SUSTAINABLYSMART

Sustainable Smart Mobile Devices Lifecycles through Advanced Re-design, Reliability, and Re-use and Remanufacturing Technologies

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Lead Author:	Christian Clemm
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Coordinator contact:	Karsten Schischke

Fraunhofer IZM

phone +49.30.46403-156

e-mail schischke@izm.fhg.de

Contributing Partners

Preliminary findings by the lead author have been discussed and developed with the members of the sustainablySMART consortium in an interactive session during the 6th General Assembly in Oulu, Finland, in March 2018. Detailed feedback and input was provided by ProAutomation and iFixit in telephone calls for additional insights into semi-automated and manual disassembly processes and to validate and revise assumptions and conclusions.

Fraunhofer IZM	Christian Clemm, Karsten Schischke
ProAutomation	Roland Ambrosch
iFixit	Bas Flipsen, Matthias Huisken

Disclaimer

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Summary

The project sustainablySMART undertakes research and development on various aspects of the life cycle of mobile information technology devices, smartphones and tablets in particular. Activities cover the redesign of smartphones and tablets as such with the intention to facilitate reuse and remanufacture of parts and components for same or different applications. The automated disassembly and rework of components, focusing on devices with large market shares, is another field of research and development in the project. Harvesting reusable components from used smartphones either as spare parts or as functional parts for secondary use is the priority target of developing disassembly processes. However, once reusable components are harvested from the devices it might be an option to also separate components in the same process that contain critical raw materials, which are otherwise lost in the conventional electronics recycling processes.

This deliverable provides an analysis of commonly found design choices in the product group smartphones and an evaluation of those against two different disassembly scenarios: A “business as usual” manual disassembly process, commonly encountered in businesses involved with disassembly processes, and a semi-automated robot-assisted collaborative approach, as is being developed by ProAutomation in work package 3 (WP3) of the sustainablySMART project. On the basis of insights gained from this analysis, this document provides concrete indications on which design aspects may hinder or facilitate disassembly in each of the scenarios.

The results indicate that the examined scenarios differ greatly regarding their compatibility with the different design choices. Consequently, the collaborative approach chosen by ProAutomation may indeed be an ideal solution for disassembly processes, being able to handle a large array of different design aspects commonly encountered in the product group.

Content

1 Introduction

The transition to a Circular Economy requires retaining the value of products for as long as possible. Reuse of components is an important means to retain value from end-of-life (EOL) electronic products. Additionally, enhanced recovery of valuable materials from EOL devices requires more sophisticated processes than the currently dominating mechanical shredding during pre-processing. Disassemblability is an essential feature in the design of devices to facilitate repair, reuse, refurbishment, and dismantling for recycling.
Currently, a considerable contrast can be observed between the technological complexity of manufacturing processes for electronic devices and the comparatively low sophistication of processes applied to EOL devices. EOL devices are treated for depollution (e.g. removal of batteries) and for material recovery (e.g. recycling of valuable metals). The processes are optimised to recover valuable metals such as gold and copper, the revenue of which needs to roughly cover the processing costs. Hence, the techniques applied to EOL devices are considerably less refined than manufacturing processes, where expected revenue is substantially greater. Nevertheless, efforts are being made by market players to establish more sophisticated technology, including research and development into high-throughput, automated equipment to disassemble complex electronic devices, such as smartphones, to obtain high-value components as spare parts or to enable recycling of technological metals (e.g. certain rare earth metals) from specific components.
Design for disassembly as a key factor in the disassemblability of EOL devices needs to account for future developments in the reuse, refurbishment and recycling sectors. The considerations described in this report are an attempt to assess specific design choices and joining techniques in terms of their compatibility with manual and (semi-)automated disassembly processes, to inform affected stakeholders on potential opportunities and barriers as well as potential contradictions between today’s processes and future scenarios. Design for Disassembly Guidelines offer concrete indications on specific design aspects to be considered in the design of smartphones to enable disassembly under various conditions.

2 Goal and Scope

The project sustainablySMART undertakes research and development on various aspects of the life cycle of mobile information technology devices, smartphones and tablets in particular. Activities cover the redesign of smartphones and tablets as such with the intention to facilitate reuse and remanufacture of parts and components for same or different applications. The automated disassembly and rework of components, focusing on devices with large market shares, is another field of research and development in the project. Harvesting reusable components from used smartphones either as spare parts or as functional parts for secondary use is the priority target of developing disassembly processes. However, once reusable components are harvested from the devices it might be an option to separate in the same process also components containing critical raw materials, which are otherwise lost in the conventional electronics recycling processes. These materials are e.g. tantalum, gallium, tungsten, indium, cobalt and rare earth elements (REE), which are used in applications such as capacitors, power amplifier ICs, vibration motors, displays, speakers, and batteries.

Design for disassembly of complex electronic devices such as smartphones is an essential prerequisite to facilitate the separation of target components for reuse or recycling with reasonable effort and cost. Disassembly of end-of-life (EOL) devices during the pre-treatment processes of the recycling chain may be carried out either manually or, in accordance with developments in the sustainablySMART WP3, with semi-automated disassembly technologies.

The goal of this deliverable is to compile evidence from research and development of WP3 - 5 into design for disassembly guidelines, and in doing so

- identify barriers and favourable design features for disassembly

- deliver input to WP1 (dedicated product designs), and WP8 (policy measures) in an iterative process
- produce guidelines generic for electronics in general or specific products (e.g. project demonstrators)

The results will be used by Telekom Austria by integrating guidelines in their green purchasing requirements for the mobile phone manufacturers. TUW will translate and implement the developed guidelines into a software tool. Intended software platform is the ECODESIGN PILOT. This software is well known Ecodesign software based on checklists to support designers in product development including improvement measures along the complete life cycle of a product.

2.1 Relevant findings from WP3-5

In the following, relevant findings from the work packages 3 - 5 of the sustainablySMART project are summarized. From those insights, conclusions are derived for the scope of the Design for Disassembly Guidelines in section 2.2.

- **Target products** for automated disassembly / separation and recovery of advanced materials were identified in Task 3.1. as described in milestone report 2:
    - Best-selling smartphones on the European market at the time: iPhones and Samsung smartphones
    - Products of a certain technological level for better reusability of components, i.e. iPhones 3GS and later, and Samsung Galaxy S II and later
    - Defect devices instead of devices in good working condition
    - Additionally: Fairphone 1 due to Fairphone's interest in getting better knowledge about Design for Disassembly and to enhance the recyclability / reuse of Fairphone 1

- **Target components** for reworking solutions in WP4 and battery and storage processes in WP5 are as follows:
    - Flash memory (BGA), Processor (CPU, DSP, Microcontroller), FPGA, QFN and QFP components of smartphones, tablets and digital voice recorder, battery

- **Disassembly scenarios**: Automation solutions for disassembly will be described in deliverable 3.2 (Task 3.3); however, as this document is not available at the time of writing, the latest document describing the developed process will be referenced[1].

2.2 Scope of Design for Disassembly Guidelines

The following decisions have been made in terms of the scope of the guidelines, according to the goals of this deliverable and taking into account the findings from relevant work packages listed in section 2.1:

- **Disassembly** is understood to be a process in which the integrity of the key components of a device is preserved (does not necessarily apply to joining elements such as screws, adhesive strips).

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[1] ProAutomation presentation of the current status at the 6th GA in March 2018 in Oulu, Finland

- **Target products**: The guidelines have been developed specifically for the product group smartphones. However, in order to increase the usefulness and achieve a potentially broader impact, the transferability to other product groups is evaluated.
- **Target components** are components relevant for reuse and as spare parts, as well as components containing materials that require separate treatment processes to be recoverable in the recycling process. Target components are:
    - Priority components[1]: Mainboard, display, battery, midframe, back cover
    - Secondary target components: Camera, speakers, microphone
    - Target components for desoldering: Flash memory, processor (System-on-Chip, SoC), FPGA, QFN and QFP components
- **Disassembly scenarios** include a largely manual process, based on processes observed during site visits to relevant companies, and a semi-automated process based on a robot-assisted disassembly process in development by ProAutomation (WP3).
- **Temporal validity**: The guidelines account for technology commonly employed in smartphones and in smartphone pre-treatment at the time of writing; best not yet available technologies are discussed in section 6 (outlook).

The following aspects are not considered to be in scope of the guidelines:

- Dismantling is understood to be a process in which the integrity of components of a device are not prioritized (destructive disassembly for recycling purposes).
- Some market players develop automated disassembly solutions (e.g. Apple 2018) which target the separation of components for enhanced recycling of materials. These solutions fall in the category of dismantling operations and are thus not considered for disassembly scenarios in this document.

3 Technical analysis

3.1 Disassembly scenarios

3.1.1 Scenario 1: Manual disassembly process

A typical process to disassemble EOL smartphones to recover spare parts is described based on company visits to repair, refurbishment and pre-processing facilities in Germany. The sequence of the disassembly steps is predetermined by the design of each specific device model. The following list is in order of a typical smartphone disassembly sequence.

- The phone is opened using techniques appropriate for the employed joining technique; either manually without tools, with hand-held tools (e.g. screwdrivers, prying tools), or using purpose-built equipment (e.g. heating units to dissolve adhesives).
- Internal joints (e.g. screws) are unfastened manually with tools as required.
- To separate the battery, adhesive is dissolved if present, using techniques appropriate for the type of adhesive applied, including manually without tools (e.g. pull strips), with hand-held heating tools, with purpose-built equipment, or using solvents and mechanical force as required (prying or g-force).
- The display unit is typically separated in its entirety without further separating front glass and LCD units.
- The mainboard and smaller subassemblies (e.g. camera module, home button assembly) are separated manually by unfastening screws and other joints as required.

[1] Denotes economic and/or environmental value

- Electronic components on the mainboard (incl. flash memory and SoC BGAs) may be desoldered to be replaced in a repair scenario (level 3 repair[1]), but are typically not desoldered for reuse.

3.1.2 Scenario 2: Semi-automated disassembly process

ProAutomation (PA) is developing advanced automated solutions for the disassembly of smartphones, among other devices. Their approach is a collaborative disassembly line, in which a human worker collaborates with robotic disassembly equipment. The machinery carries out process steps that can be automated and the human worker undertakes those steps that require individual solutions, which can currently not effectively be automated. An illustration of the developed set-up is depicted in Figure 1. The machinery equipment and its functionality is described in
Table 1.

Figure 1: Exemplary illustration of a collaborative disassembly work space by PA[1]

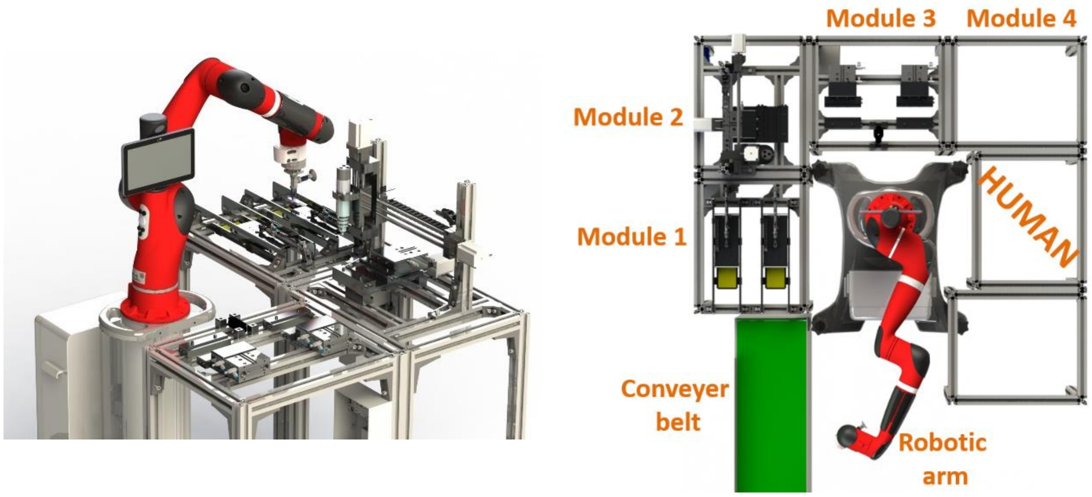


Table 1: Description of the product line for automated disassembly solutions by PA[1]

Equipment	Functionality
Robotic arm	Multi-functional tool for object recognition and placing
Conveyer belt	Input of phones to the disassembly process
Module 1: Heating tool	Heating of phone to a predefined temperature to dissolve adhesives
Module 2: Unscrew tool	Step motor driven pneumatic screwdriver
Module 3: Clamping tool	Clamping phones to keep in place
Module 4: not defined	not defined (e.g. future desoldering module)

The sequence of the semi-automated disassembly steps is predetermined by the design of each specific device model. The following list considers steps carried out by automatized equipment. Steps that may be carried out by a human worker are assumed to be carried out in a manner corresponding to the descriptions in scenario 1.

- The phone is opened using techniques appropriate for the joining technique applied;
    - by using the clamping tool and removing the back cover with vacuum suction (e.g. for snap-fits).

[1] Level 3 repair refers to repair processes that involve soldering of electronic components on a PCB, as opposed to level 1 repair (replacing components without the need for disassembly) and level 2 repair (replacing internal components, thus requiring disassembly).

    - by using the heating tool to dissolve adhesives, followed by application of vacuum suction to separate back and front parts of a smartphone.
    - by clamping the device in a vertical position to allow for horizontally placed screws to be unscrewed.
- Internal screws are unfastened using the unscrewing tool, as long as screws are accessible in a vertical (top-down) movement of the tool. Horizontally placed screws may be difficult to unfasten in this step.
- To separate the battery, adhesive is dissolved if present, using the heating tool where applicable. Suction is used to separate the battery from the phone body.
- The display unit is separated in its entirety without further separating front glass and LCD units.
- The mainboard and smaller subassemblies (e.g. camera module, home button assembly) are loosened by unfastening screws (connectors may currently not be disconnected by machines).
- The following step is carried out by a human worker: Manual extraction on the mainboard and correct placement in the following machine (e.g. remanufacturing module; not existent yet at this point)
- Electronic components on the mainboard (incl. flash memory and SoC BGAs) may be desoldered in a subsequent step or by a future desoldering module.

3.2 Design analysis

This section provides illustrative evidence for commonly used joining techniques and how they are implemented to join key target components together in smartphones. A more detailed disassembly analysis has been described in sustainablySMART deliverable 7.1 (Schischke et al. 2017).

3.2.1 Classification of joining techniques

The disassemblability of any product is predominantly determined by the choice of joining techniques applied to join its components together. Additional factors influencing the disassemblability are the choice of materials, the geometry (accessibility of joints) and dimensions of components and the product. The norm DIN 8593-0 (DIN 2003) suggests a general classification of joining techniques into solvable and unsolvable joints as described in Table 2.

Table 2: Classification of joining techniques according to DIN 8593-0 (DIN 2003)

Classification	Definition	Examples
Solvable joint	A solvable joint can be solved (unfastened) without causing damage to the joined components[1]	Form-fit and force-fit joints, such as screws, snap-fits (clips), springs or clamps
Unsolvable joint	An unsolvable joint can only be solved (unfastened) accepting damage to or destruction of the joined components[2]	Bonded joints using welding, soldering*, gluing**

* except solder joints (e.g. on PCBs) where damage to components during desoldering is negligible

** except “special cases” where glued joints can be solved without damage to joined components

[1] Original phrasing in German: „*Eine lösbare Verbindung ist eine durch Fügen hergestellte Verbindung, die ohne Beschädigung der gefügten Teile wieder gelöst werden kann.*“ (DIN 2003)

[2] Original phrasing in German: „*Eine unlösbare Verbindung ist eine durch Fügen hergestellte Verbindung, die nur unter Inkaufnahme einer Beschädigung oder Zerstörung der gefügten Teile wieder gelöst werden kann.*“ (DIN 2003)

The norm can be understood as an effort to categorize joining techniques into the categories "solvable" and unsolvable joints, to provide product designers with a simple reference document when choosing joining techniques for a new product. While this effort is appreciated by the authors, it should be noted that in practice, the classification into solvable and unsolvable depends on many other factors, including the tools and information available to a person performing a disassembly operation, in addition to their skill level and the condition of the subject to be disassembled. For instance, glue may change their properties over time and become brittle, which may drastically affect how well it can be solved e.g. via thermal energy. Another example are snap-fits, which, depending on the material used, may be easy to unfasten or may break in the processes. In conclusion, the norm may serve as a rough orientation, but is not considered to be applicable to appropriately assess the design for disassembly of devices. On a further note, the norm does not specify what constitutes a "special case" in which glued joints can be solved without damage to joined components.

Section 3.2.2 of this report illustrates several examples of joining techniques commonly found in recent examples of the product group smartphones to systematize and classify the different approaches chosen by manufacturers.

3.2.2 Analysis of key disassembly steps

A range of smartphone products from approximately 2012 to 2016 models have been disassembled at Fraunhofer IZM for the project sustainablySMART to get insights in the various design approaches, as has been described in Deliverable 7.1 "Disassembly Studies" (Schischke et al. 2017). Additional data from previous studies is referenced where more recent design features have been observed. Further, market data on the best-selling smartphone models in Europe have been evaluated to draw conclusions on trends in smartphone design over the years 2010 to 2016.

In general, the following joining techniques are commonly used to join the target components in smartphones (in no particular order):

- Screws are usually used to hold internal components in place, including the mainboard, and are sometimes used to secure the phone casing
- Snap-fits are often used to close the phone casing when the back cover is made from plastics
- Adhesives are often used to close the phone casing and to hold the battery and vibration motor in place
- Soldering is always used to join electronic components to the PCBs and is sometimes used to attach electromagnetic shields (EMS) to the PCB
- Various other form-fit joining techniques are used, e.g. for (cable) connectors

With reference to disassembly scenarios described in section 3.1, design aspects and joining techniques along the following disassembly steps will be assessed:

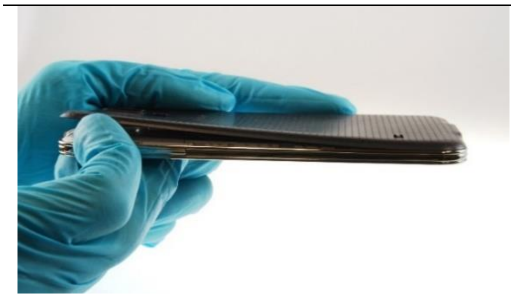
- Opening of the phone
- Separation of the battery
- Separation of the mainboard
- Separation of the display unit
- Accessibility of electronic components on the mainboard

This list does not imply a hierarchy in terms of the priority of components, but rather refers to a commonly encountered disassembly sequence.

Opening the phone

Opening the phone is the first and most essential step, as in-depth disassembly is only feasible once the phone casing is opened. Two basic variations in smartphone design have been observed in previous studies (Figure 2). For some phones, the back cover is separated to access the interior of the phone (type A). For other phones, the display unit is separated first (type B).

Figure 2: Opening the phone requires separating the back cover first for type A phones (examples on the left) while the display unit is separated first for type B phones (example right); images from (Clemm & Lang 2018)

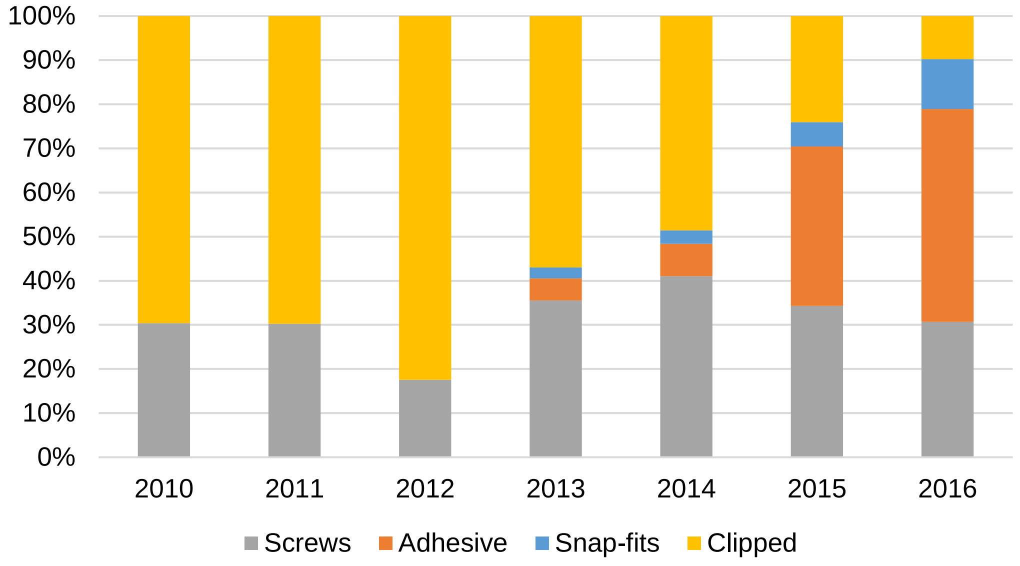
Smartphone type A	Smartphone type B
 Type A example 1: Separating the plastic back cover by unfastening clips without the use of tools	 Type B step 1: Separating the display unit by unfastening vertical screws
 Type A example 2: Separating the plastic back cover by unfastening snap-fits that require the use of a prying tool	 Type B step 2: Opening the phone casing after unfastening the screws

 Type A example 3: Separating back cover by dissolving adhesive via thermal energy and carefully prying open the phone	 Type B step 3: Separating display unit by dissolving adhesive via thermal energy[1]

Common joining techniques encountered in this disassembly step are adhesives, screws, tool-driven snap-fits (require tools to unfasten), and snap-fits that do not require tools to be unfastened (hereafter: clips). The trend towards the increased use of adhesives is illustrated in Figure 3. Between the years 2012 and 2016, the share of devices put on the market (among the best-selling smartphone models in Europe) using adhesive to close the casing has increased from 0 % to almost 50 %. Simultaneously, the prevalence of clipped back covers dropped from 70 % in 2010 to 10 % in 2016.

[1] Image: iFixit: Google Pixel Xl Teardown (2016) https://de.ifixit.com/Teardown/Google+Pixel+XL+Teardown/71237

Figure 3: Development in the prevalence of different joining techniques to close the casing of smartphones based on the best-selling smartphone models in Europe between 2010 and 2016. Models with lower sales numbers are not included. The market share of the smartphone models included in the data is between 41 and 72 % per year.



Source: Adapted from Clemm & Lang 2018, based on market data from Counterpoint Research (unpublished)

Separating the battery

In most phones, removing the back cover either grants (visual) access to the battery, or a mid-frame that needs to be removed in order to access the battery. In rare cases, copper shielding and/or tape obstruct access to the battery (not to be further exanimated in this report). At the core, the steps to remove the battery are as follows:

- Expose the battery
- Unplug connectors
- Remove the battery

Figure 4 provides typical examples of devices, illustrating the steps to be taken to remove the battery after removing the back cover.

Figure 4: Typical internal designs found in smartphones after removing the back cover.

Source: Clemm & Lang 2018

In the above example, 10 screws are unfastened to remove plastic elements covering the mainboard and daughterboard (left), after which the flex cable connecting the daughterboard to the mainboard and the battery connector is separated (middle). Finally, the battery is removed using thermal energy to dissolve the adhesive and prying the battery with a prying tool (right).

Source: Clemm & Lang 2018

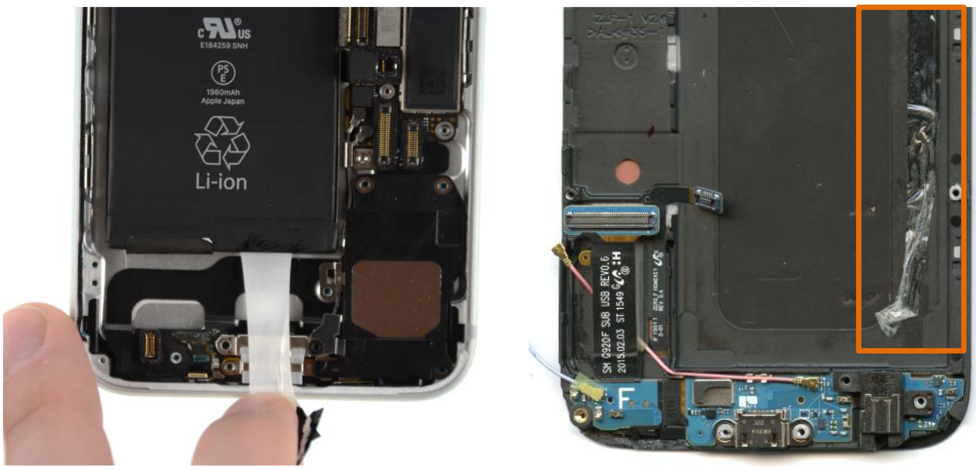
In the above example, 13 screws are unfastened (left) to remove metal midframe elements covering the mainboard, daughterboard and battery (middle), after which the battery can be removed using thermal energy to dissolve the adhesive and prying the battery with a prying tool (right). Extra care needs to be taken as the battery is basically glued to the back of the display unit.

Batteries are commonly fastened inside phones using adhesives, with the following variations:

- Liquid glue is applied to the entire area underneath the battery.
- Pull strips are used (commonly 2 pieces).
- Double-sided adhesive tape is used (commonly 2 pieces).

Examples for the most common choices, pull strips and double-sided adhesive tape, are illustrated in Figure 5.

Figure 5: Common choices to fasten the battery inside the device are pull strips (left) and double-sided adhesive tape (right)



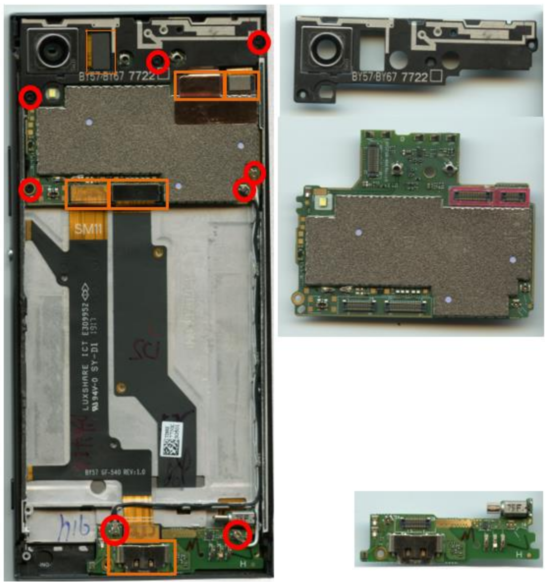
Pull strips lose their adhesive force when mechanically elongated by pulling (left), while regular double-sided adhesive tape requires the application of thermal energy (right).

Separating the mainboard

After removing the battery, the mainboard can commonly be removed after unfastening connectors (e.g. antennas), additional screws and sometimes additional structural elements (i.e. frame elements). Two illustrative examples are provided in Figure 6.

Figure 6: Illustrative examples of steps to be taken to separate the mainboard after removing the battery.

In this example, no additional screws need to be unfastened before the mainboard and daughterboard can be separated from the housing. They are separated by unfastening one connector and one antenna.

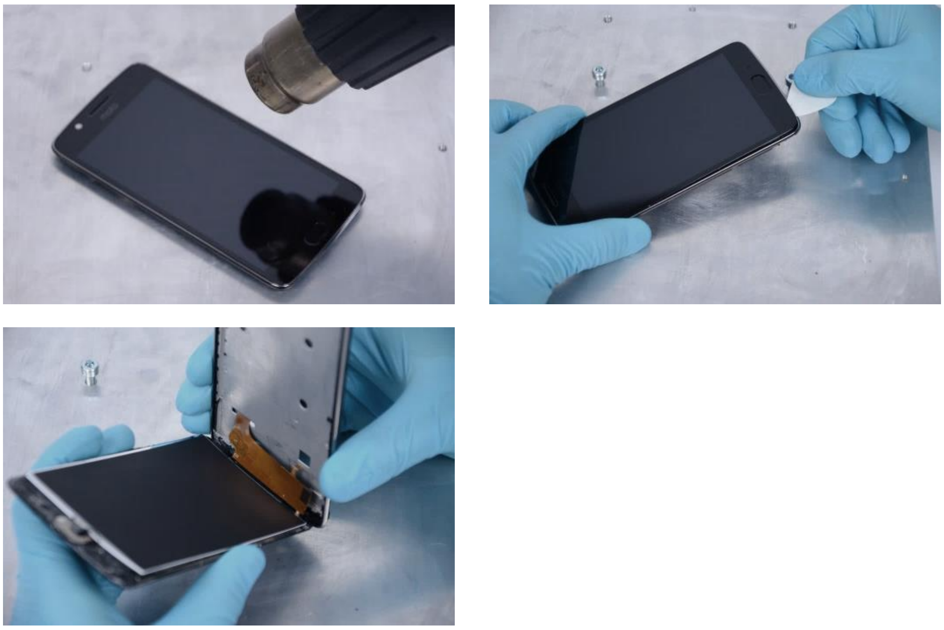


In this example, 8 additional screws need to be unfastened before a frame element, the mainboard and the daughterboard can be separated from the midframe.

Separating the display unit

In many phones, the display unit (front glass and display panel) is commonly glued to metal frame elements (e.g. device mid-frame) for stability. Accordingly, thermal energy and prying tools are required to separate the display unit as is illustrated in Figure 7.

Figure 7: Separating the display unit using thermal energy (left) and prying (right), while avoiding damage to the flex cable(s) connecting the display to the mainboard (bottom)

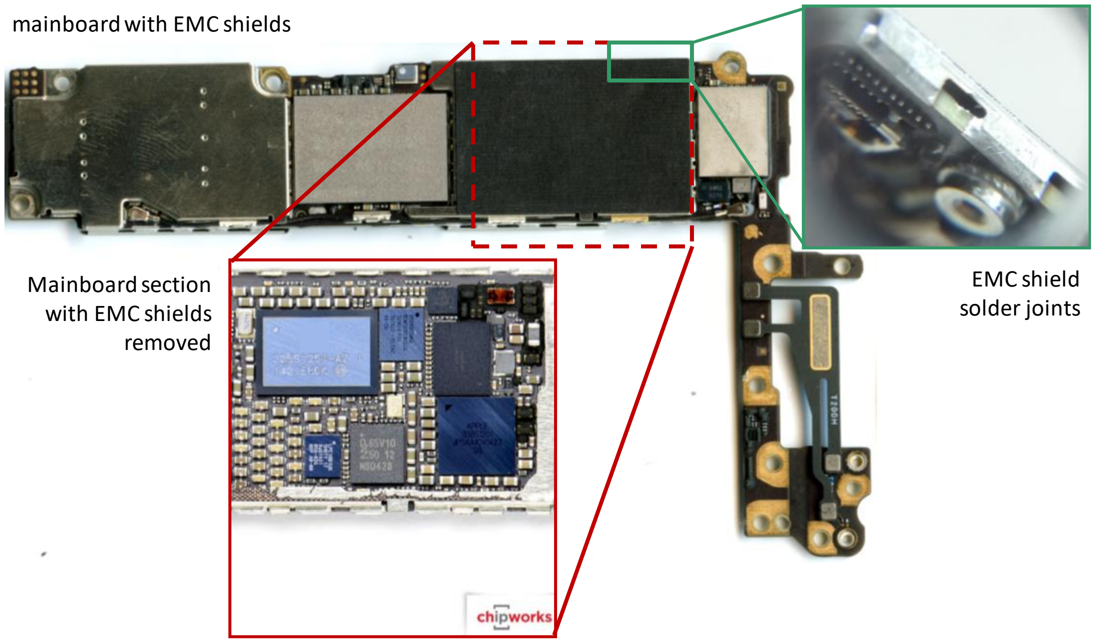


In this example, a heat gun is used to apply sufficient thermal energy to the adhesive joining the display unit and metal frame to soften the adhesive (upper left). A tool can be inserted between both components (upper right) to separate them. Care needs to be taken not to sever connecting flex cables (bottom).

Accessing electronic components on the mainboard

Key target components on the mainboard (i.e. flash memory, SoC) are commonly protected by metal shields from external influences, particularly from electromagnetic fields. Figure 8 illustrates an example of a smartphone mainboard with and without electromagnetic compatibility (EMC) shields in place, and a detailed view on the solder joint used to fasten the shield on the mainboard. In some cases, the EMC shields are not soldered to the mainboard but rather clipped to it with form-fit joints.

Figure 8: Illustrative example of a smartphone mainboard with, and a section without, EMC shields in place, and a detailed view of an EMC shield solder joint (Schischke et al. 2017)



Source: Schischke et al. 2017

Accessing additional target components

In accordance with the scope of this document, additional components of interest for separation in a disassembly process are the camera, speakers, and main microphone. These components can typically be separated from the device as part of the separation of the mainboard. Consequently, no detailed assessment of steps and joining techniques is required.

4 Evaluation of design aspects in disassembly scenarios

4.1 Design evaluation matrix

Relevant design aspects discussed in section 3.2 are assessed against conditions and requirements of the disassembly scenarios described in section 3.1 in a semi-quantitative design evaluation matrix (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

Design aspects and joining techniques are evaluated against the following value range:

- ++ = clearly favourable design choice
- + = favourable design choice
- o = neither favourable design choice nor a barrier
- - = design choice is a potential barrier
- -- = design choice is a considerable barrier

#	Disassembly step	Operation / joint	Disassembly scenarios		Comment
			Manual	Semi-automated	
1	Opening phone type A: Separate back cover	Unfasten clips	++	+	Can be removed by prying or with a pulling force (e.g. clamping tool and robotic arm with vacuum suction tool).
2		Unfasten snap-fits	+	--	Relatively easy to separate manually with a prying tool (with a minor risk to break some of the snap-fits), but no automated process exists – prying is potentially risky with regards to the internal battery.
3		Dissolve adhesive	--	+	Difficult to separate in a manual process, but relatively easy with specialized equipment (device for controlled heating to soften the adhesive, e.g. heating tool).
4		Open phone	o	o	Cables connecting the back cover to the mainboard can easily be damaged if too short (applies only if hardware such as NFC and/or wireless charging are in place). This is potentially difficult in manual and automated processes. Machines may be programmed for a more controlled process (no unintended sudden movements), however, a shattered display may prevent suction tools to work as expected. Ultimately, the connector is separated in the process of pulling the casing parts apart, or the cable is torn.
5	Opening phone type B: Separate display unit	Unfasten screws	++	++	Easy to do manually if required tools are available. In the automated process the device can be clamped down vertically to open the screws.
6		Dissolve adhesive	--	+	Refer to #3.

7		Open phone	--	o	Cables connecting the display unit to the mainboard can easily be damaged when opening the phone. This is potentially difficult in manual and automated processes (refer to #4). Separating a glued display unit in a manual process commonly requires prying and may easily lead to damage, as the components and their materials (glass) are generally thin and fragile.
8	Separating the battery	Expose the battery	++	+/o	Requires unfastening screws and removing structural/frame elements, which are comparatively easy to handle in both scenarios. However, cables and connectors may be damaged in the automated scenario, depending on the device design.
9		Unplug connectors	o	--	Unplugging connectors is a delicate process that requires sensitivity yet sufficient force. Connectors are usually small and are easier pried than pulled. Sometimes multi-stage activities are required (e.g. ZIF connectors). This is currently considerably easier to handle in a manual process. Automated solutions are not yet in place.
10		Remove the battery: pull strips	+	--	This is relatively easy to do for a human, but the pull strip may be damaged if pulled at the wrong angle, which will make it very difficult to separate the battery. Handling the pull strip is assumed to not be possible by the automated equipment, unless heating the adhesive with the heating tools is sufficient to solve the bond.
11		Remove the battery: double-sided tape or liquid adhesive	--	+	Refer to #3. The additional challenge is not to overheat the battery which may lead to thermal runaway of the battery, which is difficult to control in a manual process.
12	Separating the mainboard	Expose mainboard	++	+	Refer to #8.

13		Unplug connectors	o	--	Refer to #9.
14		Remove the mainboard	++	Handled manually	Removing the mainboard usually does not require unfastening additional joints. This step is carried out manually in both scenarios.
15	Separating the display unit	Dissolve adhesive	--	+	Refer to #3.
16		Separate LCD module	--	--	This step is potentially very prone to damage in a manual process, as the thin cover class breaks easily. It is currently not possible to automate this step. The front (display) may be smooth and thus compatible with e.g. vacuum suction devices, however, the back side of display panels varies widely between devices.
17		Unplug connectors	o	--	Refer to #9.
18	Accessibility of electronic components on the mainboard	Separate clipped EMC shield	++	o	Easy to do manually, may be more complicated for machines in a future process without damaging the board
19		Separate soldered EMC shield (alternative design to #18)	-	--	Difficult to do manually, may have to be removed using damaging techniques (e.g. grinding). Such delicate work is currently easier for a trained human worker.
		Desoldering target components	o	n/a	Soldering of specific BGA components on smartphone boards requires dedicated hardware solutions (i.e. rework stations). An automated rework tool has not been developed/integrated into the PA solution at this point.

5 Design for Disassembly Guidelines

The observable pattern from the Design Evaluation Matrix is that generally, a considerable number of the design choices that are preferable in a manual disassembly scenario have been assessed to be unfavourable in a semi-automated scenario and vice versa. Hence, a differentiation is needed between manual and (semi-)automated disassembly processes when design for disassembly guidelines for smartphones are proposed. The following subsections start with generic recommendations before proposing smartphone-specific aspects.

5.1 Generic guidelines for Design for Disassembly

Talens Peiró et al. (2017) provided a list of design strategies that favour the repair and reuse of products (case study: tablet-PCs and subnotebooks), based on previous studies. This generic list can in principle be applied to any product group, including for the design for disassembly guidelines in scope of this document.

- Use modular construction
- Minimize the number of disassembly operations
- Minimize the number of connections (i.e., to limit dependencies)
- Use tools as simple and generic as possible. Tools complexity may influence the time for tool change, thus costs, and also limit the chance for automated disassembly.
- Connectors shall be resistant to damage and reusable. The following are suggested:
    - Discrete components not deformed: bundler, spring, screw, bolt, nut, and lock washer
    - Parts of components with reversible connections: snap-fit

5.2 Joining techniques for manual disassembly

The following recommendations are based on insights of staff at Fraunhofer IZM, gathered through various project work, in addition to feedback from experts from iFixit.

- **Soldering:** Requires high temperatures to dissolve and should be avoided (except electronics components on PCB), replace by connectors where possible
- **Gluing:** Frequently requires thermal energy, solvents and/or force to loosen and should generally be avoided; adhesives may change their properties over time and become less susceptible to foreseen dissolving mechanisms (e.g. less receptive to thermal energy). Adhesive requiring thermal energy above 80°C is to be avoided entirely due to safety reasons (i.e. battery thermal runaway).
- **Snap-fits/Clips:** Range from easily loosened to requiring tools and force; prefer easily loosened clips, e.g. for back cover
- **Screws:** Low number and low variety of screws reduce the number of required tools and thus the disassembly time; should be in an easily accessible place (avoid overlapping and horizontal screws) and easily visible (e.g. colour code); should not be made from soft material to prevent damage to the head; avoid self-tapping screws, use screw head designed for disassembly (e.g. Philipps), use magnetic screws
- **Form-/Force-fitting locking mechanisms:** Generally reversible; preferable

5.3 Joining techniques for (semi-)automated disassembly

The following recommendations are based on insights of staff at Fraunhofer IZM, gathered through work mostly in the sustainablySMART project, in addition to feedback from experts from ProAutomation.

- **Soldering:** Requires high temperatures to dissolve and should be avoided (except electronics components on PCB), replace by connectors where possible
- **Gluing:** Frequently requires thermal energy, solvents and/or force to loosen and should generally be avoided, unless the industry can agree on one standardized adhesive which will reliably be used for an entire product group, as to simplify the process for machines. Change of properties over time needs to be accounted for. Adhesive requiring thermal energy above 80°C is to be avoided entirely due to safety reasons (i.e. battery thermal runaway).
- **Snap-fits/Clips:** Range from easily loosened to requiring tools and force; prefer easily loosened clips for e.g. back cover, which can be separated by pulling parts apart, without incurring damage to components.
- **Screws:** Low number and low variety of screws reduce the number of required tools and thus the disassembly time; should be in an easily accessible place (avoid overlapping and horizontal screws) and easily visible (e.g. colour code); should not be made from soft material to prevent damage to the head
- **Form-/Force-fitting locking mechanisms:** Generally reversible; however, may be difficult for a machine to optically recognize and dissolve

5.4 Smartphone-specific design for disassembly

The general recommendations on joining techniques also apply to smartphones. However, this section also addresses specific design aspects identified in smartphones.

General recommendations:

- Avoid irreversible joining techniques where alternatives exist that do not hamper functionality or reliability
- Use standardized and non-proprietary joining techniques, e.g. only use Phillips type screws of one type; if adhesive is required only used one type of a common adhesive throughout the device which requires low thermal energy input to be dissolved (e.g. markedly below 80 degrees Celsius)

Specific recommendations:

- Avoid the use of tape covering components
- Avoid the use of electronics in the back cover and thus cables/connectors to allow for easier separation of the back cover without the risk of negatively affecting the capacity of functional components
- Minimize the need to rotate the phone on its sides, e.g. place all screws so they can be accessed vertically (top-down) rather than horizontally
- Avoid fusing the LCD and mid-frame

Inconclusive aspects:

- In a disassembly scenario, it cannot clearly be stated whether a phone type A (disassembly via the back cover) or phone type B (disassembly via the display unit) is more favourable. Easy access to the display unit favours phones of type A, considering the display is one of several priority components. However, assuming that the display is the most commonly damaged components in smartphones suggests that it may rarely be one of the components actually recovered for reuse in an EOL disassembly scenario.
- Adhesives to join the phone casing together is one method applied by manufacturers to warrant ingress protection. While ingress protection may increase the durability of

smartphones, the use of adhesives is a considerable barrier for repair. In a disassembly scenario, adhesives are generally unfavourable, as ingress protection is no longer required. However, potential trade-offs with durability need to be accounted for.

5.5 Transferability to other product groups

The guidelines on joining techniques in manual disassembly processes (section 5.2) are considered to be generally valid for any product group. The validity of the guidelines on joining techniques in (semi-)automated disassembly processes (section 5.3) is considered to depend on the equipment available and which types of devices can be processed. According to Pro-Automation, the developed semi-automated disassembly solution is in principle transferable to other electronic devices, such as tablets or laptops. Furthermore, it may be transferable to entirely different product categories, such as vehicles or batteries of electric vehicles. However, it is preferable to primarily apply automated processes to devices which are less diverse and can be expected in large numbers, as is the case for smartphones – relatively few manufacturers produce a relatively small variety of models which are sold globally in substantial numbers. The market for laptops, on the other hand, may be generally more diverse and less dominated by a small group of particularly popular models. In addition, automated disassembly processes are generally more interesting for high-value products and components in terms of the economic return on investment. As such, electric mobility as well as IoT devices may be feasible target product groups.

6 Outlook

Standardized debond-on-demand solutions are a promising approach and a potential future solution for common issues with joining techniques encountered today. For example, a standardized adhesive may be used to join various components in smartphones, which may be dissolved via a specific external trigger (e.g. a pre-defined temperature or radiation). If standardization of joining techniques within each product, between product models and across an entire product group (e.g. smartphones or beyond) was to be implemented, disassembly may become a considerably less complex process, with potentially substantial benefits for resource conservation and the Circular Economy. However, until such solutions are in place and are adopted by manufacturers, design for disassembly remains a complicated set of issues. Guidelines such as this one may be consulted by product designers and/or policy makers in an effort to enable the recovery of parts to be reused, as one step towards a Circular Economy.

7 References

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