parts need to be paired to the motherboard or controller component to function; serial numbers, regional settings, or other parameters have to be entered via onboard software or external (software) tools.

To evaluate the extent of the restrictions imposed by part pairing, the aspects were categorised into three different dimensions:

1. Who has access to the firmware or interface? The access can be open to consumers or restricted to professional repair services, registered service providers, or manufacturers.
2. What is the interface or procedure? Is an external machine required, is it on the device, is specific software needed, can it be done on a website or in a cloud service?
3. What information is required? It can be the model number, region setting, device serial number, part serial number, etc.

An overview of these three dimensions is provided in Table 17.

The same dimensions are relevant for loading firmware onto the replacement parts themselves. Parts that require specific firmware to function are often supplied without such firmware preinstalled. Conditions for access to the firmware itself, or the interface needed to flash the firmware onto the part, are often restricted.

Table 17: Three dimensions of the part pairing procedure

General Framework				
Who has access?	Consumer	Professional repair	Registered service provider	Manufacturer
Interface / Procedure	External machine	On device	Specific software	Website / Cloud Service
Information required	Model number	Region setting	Device serial number	Part serial number

In addition to these dimensions on the pairing procedure, manufacturers can put restrictions on the replacement parts they accept. If the serial number is not that of a genuine OEM spare part, it can be rejected by the OEM, regardless of the quality of the part, which could even be a genuine part recovered from an identical device. Alternatively, the part could be accepted, but functionality may be reduced or lost completely.

Service manuals available to professional repairers describe in detail the procedures to replace specific components in Smart TVs. In this section, two Samsung service manuals and one Sony service manual were analysed.

For both Samsung and Sony, the service manual contains the procedure to replace the mainboard, T-con, and display panel. Entering a specific key combination via the remote control displays the service menu on the screen. In the service menu, several tests can be activated, the software can be updated, and information input related to the model number, part serial number, and region settings.

Table 18 sums up the analysis of mainboard replacement in a Sony TV. Access to the interface is restricted to professional repairers who have access to the service manual. The interface is available on the TV set. Moreover, the information required to install the component is model number, region setting, and part serial number.

Table 18: Three dimensions of the part pairing procedure for the replacement of the mainboard in a Sony TV set.

Sony TV mainboard initialisation				
Access	Consumer	**Professional repair**	**Registered service provider**	**Manufacturer**
Interface / Procedure	External machine	**On device**	Specific software	Website / Cloud Service
Information required	**Model number**	**Region setting**	Device serial number	**Part serial number**

While there is a high risk that the issue of pairing becomes more widespread over time and across manufacturers, the main data currently available focus on the smartphones of the OEM Apple. Results in this section have also been published in a policy paper on part pairing signed by the right to repair campaign [39].
In some phones (e.g. newer models of iPhones), components need to be paired to the device to achieve full functionality. While authorised service providers are provided with the means to do so, it can create major barriers to independent and self-repair, through:

- Restricted access to serial entry functionality: whilst it could be made possible to enter serial numbers for new parts via a menu in the smartphone, it is often only possible using external tools – for example, a proprietary app to enable OEM authorisation and configuration of parts. Access to such apps can be restricted to OEM authorised technicians.

- Rejection of aftermarket and reused parts: if the serial number is not that of a genuine OEM spare part, it can be rejected by the OEM, regardless of the quality of the part, which could even be a genuine part recovered from another phone.

- Functionality downgrading or loss for non-OEM and/or non-paired parts: replacement without authorisation may be possible in some cases, but smartphone functionality may be reduced or lost completely. This may even be triggered by software updates taking place long after the repair, as described in the section on software updates.

- Intrusive notifications on non-OEM and/or non-paired parts: even if a part is successfully installed, smartphone owners may be inundated with intrusive alerts that their part is not genuine if the pairing process cannot be completed. This can even be the case with genuine parts recovered from identical models. It is useful for the user to provide informed consent once if a replacement part is not a genuine OEM part (especially if that part is implicated in security functionality) and to be able to verify this whenever needed. However, multiple alerts can change a positive repair experience to a negative one.

This analysis on part pairing shows that it is curtailed to design out part pairing that hampers reparability of electronics. For this, the following recommendations are made to ensure a healthy repair ecosystem with multiple options for end-users.

- **Allow freedom to use any parts for repair or maintenance**: independent and authorised repairers must be able to purchase and use any parts or equipment for the repair and maintenance. This is similar to measures already in place in the automotive industry.

- **Enable full spare part functionality:** repairers should have access to the software or hardware tools, firmware and similar auxiliary means to enable full functionality of the spare part and device after repair, through independent authorisation or pairing of serial numbers with informed end-user consent.

- **Mitigate security concerns through end-user consent**: to complete the process of part acceptance the manufacturer, importer or authorised representative should inform the end-user of the authenticity of the parts via a single notification and/or information in the device settings for verification purposes and may require the owner of the device to re-authenticate by other means prior to full part functionality being made available.

7.3 Translation towards a scoring system

The duration of software support is essential to keep the device in a functional state but only becomes apparent over time unless manufacturer declarations on time frames can be confirmed. Software updates should ideally be reversible and accompanied by information on compatibility with hardware and previous-generation software.

Part pairing is a practice that is prevalent in smart TVs and gaining popularity in smartphones. Nevertheless, the risk of hindering repair is larger in smartphones, where the access conditions are much more restricted. Testing part pairing would require replacing different parts of the device and testing the functionality with different combinations of replaced parts over a longer time. Alternatively, a (binding) statement could be asked from manufacturers regarding the ability to pair spare parts.

8 Conclusion

This report presented an overview of research and activities conducted on physical design aspects influencing diagnosis, maintenance, repair, and physical durability for household electronic products. Based on the results, guidelines for diagnosis, maintenance, repairability, and physical durability are derived. These guidelines are intended for designers, manufacturers, and product engineers to design and develop products that can resist and postpone premature obsolescence of electrical and electronic household appliances.

The main recommendations from each chapter are as follows

- For diagnosis, nine principles and four design guidelines were identified. The diagnosis process can be facilitated by minimizing disassembly, facilitating disassembly when needed, and providing timely and understandable feedback and instructions.

- For reparability, 13 design principles were identified. Several of these principles are similar to principles of diagnosis. The main recommendations for reparability are as follows:
    - Designing products with features facilitating ease of diagnosis and enabling disassembly with basic tools could remove some of the major barriers towards repair by users, and stimulate more users to repair their products.
    - Avoid using fasteners that require proprietary tools, bundling of priority parts, and using non-reusable fasteners (eg. glueing, one-way snap-fits), as these severely hamper the reparability of the product.
    - Safety during and after repair could be facilitated by diagnosis without disassembly, and facilitating correct reassembly of especially wiring and hoses.
    - Regarding Information accessibility, clear information to maintain, diagnose, repair, are important to facilitate reparability.

- The general principles for maintenance are largely similar to repair. Maintenance can be facilitated by providing visual and auditory indicators, minimizing the number of steps and tools required for maintenance, and providing maintenance instructions.

- 15 design principles for robustness were identified. These principles could be categorized into five main strategies: decouple, shield, distribute, dissipate, and endure. The robustness of a design can be achieved by different combinations of design principles. As a result, it is difficult to reliably assess the robustness of the product by features related to assessing the product architecture. Therefore, experimental testing on the ease of inducing failure (as covered in WP3) is considered a more effective method for assessment.

- To prevent software-related obsolescence, software updates should be transparent, and reversible and should not hamper the functional performance or the reparability of the product in any way. Pairing of spare parts (including 3rd party spare parts) for repair and maintenance should not hamper the functional performance of the device.

The insights from this report act as a basis for creating a testing program for obsolescence of the products, Translation of the insights to a testing program will be reported in the Deliverable 4.4

9 References

[1] Pozo Arcos B, Dangal S, Bakker C, Faludi J, Balkenende R. Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. J Clean Prod 2021;319:128741. https://doi.org/10.1016/j.jclepro.2021.128741.

[2] Pozo Arcos B, Bakker CA, Flipsen B, Balkenende R. Practices of Fault Diagnosis in Household Appliances : Insights for Design. Under Rev 2020:1–31.

[3] Brusselaers J, Bracquene E, Peeters J, Dams Y. Economic consequences of consumer repair strategies for electrical household devices. J Enterp Inf Manag 2019. https://doi.org/10.1108/JEIM-12-2018-0283.

[4] Environmental standardization for electrical and electronic products and systems - Glossary of terms. 2013.

[5] Vanegas P, Peeters JR, Cattrysse D, Tecchio P, Ardente F, Mathieux F, et al. Ease of disassembly of products to support circular economy strategies. Resour Conserv Recycl 2018;135:323–34. https://doi.org/10.1016/j.resconrec.2017.06.022.

[6] Peeters JR, Tecchio P, Vanegas P. eDIM: further development of the method to assess the ease of disassembly and reassembly of products: Application to notebook computers. 2018. https://doi.org/10.2760/864982.

[7] Bonvoisin J, Halstenberg F, Buchert T, Stark R. A systematic literature review on modular product design. J Eng Des 2016;27:488–514. https://doi.org/10.1080/09544828.2016.1166482.

[8] Bovea MD, Pérez-Belis V. Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. J Environ Manage 2018;228:483–94. https://doi.org/10.1016/j.jenvman.2018.08.014.

[9] Hollander D, Version D, Hollander D. Design for managing obsolescence. 2018. https://doi.org/10.4233/uuid.

[10] Flipsen B, Huisken M, Opsomer T, Depypere M. IFIXIT Smartphone Reparability Scoring: Assessing the Self-Repair Potential of Mobile ICT Devices. PLATE Conf 2019 2019:18–20.

[11] Keoleian G., Menerey D. Life cycle design guidance manual: Environmental requirements and the product system. 1993.

[12] Ingemarsdotter AE, Stolk M, Balkenende R. Design for Safe Repair in a Circular Economy 2021.

[13] S VMA, V VHKB. Review study on Vacuum cleaners Final report 2019.

[14] Moss M. Designing for minimal maintenance expense: The practical application of reliability and maintainability. Quality and Reliability series part 1. New York, NY, USA: Marcel Dekker; 1985.

[15] Perera HSC, Nagarur N, Tabucanon MT. Component part standardization: a way to reduce the life-cycle costs of products. Int J Prod Econ 1999;60:109–16. https://doi.org/10.1016/S0925-5273(98)00179-0.

[16] Deloitte. Study on Socioeconomic impacts of increased reparability – Final Report. Prepared for the European Commission, DG ENV. 2016. https://doi.org/10.2779/463857.

[17] Shahbazi S, Jönbrink AK. Design guidelines to develop circular products: Action research on nordic industry. Sustain 2020;12:1–14. https://doi.org/10.3390/su12093679.

[18] Victoria P, Braulio-gonzalo M, Juan P, Bovea MD. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment . A Spanish case study 2017;158. https://doi.org/10.1016/j.jclepro.2017.04.143.

[19] Dangal S, van den Berge R, Pozo Arcos B, Faludi J, Balkenende R. Perceived capabilities and barriers for do-it-yourself repair 2021.

[20] Flipsen B, Bakker C, Van Bohemen G. FLIPSEN Developing a reparability indicator for electronic products. 2016 Electron Goes Green 2016+, EGG 2016 2017:1–9. https://doi.org/10.1109/EGG.2016.7829855.

[21] 45554 E. en 45554 2021;45554.

[22] Arcos BP. Fault Diagnosis in Household Appliances : A Design Prespective. TU Delft, 2022.

[23] Vezzoli C, Manzini E. Design for environmental sustainability. Springer; 2008.

[24] Bijen J. Durability of engineering structures: Design, repair and maintenance. Elsevier; 2003.

[25] Bertsche, B., Lechner G. Reliability in Automotive and Mechanical Engineering. New York: Springer-Verlag; 2007.

[26] Tillmann F, Jan W, Julian L, Carmen R, Eckhard K. Design for robustness-systematic application of

design guidelines to control uncertainty. Proc Int Conf Eng Des ICED 2017;4:277–86.
[27] Wohlin C. Guidelines for snowballing in systematic literature studies and a replication in software engineering. ACM Int Conf Proceeding Ser 2014. https://doi.org/10.1145/2601248.2601268.
[28] Blackwell GR. The electronic packaging handbook. CRC Press; 2017.
[29] Bazu M, Bajenescu T. Failure analysis: A practical guide for manufacturers of electronic components and systems. vol. 4. John Wiley & Sons; 2011.
[30] Becker WT, Shipley RJ, Lampman SR, Sanders BR, Anton GJ, Hrivnak N, et al. ASM handbook. Fail Anal Prev 2002;11:107.
[31] Willems G. Electronics Design-for-eXcellence Guideline Design-for-Robustness of Electronics 2019:1–36.
[32] Mulder W, Blok J, Fokkeler SHF. Design for maintenance. 2012. https://doi.org/10.4271/560110.
[33] Ebro M, Howard TJ. Robust design principles for reducing variation in functional performance. J Eng Des 2016;27:75–92. https://doi.org/10.1080/09544828.2015.1103844.
[34] Söderberg R, Lindkvist L, Dahlström S. Computer-aided robustness analysis for compliant assemblies. J Eng Des 2006;17:411–28.
[35] Lee KD, Suh NP, Oh J-H. Axiomatic design of machine control system. CIRP Ann 2001;50:109–14.
[36] Andersson PAH. A process approach to robust design in early engineering design phases. 1998.
[37] Ebro M, Howard TJ, Rasmussen JJ. The foundation for robust design: Enabling robustness through kinematic design and design clarity. Proc Int Des Conf Des 2012;DS 70:817–26.
[38] Chowdhury S, Taguchi S. Robust Optimization: World's Best Practices for Developing Winning Vehicles. John Wiley & Sons; 2016.
[39] European Commission. Shaping Europe's digital future: Eurobarometer survey shows support for sustainability and data sharing 2020:66–7.
[40] Willliams A. Security updates for smart appliances could end after just two years, finds Which? Read more: https://www.which.co.uk/news/article/the-truth-behind-smart-appliance-security-updates-aERdx7b1sdHq - Which? WhichCoUk 2020. https://www.which.co.uk/news/2020/06/the-truth-behind-smart-appliance-security-updates/ (accessed April 1, 2022).
[41] Statt N. Nest is permanently disabling the Revolv smart home hub. The Verge 2016. https://www.theverge.com/2016/4/4/11362928/google-nest-revolv-shutdown-smart-home-products.
[42] S R. End of Software Updates for Legacy Products. Sonos News 2020. https://en.community.sonos.com/announcements-228985/end-of-software-updates-for-legacy-products-6835470.
[43] Obtaining service for your Apple product after an expired warranty. Apple Support n.d. https://support.apple.com/en-us/HT201624.
[44] Introduction to Samsung Security Updates. Samsung Secur n.d. https://security.samsungmobile.com/workScope.smsb (accessed April 14, 2022).
[45] Wiens K. Apple Shouldn't Get to Brick Your iPhone Because You Fixed It Yourself. WIRED 2016. https://www.wired.com/2016/02/apple-shouldnt-get-to-brick-your-iphone-because-you-fixed-it-yourself/.

APPENDIX 1: LITERATURE REVIEW PAPER ON REPARABILITY

Design aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness *–Draft, To be submitted-*

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1 Abstract

The Circular Economy Action Plan adopted by the European Commission sets out to keep value in products as long as possible through developing product-specific requirements for durability and repairability. In this context, various scoring systems have been developed for scoring product repairability. This study assesses the objectivity and completeness of six major repair scoring systems, to see what further development may be required to make them policy instruments for testing products for repairability. The completeness of the scoring systems was assessed by comparing them to the latest literature on what design features and principles drive product repairability. Similarly, their objectivity was determined by assessing whether the presented scoring levels per criteria are clearly defined with a quantifiable and operator-independent testing method. The result shows that; Most of the criteria in the scoring systems were objective and complete. However, health and safety, was least objective criteria and has not been fully addressed. Additionally, assessing disassembly using eDiM method instead of disassembly steps would be more reliable. Furthermore, aspects of reassembly should be addressed further. Moreover, information dependant on specific fault should be addressed at fault level. Addressing these gaps leads to development of a scoring system that could be used in policy making, and for assessment by consumer organizations, MSA, and other interested stakeholders, to promote repairability of products.

2 Introduction

Consumer goods are nowadays less durable and repairable than in the past, and the average product lifetime of products seems to be decreasing [1]. This contributes towards an increase in Waste Electronic and Electrical Equipment (WEEE), which has been growing at the rate of 2-5% per year [2]. A report by the Organization for Economic Co-operation and Development (OECD) indicates that extending product lifetime could help solve this issue [3]. As a response, The Circular Economy Action Plan adopted by the European Commission sets out to keep value in products as long as possible through developing product-specific requirements for durability and repairability [4]. In this context, various scoring systems have been developed for scoring repairability of electronic and electrical equipment (EEE) [5–10]. Such scoring systems could also contribute to ongoing and future standardization to provide designers and market surveillance authorities (MSA) with recommendations on improving the repairability of products. Additionally, this could empower consumers to make informed choices when buying their products.

A good scoring system should be objective and provide complete assessment of the repairability of products (completeness) [11]; the scoring system should be assessed on whether it reflects science-based literature on design aspects related to repairability. These elements are crucial for application in policy making, and for assessment by consumer organizations, MSA, and other interested stakeholders, to promote repairability of products.

Bracquene et al. [12] provide an assessment between three scoring systems; AsMeR (Assessment Matrix for ease of Repair) [6], ONR:192012 (Label of Excellence for Durable, Repair Friendly, Designed Electrical and Electronic Appliances) [7] and IFixit 2018 [9]) for vacuum cleaners. Following this, Bracquene et al., [13] provides comparison of AsMeR and RSS (Joint Research Centre Repair Scoring System) [5] for washing machines. However, this research does not assess the completeness of these scoring system. Furthermore, the recent scoring system; iFixit:2019 (Smartphone Repairability Scoring system) [8], FRI (French Reparability Index) [14], and EN45554 (general methods for the assessment of the ability to repair, reuse and upgrade energy-related products) [15] , have not been assessed.

This paper fills the gaps by answering the following questions. How does the current scoring system reflect science-based literature on design aspects related to repairability? How objective are the current scoring systems? By answering these research question, this study aims to provide insights and opportunities for improvements in repairability scoring systems in general.

This research was conducted in two steps: firstly, literature research was conducted on what design features and principles influence the repairability of the products. This is done to determine what design elements should be captured by repairability scoring system. Afterwards, these design features and principles from the literature research were compared with six chosen scoring systems and standards; Assessment Matrix for ease of Repair (AsMeR) [12], Joint Research Centre Repair Scoring System (RSS) [5], iFixit 2019 Smartphone Repairability Scoring system [8], General methods for the assessment of the ability to repair, reuse and upgrade energy-related products (EN 45554) [15], Label of Excellence for Durable, Repair Friendly, Designed Electrical and Electronic Appliances (ONR:192012) [7], and French Reparability Index (FRI) [14]. This comparison assesses the completeness of the scoring systems. Secondly, this study assesses the objectivity of the scoring system by analysing and comparing the scoring methods between different scoring systems.

2.1 Scoring Systems for Repairability

Several repairability assessment systems are currently available, The following six scoring systems were chosen for this study based on the following criteria:

- The criteria for these scoring systems are publicly available in the English language.
- The evaluation method is quantitative or at least semi-quantitative in nature, to provide a more objective assessment and enable ranked comparisons of products.

It must be the latest iteration or version of the assessment system from the organisation/group.
Table 1 provides an overview regarding the chosen six scoring systems. These criteria are expected to overlap as firstly they all are measuring the repairability of Electrical and Electronic Equipment (EEE), but also because the newer scoring system tends to consider and study previous scoring systems before developing it.

Table 1: Overview of the chosen six-scoring system

Scoring System	**Mainly based on**	**Products that can be tested**	**Details**
EN 45554 (2020)	• literature research on aspects influencing the repairability of products • Co-construction by: professional organizations, manufacturers, distributors, repairers, NGOs, and experts.	All EEE	General method for assessment for repair, reuse, and upgrade. Provides generic set of tools and is not tailored towards specific products. Intended for both professional and self-repairers.
FRI (2020)	• literature research on aspects influencing the repairability of products • Co-construction by: professional organizations, manufacturers, distributors, repairers, NGOs, start-ups, and experts.	Washing machine, TV, Laptop, Smartphones, Lawnmowers,	Based on five criteria including documentation, disassembly, spare part availability, spare part price, and additional product-based criterion. Intended for both Professional Repairer, Self-Repairer

IFixit (2019)	• literature research on aspects influencing the repairability of products • Co-construction by iFixit experts, and sustainability (SMART) consortium.	Mobile phones	8 criteria focused towards assessing ease of self-repair.
RSS (2019)	• Literature research following preliminary EN45554 and AsMer2018 • Co-construction by; Industry, trade associations, repairers, academia). • Case studies.	VC, laptop, TV, mobile phones, WM, DW	Assessment on repair reuse and upgrade. Intended for Professional Repairer.
AsMer (2018)	• Literature research on aspects influencing the repairability of products • Case studies.	All EEE	Based on five main repair steps (product identification, failure diagnostic, disassembly and reassembly, spare parts replacement, and restoring to working condition) and three different repairability criteria (Information provision, product design, and service). Intended for Professional Repairer and Self-Repairer.
ONR 192102 (2014)	• Co-construction by repairers and Federal ministry of land, forestry, environment, and water.	Brown goods and white goods	Assessment on both durability and repairability. Criteria related to product design and provision of information and services. Intended for Professional Repairer

3 Method

3.1 Assessing completeness of the Scoring Systems

From December 2020 to February 2021, a literature review was conducted to identify design principles, features, and guidelines related to the repairability of household electronic and electrical equipment. Relevant scientific literature related to design aspects of repairability were identified via google scholar search engine and SCOPUS citation database.

Search terms consisted of “design” , “features”, “principles”, “guidelines”. This was followed by “repair OR maintain”. Additionally, the search term focused on the following product categories: “appliance”, “Household products”, “EEE”, “white goods”, “brown goods”, “electrical and electronic equipment”, “mobile phones”, “vacuum cleaner”, “laptop”. This was an iterative process where different combinations of the provided terms were used. Wildcards were used to ensure wide coverage, and proximity criterion of within 5 was used to narrow down the relevant results with co-occurring search terms (see Figure 1). The search was conducted within Title, Abstract, and Keywords, ranging from 2000 to 2021. Additionally search was focused on following subject area: engineering, material science, environmental science, industrial design, and design.

This review focuses on aspects related physical design of the product. This includes design features, principles, and guidelines related to the repairability of household electronic and electrical equipment. Articles beyond the aforementioned scope were excluded. This includes elements related to automotive, textiles, and user and market aspects related to repairability (such as spare part price and availability). The results were screened for their relevancy by firstly, checking headings, then reviewing abstract and conclusion, then a full review of the paper is conducted, and relevant articles are selected. Additional papers were identified via snowballing using the reference list of a paper or the citations to the paper to identify additional papers [16].

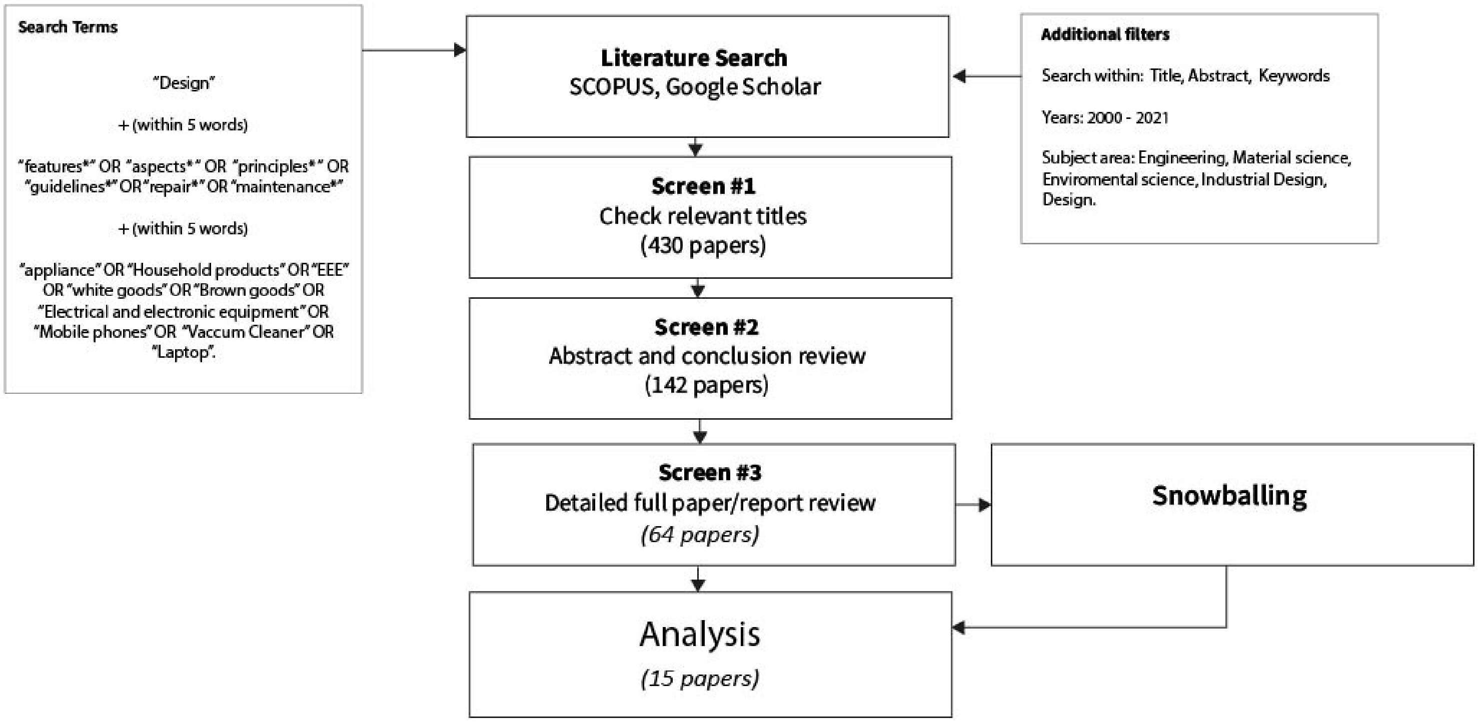


Figure 1: Overview of the search process followed

During the analysis phase, each chosen paper was read marking sections wherever design-related aspects related to repairability were mentioned. The design aspects were considered relevant only if the addressed repairability aspects were an outcome of an empirical study.

Two studies have been conducted previously on design guidelines and principles related to repairability: The paper by Boeva et al. [17] provides nine relevant recommendations related to repairability originating from 34 different sources. Similarly, Den Hollander provides 16 design principles related to the repairability of products originating from six different literatures published before 2016. To avoid multiple referencing, literature already addressed by Boeva et al. [17] and Den Hollander [18] was not considered.

The result was clustered into design features and principles empirically shown to improve repairability from the literature, to compare to the criteria measured by the different scoring systems. The completeness of the scoring system was determined by checking whether the identified design elements are reflected in the scoring system.

3.2 Assessing Objectivity of the Scoring Systems

Objectivity is important for repeatability of scores. To assess It, the criteria presented in the different scorings systems were clustered within the identified design elements (see table 2). Afterwards, each criterion and its testing method is categorized into three levels: Objective, Semi-objective, and Subjective, based on the following criteria:

- Objective: Each level score that can be achieved is clearly defined, the testing action to achieve the score can be quantified and is operator independent.
- Semi-objective: Whilst the testing action can be quantified, no clear indication is given on how each level of the score is achieved, causing a degree of operator dependence.
- Subjective: One or more testing actions cannot be quantified objectively; the result is operator dependent.

4 Results and Discussion

This section first shows how well each analysed scoring system captures the design elements that have been empirically shown to drive repairability in literature. It then assess the completeness, and objectivity of each scoring system, as well as showing differences between them.

Considering both literature and different scoring systems, in total 17 different design elements were identified that are considered important for repairability in EEE. Table 2 provides the list of design elements and their descriptions based on the literature. Table 3 provides an overview of scoring systems compared to the literature. In general, all criteria in the scoring system seem to be reflected in the literature.

Table 2: Overview of design aspects empirically shown to drive repairability, and their descriptions in the literature.

Design principles and Features	Definition and how it relates to repair
Disassembly	The product is taken apart such that it could subsequently be reassembled and made operational [19]. Required to access components for most repairs [20].
Reassembly	Assembling a product after disassembly, to its original configuration [21] . Required to return a product to operation.
Fastener removability and Reusability	Facilitation on removability of fasteners while ensuring that there is no impairment of the parts [or product] due to the process. Required for disassembly and ease of reassembly.
Fastener Visibility	Whether more than 0.5 mm2 of the fasteners surface area is visible when looking at fastening direction [20] and visual cues [8]. Facilitates product disassembly.
Tools Required	Number and type of tools necessary for repair of the product [15].
Modularity	Grouping of the components based on their function [22]. Enables functionally independent components to be replaced individually [6], promotes diagnosis [23], and product disassembly [24].
Diagnosis	Process of isolating the reason for product failure. Facilitated by Designed signals (text, light, sound, or movement) [23]. In absence of these features, visible surfaces and accessibility of a component for inspection promote failure isolation [25].
Health and Safety	Health and Safety risk to the user during and after repair. Features minimizing safety risks also increases confidence in product disassembly and reassembly [26].
Standard parts and interface	Enforcing “the conformance of commonly used parts and assemblies to generally accepted design standards for configuration, dimensional tolerances, performance ratings and other functional design attributes” [27]. Standardization reduces spare part costs and availability, tooling, component identification complexity, skill level required, and increases interchangeability of components during maintenance and repair [28].
Information accessibility	Information availability to the product user and repairers. Whilst this is not directly a design element, manuals and labels are provided with the product. Guides repair process [23,25,29–31].
Design simplicity/ Complexity	This is defined by disassembly steps and disassembly time [24]. Simplicity in understanding the interface and malfunction feedback assists failure diagnosis [25]

Adaptability/ Upgradability	Adaptability allows performing the designed functions in a changing environment. Upgrading enhances the functionality of a product [18]. Software related issues in the product sometimes could be repaired through updates.
Ease of Handling	Features such as small size, low centre of gravity, & handle promote handling of the product [17,18]. Facilitates disassembly process during product manipulation.
Interchangeability	Assuring components can be replaced in the field with no physical rework required for achieving a physical fit. Allows for component testing [23,25] & facilitates component replacement.
Robustness	Selecting designs that are robust. Assures products do not break during repair [8], increases confidence during disassembly [25].
Redundancy	Providing an excess of functionality and/or material in products or parts. Allows removal of material as part of a recovery intervention (Keoleian & Menery, 1993). Functional redundancy assists fault location and isolation [23]
Firmware Reset	Software and the electronics-related issue could be fixed via reset (Viegand et al. 2019) Reset functions facilitate cause oriented diagnosis (Pozo Arcos et al., 2020).

Table 3: Overview of scoring systems compared to the literature [17,18,36–40,23,29–35]. *Red rows = missing or partially addressed design elements in the scoring system. Hollow bullet points = partially addressed aspects. Numbers in the column of Bovea et al (2018) and Den Hollander et al., (2018) = the number of papers they list relating to each design principle.*

Design aspect related to reparability	Scoring system						Literature														
	EN 45554	RSS(JRC)	AsMer (Benelux)	ONR 192102	FRI	iFixit 2018	Bovea et al., 2018	Den Hollander, 2018	Shahbazi et al., 2020	Techhio et al., 2019	Pozo Arcos et al., 2019	Victoria et al., 2017	Deloitte, 2016	Sabaghi et al., 2017	Dewberry et al., 2016	I-Fixit 2019	Filpsen et al., 2016	Jaeger et al., 2020	Ackermann et al., 2018	Vanegas et al., 2018	Laitala et. Al 2021
Disassembly	●	●	●	●	●	●	24	6	●	●	●	●	●	●	●	●	●			●	
Reassembly	●	●	●					6									●				
Fastener removability and Reusability	●	●		●	●		16		●	●						●	●	●		●	
Fastener Visibility	●					●	11													●	
Tools Required	●	●	●	●	●	●	3		●	●				●	●	●	●			●	
Modularity			●	●			13	5	●		●					●					
Diagnosis	○	○	○	○			1	3	●	●	●	●					●	●			
Health and Safety risk (design)		○		○		○					●			●							
Standard parts and interface	●	●	●	●				4	●												
Repair Information to user	●	●	●	●	●	●			●		●	●	●	●	●	●			●		●
Updatebility / Adaptability	●	●		●			28	2								●					
Design simplicity/ Complexity				●			29	1		●				●	●						●
Handling							7	1													
Interchangeability								2	●		●										
Functional Packaging							1	2													
Material selection/ Robustness								1	●								●				
Redundancy								2													
Firmware Reset	●	●	●	●	●						●										

Table 3 shows that six out of 18 aspects related to repairability from the literature are reflected well in most (more than three) of the scoring systems. This includes disassembly, fastener type, tools required, Information content, standardized parts and interface, and firmware reset. In contrast, seven aspects (coloured in red) were not addressed or partially addressed, described below.

Elements not addressed or partially addressed by the scoring system.

Five elements were not addressed directly by any of the scoring systems: “Ease of handling”, “Interchangeability”, “Redundancy”, and “Material selection”. These may be missing from scoring system because, as the table shows, there is much less literature on them than other aspects of repair. Similarly, “Diagnosis” and “Health and Safety risk” is partially addressed. However, they may still be important to include in the scoring.

The first aspect not addressed in the scoring system is “Ease of handling”. Features such as small size, low center of gravity, & handles make product manipulation (flipping, tilting etc.) easier during disassembly, and taking the product for repair easier. However, the absence of these features does not seem to severely alter the repairability of the product.

The second aspect not addressed by the scoring system is "Interchangeability". Interchangeability allows for component testing [23] as well as facilitates the removal and replacement of the component. Interchangeability of components could also enable extracted components from old products to be used for repair; however, little data is available on how often this is used in EU repair scenario. Further investigation may be required to consider the importance of interchangeability in the scoring system.

The third aspect not addressed is "Robustness". This principle ensures that handling and disassembling actions during repair do not break or damage the product [36], It also increases confidence during disassembly [25]. The majority of the scoring systems (4/6) indicate that if breakage occurs during the disassembly process, the fastener for the part being disassembled is considered "non-Removable", this "Fastener removability and reusability" criterion partially addresses the "Material selection"/" Robustness". However, testing the robustness of the product is normally done through complex simulations, destructive stress tests and accelerated life tests [41], all requiring significant resources. This most likely outweighs the benefit of having this criterion in the repairability scoring system. Further research may be needed to determine if an easier testing method could be developed to test for Material selection/Robustness of products.

Similarly, the literature is unclear on to what extent having redundancy in a product promotes repair. "Redundancy" relates to providing an excess of functionality and/or material in products or parts allows for normal wear or removal of material as part of a recovery intervention [42]. This principle was found to help users locate and isolate the fault [23,25]. However, this redundancy normally increases the materials and cost of the product. Therefore, this design feature may not justify the additional cost and materials needed for manufacture.

One of the two partially addressed aspect is diagnosis. For most of the scoring systems (4/6), the ability of the products to sense faults and signal the user via a display or error codes is regarded as diagnosis, and a criterion for it is developed accordingly. However, according to Arcos et al., [25], various other design features also play a role towards ease of diagnosis for users (such as transparent housing, and having easily accessible testing points) . The parameter in the scoring systems could be developed incorporating the results from Across et al. [25]. Additionally, ONR 192102 consists of "low-level function when faulty" and "operation after removal of the cover" as a criterion for diagnosis, these two features have not been addressed by any other scoring system and could be an interesting feature to be incorporated towards assessment of diagnosis.

The other partially addressed aspect is health and safety risk. Safety concerns include the safety of the person performing the repair, safety of using the product after repair, and safety-related to damaging the product during or after the repair. Aspects of safety during repair has been addressed by the majority of scoring system (En 45554, RSS, ONR192102, iFixit), but safety after a repair has not been addressed by any. Safety after the repair is important if a product that has been incorrectly repaired becomes dangerous when operated (e.g., an incorrectly reattached lawnmower blade might fly out at high speed). There is limited literature on aspects of safety to the product and user during and after repair for EEE. Public report of Inegmardotter et al., [43] indicate that most of the repair actions are safe to perform and others could be made safe through relatively small design changes. However, repair safety has been identified as one of the barriers towards pushing forward product repair from political and company's perspectives [44]. Therefore, to overcome this barrier, it is crucial that health and safety aspects are fully and transparently addressed in a reparability scoring system. However,

Interdependencies between design elements

Several interdependencies were observed between the design elements: fastener type, tools required, fastener visibility, reassembly, modularity, interchangeability, material robustness, design simplicity, information availability and handling. These mentioned elements have been identified to influence the overall ease of disassembly of the product [8,18,20,21,36]. Additionally, diagnosis-related to physical design seems to be influenced by aspects of interchangeability, modularity, disassembly, design simplicity/complexity, robustness, and information availability [23,25].

These interdependencies between different design elements might lead to double counting in scores, and also indicate that not all the identified design elements need to be scored to provide a useful assessment of repairability. An assessment addressing the relation between disassembly and the related repairability elements can be observed in the Ease of disassembly Metric (eDiM) [20]; eDiM already addresses the following elements;: disassembly, reassembly, tool type and fastener visibility. If a scoring system (such as, AsMer) already uses eDIM, then these aspects are implicitly covered and may not need separate scoring criterion. In essence, scoring system might be simplified by eliminating some metrics without losing important information. Simplifying a scorecard could ease its application since it simplifies implementation and testing by manufacturers and surveillance authorities [20].

4.1 Comparing Scoring Systems

Table 4 shows how well the scoring system reflect design principles and features from the literature. Additionally, this table how the score is determined, and their objectivity. All the criteria from the French repairability index were identified as objective. However, it was the least complete of the scoring system, and lacks criteria that currently are more qualitative (such as diagnosis and safety aspects). RSS was the most complete scoring system, covering 11 criteria, out of which 6 were objective. The scorecard with the least objectivity was ONR 192102, specifically because most of the criteria could be scored out of 5 or 10 but no specific instruction was provided on how each increment should be assessed.

Two criteria (diagnosis and health and safety) were semi-objective across the majority of the scoring system. Firstly, for diagnosis, the term “Intuitive interface” (in EN 45554, RSS, AsMer) needs further clarification to provide better objectivity. In terms of safety, the iFixit score is clear and objective, indicating specific tools (e.g., wire cutter and knife) and features (open pouch battery) that relate to safety risks. However, the RSS system is more subjective: it refers to the low voltage directive (2006/95/EC) and machinery directive (2006/42/EC) saying "Machinery must be designed and constructed in such a way as to allow access in safety to all areas where intervention is necessary during operation, adjustment and maintenance of the machinery, and other safety information needed.” Similarly, as a part of safety, EN45554 and RSS indicates whether the process can or cannot be carried out in specific environments (use, workshop, production) and whether specific skill (Layman, Generalist, Expert, mfr., Not feasible) is required to carry out the repair process. However, the details on what aspects are measured to determine repair environment and skill required are lacking and are susceptible to subjectivity. Ingemarsdotter et al., [43] provides a risk assessment framework that could be applied to analyse safety risk of household products. This framework builds on FMEA (a widely applied method for failure analysis of products), and RAPEX (a commonly agreed framework for risk assessment of consumer product). This framework could be further developed and implemented to assess the safety risk objectively during and after the repair.

Table 4: Scorecard analysis for criteria on diagnosis and component accessibility. Green cells = objective, yellow cells = semi-objective, and red cells = subjective. "Dis." = Disassembly, "Rea." = Reassembly, "Mfr." = Manufacturer, "c." = check.

Design Elements		Scoring System						Testing method details
		EN 45554	RSS (JRC)	AsMer (Benelux)	ONR 192102	FRI	IFixit	
Disassembly	Test	**Dis. time or # steps**	**Dis. time or # steps**	**Dis. time**	**Dis. possibility**	**Dis. # steps**	**Dis. time, Path**	• Dis. required • "Possibility" = Possibility of full Dis. • * = c. with reference value • cont.: Continuous levels
	scoring levels	levels not determined. Dis. step or time (EdiM)*	4 levels of Dis. step / time (EdiM)	4 levels of Dis. step / time (EdiM)	10 levels for possibility of Dis. 5 levels of Dis. Effort	4 levels of Dis. Step	Continuous Dis. time, Path of entry*	
Reassembly	Test	**Rea. time**	**Rea. time , c. info**	**Rea. time**	------	------	------	• Dis. & Rea. required • " c. info" = check Information on Rea. • * = check with reference value
	scoring levels	Rea. time (EdiM)*	2: Description of Rea., Reass. time (EdiM)*	4: Rea. time (EdiM)*	N/A	N/A	N/A	
Modularity	Test	------	------	**Dis. Ability**	**Dis. Ability**	------	------	• Dis. & c. disassemblity & possibility for critical components to be reducible
	scoring levels	N/A	N/A	3: 50% replaceable, 75% replaceable, all replaceable	10: all reducible to individual components	N/A	N/A	
Fastener Type	Test	**Dis. & c. type**	**Dis. & c. type**	------	**Dis. & c. type**	**Dis. & c. type**	------	• Disassemble & check fastener type * = (reusable > removable > non removable)
	scoring levels	3*	3*	------	10: Non removable	3*	N/A	
Fastener Visibility	Test	**Dis. c. visibility**	------	------	------	------	**Dis c. visibility**	• check fastener visibility during • Dis: Dis. required
	scoring levels	3: Visible, not visible > hidden	N/A	N/A	N/A	N/A	3: highlighted, visible, not visible	
Tools Required	Test	**Dis. & c. tools**	**Dis. & c. tools**	**Dis. & c. tools**	**Dis. & c. tools**	**Dis. & c. tools**	**Dis. & c. tools**	• check tools needed during Dis. • dis: Dis. required • "prop." = propriteory
	scoring levels	4: No or basic, product specific, commercially available, prop., not removable	3: Basic, product specific, prop.	3: Basic, product specific, prop.	5: Intuitive device operation	4: Basic or supplied, product specific, prop., not removable	4: basic, product specific, prop., requires heat gun	
Diagnosis	Test	**cause f. & c. interface operability, c. interface, c. available documents.**	**cause f. & c. interface operability, c. interface, c. available documents.**	**cause f. & c. interface operability, c. interface,**	**cause f. & c. interface operability**	------	------	• "f." = fault • documents availablity could be: manual, official website or through service centre call.
	scoring levels	4: Intuitive, coded, additional software/Hardware & prop.)	4: Intuitive, coded, additional software/Hardware & prop.)	4: Intuitive interface , coded, additional software/Hardware & prop.)	10: display & test mode, 10: low level operation, operation after cover removal	------	N/A	
Health & Safety risk during repair (design)	Test	------	**c. mfr. instructions**	------	**Dis. & c. features**	------	**Dis. & c. features**	Instructions could be included via, manual, official website or through service centre call.
	scoring levels	N/A	1: Instruction from mfr.	N/A	5: Protection in control processors, 4: danger warning signs, 5: warnings on sensitive components.	N/A	8: Battery case type, adhesive use, adhesive type. Tools required: Gel pad, heat gun, shears, wire cutter, knife	
Working Environment (safety)	Test	**c. mfr. Instruction**	**c. mfr. Instruction**	------	------	------	------	check Instruction from mfr. for work enviroment required for repair (via, manual, official website or through service centre call.)
	scoring levels	3: any condition, workshop, production environment	3: any condition, workshop, production environment	N/A	N/A	N/A	N/A	
Skill Required (safety)	Test	**c. mfr. Instruction**	**c. mfr. Instruction**	------	------	------	------	check Instruction from mfr. for skill required for repair (via, manual, official website or through service centre call.)
	scoring levels	4: Layman, Generalist, Expert, mfr., Not feasible	3: Layman, Expert, mfr.	N/A	N/A	N/A	N/A	
Information media	Test	------	------	**c. info media**	**c. info media**		**c. info media**	check information media as listed on the criteria.
	scoring levels	N/A	N/A	4: Attached to product, manual, website, not available	4: Attached to product, Manual, website, toll free contact support, local fee contact support	N/A	3: Attached to product, video, on website	
Information Content	Test	**c. mfr. Instructions, c. media**	**mfr., c. media**	**mfr., c. media**	**mfr., c. media**	**mfr.**	**c. media**	• check actual availability in different media • check manufacturers declaration
	scoring levels	9: c. presence (Table 5)	9: c. presence (Table 5)	9: c. presence (Table 5)	13: c. presence (Table 5)	13: c. presence (Table 5)	5: c. presence (Table 5)	
std. parts & interface	Test	c. mfr. Info.	c. mfr. Info.	c. mfr. Info.	dis. c. type	------	------	• check manufacturer Information • "std."= st&arised • "prop." = propriteory
	scoring levels	3: std. part & interface , prop. part with std. interface, prop. part with non-std. interface	2: non-prop. & has a std. interface, prop. or lacks std.	3 (all parts std.ized , few parts std., no std.	2: std.ized interface, non std. interface	N/A	N/A	
Reset (firmware & Card)	Test	**c. Possibility**	**c. possibility, c. information**	**c. information**	**c. possibility, c. information**	**c. instruction**	------	• c. possiblity to reset by trying to reset the product • c. information & instruction on firware reset
	scoring levels	4: Integrated, external, service, not possible	4: Integrated, external, service, not possible	1: Possibility to reset	1: Possibility to reset	1: Possibility to rest	N/A	
Design Simplicity	Test	------	------	------	**operate. c.**	------	------	operate: operate the device & c. intuitiveness.
	scoring levels	N/A	N/A	N/A	intuitive device operation (5)	N/A	N/A	

Majority of these scoring systems (RSS, ASMER, FRI, IFixit) have to be calibrated with a reference value to work effectively. This reference value is normally calibrated through scoring range of product (cheap to expensive, and variation in designs) from the specific product category, and determining the average, a minimum, and a maximum thresholds [45]. However, the number and range of products required for this calibration, and how often this should be calibrated are still unclear and there is an opportunity to further research and establish a standard protocol to identify this reference value.

For ease of disassembly, most of the scoring systems (5/6) either measure time or the number of disassembly steps, and each has its benefits and drawbacks; Disassembly time is subjective to the user disassembling the product[20]. A more objective measurement is to record disassembly action based on Maynard operation sequence techniques (MOST), where time represents the performance of an average skill operator, under standard conditions at a normal pace [46] . This lets us create a proxy time as done in Ease of Disassembly Metric (eDiM) [21]. This method is recognized as more representative of ease of disassembly of the product than the number of disassembly steps. Furthermore, there is a significant difference between eDiM and Disassembly steps when assessing ease of disassembly [13] ; and eDiM is able to capture the diversity of product designs better and disassembly step. However, fully implementing eDiM would require a disassembly time database of all possible disassembly actions required to disassemble a product. Currently, this database is limited to ICT products and the process of calculating eDiM is more labour intensive than disassembly step. Providing better representative of ease of disassembly might be important for scoring system that have high weightage on disassembly; and for consumer organisations, manufacturers, designers and MSA's that would like to assess the ease of disassembly of the product. Therefore, further research may be required to expand the database and simplify eDiM methodology.

The iFixit scoring system also has another disassembly criteria called the "path of entry"; Ease of disassembly to the point where critical components are visible [8]. This combines the criteria of disassembly time and tools required to disassemble until the critical components are visible and therefore seem to have a similar testing method as ease of disassembly. Although iFixit already have a separate criterion related to disassembly time and tools, path of entry only assesses tools required and disassembly until the point where all the critical component are visible. Furthermore, criteria related to the path of entry is reflected in the report of iFixit market observations [35], where an easy path of entry builds confidence users self-repairing their product. Additionally, this criteria also helps in diagnosis, since viewing the critical component could be required by users during diagnosis process [23,25].Therefore, "Path of entry" is a good addition to the disassembly for a scoring system assessing self-repair.

An aspect of reassembly; "fastener removability and reusability" has been addressed by most of the scoring system. However, only three out of six scoring systems have considered re-assembly time in the criteria (EN 45554 and the AsMer scoring system indicate to check reassembly time using the EDIM). However, the newer Scoring criteria RSS and iFixit only instruct to check if reassembly is possible; and they consider reassembly the opposite of disassembly. Therefore, there is a discrepancy in its importance between the scoring methods. However, the report by Peters et al., [21] shows that reassembly time in some cases is higher than disassembly time. This is generally due to an additional action required to position the fasteners (such as screws) and components. Furthermore, positioning design features such as spring-loaded components, long routed cables further add to the reassembly time. eDiM partially covers the additional actions for positioning fasteners in its method, however specific reassembly actions such as assembling spring-loaded components and routing long cables are not considered the method. Therefore, eDiM database could be further expanded to address more reassembly specific actions. Additionally, If eDiM is not considered in a scoring system, then additional elements influencing the reassembly should be added as separate criterion.

Two design elements for which most scoring system agree and provided straightforward objective test procedures were "Fastener removability and reusability" and "Tools required". ADEME, EN 45554, and RSS use similar criteria on fasters (reusable, non-reusable, non-removable). This criterion and testing method (disassemble and check fastener type) seems to be coherent across the different scoring systems and testing parameters seem to be straightforward and objective. Similarly, the "Tools required" parameters seem to be in agreement across the scoring system. The list of tools is well defined, and most of the scoring system (4/6) reference EN 45554 standards. The criterion and test for tools required seem to be clear and objective.

In terms of standardized parts and interface, no list or reference of standardized parts is given for any of the scoring system. Whilst RSS and EN 45554 look at the presence and absence of standard interface per part, AsMer and ONR 192102 look from a more subjective perspective. RSS mentioned checking the manufacturer's information, whilst ONR 192102 suggests disassembling and checking the interface/part. However, objectively assessing standard parts and interface would require list of standard parts and interfaces similar to that of the "tools required" criterion. Listing these standard parts, however, seem difficult given the large diversity of parts and components. Additionally, enforcing standardisation may impede on innovation. Instead, the benefits of standardisation (as discussed in Table 2) could be addressed by the following criteria: (a) spare parts cost and availability, (b) tool required, (c) information accessibility for product identification, (d) ease of diagnosis, disassembly, and safety, and (e) interchangeability of components. Most of these criteria are already present in scoring systems, therefore, if the forementioned criteria are addressed, standardisation as separate criterion may not be required.

Information accessibility scores the ability of the public and repairers to access repair information. The information content required by the different scoring systems is presented in Table 5. This table shows that; "Repair instruction", "Diagnosis information", "Safety measures", "Procedure to reset to working condition", and "Disassembly sequences" have been addressed by most (4/6) scoring systems. This is followed by; "Product identification", "Tools required", "Replacement/supplier information", "Circuit diagram", "Component identification", "Maintenance instructions", and "Error codes". Most of the scoring systems seem to agree that information on diagnosis, safety, disassembly, and reset are important information that should be provided by the manufacturer. The testing procedure for obtaining this information seems to be by checking the official website, provided manual and calling the customer service. This criterion and its testing procedure seem straightforward and objective and could be easily implemented. However, apart from information on diagnosis, safety, disassembly sequences and factory reset, there is a discrepancy between scoring systems on what additional information from the manufacturer could be important. This may require this may need further research.

In addition, all the scoring system assess information accessibility from a product level, and do not specify to what extend this is aimed at most frequently occurring faults. This could result in invalid scoring (e.g., If the company gives repair information on just one fault, they may still get a favourable score). Therefore, for information that is dependent on specific faults (such as repair information, diagnosis information), it is important to provide information covering most frequently failing faults.

Table 5: Information required in different scoring systems.

Information Availability	Scoring System EN 45554	RSS (JRC)	AsMer	ONR 192102	FRI	IFixit
Features being claimed in update	•					
Update method	•					
Documentation of time updates are offered after the point of sale	•					
repair Instructions/manual/bulletin	•		•		•	•
Product identification		•			•	•
Component identification						•
exploded view		•		•	•	•
Regular maintenance instructions		•		•	•	
Diagnosis information/ Troubleshooting chart	•	•	•	•	•	
Repair/Upgrade service offered by the manufacturer		•			•	
safety measures related to use, maintenance and repair		•	•	•	•	
List of available updates		•				
Disassembly sequences	•	•	•		•	
Reassembly sequence			•			
Product identification			•			
Fault detection software			•			
PCB/Electronic board diagram			•		•	
Error codes			•	•	•	
3D printing of spare parts			•			
Reconditioning			•			
Procedure to reset to working condition		•	•	•	•	
Service centre accessibility				•		
Transportation instructions				•		
Circuit/Wiring diagram	•			•	•	
Replacement supplier/supply information			•	•		•
Tools required	•			•	•	
Service plan of electrical boards				•		
Access to training available to all technicians				•		
Recommended torque for fasteners	•					
Compatibility with other products	•					

The medium for communicating this information could include printed manuals, websites, digital information carriers such as QR codes, DVDs, or flash drives, and by phone [15,45]. AsMer, ONR 192102, and iFixit have clear criteria on how the information on safety, disassembly, and product and component identification is relayed ; with "attached to the product" scoring highest, followed by manual or website vide. For the rest of the scoring system, the medium of information does not seem to matter as long as it can be accessed by the public. Again, there is a discrepancy importance of medium of information for the aforementioned aspects. However, literature show that providing visual markings in the product (such as numbering wires, or warning signs) assist in correct reassembly and decrease the safety hazard [43]. Similarly, providing component identification number in the assists in buying the correct spare parts for replacement [36]. Therefore, it could be important to assess medium of information for disassembly, safety, and component identification

4.2 Conclusion and Future Work

This study assesses the objectivity, completeness, validity and testability of six major repair scoring system, to see what further development may be required to make them policy instruments with standardized testing. The scoring systems tested were FRI, RSS, iFixit 2019, AsMer, EN 45554 and ONR 192102. The completeness of the scoring system was assessed via comparing it to the latest literature on what design features and principles drive product repairability. Similarly, the objectivity of the scoring system was assessed by comparing whether the presented scoring levels per criteria in the scoring system is clearly defined with a quantifiable and operator-independent testing method. Through this analysis, this paper provides an overview and gaps for some of the latest scoring systems and suggests what aspects should be further be improved. The major gaps are as follows:

- Assessment of health and safety were semi-objective across the majority of the scoring system Therefore, there is an opportunity to develop an objective criteria and testing methodology for assessing and safety of the user and the product during and after repair.

- eDiM method database could be expanded and further simplified for it to more universally measure ease of disassembly. Furthermore, since time for reassembly sometimes is higher than disassembly, it might be important to consider ease of reassembly as separate criterion whenever eDiM is not considered.

- In terms of repair information content, it is important to establish which information are critical to promote repair. Additionally, all current scoring system checks information from a product level, risking a chance of invalid scoring. Therefore, information dependent on specific faults should be addressed at the same level.

Whilst a scoring system could be complete and objective with all the required aspects to score repairability, it could render the scoring system too complex to score products within feasible budget and time. Therefore, a balance between ease of testing against the objectivity and completeness of the testing program is required. This paper gives an overview of how well current scoring systems achieve objectivity and completeness; however, ease of testing has been partially discussed, therefore this analysis could be further done in the future. Additionally, insights presented in this paper could be further verified and developed through testing different products with each scoring system and as well as using the same products tested through different users to understand the objectivity, validity and testability of the scoring system and its criteria. This is planned for upcoming research.

This review focuses on how current scoring systems reflect physical design features, principles, and guidelines related to the repairability of household electronic and electrical equipment from literature and how they are tested. However, research also shows the importance of user and market aspects, it would be interesting to al-so look at how the current scoring systems reflect, and test user and market aspects related to repairability.

Addressing gaps presented in this paper could lead to development of a strong scoring system with an effective testing program that could be used for policymaking. Additionally, this scoring system could also be used for assessment by consumer organizations, MSA, and other interested stakeholders, to promote repairability of products.

5 References

[1] Bakker C, Wang F, Huisman J, den Hollander M. Products that go round: exploring product life extension through design. J Clean Prod 2014;69:10–6. https://doi.org/10.1016/j.jclepro.2014.01.028.

[2] Baldé C, Forti V, Gray V, Kuehr R, Stegmann P. Suivi des déchets d'équipements électriques et électroniques à l'échelle mondiale 2017: Quantités, fl ux et ressources. 2017.

[3] OECD. MATERIAL RESOURCES , PRODUCTIVITY AND THE ENVIRONMENT. OECD 2015:1–14.

[4] Circular economy action plan. Eur Comm 2020. https://ec.europa.eu/environment/topics/circular-economy/first-circular-economy-action-plan_en (accessed August 10, 2021).

[5] Sanfelix J, Cordella M, Alfieri F. Methods for the Assessment of the Reparability and Upgradability of Energy-related Products: Application to TVs Final report. 2019. https://doi.org/10.2760/501525.

[6] Bracquené E, Brusselaers J, Dams Y, Peeters J, De Schepper K, Duflou J, et al. ASMER BENELUX Repairability criteria for energy related products Study in the BeNeLux context to evaluate the options to extend the product life time. BeNeLux: 2018.

[7] ONR 192102. ONR 192102 Label of Excellence for Durable, Repair Friendly, Designed Electrical and Electronic Appliances. 2014.

[8] Flipsen B, Huisken M, Opsomer T, Depypere M. IFIXIT Smartphone Reparability Scoring: Assessing the Self-Repair Potential of Mobile ICT Devices. PLATE Conf 2019 2019:18–20.

[9] iFixit. Smartphone Repairability Scores 2021. https://www.ifixit.com/smartphone-repairability (accessed August 2, 2021).

[10] Hervier Marie, De A, Camille Z, Alma D, Eric EWM, Virginie L, Guillaume ED, et al. BENCHMARK INTERNATIONAL 2018.

[11] Franceschini F, Galetto M, Maisano D. Management by measurement : designing key indicators and performance measurement systems : with 87 figures and 62 tables. 2010.

[12] Bracquene E, Peeters JR, Burez J, De Schepper K, Duflou JR, Dewulf W. Repairability evaluation for energy related products. Procedia CIRP 2019;80:536–41. https://doi.org/10.1016/j.procir.2019.01.069.

[13] Ellen Bracquené1, Jef Peeters1, Felice Alfieri2, Javier Sanfélix3, Joost Duflou1, Wim Dewulf1 MC. Reparability Evaluation JRC vs ASMER. Anal Eval Syst Prod Repairability a Case Study Washing Mach 2020:124658. https://doi.org/10.1016/j.jclepro.2020.125122.

[14] Indice de réparabilité 2021. https://www.ecologie.gouv.fr/indice-reparabilite (accessed April 19, 2022).

[15] 45554 E. en 45554 2021;45554.

[16] Wohlin C. Guidelines for snowballing in systematic literature studies and a replication in software engineering. ACM Int Conf Proceeding Ser 2014. https://doi.org/10.1145/2601248.2601268.

[17] Bovea MD, Pérez-Belis V. Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. J Environ Manage 2018;228:483–94. https://doi.org/10.1016/j.jenvman.2018.08.014.

[18] Hollander D, Version D, Hollander D. Design for managing obsolescence. 2018. https://doi.org/10.4233/uuid.

[19] Environmental standardization for electrical and electronic products and systems - Glossary of terms. 2013.

[20] Vanegas P, Peeters JR, Cattrysse D, Tecchio P, Ardente F, Mathieux F, et al. Ease of disassembly of products to support circular economy strategies. Resour Conserv Recycl 2018;135:323–34. https://doi.org/10.1016/j.resconrec.2017.06.022.

[21] Peeters JR, Tecchio P, Vanegas P. eDIM: further development of the method to assess the ease of disassembly and reassembly of products: Application to notebook computers. 2018. https://doi.org/10.2760/864982.

[22] Pamminger R, Glaser S, Wimmer W. Guideline development to design modular products. Going Green - Care Innov 2018:1–12.

[23] Pozo Arcos B, Bakker CA, Flipsen B, Balkenende R. Practices of Fault Diagnosis in Household Appliances : Insights for Design. Under Rev 2020:1–31.

[24] Cordella M, Sanfelix J, Alfieri F. Development of an Approach for Assessing the Reparability and Upgradability

of Energy-related Products. Procedia CIRP 2018;69:888–92. https://doi.org/10.1016/J.PROCIR.2017.11.080.
[25] Pozo Arcos B, Dangal S, Bakker C, Faludi J, Balkenende R. Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. J Clean Prod 2021;319:128741. https://doi.org/10.1016/j.jclepro.2021.128741.
[26] Dangal S, van den Berge R, Pozo Arcos B, Faludi J, Balkenende R. Perceived capabilities and barriers for do-it-yourself repair 2021.
[27] Moss M. Designing for minimal maintenance expense: The practical application of reliability and maintainability. Quality and Reliability series part 1. New York, NY, USA: Marcel Dekker; 1985.
[28] Perera HSC, Nagarur N, Tabucanon MT. Component part standardization: a way to reduce the life-cycle costs of products. Int J Prod Econ 1999;60:109–16. https://doi.org/10.1016/S0925-5273(98)00179-0.
[29] Deloitte. Study on Socioeconomic impacts of increased reparability – Final Report. Prepared for the European Commission, DG ENV. 2016. https://doi.org/10.2779/463857.
[30] Shahbazi S, Jönbrink AK. Design guidelines to develop circular products: Action research on nordic industry. Sustain 2020;12:1–14. https://doi.org/10.3390/su12093679.
[31] Victoria P, Braulio-gonzalo M, Juan P, Bovea MD. Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment . A Spanish case study 2017;158. https://doi.org/10.1016/j.jclepro.2017.04.143.
[32] Tecchio P, Ardente F, Mathieux F. Understanding lifetimes and failure modes of defective washing machines and dishwashers. J Clean Prod 2019;215:1112–22. https://doi.org/10.1016/j.jclepro.2019.01.044.
[33] Sabbaghi M, Cade W, Behdad S, Bisantz AM. The current status of the consumer electronics repair industry in the U.S.: A survey-based study. Resour Conserv Recycl 2017;116:137–51. https://doi.org/10.1016/j.resconrec.2016.09.013.
[34] Dewberry E, Saca L, Moreno M, Sheldrick L, Sinclair M. A Landscape of Repair. Sustain Innov 2016nable Innov 2016 2016:76–85.
[35] IFixit. Repair Market Observations from Ifixit. 2019.
[36] Flipsen B, Bakker C, Van Bohemen G. FLIPSEN Developing a reparability indicator for electronic products. 2016 Electron Goes Green 2016+, EGG 2016 2017:1–9. https://doi.org/10.1109/EGG.2016.7829855.
[37] Jaeger-Erben M, Frick V, Hipp T. Why do users (not) repair their devices? A study of the predictors of repair practices. J Clean Prod 2020;286:125382. https://doi.org/10.1016/j.jclepro.2020.125382.
[38] Ackermann L, Mugge R, Schoormans J. Consumers' perspective on product care: An exploratory study of motivators, ability factors, and triggers. J Clean Prod 2018;183:380–91. https://doi.org/10.1016/j.jclepro.2018.02.099.
[39] Jef R. P, Paul V, Cattrysse D, Tecchio P, Mathieux F, Ardente F. Study for a method to assess the ease of disassembly of electrical and electronic equipment. Method development and application to a flat panel display case study. 2016. https://doi.org/10.2788/489828.
[40] Laitala K, Klepp IG, Haugrønning V, Throne-Holst H, Strandbakken P. Increasing repair of household appliances, mobile phones and clothing: Experiences from consumers and the repair industry. J Clean Prod 2021;282:125349. https://doi.org/10.1016/j.jclepro.2020.125349.
[41] Willems G. Electronics Design-for-eXcellence Guideline Design-for-Robustness of Electronics 2019:1–36.
[42] Keoleian G., Menerey D. Life cycle design guidance manual: Environmental requirements and the product system. 1993.
[43] Ingemarsdotter AE, Stolk M, Balkenende R. Design for Safe Repair in a Circular Economy 2021.
[44] Svensson-Hoglund S, Richter JL, Maitre-Ekern E, Russell JD, Pihlajarinne T, Dalhammar C. Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. J Clean Prod 2021;288. https://doi.org/10.1016/j.jclepro.2020.125488.
[45] Cordella M, Alfieri F, Sanfelix J. JRC Analysis and development of aJ JRC Repair- scoring system for repair and upgrade of products - Final report. 2019. https://doi.org/10.2760/725068.
[46] Zandin KB. MOST work measurement systems. 4th ed. Taylor & Francis Group; 2002.

APPENDIX: 2
DESIGN ANALYSIS OF WASHING MACHINE AND VACUUM CLEANERS

Design analysis of Washing machine and Vacuum cleaners (RUSZ)

1 Introduction

The analysis of 10 washing machine (WM) and 10 vacuum cleaners (VC) (see table below) has shown different aspects which positively and/or negatively influence the ease of disassembly. Aspects which were neither positively nor negatively standing out were not considered. The following sections showcase the main findings.

To complete the picture, the findings made during the disassembly of all samples of both product groups concerning other parts or components than Priority Parts (PP) were added.

Complete disassembly: If repair or servicing is required, it must be possible to disassemble all compounds and components of a product. Screw and plug-connections and components must be easily accessible and removable.
For example, doors of WM cannot be taken apart in several cases and must be exchanged as a complete set, whereas other doors could be disassembled completely within a short amount of time.

List of WM:

#	Brand	Model
1	Samsung	WW7XM642OPA/EG
2	Siemens	E-Nr.: WM14N270 /01
3	Bauknecht	WM Care 8418 Z
4	AEG	L6FB64470
5	Gorenje	W2A744T
6	Miele	WDB330 WPS
7	Siemens	WM6HXF90NL/01
8	LG	910PWAWL2808
9	Beko	WQY 9736 XSW BT
10	LG	FH4J3TDN0

List of VC:

#	Brand	Model
1	Siemens	VSZ1RK212/04
2	Siemens	VSQ8MSA332/12
3	AEG	VX9 - 4 - 8IBM
4	Dyson	SV 12 V10 FL SRAR EU
5	Bosch	BBS1U224
6	AEG	SH360L25
7	INVENTUM	STS725RC
8	Vorwerk	VK200- 1
9	Grundig	VCC 5850 A
10	Rowenta	RO7230EA

Ease of reassembly: The simplicity of reassembly also plays a major role, especially with VC, as it can significantly influence repair time and therefore repair costs.

Accessibility: With WM accessibility associated mainly with the need to move the machine to reach all components.
The accessibility of components in VC is often made difficult by the presence of hidden screws.

Complexity: Complex design can be justified to ease the use of the device or increase user comfort. On the other hand, complex design results in increased resource consumption, increases the failure possibility with more components, and required longer disassembly times with a corresponding negative impact on repair costs.

1.1 Vacuum Cleaners

Throughout the years technology has been improved by the increase of know-how in the field and the enhanced use of material and design. This is visible in the examples where the repair safety, correct reassembly and energy efficiency have been improved.

Positive findings:

- VC1 - **dust compartment cover** (PP 3): This VC has one cover for the dust compartment and the motor filter. By opening the cover, one has direct access to all the inner components which need to be maintained/exchanged by the user (dust bag, filters), therefore increasing the ease of disassembly and maintenance.

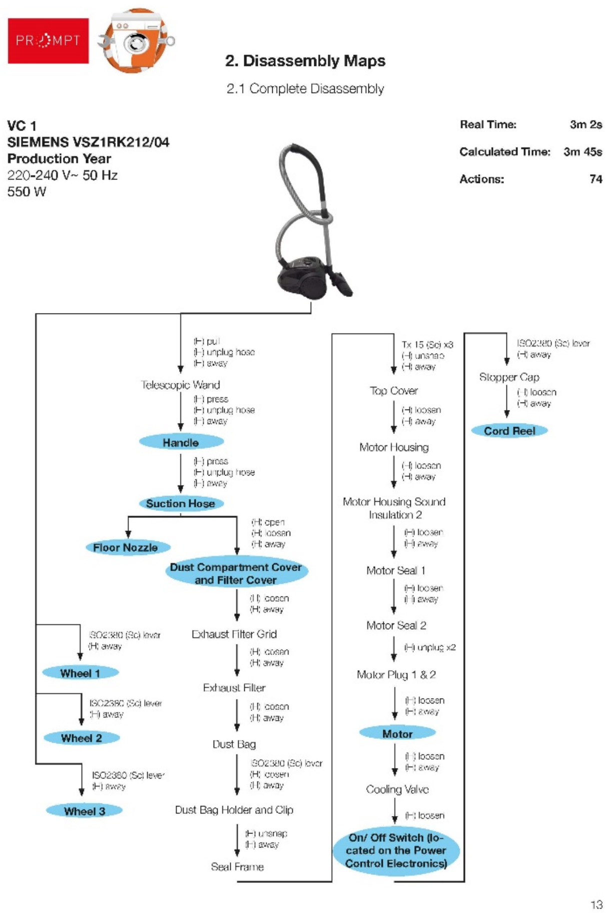


Figure 1 VC1_Dissasembly_Map

- VC9 and VC 10 - **motor** (PP 6): The carbon brushes would be very easy to exchange as only a screw needs to be unscrewed for each carbon brush.

Figure 2 VC9_Motor

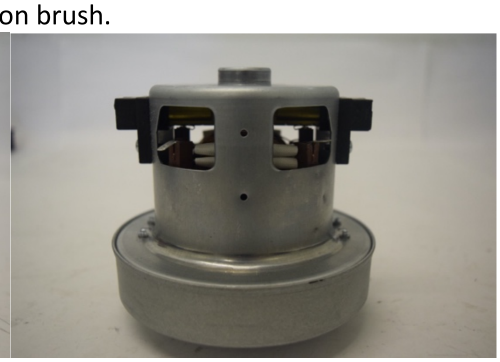


Figure 3 VC10_Motor

Findings which can be interpreted as positive and negative:

- VC3 - **sensors**: This VC had many sensors to measure the air flow and its differences to regulate the automatic power setting. One sensor hose goes all the way to the suction hose. The second sensor hose goes all the way to the dust compartment. The third hose probably measures the air pressure within the motor housing. This is both a positive and a negative example. On the one hand it can **improve** the **energy efficiency** of the device, but on the other hand more sensors and therefore **more material resources** are **needed**. In addition, the **repair time** increases as there are more parts to disassemble and reassemble, and the **failure possibility** rises with more electronic components.

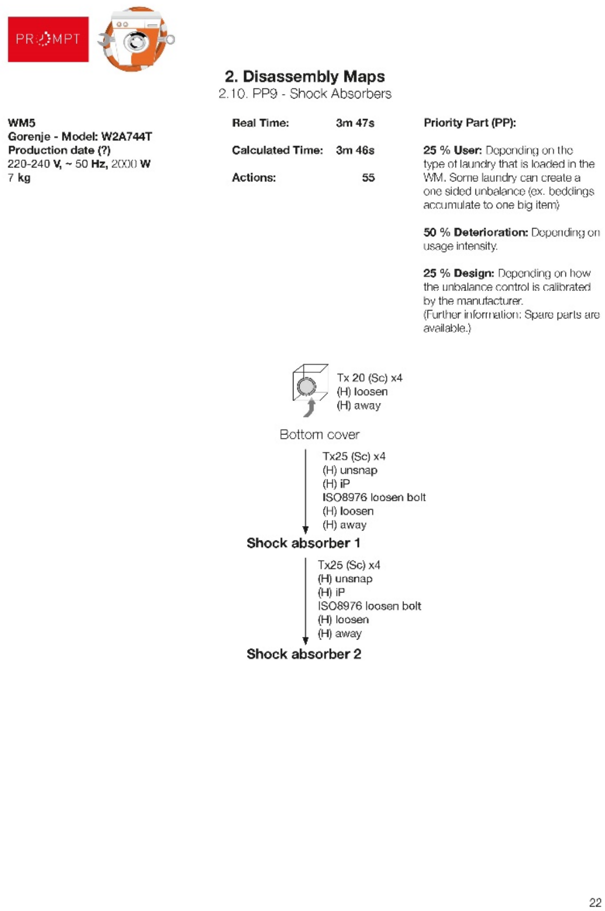
Negative findings:

- VC7: The **reassembly** of the VC was very difficult, because the motor and the cables had to be positioned very precisely and the VC housing was very tight. Therefore, it took several attempts to reassemble the VC properly.
- VC8: For an easy reassembly, the **correct reassembly sequence** needs to be followed. It was not self-explanatory as there were many parts which were closely interconnected and needed a precise disassembly and reassembly. Features such as identifiable shapes or with colour marked areas could make the reassembly self-explanatory. VCs with a small amount of parts make the reassembly rather logical.
- The analysis showed that in especially 5 out of 10 VC the ease of disassembly has been decelerated or hindered by **barely visible and hidden screws**. Any device with a barely visible or hidden screw has been given a negative grading. A detailed description is listed in the following overview:
  - VC1: To access the electronics, motor, and other components, one must unscrew 3 screws. One of these screws is less visible.
  - VC3: This VC had several screws which were barely visible.
  - VC5: This VC proved to be more challenging during the disassembly, as it had several hidden screws below snap fitted plastic covers.
  - VC8: This VC had a few hidden screws. Example: to reach the main inner components one must pull the release button for the floor nozzle on the top of the VC and reach the screw which is now revealed underneath the lower button.
  - VC10: Also in this VC, hidden screws were right below the snap fitted top cover.

1.2 Washing machines (WM)

Specific positive features found in WM5, creating an example for a repair friendly WM regarding **accessibility**:

- The **shock absorbers** (PP 9) are well accessible as there are only a few actions needed and replaceable, after the WM hast been tilted. To replace the shock absorbers 4 screws of the bottom cover must be unscrewed. Then 4 screws of the shock absorbers must be unscrewed from one side and on the other side a bolt must be loosened.


2. Disassembly Maps
2.10. PP9 - Shock Absorbers

WM5
Gorenje - Model: W2A744T
Production date (?)
220-240 **V**, ~ 50 **Hz**, 2000 **W**
7 **kg**

Real Time:	**3m 47s**
Calculated Time:	**3m 46s**
Actions:	**55**

Priority Part (PP):

25 % User: Depending on the type of laundry that is loaded in the WM. Some laundry can create a one sided unbalance (ex. beddings accumulate to one big item)

50 % Deterioration: Depending on usage intensity.

25 % Design: Depending on how the unbalance control is calibrated by the manufacturer.
(Further information: Spare parts are available.)

22

Figure 4 WM5_PP9_Shock_Absorbers

- The **sheet metal forming** of this WM has no sharp edges, reducing therefore the risk of injuries during repair.
- When opening the service door, the emergency release pops out at the same time. The emergency release is a hose which makes it possible for the user and the repair person to release water from the washing machine even if the door is still locked.
- The WM has very repair friendly **reusable cable ties for the cable harness and hoses**. Without the use of tools, the cables can be easily unthreaded and threaded in short time. The reusable cable ties always stay fixed on the WM housing.

Figure 5 WM5_Reusable_Cable_Ties

Negative finding:
The **shock absorbers** (PP 9) of WM1 can be exchanged from the back. Which means, that the repair person must move the WM from its original position.

2 Features that affect repair time.

A longer repair time can be explained, among other things, by
- the constructive design
- the complexity (partly unnecessary concerning functionality)

of the appliance or its parts.

2.1 VC

Time is a crucial factor for grading the ease of disassembly. In the following overview 1 positively and 3 negatively graded examples are listed:

Positive finding:
- VC8: priority part 6 - motor - This VC has a small but strong reluctance motor. The **motor** is **not screwed**, **but just well-placed within the housing**, therefore decreasing the time of disassembly and reassembly.

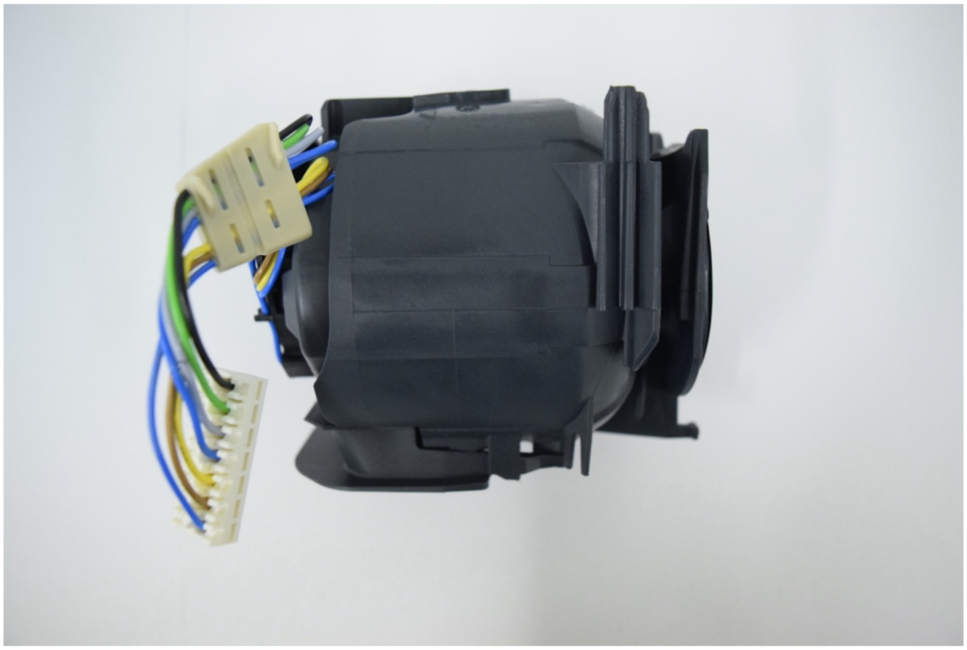


Figure 6 VC8_PP6_motor

Negative findings:

- VC3: It was **not clearly visible how to unsnap the filter cover** as it was screwed and snapped. Therefore, disassembly was more time-consuming

Examples for (complex) **constructive design** implying a longer disassembly time:

- VC6 - **suction hose** (PP 2): This VC has a suction hose which can be pulled out of the VC for more flexible manual cleaning. This suction hose is also available as a spare part, but **to be able to exchange it, one must completely disassemble the VC**, which is very time consuming in comparison to the other VCs.
- VC6: The **telescopic wand** enables the user to position the main compartment (motor housing, dust bin, etc.) of the VC on different heights, creating a different weight distribution. To exchange spare parts such as some electronics, the motor, and the battery one must disassemble the telescopic wand too. This proves to be more difficult, as the construction of the telescopic wand is especially laborious. The telescopic wand consists of two metal pipes which fit within each other. A leaf spring was built in the telescopic wand to enable its lengthening and shortening function. This leaf spring, the cables and the suction hose which are within the telescopic wand make the disassembly and especially the reassembly very time consuming.

Figure 7 VC6_telescopic_wand

Figure 8 VC6

2.2 WM

The *Table PROMPT Proposed accessibility of all WMs* in the Annex shows a graphic overview of the accessibility of PP of the tested WMs. The sectors marked in red show the need of **moving the machine** to access certain PP **which is more time consuming**.

General remarks on the significant differences observed regarding time for repair (disassembly / reassembly).
The **summarized disassembly actions** of all WMs (without tub, as some of the WM had a sealed tub) range from 270 (WM 2) to 402 (WM 9) as seen in figure 9 and 10. These variations can lead to differences in time. Please also see the Table PROMPT summarized Data Sheet of ACTIONS of all WMs in the Annex.

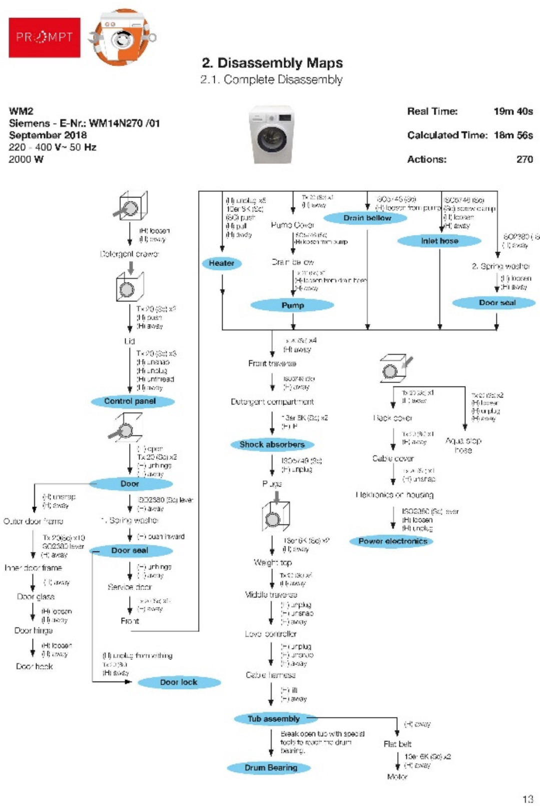


Figure 9 WM2_disassembly_map

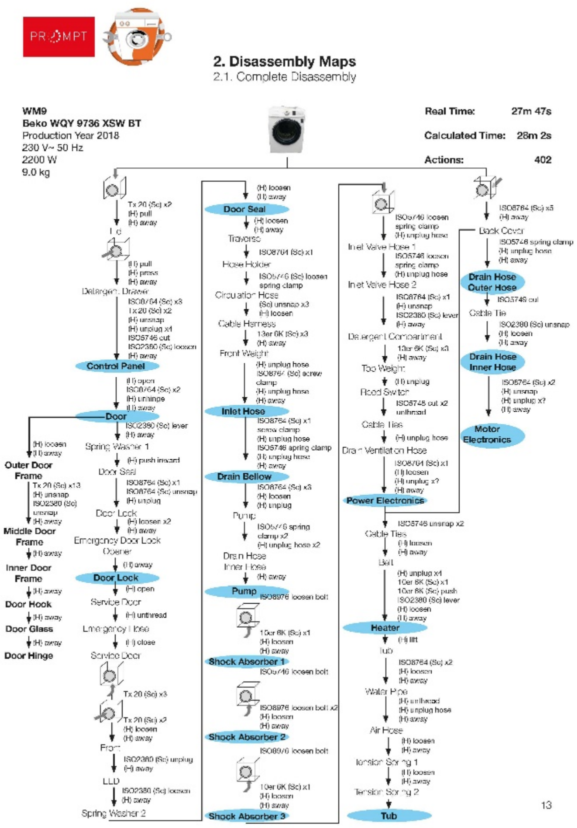


Figure 10 WM9_disassembly_map

The **disassembly time of all WMs** (without tub, as some of the WM had a sealed tub) range from 18 minutes (WM 3) to 29 minutes (WM 9). Please also see the Table PROMPT summarized Data Sheet of TIME of all WMs in the Annex.

Positive finding:
The **door of WM2** is an example of a repair friendly design, as it can be fully disassembled. One minor difficulty is to find the correct lever point after unscrewing the door.

Findings which can be interpreted as positive and negative:
WM6 has a **special motor** for leading the water in the wanted direction (Water Way Selector Motor).

Negative findings:
Examples for **constructive design** implying a longer disassembly time:

- All the disassembled WM vary in their **amount of built-in electronics** (PP 5) between 1 to 3 parts. The WM1 has 3 electronics. The WM2 has 2 electronics. The WM3 has 2 electronics. The WM4 has 3 electronics.
- Different construction of **door seals** (PP 3):
  - The door seal of WM 3 can only be pushed behind the front and not inside the drum. Being able to push the door seal behind the front would ease the repair. The brands Bosch, Siemens and Miele have door seals which can be pushed into the drum.

- From the repairman's experience AEG door seals are more difficult to install. This is due to their many tucks, which will need to be carefully placed around the tub's opening.

- WM1 – **Electronics** (PP 5): The power and motor electronics can only be reached by unscrewing the motor. Other machines have shown that their power and motor electronics can simply be accessed by unscrewing the back cover. In an even simpler case (WM 10 - LG TYPE: FH4J3TDN0), all the electronics were mounted together with the control electronics. This has on the one hand the positive side of easy accessibility, as there is no need to move the WM from its original position. On the other hand, if one of these electronics have a default, then it might be, that all of them must be exchanged.

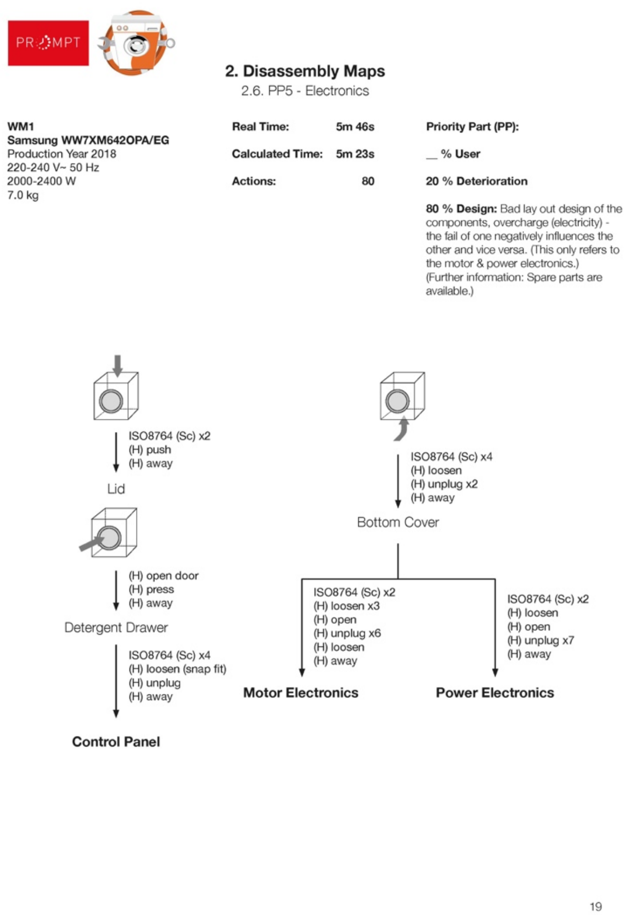


Figure 11 WM1_PP5_Electronics

- WM2 – **Electronics** (PP 5): The disassembly of the power electronics has shown to be more difficult, as the correct lever point is not clearly visible and a tool to lever is needed. Here a mark for levering or an easier disassembly design would be helpful. This disassembly design could be for example that the electronics are held by two visible screws.
- WM2 – **Shock Absorbers** (PP 9): The shock absorbers can only be replaced after lifting the tub out of the WM's housing. Then the tub must be drilled with special siemens tools. This is done to reduce steps in the production. While exchanging the shock absorbers one must be very careful to not harm the tub. Simple techniques such as bolts, or screws can be an alternative.

- WM3 - **Shock Absorbers** (PP 9): The shock absorbers of this WM are fixed with snap fits and a bayonet lock. They are more difficult to replace if the tub is still in the WM.
- WM3 - **Cable Tie/Snap Fit**: The cable harness was mounted with cable ties which snap fit into the wanted position and can be unsnapped with the combination pliers (ISO5746). A few cable ties were very difficult to loosen as they were difficult to reach with the tool. E.g., the cable tie next to the pressure switch took three times longer than an average loosen action.
- WM1 - **Hidden screws**: The WM had **4 screws hidden by stickers**, which prolonged the repair. The analysis shows that without hidden screws the repair process is faster. In case the stickers were chosen because of the screws‘ possible corrosion, one could either place them differently or use screws which are not affected by corrosion.
- WM7: If a component of the **water inlet system** is broken, one must replace the aqua stop, the inlet system, and the hose.
- The **triple valve** of WM8 has also electric functions and therefore was suggested as a priority part for this WM. If the triple valve fails, the WM might not work.

Examples for (unnecessary) complex design implying a longer disassembly time:

- WM1 has a **door** (PP 1) with **integrated add wash door** giving the consumer the opportunity to add laundry while the washing machine is washing. To realize this special function the WMs door needs more parts and integrated electronics. Therefore, the repair takes more time (compared to a door without special functions) and lowers the door‘s life span, as there are more parts that can break.

  In the analysis it was found out that a door with the same function can be created with a simple and repairable design and without using more resources. As many washing machines already can be opened during washing with either a long press on the button ‚door‘ or by pulling the emergency release, the probably most resource friendly change would be informing the consumer about these possibilities, instead of using a complex design.

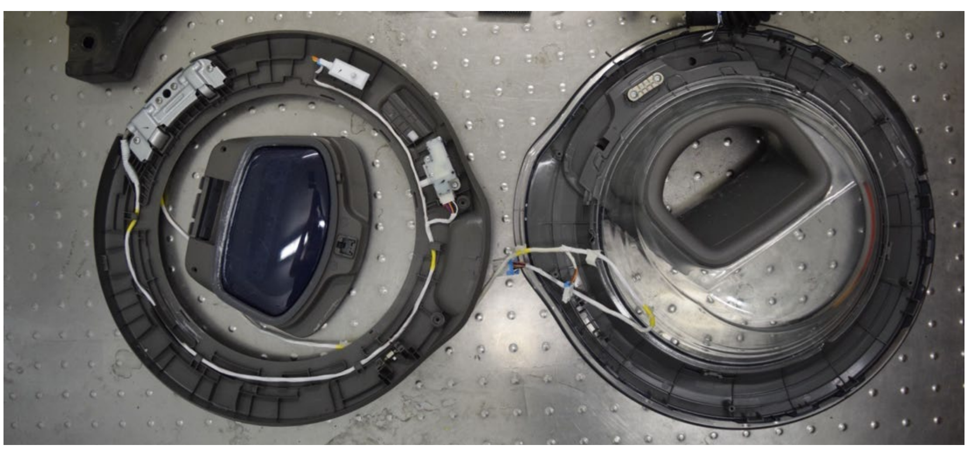


Figure 12 WM1_PP1_Door

- WM1 is equipped with a **drum with a back wall spinning in another direction**: To realise this function the WM must have built in 2 motors, 2 drum bearings, 2 belt pulleys and 2 flat belts which is twice the number of resources needed compared to an average WM which is assumed to deliver clean laundry in any case. The goal of having more clean laundry could also be tackled by creating special washing programs for different laundry types, by education the consumer or by having an eco-friendly soap for special laundry.

- WM 1 – **Heater** (PP 6): As this WM has built in **more functions**, **more screws and holding compartments** are needed. In this case this especially leads to a longer repair time for the heater, as there are many compartments and screws to be unscrewed and loosened before.
- WM7 – **Electronics** (PP 5): This WM has new electronics called sensor fresh electronics to further sanitise the laundry with a sensor fresh system. This system is connected to the water system and the power electronics. The sensor fresh electronics were added to the Priority Parts 5, as the WM might not work if that system fails. Furthermore, the sensor fresh system can be taken apart, but it is not clear, if there are any spare parts on the market. This WM‘s previous model didn‘t have a sensor fresh system yet.
- WM6 – **Pumps** (PP 8): The WM has **2 pumps - a drain pump and a circulation pump**. The pump circulation system includes a new power wash system which washes by spraying water on the laundry. Due to this system and the mechanic washing process the laundry gets cleaned with less water and heat.

- Rinse Hose: as some of the other tested WMs, WM8 has **hoses which are not necessary**. In this case it is the rinse hose which sprays water on the laundry. It is seen as an unimportant hose, because there are other options to spray water on the laundry. (Example: the Siemens WM has a hydraulic system, like here, where there is a little bypass through which water can be sprayed on the laundry.)

Complexity can additionally influence the **reassembly**. For example, the reassembly of the **door seal of WM5** is very difficult, when the tub is in the WM as it can be barely accessed. This also affects the repair, as for easier reassembly the repairman must first lift the tub out of the WM to properly mount a new door seal. Another feature of a complex design are small interconnected parts, which make the disassembly and reassembly not self-explanatory at first sight.

3 Features that could damage the product

3.1 VC

During the analysis of the 10 VC several features that could damage the product were found. In some cases, the possible damage was a result of complex design.

Findings which can be interpreted as positive and negative:

- VC5: priority part 1 - **floor nozzle** - The floor nozzle has a **transparent plastic area** from which one can see the brush turning. This is enabling the user to see if the brush is turning or if it is stuck. As with the Dyson V10, this transparent plastic area is prone to get many scratches from the sucked in dirt. This might be seen by the user as a product damaging feature.
- VC5: In total the complete VC can be disassembled without breaking parts. The most challenging disassembly areas are the **plastic covers** which are **held by snap fits**. Besides this and after finding the **hidden screws**, the VC can be opened easily.

Negative findings:

- VC3: This VC is **built very complex**; it takes a lot of time to disassemble it without breaking it.

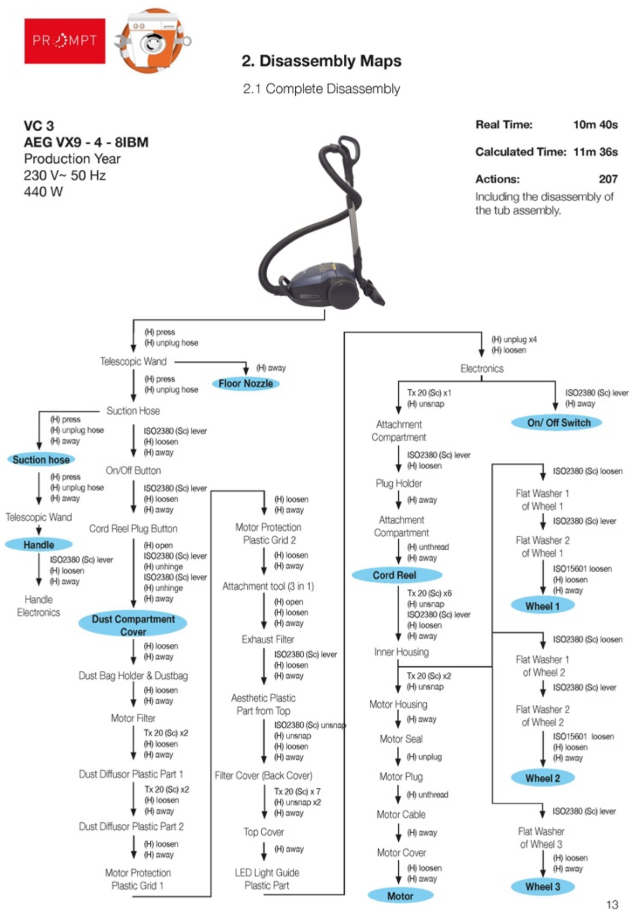


Figure 13 VC3_Disassembly_Map

- VC10 - **cord reel** (PP 5): The **transparent plastic components might break after frequent use**, as one part of the components is being bent. It is not premature obsolescence, but easy design which is seen as a product damaging feature.

- VC10: In the beginning it was unclear how this VC should be disassembled, as there were **many hidden screws**. The **buttons** were very difficult to disassemble and might break with a slight wrong angle of the tool as the plastic is thin and very stiff and there is barely any space for levering. In production the button fixation could have been designed for disassembly and without hidden screws..

Figure 14 VC10_Buttons_upside_down

3.2 WM

Positive finding:
WM4 – **Door** (PP 1): The door is very easy to disassemble. The moment the door is unscrewed the door parts can be exchanged with no effort. The only part which would need more skills for repair is the door hinge, as one would need to carefully hammer out the door hinge‘s stud. Furthermore, door hinges barely break and usually do so only after improper use.

Findings which can be interpreted as positive and negative:
WM6 – **Heater** (PP 6): This heater is held in the WM by the strong friction of the heater‘s seal. Therefore, the heater is **not screwed**. For fast repair and when it is certain, that the heater is broken, it can be ripped out of the WM. In case of just checking the heater, one must be careful to not damage the seal while levering the heater.

Negative findings:
WM2 – **Shock Absorbers** (PP 9): The shock absorbers can only be replaced after lifting the tub out of the WM‘s housing. Then the tub must be drilled with special siemens tools. This is done to reduce steps in the production. **While exchanging the shock absorbers one must be very careful to not harm the tub**. Simple techniques such as bolts, or screws can be an alternative.

Figure 15 WM2_PP9_shock_absorber

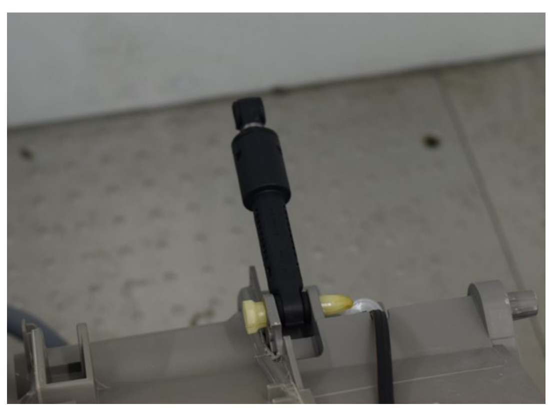


Figure 16 WM4_PP9_shock_absorber

WM9 – **Tub Assembly** (PP 10): This WM is an example with a tub where the **tension springs can cut through the tub suspension**. Here the connection point appears very edgy. In comparison Siemens WM‘s tub suspensions are rounder.

Figure 17 WM9_tension_spring

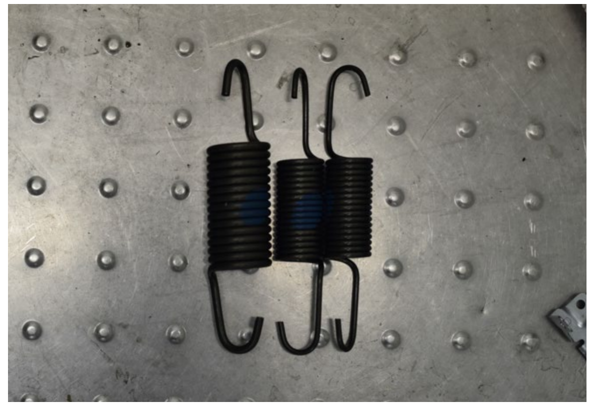


Figure 18 WM7_tension_spring

Drum Lifters: (Paddles used to help move clothes around the drum during washing.)

- WM9: The drum lifters can only be exchanged by breaking them out of the machine.
- WM10: The drum lifters cannot be disassembled. It is not clear, if even new drum lifters can be installed, as there is so little space in the tub. In case this is not a problem, one must break the drum lifters out and then reconnect the new drum lifters on the metal tongues.

The **belt pulley** of WM5 was not disassembled during the analysis, as the screw was very tight and the belt pulley, **made of plastic**, could have been harmed.

The **front** of WM6 has 2-4 **snap fits**, which are known as problematic, as people who don‘t know about the snap fits and don‘t look carefully, might just tear the front down and break the snap fits.

A small **snap fit of the backflow prevention** of WM6 broke during disassembly. It is assumed that is not meant to be disassembled.

4 Features that require special tools

All WM were disassembled using only class A tools. During the analysis, no combination wrench was used, but instead a socked wrench with hex sockets. The disassembly is also possible with a combination wrench, but the time might differ.

Apart from specific siemens tools required for All mentioned specific tools were provided with the WM and are therefore also class A tools, e.g., WM2:

- Drum Bearings (PP 4): The drum bearings can only be reached and repaired with special tools.
- Shock Absorbers (PP 9): The shock absorbers can only be replaced after lifting the tub out of the WM‘s housing. Then the tub must be drilled with special siemens tools. This is done to reduce

steps in the production. While exchanging the shock absorbers one must be very careful to not harm the tub. Simple techniques such as bolts, or screws can be an alternative.

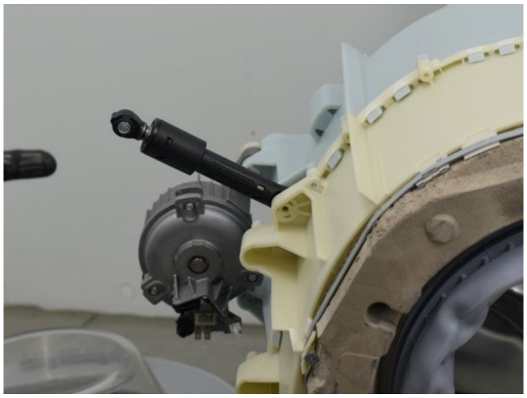


Figure 19 WM2_PP9_shock_absorber

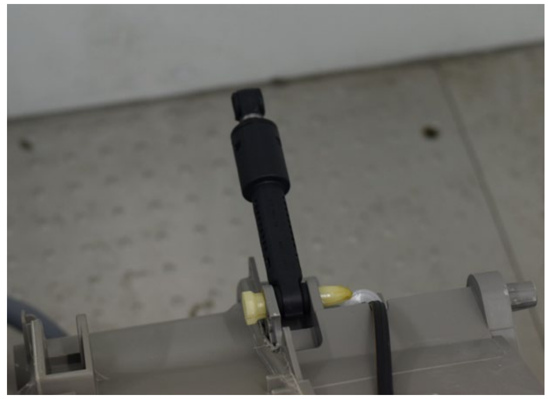


Figure 20 WM4_PP9_shock_absorber

5 Features that render the product unrepairable

5.1 VC

Findings which can be interpreted as positive and negative:

- VC6 - **floor nozzle** (PP 1): The floor nozzle has a parking position, so the VC can stand by itself. The front plexiglass is available as a spare part, but during the disassembly it was unclear how to loosen this plexiglass, as it seemed to be glued to the top part of the floor nozzle.
- VC8 - **floor nozzle** (PP 1): The bristles are very soft. There is a lot of electronics in the floor nozzle. It has many sensors. Instead of a belt, there is a gearbox to connect the brush bar with the motor. The floor nozzle cannot be further disassembled. It is assumed that for repair the lower part of the floor nozzle is exchanged. With this floor nozzle there is no premature obsolescence

Negative finding:

- The **handle** (PP 4) of VC10, which has several functions, is not further dismountable.

5.2 WM

Findings which can be interpreted as positive and negative:

Electronics (PP 5):

- WM8 has only two electronics which are right next to each other and are reachable from the front. The **power and motor electronics (which are one component) are encased in synthetic resin** which is positive as there is no risk of damage by humidity. The negative aspect is that they are not repairable. The electronics of the control panel are not encased.

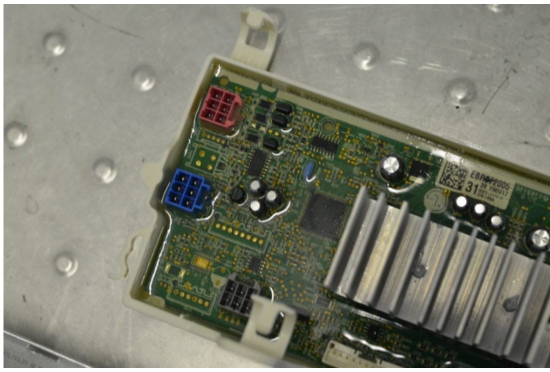


Figure 21 WM8_PP5_electronics

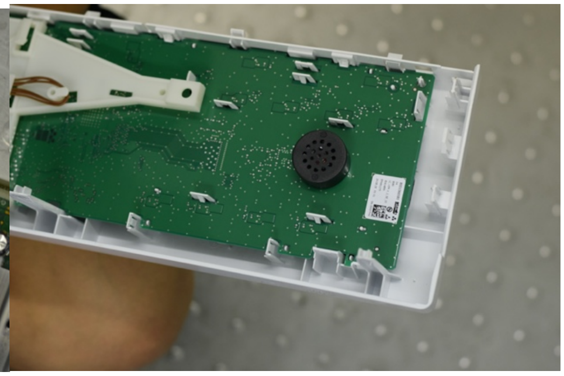


Figure 22 WM7_PP5_electronics

- The **control electronics, power electronics and motor electronics** of WM 10 **are one component**. They can be reached by disassembling the control panel. This makes the whole electronics area very accessible. At the same time, when one of the electronics fails, one must replace the whole part with the other electronics on it too. Furthermore, the electronics are **coated with synthetic resin** making them not repairable.

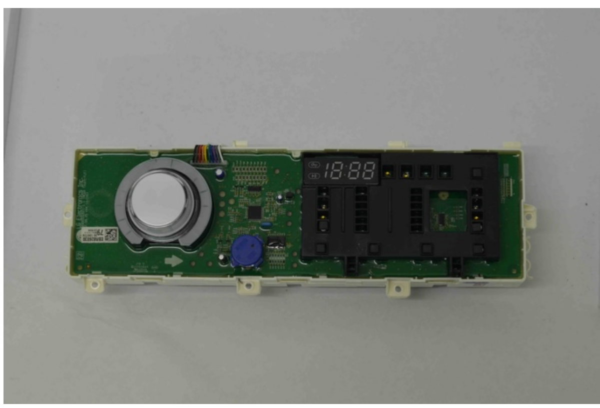


Figure 23 WM10_PP5_electronics_front

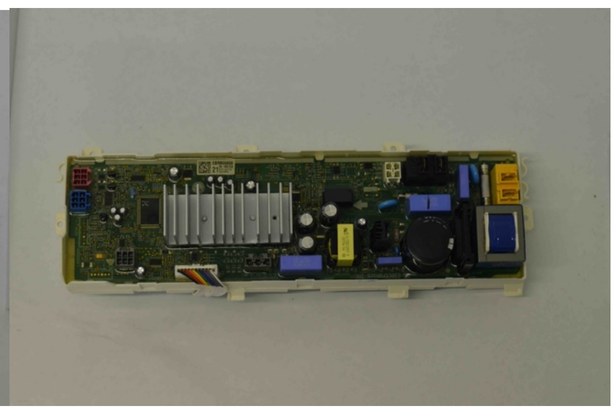


Figure 24 WM10_PP5_electronics_back

Negative findings:

- **Door (PP 1):**
  - The door of WM5 cannot be disassembled. To replace it, one must buy a new door.
  - The door of WM6 cannot be further disassembled after separating it from the WM. The door is screwed from the backside of the front, which is quite common for Miele WMs. When disassembling with common tools one must unscrew the front to reach the screws of the door, which increases the repair time. With a special tool, the door can also be disassembled without unscrewing the front. In case a part of the door breaks one must replace the whole door. It is known that Miele doors are quite expensive.
  - **On the company's website there are no spare parts for the door of WM7**, therefore it was not disassembled, as it might break in the disassembly process.

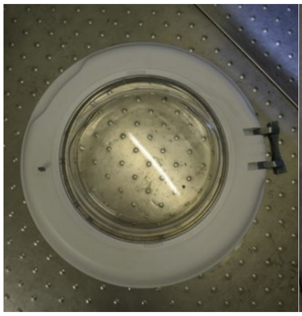


Fig. 25 WM5_PP1_door

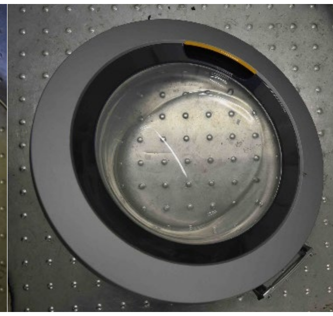


Fig. 26 WM6_PP1_door_front

Fig. 27 WM6_PP1_door_back

Fig. 28 WM7_PP1_door

- **Sealed tubs** rendering the replacement of drum bearings (PP 4) impossible were encountered during disassembly of WM3 and WM4.
- During disassembly of WM6 it was not clear if the **tub assembly** (PP 10) made out of metal is meant to be taken apart, as during the reassembly the metal spring needs to be placed precisely and strong to make sure that the tub assembly does not leak during usage.

6 Preventable Design Damages (less durability)

Negative finding:
The **circulation hose** of WM9 is **very close to the power electronics**. During the spinning process of the tub, the hose's and or power electronics' material can deteriorate over time.

7 Aspects regarding Information content and information accessibility

7.1 VC

Positive finding:
- VC6: This VC comes with **manuals** for the battery, the VC, and the charger.

Findings which can be interpreted as positive and negative:
- VC3: The dust bag is snapped in the dust bag handle to ensure a correct positioning of the dust bag in the VC. The dust bag can be exchanged by pulling the handle with the dust bag attached out of the VC. Then one must press with one hand on the handle to release the snapping function and to pull with the other hand in the opposite direction. It is an appealing design but needs more resources (plastic) than other designs and requires specific information on maintenance (see fig. 29). More sustainable design would be achieving the same function without having to add another part to the VC or reducing the amount of plastic needed on the dust bag and therefore increasing the need for the handle.


Fig. 29 VC3 dust_bag_handle *Fig. 30 VC3 dust_bag*

7.2 WM

Positive findings:

- **Miele WM Part Numbers**: Almost every component of a Miele WM has a part number. Spare parts can therefore easily be searched on the Miele Website.
- The back cover of WM8 has **graphic information** on how to loosen the transit bolts.

Negative finding:
Siemens WM repair manuals: To access the repair manuals of Siemens WMs one needs a license.

APPENDIX 3: PERCEIVED CAPABILITIES AND BARRIERS FOR DO-IT-YOURSELF REPAIR

4th PLATE 2021 Virtual Conference
Limerick, Ireland - 26-28 May 2021

PLATE
Product Lifetimes And The Environment

Perceived Capabilities and Barriers for Do-It-Yourself Repair

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Keywords: Repair; DIY; Repair tools; Repair experience; Repair barriers.

Abstract: Understanding the extent of common users' capabilities to repair products themselves, and the barriers during the repair could help legislators and manufacturers improve the design of products. This paper investigates users' capacity for using various common repair tools, their experience in repairing different household appliances, and the degree to which greater repair experience enables them to overcome related barriers to repair. Data was collected through questionnaires by 276 participants. Most respondents said they were able to use basic mechanical tools, but less than half stated proficiency in using soldering irons or multi-meters for repair. This indicates that more users may be able to perform diagnosis and repair of mechanical problems than electrical problems. However, 74% have repaired an electronic household appliance at least once in their lifetime (even if the repairs were mechanical). This suggests that repair could be a widespread activity. Users with no repair experience listed significantly more design-related barriers to repair than users with repair experience. These design-related barriers mostly concerned diagnosis and disassembly. Thus, designing products with features facilitating ease of diagnosis and disassembly with basic tools could remove some of the major barriers towards repair, and stimulate more users to repair their products.

Introduction

Consumer goods are nowadays less durable and repairable than in the past. Their average product lifetimes have been decreasing over the years (Bakker et al., 2014). This contributes towards an increase in Waste Electronic and Electrical Equipment (WEEE), which has been growing at the rate of 2-5% per year (Baldé et al., 2017). Extending products' lifetimes could contribute towards solving this issue (OECD,2015). As a response, The Circular economy action plan, adopted by the European Commission, sets out to keep value in products as high as possible throughout its lifetime by developing product-specific requirements for durability and reparability (European commission, 2020). Moreover, an increase in users' repair activities could contribute to longer product lifespans (Cooper, 2005; Raihanian Mashhadi, 2016).

Current studies on barriers towards repairs distinguish between two types of repair actors, namely professionals (Deloitte, 2016; Sabbaghi et al., 2017; Stamminger et al., 2018; Tecchio et al., 2019) and common users (Bovea & Pérez-Belis, 2018; Coppens et al., 2018; Jaeger-Erben et al., 2021; Laitala et al., 2021; Rogers et al., 2021; Victoria et al., 2017). however, research investigating the distinction in barriers between users with little or no repair experience (i.e., users who have never or once self-repaired a product of a specific category) and users with experience in repair (i.e., users who have self-repaired a product of a specific category 2 or more times) seems to be lacking.

Understanding whether there is a significant difference between barriers for self-repair between users with little or no repair experience and users with experience in repair, and what the difference is, may open an opportunity for future studies to make a distinction based on what type of users the study would like to focus on. This difference in barriers could provide an indication of the design-related aspect of a product that may need to be improved to promote users with little or no experience to dive into self-repairing the products. Therefore, the foremost contribution of this paper is to shed light into the difference in design-related barriers for self-repair in users with almost no repair experience against more experienced users.

In addition, this paper also provides insights into users' capacity for repairing products based on their ability to use basic tools and their previous experience.

These insights could guide designers, product manufacturers, and legislators to guide the design of the products in such a way that it promotes product repair activities. This may in turn increase the overall repair rate of household appliances.

literature

Factors influencing repair

Flipsen et al., (2017) establish that the main influential factors during self-repair are: repair manual, tools, and spare parts availability, ease of access to components (incl. not excessive adhesives), effort to repair, cost to repair, risk of injury, ease of identification of the problem, no damage to other components and time to repair a component. Similarly, Ackermann et al., (2018) indicate that users' ability, motivation, and triggers are influential for repair; For factors during self-repair, the following ability related factors are found to be relevant: users perceived knowledge and skill for repair, time and effort, lack of tools, and general reparability of products. Additionally, Victoria et al., (2017) indicate that a major barrier towards repair repairs being too expensive relative to buying a new product. The same survey indicates the following barriers to self-repair: "no time or too complicated", "repair impossible without breaking it" and "diagnosing it too expensive". Furthermore, Jaeger-Erben et al., (2021) present that low competence and high perceived costs of repair (time, energy, and money) could be the main indications for low repair rates.

Overall, the studied literature indicates that the following factors are influential for self-repair:

- High effort
- Expensive spare parts
- Spare parts unavailability
- Not enough time for repair
- Not knowing what is wrong
- Not knowing how to take the product apart
- Not having the right tools
- Chance of further damaging the product
- Chance of injury

Repair tools

According to the standard on general methods for the assessment of the ability to repair, reuse and upgrade energy-related products (CEN/CLC, 2020), we distinguish between basic tools (screw drives, Alen keys, wrench, pliers) and advanced tools (soldering iron and multi-meter). This list of tools served as the basis of the survey in determining the ability for users to use common tools for repair

Method

A questionnaire was sent to a user panel who lived within a radius of 30 km from TU Delft. This panel includes over 1000 volunteers (53% male and 47% female) aged 21-70, with different professional backgrounds. 47% of the panelists have Bachelor's or higher education level. We received 276 responses, with a median age of 57, 46% of the respondents being female and 54% male.

The participants were asked about: (a) their experience using standard tools for repair (with a picture): a plier, a screwdriver, a wrench, an Allen key, a soldering iron, and a multi-meter; and (b) previous experience repairing different durable goods: small and large household appliances, and electronic products. The participants specified how often they had repaired the appliances themselves from 5 options: never, once, a few times (2-5 times), several times (more than 5 times), or "at a professional level".

Additionally, participants were asked to indicate their level of agreement or disagreement via a 5 point Likert scale (1 = strongly disagree, 2= somewhat disagree, 3= neither agree or disagree, 4= somewhat agree and 5 = strongly agree) on statements related to barriers towards self-repair 'I don't know what is wrong with the product', 'I don't know how to take it apart properly', 'I could damage the product even more', 'I don't have the necessary tools', 'it requires too much effort', 'Spare parts were too expensive', 'Spare parts were unavailable', 'I could injure myself', 'I don't have enough time', 'I don't see any barriers'. For visual representation, the percentage of respondents in agreement with the barriers was calculated by the sum of the respondents indicating either "somewhat agree" or "strongly agree".

The statistical significance in the difference between perceived barriers for self-repair between users with little or no repair experience and users with experience was calculated using Mann Whitney U test (based on the points associated with the Likert scale) as the data is ordinal with independent samples (Field, 2005). Furthermore, pairwise comparison of barriers was conducted using related-samples Friedman's two-way analysis of variance by ranks.

Additionally, a random sample of 12 participants who have repaired more than once was interviewed and asked the types of activities they considered as repair activities.

Results and discussion.

Barriers to self-repair
The statistical analysis (Table 1) showed that users who have never repaired a household appliance rated the following barriers significantly higher than users who have repaired a household appliance before; "I could damage product even more", "I don't have necessary tools", "I could injure myself", "I don't know how to take apart properly", and "I don't know what is wrong with the product". Interestingly, these barriers are all affected by how products are designed (Figure 1). Predictably, experienced repairers listed "I don't see any barriers" much more than inexperienced repairers. They also more frequently listed "spare parts were too expensive" and "spare parts were unavailable". This large variation in barriers for self-repair between users with repair experience and users with no repair experienced may indicate that users with little or no repair experience are more affected by their perception of design-related barriers than users with repair experience.

In addition, the barriers, "I don't know what is wrong with the product", "I don't know how to take apart properly", and "I could damage product even more" are significantly higher than other barriers for users with little or no repair experience. These barriers closely relate to the processes of fault diagnosis and product disassembly. Hence, facilitating the design of the product for disassembly and diagnosis could potentially lower this barrier.

The barrier from "not having the necessary tools" could be lowered by designing products that require only basic tools to diagnose and repair. However, it also could be that part of these users do not have tools because they do not intend to repair products. Additional

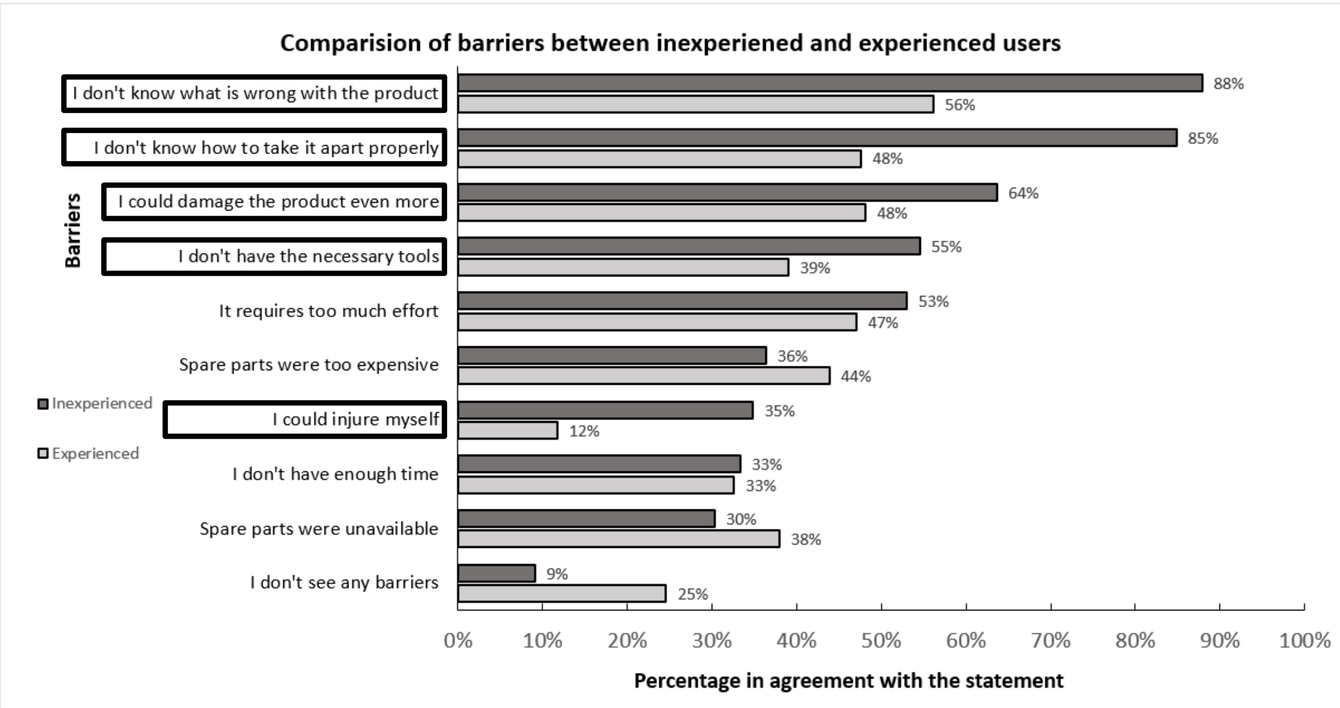

Figure 1: Percentage of respondents listing barriers to repair, in order of agreement. Barriers listed significantly more often by inexperienced users are outlined in boxes.

research is needed to investigate how to incentivize such users.

Mann whitney U test	I don't know what is wrong with the product	I don't know how to take it apart properly	I could damage the product even more	I don't have the necessary tools	I could injure myself	I don't see any barriers	I don't have enough time	Spare parts were unavailable	Spare parts were too expensive	It requires too much effort
Z Score	-4.77	-5.892	-2.654	-3.205	-4.989	2.987	0.218	1.578	0.552	-0.871
P value	<0.001	<0.001	0.008	0.001	<0.001	0.003	0.826	0.114	0.582	0.384
Significance	Significant	Significant	Signifcant	Significant	Significant	Significant	Not Significant	Not Significant	Not Significant	Not Significant

Table 1: Mann Whitney U test indicating significance of differences in barriers between inexperienced users and experienced users.

In addition, the barrier related to safety "I could injure myself" seemed to be significantly higher for users with little or no experience than users with experience in repair. This might be attributed to users' increased confidence in safety as their experience with repair increases.

Tool Proficiency
Figure 2 indicates that the majority of respondents were able to use basic tools for repair (screwdriver, Allen-key, Wrench, Plier). However, only 43% stated to have proficiency using a soldering iron and 33% knew how to use a multi-meter. This indicates that more users are likely to be able to perform mechanical repair related activities than electrical.

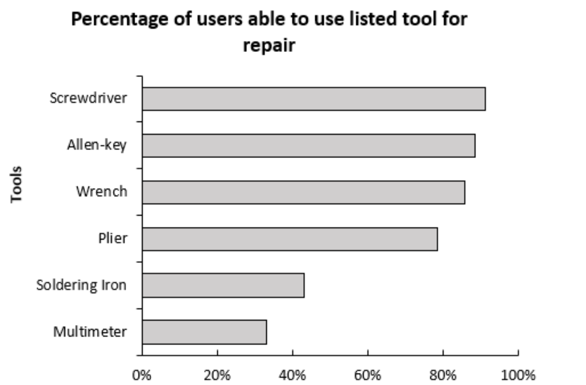

Figure 2: Percentage of users able to use listed tool for repair

Repair Experience
Figure 3 indicates that 74% of the users have repaired their household appliance more than once. A small sample of users (n=12) was further interviewed on what activities were carried out during repair. Two out of twelve (16.7%) users indicated that they performed a maintenance activity such as changing the vacuum cleaner filter but called it a repair activity. Adjusting for this discrepancy, the result still indicates that majority of users have repaired their own household appliance more than once. The reported past repair experience seems to be much higher compared to other studies (Jaeger-Erben et al., 2021; Rogers et al., 2021; Victoria et al., 2017), where less than 10% would attempt repair. There may be some selection bias as people interested in repair may be more likely to participate in the survey and also the panel itself is on average relatively high-educated. However, recent literature by Laitala et al. (2021) also found a relatively high percentage of users (31.6%) attempting repair on household appliances, out of which 24% attempted to repair household appliance themselves in past two years. This result may therefore indicate that users may be more experienced to repair their household products than previously thought.

Limitations and Further research
Whilst this research mostly focused on design- and product-related factors influencing self-repair, other factors, e.g., related to motivation, and triggers also play a large role in the repair rate of product. This research could be expanded to compare the effect of other factors influencing repair between users with little to no repair experience against users with repair experience.

Additionally, a wider study sample that is more representative for all users could unveil bias that may be attached to this study.

Conclusion
Overall, this research shows a large variation in the perception of design-related barriers for

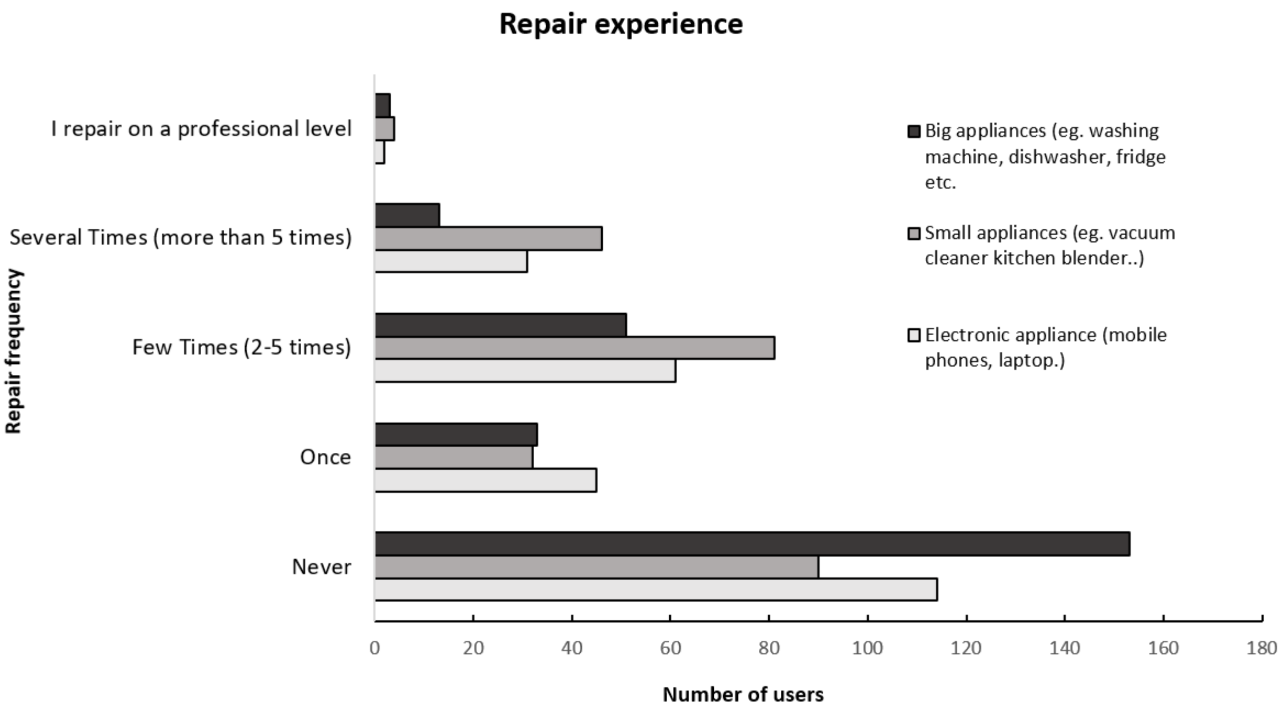

Figure 3: Repair frequency from number of users who have reported to self-repaired the listed category of appliances in the past.

self-repair between users with repair experience and users with limited or no repair experience. It indicates that Inexperienced users are more affected by design-related barriers than users with repair experience. This perception of barriers seems to be related to the ease of diagnosis and disassembly. Additionally, the majority of the users are able to use basic mechanical repair tools, but are not proficient in using electrical repair tools such as a soldering iron or multimeter. Thus, electric or electronic faults will be more difficult to diagnose and repair; product design strategies should consider how to lower these barriers. Finally, this study indicates that users may be more experienced to repair their household products than some other studies indicate. Therefore, designing products with features facilitating repair could stimulate users to repair their products.

These insights can guide designers, product manufacturers, and legislators to promote repairability in product design. This could, in turn, increase product lifetimes and reduce waste, especially waste electrical and electronic equipment.

Acknowledgments

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References

Ackermann, L., Mugge, R., & Schoormans, J. (2018). Consumers' perspective on product care: An exploratory study of motivators, ability factors, and triggers. *Journal of Cleaner Production*, *183*, 380–391. https://doi.org/10.1016/j.jclepro.2018.02.099

Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014). Products that go round: exploring product life extension through design. *Journal of Cleaner Production*, *69*, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Baldé, C., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2017). *Suivi des déchets d'équipements électriques et électroniques à l'échelle mondiale 2017: Quantités, fl ux et ressources*. http://collections.unu.edu/eserv/UNU:6341/GEM_2017-F.pdf

Bovea, M. D., & Pérez-Belis, V. (2018). Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. *Journal of Environmental Management*, *228*, 483–494. https://doi.org/10.1016/j.jenvman.2018.08.014

Cooper, T. (2005). Slower consumption reflections on product life spans and the “throwaway society”. *Journal of industrial Ecology*, *9*(1-2), 51-67.

Deloitte. (2016). *Study on Socioeconomic impacts of increased reparability – Final Report. Prepared for the European Commission, DG ENV*. https://doi.org/10.2779/463857

Flipsen, B., Bakker, C., & Van Bohemen, G. (2017). Developing a reparability indicator for electronic products. *2016 Electronics Goes Green 2016+, EGG 2016*, 1–9. https://doi.org/10.1109/EGG.2016.7829855

Jaeger-Erben, M., Frick, V., & Hipp, T. (2021). Why do users (not) repair their devices? A study of the predictors of repair practices. *Journal of Cleaner Production*, *286*, 125382. https://doi.org/10.1016/j.jclepro.2020.125382

Laitala, K., Klepp, I. G., Haugrønning, V., Throne-Holst, H., & Strandbakken, P. (2021). Increasing repair of household appliances, mobile phones and clothing: Experiences from consumers and the repair industry. *Journal of Cleaner Production*, *282*, 125349. https://doi.org/10.1016/j.jclepro.2020.125349

OECD, Material Resources, Productivity and the Environment. OECD, 2015.

Raihanian Mashhadi, A., Esmaeilian, B., Cade, W., Wiens, K., & Behdad, S. (2016). Mining consumer experiences of repairing electronics: Product design insights and business lessons learned. *Journal of Cleaner Production*, *137*, 716–727. https://doi.org/10.1016/j.jclepro.2016.07.144

Rogers, H. A., Deutz, P., & Ramos, T. B. (2021). Repairing the circular economy: Public perception and participant profile of the repair economy in Hull, UK. *Resources, Conservation and Recycling*, *168*(December 2020). https://doi.org/10.1016/j.resconrec.2021.105447

Sabbaghi, M., Cade, W., Behdad, S., & Bisantz, A. M. (2017). The current status of the consumer electronics repair industry in the U.S.: A survey-based study. *Resources, Conservation and Recycling*, *116*, 137–151. https://doi.org/10.1016/j.resconrec.2016.09.013

Stamminger, R., Tecchio, P., Ardente, F., Mathieux, F., & Niestrath, P. (2018). Towards a durability test for washing-machines. *Resources, Conservation and Recycling*, *131*, 206–215. https://doi.org/10.1016/j.resconrec.2017.11.014

CEN/CLC TC10 European Standard. (2020).

General methods for the assessment of the ability to repair, reuse and upgrade energy related products (EN 45554).

Tecchio, P., Ardente, F., & Mathieux, F. (2019). Understanding lifetimes and failure modes of defective washing machines and dishwashers. *Journal of Cleaner Production*, *215*, 1112–1122. https://doi.org/10.1016/j.jclepro.2019.01.044

Victoria, P., Braulio-gonzalo, M., Juan, P., & Bovea, M. D. (2017). *Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment . A Spanish case study*. *158*. https://doi.org/10.1016/j.jclepro.2017.04.143

APPENDIX 4: FAILURE CAUSE ANALYIS OF FOR PHYSICAL DURABILITY OF PRODUCTS

Product	Failure idicators	Failure cause	Root cause (Design Aspects)	Susceptible component	Design opportunity facilitating Robustness
TV	1. No audio in any input [1] 2. TV turns on and off repeatedly [1] 3. TV will not turn on and red power LED blinks continuously [1] 4. No power , standby on [2] 5. Lines/ partial images [5] 6. Entire LCD defective 7. lines in the images 8. Image showed with mosaic effect	1. Audio chip (main board) malfunction (a1) [1] 2. IC chip malfunction (a1,2,3,4)[1] [2][6] 3. Capacitor malfunction (a1,2,3,4) [1][4][6] 4. Image processor overheating (a6) [5]	1. Under-dimensioned/indadequate capacitors and chips (voltage, current) [4][6] 2. Capacitors and chip Under-dimensioned to withstand extreme temperatures and humidity cycles. [4][6] 3. Overheating of capacator and chips due to insufficient cooling and near high temperature source [4][6] 4. Current/Voltage surge [4][6]	Main board (including sound board and ethernet port) TCon board (attached to display)	1. Proper Specifications of capacitors and IC chips 2. Placement of capacitor and chips relative to heat source 3. Placement of Features facilitating cooling (thermal pads, heat sink etc) 4. Surge protection system
	1. Cracked screen 2. Screen not working properly	1. Failure in transference of LVDS (Low-voltage differential signalling) (a5) [5]). 2. Drop, bumps	1. unstable TV stand (b1) 2. Under-dimensioned signal cables and connectors (b2)	Display assembly (failure rate including related lighting technology)	1. Stable stand 2.Proper Dimensioning/specifications
	1. Turns on but no images/image disappears	1. Weakening of the backlight [5] 2. LED inverter malfunction [5]	1. Under-dimensioned capacitors and chips (voltage, current) [4][6] 2. Capacitors and chip Under-dimensioned to withstand extreme temperatures and humidity cycles. [4][6] 3. Overheating of capacitor due to insufficient cooling and near high temperature source [4][6] 4. Current/Voltage surge [4][6]	LED board / backlighting	1. Proper dimensioning/specifications of IC chip and capacitor to withstand environmental and electrical factors 2. Placement of capacitor relative to heat source 3. Placement of Features facilitating cooling (thermal pads, heat sink etc) 4. Application of the surge protection system
	1. Doesn't turn on [1][2]	1. Transformer malfunctions [5] 2. IC chip malfunction (MOSFET) [8] 3. Capacitor malfunction [6] 3. Fuse blown [7][8]	1. Under-dimensioned capacitors and chips (voltage, current) [4][6] 2. Capacitors and chip Under-dimensioned to withstand extreme temperatures and humidity cycles. [4][6] 3. Overheating of capacitor [4][6] 4. Current/Voltage surge [4][6]	Internal power supply / power board (including inverter board)	1.Proper Dimensioning/specifications 2. Placement of capacitor relative to heat source 3. Placement of Features facilitating cooling (thermal pads, heat sink etc)
Phone	1. Crack visible	1. Cracking of the display due to drops and bumps	2. Weak screen polymer 3. No screen protection placed by user 4. physial design susceptible to brekage (eg, folded / curved screen)	Display assembly	1. Standard screen > Bezel-less screen > Curved screen [10] 2. Indication to add screen protection 3. Supplying screen protection with the phone 4. Complaince with drop test
	1. Battery draining quickly 2. Phone not powering on 3. Sudden shutdown of phone	1. Battery degradation [4] [6] 2. Cell failure (a3) [4] [6]	1. poor battery management system [4] 2. Improper charger used [4] 3. poor heat dissipation [4] 4. poor quality battery [4]	Battery	1. Placement of Features facilitating cooling (thermal pads, heat sink) 2. Proper Dimensioning/specifications (deliverable 3.1) 3. Indicating volt and current range charger that could be used (not just use official company charger).
	1. Phone not charging 2. Loose connection	1. Charging connection breakage/loose in soldering 2. Port pin misalignment	1. Connector fatigue failure due to improper attachment or shock (b1) 2. Under-dimensioned Soldering	Charging connector (USB C)	1. reinforcements in soldered area 2. Proper Dimensioning/specifications (deliverable 3.1) 3. Simpler design (certain amount) - Defined on the USB standandard.
	1. Phone not charging 2. Display not working 3. Phone not turning on	1. Liquid damadge	1. Phone not protected against water	Electronics	1. Provide water ingress protection

Product	Failure idicators	Failure cause	Root cause (Design Aspects)	Susceptible component	Design opportunity facilitating Robustness
Vaccum Cleaner	1. No power 2. Irregular power 3. Cord not retracting	1. Break in the cord (a1,2) [4] 2. Reel winder failure (a3) [4]	1. Sharp edges in housing of cable reel (b1) [4] 2. Poorly dimensioned cable and cable winder [4] 3. poor quality cable and or cable winder [4]	Cord Reel	1. No sharp edges in the housing 2. Proper dimensioning and material selection 3. Cable handling instructions attached/ provided in manual.
	1. Battery draining quickly 2. VC not powering on 3. Sudden stop of VC	1. Battery degradation [4] [6] 2. Cell failure (a3) [4] [6] 3. Improper charger used [4]	1. poor battery management system [4] 2. (use instructions) 3. poor heat dissipation [4] 4. poor quality battery [4]	Battery	1. Placement of Features facilitating cooling (thermal pads, heat sink) 3. Indicating volt current range of charger of charger that could be used (not just use official company charger)
	1. low suction [4] 2. VC stops working after a while 3. No power	1. Impeller clogged 2. Motor burnout 3. Motor overheat 5. Carbon Brush used up	1. Motor filter damaged (b1) 2. stress due to clogged airway or filters (b2,b3) 3. Water damage (b2) 4. Poor quality carbon brush, short carbon brush (b4)	Motor	1. Proper dimensioning of motor and carbon brush 2. Motor overheat indicator 3. Water/Moisture indicator 4. Auto shutdown feature in presence of water or overheating 4. Filter change indicator. 5. Use of brushless motor
	1. low suction [4]	1. Dirty, full filter 2. Filter damaged	1. Inadequate filter cleaning schedule (b1) 2. Improper cleaning (b2)	Filter (Dust Bag, Exhaust Filter, Motor Filter, etc.)	1. Filter replacement/maintenance indicators (alert, visual indication) 2. Ease of filter accessibility 3. Maintenance schedule
	1. low suction [4] 2. Brush not spinning 3. Slow spinning of the brush	1. Clogged hose/ brush (a1) 2. Motor burnout (a2,3) 3. Belt damage (a2,3) 4. Bearings of the brush roller blocked due to dirt	1. stress due to clogged brush (b2,b3) 2. poor quality belt.	Floor nozzle	1. Indicator whenever brush clogs. 2. Maintenance instructions 2. Ease of brush accessibility 3. Dimensioning/Specifications of belt
Washing Machine	1. Leakage	1. Wear and tear in rubber door seal due to tension, fatigue, creep, stress relaxation exposure to chemicals [10][11][12]	1. Inadequate material selection and dimensioning (b1)[10] 3. Thin rubber [10] 4. Improper maintenance/cleaning of the seal by user [10]	Door Seal	1. Proper Dimensioning/specifications 2. Maintenance indicator to user (leave the door open afte washing cycle, dry the seal)
	1. Leakage 2. Door not closing properly 3. Door lock don't open 4. Error code	1. mechanical deformation of the lock or hinge (a1,2,3) [10] 2. Cracking of the lock or hinge (a1,a2,a3) 3. Unnecessariliy large force applied by the user. (if it is locked)	1. Inadequate dimensioning and material specifications. (b1,b2) 2. Inadequate use and maintenance indication (b3), (inadequate	Door Lock & Hinge	1. Proper Dimensioning/specifications 2. Material selection[4][10] 3. Indicator when door is locked or when it could be opened. 4. Design door handle so that stress to lock and hinge is minimized [4][10]
	1. grinding noise (slowily growing)	1. Uneven load, overload [13] 5. Unrepaired shock absorbers [10][4] 6. Corrosion due to leakage (& humidity) [10][4] 9. wearing (abrasive, scuffing)	1. Insufficient/Inadequate sealing (9) 8. Inadequate lubrication 5. Unrepaired shock absorbers [10][4] 7. Poor quality/Under-dimensioned shock absorbers [10][4] 4. Inadequate material selection and dimensioning of the bearing [10][4]	Drum Bearings / Tub assembly (if bearings are attached)	1. Proper Dimensioning/specifications 2. Indicator when shock absorber needs replacement 3. Indicator for uneven loading and overload. 4. Self adjustment feature if uneven loading is placed 5. Instruction/label for loading

Product	Failure idicators	Failure cause	Root cause (Design Aspects)	Susceptible component	Design opportunity facilitating Robustness
	1. High vibration 2. High noise	1. Uneven load, overload [13] 5. Corrosion due to leakage [10] 6. Abrasive wear 7. Suspension ring failure	1. No protection in suspension ring (3)[10] 2. Inadequate dimensioning of shock absorbers [10] 3. Underdmension suspension ring 4. Inadequate lubrication 2. Poor quality shock absorbers (dry friction < fluid friction < pneumatic) [10] 4. Inaduquate load maintanence system or indicators.	Shock Absorbers	1. Proper Dimensioning/specifications 2. Indicator for uneven loading and overload. 3. Self adjustment if uneven loading is placed 4. (shock absporper damadge indication, paternt or literature) 5. Provide protetion against the the vibration in cotact area of the housing. (through plastc etc.)
	1. Water leakage during operation 2. no drainage during operation 3. Error code	1. Pump coil burnout [10][14] 2. Foreign object clogged in drain, filter, impeller. [10][14] 3. Impeller broken[14]	1. Poor quality filter leading to broken fliter leading to impeller clog and breakage. (b1) [10] 2. overheating from stress caused by cloge (b1). [10] 3. Poor filter maintanence (b2)	Pumps	1. Filter maintenance instruction 2. Filter clog abd motor overheat indication 3. Ease of mantanence 4. (Auto sutdown or throttle feature) - 5. Adequate material and component selection (1b)
	1. No power 2. No Feedback 3. Error code 4. No heating, spin, water flow in/out, 5. No wash	1. Capacitor Malfunction [10][14] 2. IC Malfunction [10][14]	1. Under-dimensioned/Specified capacitors and IC (b1,b2) 3. Electrical overstress (b1, b2)	Electronics	1. Proper specifications for capacitors and IC chips 2. Placement of capacitor and chips relative to heat source 3. Encase control board in moisture tight box 4. Place far away from potential water contact area 5. Provide water ingress protection 6. Software settings. 7. Instructions for placement.
	1. Wont finish wash cycle 2. Poor wash 3. Error code	1. Accumulation of cloth abrasive on heater 2. mineral accumulation 3. Heating rod failure 4. Thermostat failure	1. Electrical overstress (b3,4) 2. Inadequate maintanence (b1, b2) 3. Inadequate design promting accumulation of forieign debris. (b1, b2) 4. Overheating of electronics (b3, b4)	Heater	1. De-mineralization feature (via salt etc.) 2. Use and maintenence instructions
	1. leakage 2. loose hose	1. Hose ruptures 2. Crack and degradation of material properties	1. Inadequate use and maintainence 2. Inadequate material choice ability to resist chemicals causing hose to loose it properties 2. Hose positionined close to sharp objects	Hoses (outlet hose tub, inlet hose tub)	1. Adequate selection of material 2. Correct positioning of hose/components

Sources	Title	Link	Date (Accessed)	Contributing Author/Partner
[1]	Main Board Repair Kit for Board Number BN41-00975	https://www.youtube.com/watch?v=oC4f2Ik8rCI	12/8/2021	ShopJimmy.com
[2]	SAMSUNG UN60H6350 TV no power motherboard repair	https://www.youtube.com/watch?v=9vcmV6eUN-U	12/8/2021	SOSfix Electronics
[3]	Rusz Repair Analysis	PROMPT	2021	RUSZ
[4]	Wp4 workshop	PROMPT	12/8/2021	Wp4 workshop (2019)
[5]	Methods for the Assessment of the Reparability and Upgradability of Energy-related Products: Application to TVs Final report		2019	JRC (J.Sanfelix et al.)
[6]	D3.1 Test Plan, Batteries and Electronics	PROMPT		IZM
[7]	LCD TV Repair - No Power, Power Supply Common Symptoms & Solut	https://www.youtube.com/watch?v=TR2iWN6b-LY	12/9/2021	ShopJimmy.com
[8]	Samsung UN60J620DAFXZA deat set, power supply board repair	https://www.youtube.com/watch?v=O5tFc_qLGww	12/9/2021	bigdog8882
[9]	LG 42LB550V TV - No power - Board repair	https://www.youtube.com/watch?v=77B-ZhsY6c0	12/9/2021	Electronics repair school
[10]	Expert interview	PROMPT	2021/2020	RUSZ/Ifixit/IZM
[11]	Rusz database	PROMPT	2020	RUSZ
[12]	Test Report ONR 192102:2014 ET15194: Early Obsolescence and Reparability of Washing Machines	PROMPT	7/8/2016	RUSZ
[13]	EN 45552 Study for the development of an endurance testing method for washing machines			
[14]	10 Most Common Problems With Laundry Washing Machines	https://www.youtube.com/watch?v=lC5eqysbdsk	12/9/2021	Word of Advice TV
[15]	Durability of smartphones: A technical analysis of reliability and repairability aspects		2021	Cordella, M