sustainablySMART

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

Project Duration: **01/09/2015 - 31/10/2019**

Deliverable No.:	**7.1**
Deliverable Title:	**Disassembly Studies**
Version Number:	v1
Due Date for Deliverable:	**28/02/2017**
Actual Submission date:	**28/02/2017**
Lead Beneficiary:	**Fraunhofer IZM**
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Deliverable Type:	R
Dissemination Level:	PU

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Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 680604

Summary

Repairability and remanufacturability of smartphones as well as component reuse and overall product lifetime is largely determined by design. This report looks at the hardware aspects of smartphone designs found in the market. Indirect figures about smartphone repair give a clear indication, that approximately 1/3 of all repairs is related to the display, 1/6 to battery replacement and the remaining 50% to miscellaneous other parts and components. With this in mind disassembly processes to access key components can be evaluated. Fraunhofer IZM disassembled a range of smartphone models to analyse design features on the product and on the component level. On the product level two main design approaches (rigid metal backcover and rigid metal midframe) can be observed. Magnesium is a frequently used metal in smartphones, but also aluminum as either backcover or midframe. Regarding the disassembly sequence several smartphone models can be grouped together under the same "archetype". In particular Samsung Galaxy models from Ace to S4 feature a pretty similar design and thus allow for a joint disassembly process with only minor model adaptations for individual process steps.

Reuse and remanufacture of components faces significant technical challenges as product design options hardly ever unambiguously favor all aspects of a circular economy: LCD modules are usually either fixed with full-area adhesives on the cover glass, making replacement of a broken cover glass very difficult, or the cover glass is attached to a frame only, but then frequently the LCD module is fixed with adhesive in this metal frame. Both options are critical for an easy separation of cover glass, LCD module and a potential LCD frame. Batteries used to be removable by the end-user in many models introduced to the market 3 to 5 years ago, but are now typically integrated in the smartphone, fixed with adhesives on the backcover or midframe. Integrating the battery facilitates a design, which is of a higher IP class (dust and water protection) and thus on the one hand reduces the risk of accidental product damages, but on the other hand is a barrier for replacing a battery with low remaining charge capacity. Thickness of the battery as seen in a comparison of the Galaxy S3 (removable) and Galaxy S7 (integrated) might remain the same with integrated ones. Actually the battery volume might even increase. Battery capacity also increased significantly. The power requirements of latest smartphones and standby times being a critical sales argument apparently lead to the design trend, that battery capacity (and thus volumetric size) is maximized, and volume is saved elsewhere, e.g. the mainboards in smartphones get smaller thanks to advanced integration and chip packaging technologies. Reliability concerns lead to an increasing use of epoxy underfiller for some major semiconductor packages, which actually hinders board-level repair and component reuse.

Content

1 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 intention to facilitate reuse and remanufacture of parts and components for same or different applications. The automated disassembly and rework of components, rather focusing on those devices which represent large market shares, is another field of research and development in the project. Repairability, reusability, remanufacturability are ultimate goals of these developments. Disassembly studies are supposed to provide guidance on relevant technology trends, design differences among various models and manufacturers and to outline suitable approaches for component harvesting.

2 Introduction

Back in 2014 Fraunhofer IZM investigated design and disassembly features of most recent tablets at that time (Schischke et al., 2014). Findings of that study and the obvious design conflicts between minimal form factors, maximum performance integration, robustness, repairability and recyclability inspired the project sustainablySMART. A short-coming of the 2014 study has been limited insights in actual repair requirements of devices. Only knowledge about typical failures can help to guide design decisions. Analytical evidence of design features can guide the development of appropriate disassembly strategies.

2.1 Repair Requirements: Smartphones

Both, repairability of a smartphone and spare parts to be harvested from smartphones through automated processes has to be judged on the basis of actual needs for repair. As there is no solid statistics available, which parts of smartphones require repair or replacement an indication can at least be gained from the view statistics of online repair guides. The most comprehensive repository of repair guides for smartphones is provided by iFixit at www.ifixit.com [1]. For each repair guide view statistics are published on the respective website. Taking the number of views per repair guide as an indication of the number of required repairs has some shortcomings, namely

- not for all models the same set of repair guides is published, so not for all models the same level of detail can be achieved
- not all repair guides for a given model have been published at the same time (thus, the view counter did not start counting at the same time)
- some repairs (particular exchange of batteries at some of the older smartphone models) are done easily and do not consultation of a repair guide to get the replacement done (thus, the view statistics underestimate the number of actual replacements taking place)
- a repair guide might be consulted more than once in the course of a single repair, but also professional repair staff might not need always consult a repair guide for a job he is already used to

[1] Repair guide views have been retrieved from iFixit.com end of November 2016

- a repair guide will be consulted only, once the failure (e.g. hardware vs. software) has been identified, which might not always be possible

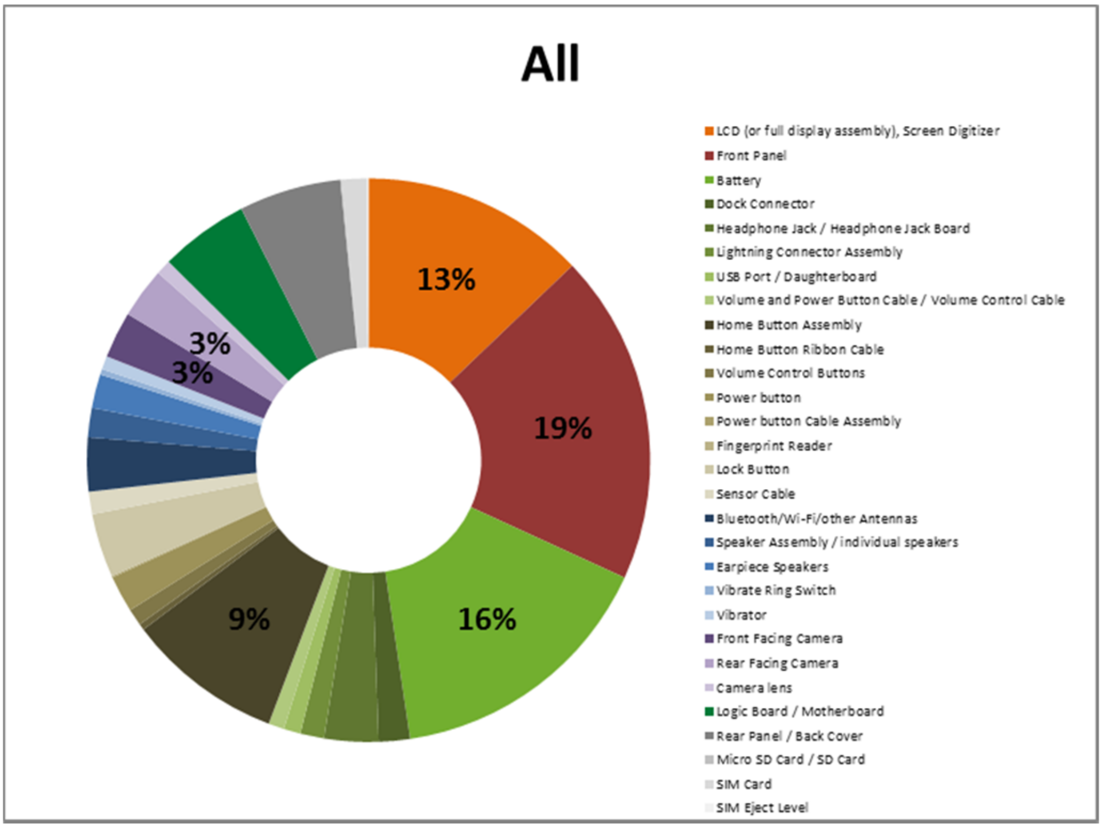
- requirements for repairs change over time, e.g. broken displays will be an issue from day 1, but battery replacements will kick in much later, thus the correlation of repairs changes over time

but is nevertheless considered a valid proxy for the share of dedicated repair requirements. More than 30 million views of repair guides for best-selling (but not too recent, see last bullet point item above) smartphones have been taken into account. Following products have been covered:

- Huawei Ascend P7
- Huawei Ascend P6-U06
- HTC One
- HTC One M8
- Motorola Droid RAZR
- LG G3
- iPhone 4
- iPhone 5
- iPhone 5s
- iPhone 6
- iPhone 6plus
- iPhone 6s
- iPhone 6s plus
- Samsung Galaxy SIII
- Samsung Galaxy SIII mini
- Samsung Galaxy S4
- Samsung Galaxy S4 mini
- Samsung Galaxy Ace 2
- Samsung Galaxy Ace 3
- Samsung Galaxy S5
- Samsung Galaxy S6
- Samsung Galaxy S7

According to the iFixit statistics most frequently the LCD display and/or front panel, i.e. cover glass requires repair (1/3 of all repair guide views), followed by batteries (1/6 of all repair guide views). All other parts cover the remaining 50% of repair guide views.

Figure 1: Repair view shares per repair guide – all considered smartphones



Among those remaining parts the most frequent repair cases are (in the following order, see Table 1):

- home button assembly (a major issue with e.g. the iPhone 4)
- rear panel / back cover
- rear or front facing cameras
- logic board
- lock button (a major issue with e.g. the iPhone 4)
- headphone jack
- antennas

These parts therefore qualify also as potential targets for harvesting spare parts, although product specific deviations from this priority list need to be considered.

Table 1: Repair view shares per repair guide – all considered smartphones

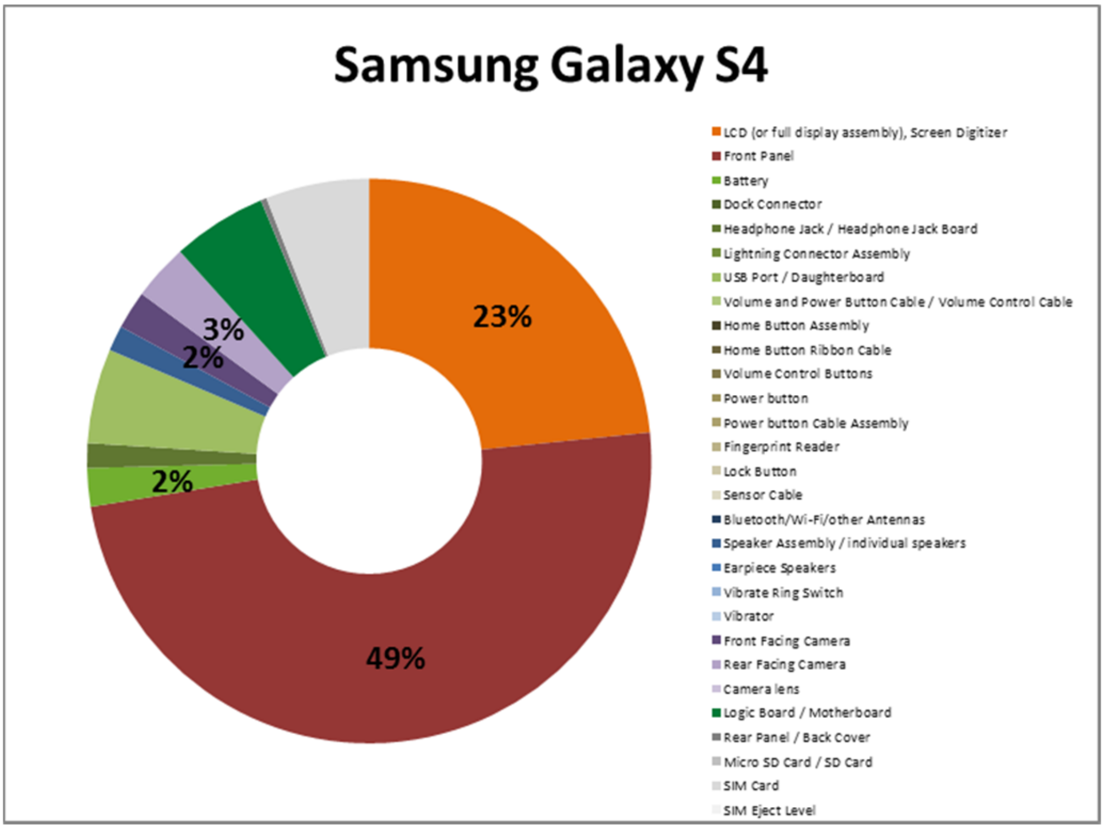
Repair guide	Views
Display and cover glass	
LCD (or full display assembly), Screen Digitizer	12,9%
Front Panel	19,1%
Battery	15,9%
Connectors and related assemblies	
Dock Connector	1,8%
Headphone Jack / Headphone Jack Board	3,1%
Lightning Connector Assembly	0,9%
USB Port / Daughterboard	1,0%
Volume and Power Button Cable / Volume Control Cable	0,9%
Home Button Assembly	9,0%
Home Button Ribbon Cable	0,4%
Volume Control Buttons	1,0%
Power button	2,1%
Power button Cable Assembly	0,1%
Fingerprint Reader	0,0%
Lock Button	3,7%
Discrete internal parts	
Sensor Cable	1,3%
Bluetooth/Wi-Fi/other Antennas	3,1%
Speaker Assembly / individual speakers	1,7%
Earpiece Speakers	2,0%
Vibrate Ring Switch	0,3%
Vibrator	0,8%
Front Facing Camera	2,7%
Rear Facing Camera	2,9%
Camera lens	0,9%
Logic Board / Motherboard	5,1%
Back cover and removable cards	
Rear Panel / Back Cover	5,9%
Micro SD Card / SD Card	0,1%
SIM Card	1,4%
SIM Eject Level	0,1%

Taking the Samsung Galaxy S4, which is one of the target products for automated disassembly, as an example shows a different picture: LCD and front cover glass account for 72% of all repair guide views. Batteries are not relevant (2%) in this statistics as they are placed underneath the back cover and easily removable, so do not need consultation of a repair guide to be replaced. Other relevant parts are

- USB port board
- Cameras

- Logic board

Figure 2: Repair view shares per repair guide – Samsung Galaxy S4



Occasionally very specific components show up in these statistics, such as the camera lens among the Samsung Galaxy S6 devices (20% of all repair guide views for this model). Where repair guides distinguish between cover glass and the LCD module, it is evident, that not surprisingly it is rather the cover glass than the LCD module, which requires replacement.

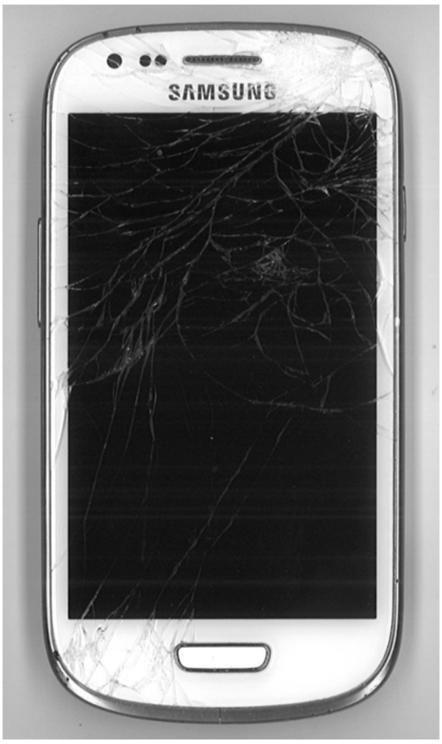
2.2 Screen Damages

Acknowledging that the display is a typical component which frequently fails, i.e. breaks, and limits the product lifetime, it is important to know for an improved long-lasting design and protection of the display glass to understand how smartphone screen glasses break.

A range of products collected by a large network operator and intended for recycling serves as a random sample of devices, which are returned with broken displays. From the visible glass cracks a solid assumption can be made, from which direction the impact occurred. This assumption is not always unambiguous and in several cases the phone obviously broke through two or more distinct incidents.

This investigation covered in total 76 smartphones (61 Samsung Galaxy SIII mini, 13 Samsung SIII, 2 Nokia Lumia). The design of these devices already has an impact on the way the glass breaks. The Samsung Galaxy SIII and SIII mini devices feature rounded corners with a larger radius than other smartphone devices, which might mean they break less likely when being dropped on the corners, but this thesis has not been verified. Figure 3 depicts one of the sample devices.

Figure 3: Exemplary sample device of screen damage investigation – Samsung Galaxy SIII mini

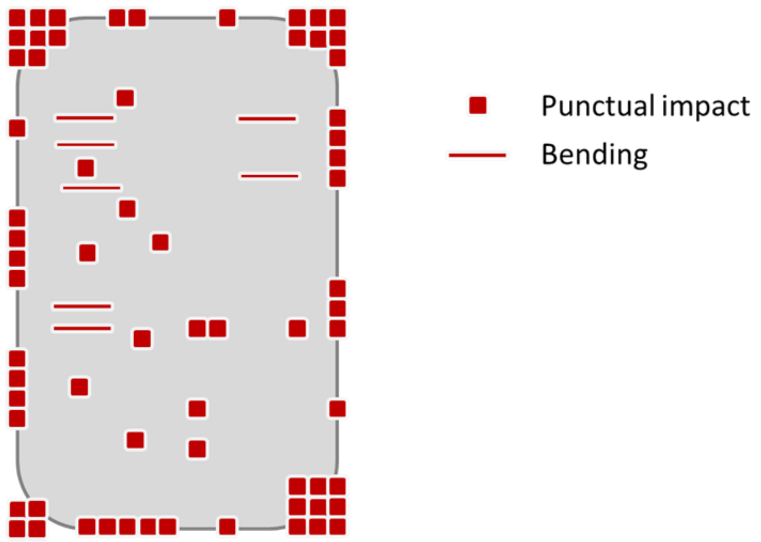


A distinction has been made of punctual impacts and bending impacts:

- Corner impact: the breakage has been initiated from one corner and the phone presumably first dropped on this corner
- Edge impact: the breakage has been initiated from one edge and the phone presumably first dropped on this edge
- Area impact: the breakage has been initiated from a distinct point on the display surface, most likely the phone either dropped upside down on a non-flat object or an object dropped on the screen
- Bending impact: there is no obvious point from where a break has been initiated and the kind of damage gives the impression, that the phone might have been bended leading to the glass breakage.

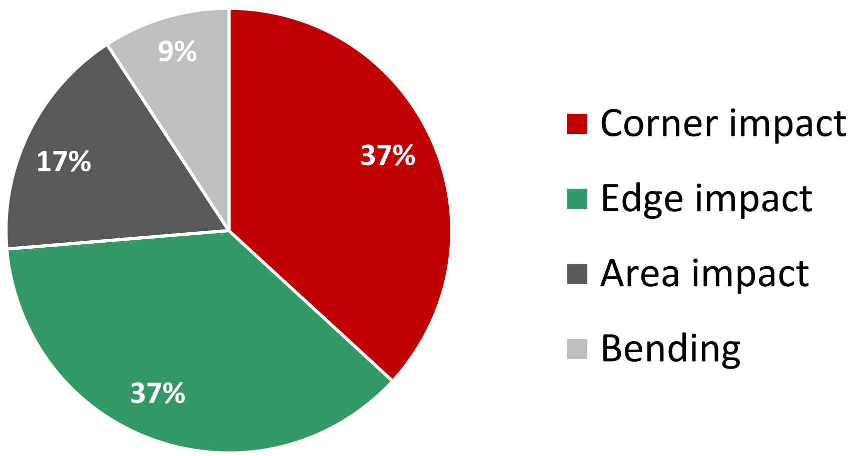
Figure 4 depicts all these identified impacts plotted individually as a red square on a smartphone outline, Red lines indicate major cracks due to bending. As expected, corners are weak spots of smartphone screens. Similarly, many cracks are initiated from edges. Significantly less damage is due to area impact. Bending is less relevant. Percentages are depicted in Figure 5.

Figure 4: Full sample of identified impacts



Almost 3/4 of all screen damages are due to drops on corners or edges.

Figure 5: Percentage of identified screen impacts



As a conclusion of these findings it is important to protect with priority edges and corners against accidental damage. Various design approaches can support the robustness of the display assembly: The design of the frame and protective features of the frame are essential to keep the screen glass in good order. The overall design and stiffness of the smartphone as a whole protects against breakage through bending.

3 Disassembly sequence

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 of smartphones potentially coming back now for refurbishment or recycling, but also most recent models to identify upcoming technology trends, which definitely will influence also future repair, refurbishment and recycling evidence. With this in mind the following models have been investigated:

- Nokia Lumia 830
- Nokia Lumia 930
- Samsung Galaxy Note 2
- Samsung Galaxy Ace 2
- Samsung Galaxy Ace 3
- Samsung Galaxy S3 (and S3 LTE)
- Samsung Galaxy S3 mini
- Samsung Galaxy S4
- Samsung Galaxy S4 mini
- Samsung Galaxy S5
- Samsung Galaxy S6
- Samsung Galaxy S7
- Sony Xperia M4 Aqua
- iPhone 6
- iPhone 7
- Huawei P9
- Fairphone 2

3.1 Disassembly process: Case study Galaxy Ace 3

On the example of the Samsung Galaxy Ace 3 the sequence of disassembly processes is documented (Figure 6). Disassembly targets where removal of the battery, separation of the display unit and extraction of the mainboard. These three target components correspond with the findings of statistically evaluating the repair guideline views on iFixit's website (see above).

Figure 6: Stepwise disassembly process (Galaxy Ace 3)

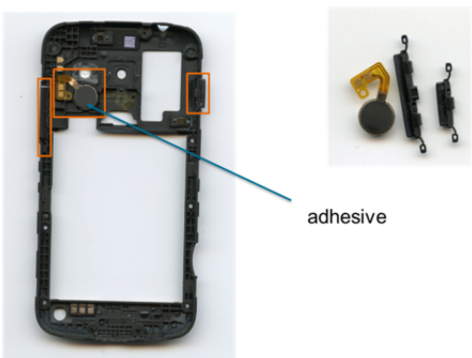
Step 1: Removal of backside cover

The backside cover is clipped on the phone.

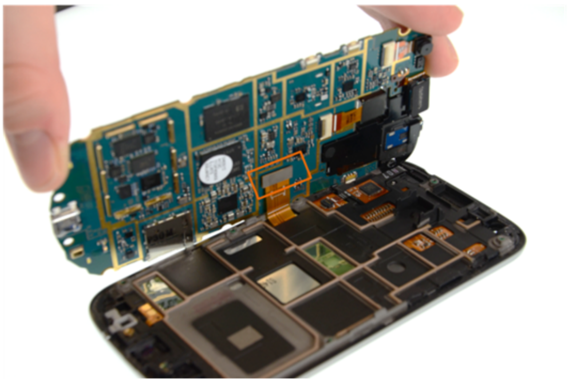
Step 2: Removal of the battery

Step 3: Loosening of 10 Screws #00 to take off the frame

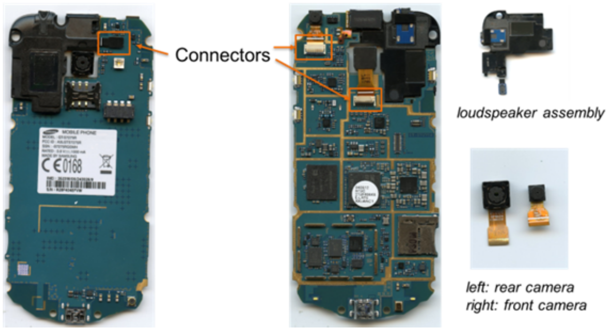
Step 4: Remove Power and Volume Buttons and vibration motor



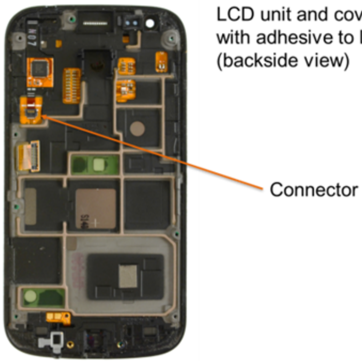
Step 5: Lift up the motherboard and disconnect the ribbon to the display



Step 6: Disconnect the ribbons of the front/rear camera and the loudspeaker



Step 7: Disconnect the ribbon and heat-up the display frame



LCD unit and cover glass are fixed with adhesive to LCD frame (backside view)

Step 8: Remove the cover glass

3.2 Identified disassembly archetypes

The sequence of processes and tools the Samsung Galaxy Ace 3 can be disassembled corresponds to the sequence for several other models. Actually the following models share a similar design:

- Samsung Galaxy Ace
- Samsung Galaxy Ace 2
- Samsung Galaxy Ace 3
- Samsung Galaxy S3
- Samsung Galaxy S3 mini
- Samsung Galaxy S4
- Samsung Galaxy S4 mini
- Fairphone 1

Later Galaxy generations and products from other brands are of a different design archetype and cannot be disassembled with the same process sequence.

4 Material composition

Disassembling a smartphone by whatever means at end of life potentially yields material fractions which could be recycled separately. Table 2 lists the bulk materials used for the backcover for a range of smartphone models under study and the material for the midframe if any. Mainboard weights are stated to indicate the extractable main value bearing sub-assembly of a smartphone.
It has to be noted that the stated materials in almost all cases are still part of complex compound materials, e.g. frequently the LCD module is glued onto the midframe, plastic parts contain structured metal antennas (see later comparative analysis of design aspects).
Polymer types are stated as labelled on the plastic parts. Plastics used in these smartphones for larger frame parts are:

- PC: Polycarbonate, in several cases glass fiber reinforced (labelled -GF20 or –GF30)

and much less frequently:

- PPA: Polyphthalamide
- ABS: Acrylonitrile butadiene styrene
- PBT: Polybutylene terephthalate
- PPS: Polyphenylene sulfide

Table 2: Material aspects of various smartphones

Smartphone model	Backcover	Midframe, not attached to the LCD unit	Midframe as LCD frame or shielding	Mainboard weight (g)
Sony Xperia M4 aqua	PC*	none	PC* / steel*	13,5 g
Nokia Lumia 830	PC	PC	aluminum	14,5 g
Nokia Lumia 930	PC*	ABS / PC	aluminum / PPS	18,7 g
Galaxy Ace 2	PC	PC	magnesium	18,0 g
Galaxy Ace 3	PC	PPA	magnesium	16,1 g
Galaxy Note 2	PC	PC	magnesium	14,0 g
Galaxy S3	PC	PPA	magnesium	13,7 g
Galaxy S3 mini	PC	PPA*	magnesium	16,4 g
Galaxy S4 mini	PC	PC	magnesium / PC	14,6 g
Galaxy S5	PC	PC	aluminium	12,1 g
Galaxy S6	glass	aluminum* / PBT	aluminum	10,7 g
Galaxy S7	glass	none	aluminum	12,5 g
iPhone 6	aluminum	none	steel	10,6 g
iPhone 7	aluminum	none	steel	11,4 g
Huawei P9	aluminum	none	magnesium	12,3 g

* Assumption only, no marking

Magnesium is frequently used in most of the non-iPhone designs. Magnesium enhances overall stiffness of the smartphone and serves in many cases as a kind of base plate to fix numerous subassemblies on. Smartphones with an aluminum housing do not necessarily need an inner magnesium frame. This leads actually to two main design philosophies seen before already among tablets (Schischke et al., 2014):

- Aluminum housing and no inner frame
- Plastics housing and inner magnesium frame

There are some deviations from these “design families”, such as the Huawei P9 with an aluminum backcover and a magnesium LCD frame. Occasionally the stiff LCD frame is not magnesium, but aluminium, for example, in the Nokia Lumia 830, where the midframe also serves as device frame, which directly visible, and thus has to fulfill certain aesthetic requirements, which a greyish, mate magnesium cannot.
Bulk parts backcover, and midframes weigh typically in the range of 5-25 g each.
The mainboard weight as a tendency goes down slightly with progressing product generations, which is mainly due to a higher packaging density, also to save volume for e.g. larger batteries. Stated mainboard weights include electromagnetic shields, but as these (presumably steel) sheets only weigh in the range of 1 g these are of marginal interest for recycling.

Several other material aspects are covered under the following component design chapter, such as cobalt with respect to battery integration design, or tungsten in conjunction with vibration motor design.

5 Component design differences

Disassembly of smartphones unveils that for same functions frequently two or three different basic design and system integration options can be defined. The following sub-chapter analyse and document these designs for those components and sub-assemblies, which are crucial for repairability, reuse and remanufacture.

5.1 Batteries

Batteries are a key element of smartphones and related to several circular economy aspects (see also Clemm et al. 2015):

- Li-ion batteries contain a significant content of Cobalt, which is a valuable resource, but can be recovered at a high rate only, if the battery is separated at end-of-life
- Battery lifetime is limited (limited number of charging cycles), and thus could also determine the product lifetime, if an exchange cannot be done easily
- Similarly a product reuse or remanufacture requires non-destructive, fast process at end-of-(first-)life for replacing the battery

5.1.1 Weight

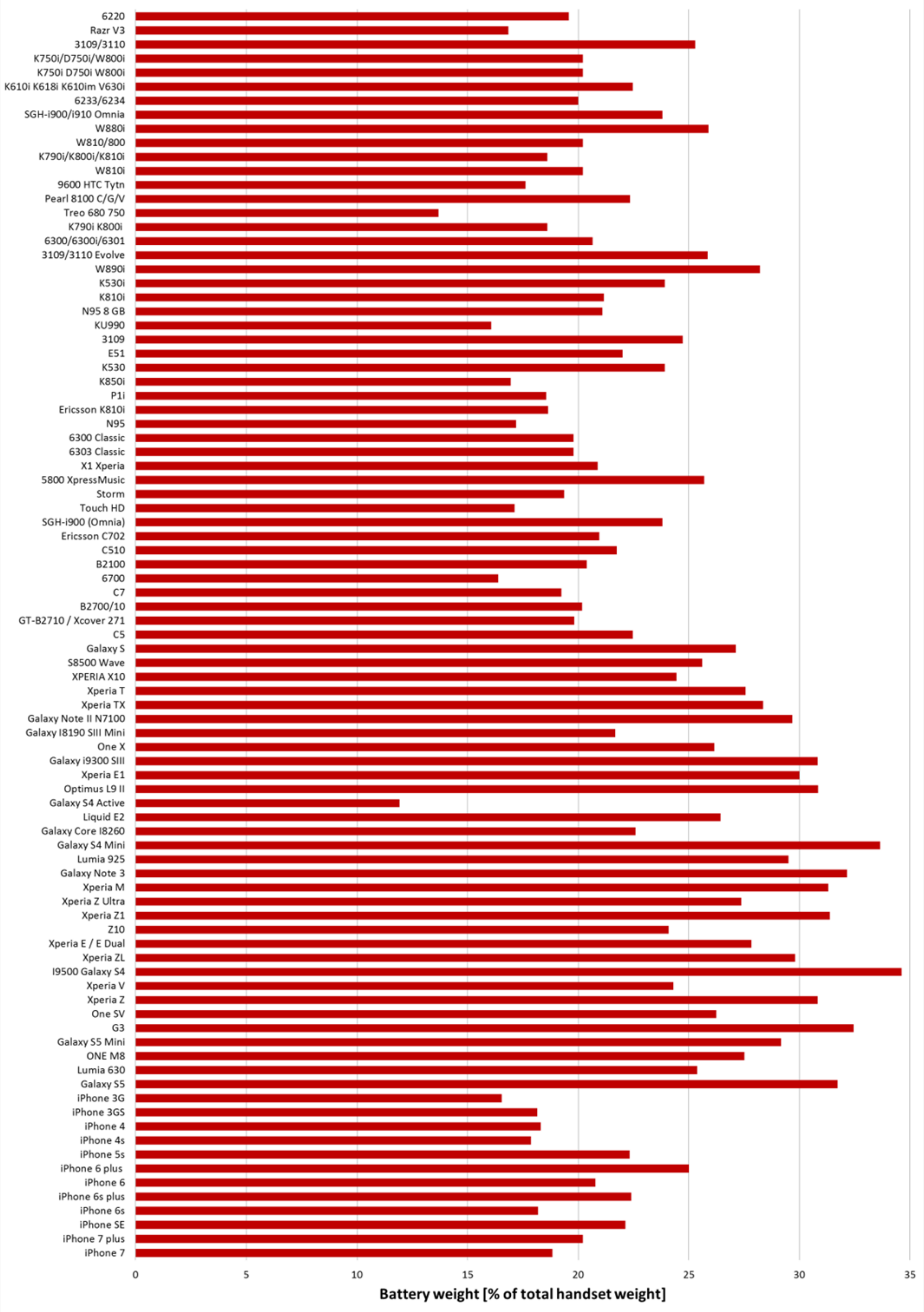
From public sources Fraunhofer IZM researched weights of all major smartphones and some featurephones put on the market in recent years, and the battery weights respectively. In total this statistical database includes 91 models of the following brands:

- Apple
- Samsung Galaxy
- Sony Xperia
- Sony Ericsson
- HTC
- Acer
- LG
- Nokia
- Blackberry
- Palm

The following Figure 7 depicts battery weight shares per model: Among iPhones the battery weight is always close to 20% of the total handset weight. For many other devices the weight of the battery is rather in the range of 20 to 30%. The battery of Samsung smartphones weighs in average 26% of the handset, with some variation: Some models contain a battery up to 35% of the total weight. An example for this rather high weight share of the battery is the very popular Samsung Galaxy S4.
In average the battery weighs 23% of the total smartphone or feature phone.

The weight of an average smartphone or feature phone is 125 g, the battery weight is 29 g. This is also exactly the weight of an iPhone battery across all product generations, but the total weight of an iPhone is 144 g and thus is higher than that of the all-brands-average.

Figure 7: Battery weight share of total handset weight for feature phones and smartphones



5.1.2 Integration

In many feature phones the battery used to be removable without any tools, being accessible by removing the clipped-in back cover. This design approach has been followed also by some early smartphone generations, see Figure 8: In the Samsung Galaxy series, such as the Galaxy S3 mini, but also in the Fairphone 1, the battery was easily replaceable. Usually even the battery had to be removed to change the SIM card.

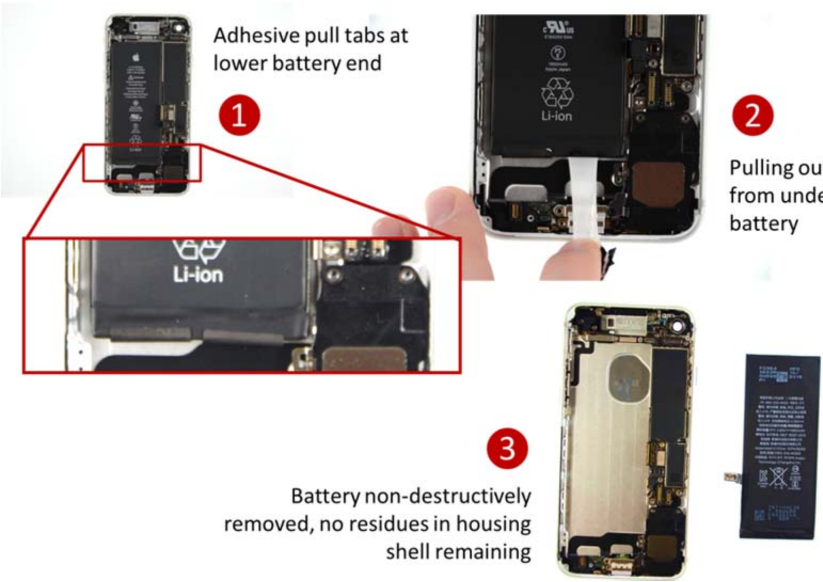
Figure 8: Battery removable without tools (Galaxy S3 mini)

Later on the level of integration increased and batteries where not designed for being exchanged by the user. A typical example is the Galaxy S5, where the battery is fixed to the backside of the display unit with two double-sided adhesive strips. These adhesive strips can only be removed with a prying tool, which still leaves adhesive strip residues on either the battery or display side. Also the foil enclosing the battery might be damaged when removing the battery, see Figure 9.

Figure 9: Battery fixed with adhesive strips (Galaxy S5)

Fixing the battery with adhesive strips with pull tabs allows removing the battery without the risk of damaging the battery and with a simple pull on the strips. Such a design feature has been implemented already in 2013 in the Asus Google Nexus 7 tablet (Schischke et al., 2014), and is found now also in the iPhone 6, the iPhone 7 (see Figure 10) or the Huawei P9.

Figure 10: Battery integration with removable adhesive strips (iPhone 7)



Integrated batteries are not necessarily thinner than those batteries which are removable. Figure 11 compares the batteries of two Samsung Galaxy S models, the S3 from 2012 and the S7 from 2016. In the Galaxy S3 the battery is removable without tools, the battery of the Galaxy S7 is not meant to be replaced by the user, only accessible after opening the whole device and fixed with adhesives. The thickness of both batteries is actually the same, 6 mm. the volume of the Galaxy S7 battery is slightly larger and nominal capacity is almost 50% higher, 3000 mAh vs. 2100 mAh.

Figure 11: Comparison removable battery (Galaxy S3) and adhesive-fixed battery (Galaxy S7)

5.1.3 Energy density

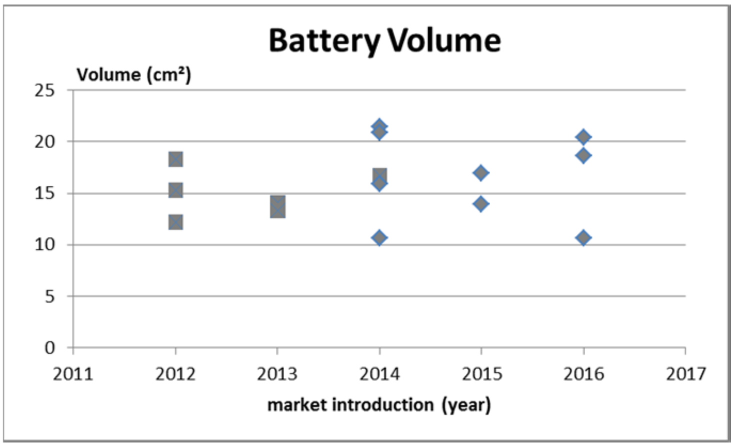
Volume, rated capacity and rated energy of the disassembled smartphone batteries plotted against the year of market introduction show some interesting battery trends (Table 3: Battery characteristics).
It has to be stressed again, that the sample of disassembled smartphones was defined by the need-to-know of the project sustainablySMART and is not meant to be a representative sample of smartphones over time.
Although the table gives the impression, that up to 2014 smartphones had removable batteries and thereafter all batteries are integrated, this actually not the case. Right from the beginning there have been integrated batteries and still today there are smartphones with removable ones. However, the trend towards battery integration actually is apparent in the market.

Table 3: Battery characteristics

Smartphone model	market introduction, year	removable (w/o tools)	Integrated design	volume (cm³)	capacity (mAh)	energy (Wh)	energy density (Wh/cm³)
Galaxy S3 LTE	2012	x		18,3	2100	7,98	0,44
Galaxy S3 mini	2012	x		12,2	1500	5,7	0,47
Galaxy Ace 2	2012	x		15,3	1500	5,7	0,37
Galaxy S4 mini	2013	x		14,1	1900	7,22	0,51
Galaxy Ace 3	2013	x		13,3	1800	6,84	0,51
Fairphone 1	2014	x		16,7	2000	7,4	0,44
iPhone 6	2014		x	10,6	1810	7,01	0,66
Galaxy S5	2014		x	21,4	2800	10,78	0,50
Nokia Lumia 830	2014		x	15,9	1905	7	0,44
Nokia Lumia 930	2014		x	20,9	2420	9,2	0,44
Galaxy S6	2015		x	16,9	2550	9,82	0,58
Sony Xperia M4 aqua	2015		x	13,9	2400	9,1	0,65
iPhone 7	2016		x	10,6	1960	7,55	0,71
Galaxy S7	2016		x	20,4	3000	11,55	0,57
Huawei P9	2016		x	18,6	2900	11,08	0,60

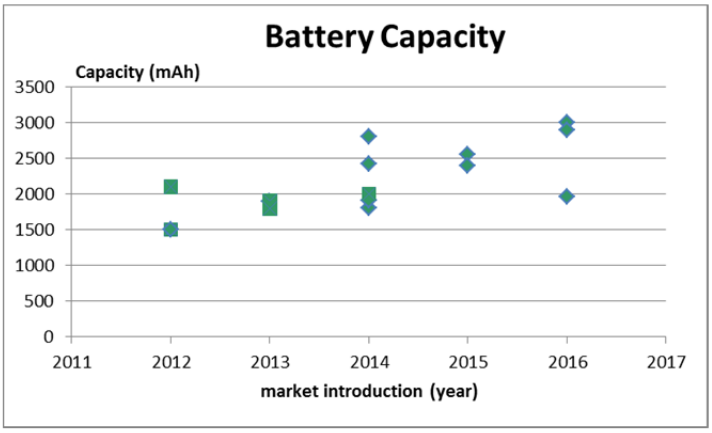
The Galaxy Note 2 is not included in the above list as the device as such is significantly larger than the others and characteristics are therefore not comparable. However, also among the listed models there are size differences, which have an influence on chosen battery design characteristics.
Battery volume largely remained the same over the years. At least the integration of batteries with less housing requirements (use of pouch cells) did not lead to smaller batteries (Figure 12).

Figure 12: Measured battery volume of disassembled smartphones



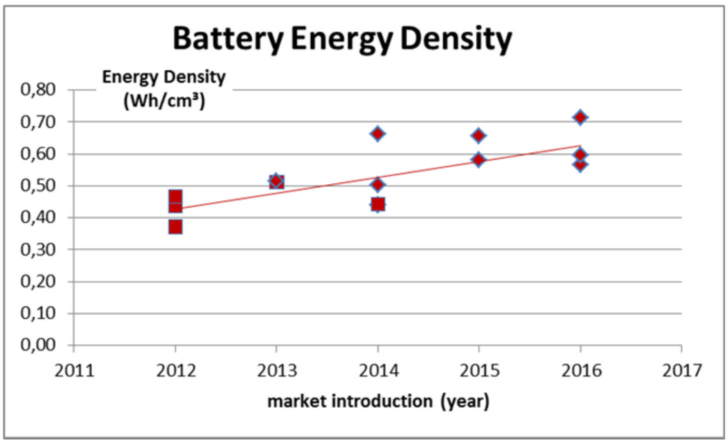
In the table above and the following ones, batteries which are replaceable without tools are marked (■). Those which are fully integrated are marked (♦).
Rated battery capacity increased (Figure 13) as battery technology improved and power requirements of the smartphones grew as well.

Figure 13: Rated battery capacity of disassembled smartphones



This leads also to a clear trend of increasing battery energy density, which in average for the disassembled batteries increase by almost 50% from 2012 to 2016 (Figure 14).

Figure 14: Volumetric battery energy density of disassembled smartphones



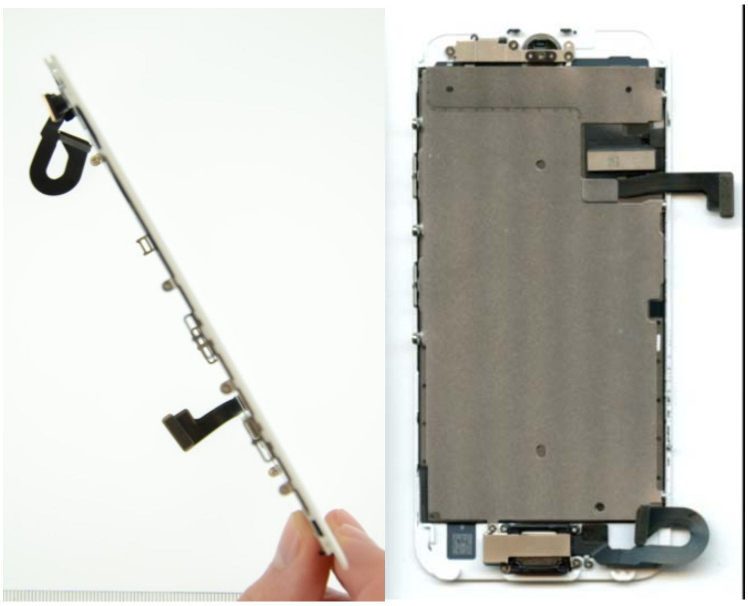
5.2 Display

The display design is crucial for disassembly under various aspects:

- Repair / replacement of the full LCD unit
- Repair / replacement of the cover glass only
- Repair / replacement of the LCD unit only
- Spare parts harvesting full LCD unit or cover glass and LCD unit
- Separate material recycling of the full LCD unit

As seen in the repair statistics above, frequently the cover glass only breaks, but not the LCD unit. In many products the cover glass is full-area glued to the LCD unit (see e.g. Figure 15). Separating both is a delicate process then, and residues of the adhesives remain on the glass and the LCD module. The backside of the LCD module is covered by a thin metal shield, apparently steel.

Figure 15: Display design with cover glass being full-area glued onto the LCD module (iPhone 7)

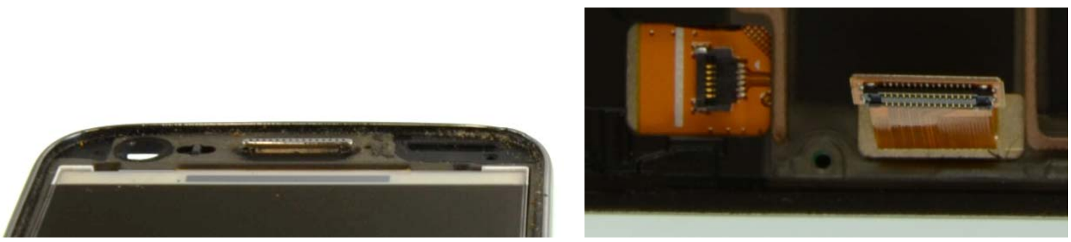


This cover glass / LCD module sandwich allows for a very slim design. There are other smartphone designs, where the cover glass is glued not full-area to the LCD module, but only at the edges on another internal frame (Figure 16). The LCD module then is typically glued into this frame and cannot be separated further. This internal frame is made of magnesium co-molded with polycarbonate in the Galaxy Note 2 and the Galaxy Ace 3. Similarly, in the Galaxy S6 or the Huawei P9 the LCD frame is apparently made of magnesium.

Figure 16: Display design with LCD module being glued into an internal frame, cover glass being glued to the edges of the LCD module frame (Galaxy Note 2)

Nowadays the display unit is recycled together with the rest of a smartphone in a copper smelter or precious metal smelter. In a recycling scenario, where the display is separated and recycled in a dedicated display recycling process (e.g. perspectively for the recovery of indium), it is important that no other valuable materials are lost in a hypothetical attempt to recover indium: In case of the LCD design, where the LCD module is integrated in a separate frame, magnesium is lost. These materials are also lost in a copper or precious metal smelter, but it would be worthwhile to consider rather a magnesium recycling, once this part is separated from the rest of the device. The amount of magnesium used in such LCD frames is estimated to be 10-20 g. Further materials are attached to the LCD frame, which are potentially lost: Copper in smaller flex connectors is typically contained.
There are also integrated circuits contained in the display module, in particular the line/row controller to address the LCD matrix (Figure 17). These chips are either placed on flex connectors or soldered in Chip-on-Glass technology directly on the LCD glass. In the latter case a gold indium solder is frequently used, which means a potential loss of gold in case the display unit is separated exclusively for indium recovery. Minor amounts of gold are also found elsewhere in the display unit, such as LED backlights and the board connectors.

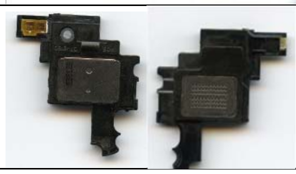
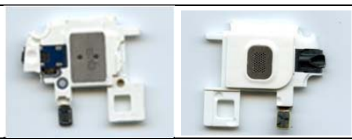
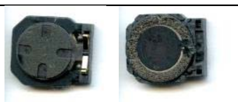
Figure 17: LCD line/row controller chip at upper end of LCD unit, left, and board connectors at LCD unit backside, right (Galaxy Ace 3)



5.3 Loudspeaker

Loudspeakers in mobile IT devices contain neodymium, which is a candidate for separation and material recycling. Neodymium is not as valuable as many other rare earth elements, but can be unambiguously located in a smartphone or tablet and therefore might qualify for separation (Table 4).
The weight of the loudspeaker modules varies between 1,35 g (Fairphone 2) and 4,70 g (Samsung Galaxy S7). Loudspeakers are frequently integrated in molded plastic parts. Where the loudspeaker comes as distinct component (Galaxy S5, Fairphone 2), the weight is below 2 g.

Table 4: Loudspeaker components

Smartphone model		Weight (g)
Sony Xperia M4 aqua		4,23
Nokia Lumia 830		3,52
Galaxy Ace 2		3,18
Galaxy Ace 3		4,33
Galaxy S3 mini		4,22
Galaxy S4 mini		4,00
Galaxy S5		1,88
Galaxy S7		4,70
iPhone 6		3,38
iPhone 7		3,22
Huawei P9		2,74
Fairphone 2		1,35

Besides the loudspeakers there are earspeakers and microphones contained in smartphones, which also potentially contain Neodymium.

5.4 Vibration Motors

Vibration motors contain tungsten as counterweight. Accessibility therefore is important in case tungsten recycling is intended.

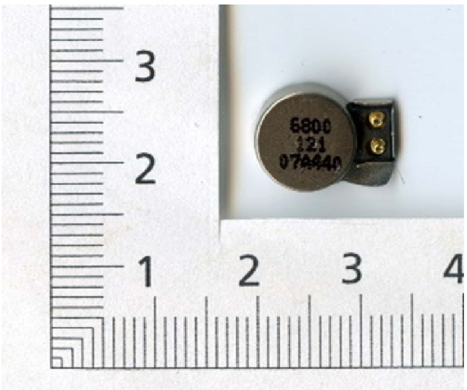
Table 5: Vibration motor designs

Cylindrical design	Coin design	Horizontal design
soldered on board: Nokia Lumia 930 spring contacts: *iPhone 4* *iPhone 5* *iPhone 5s* flex wired: *Huawei P7*	housing-extension with springs: Nokia Lumia 830 *iPhone 4s* cable-wired, wires soldered: Samsung Galaxy Ace 2 cable-wired, cable connector: Fairphone 1 Sony Xperia M4 Aqua flex wired, spring contacts: Samsung Galaxy Ace 3 Samsung Galaxy S3 Samsung Galaxy Note 2 Samsung Galaxy S3 mini Samsung Galaxy S4 mini Samsung Galaxy S7 Huawei P9	iPhone 6 "Taptic engine" *iPhone 6s* iPhone 7

(models in *italics* have been disassembled by third parties and evidence on vibration motor is derived from public sources; these models are included here to demonstrate trends beyond those units disassembled in the project sustainablySMART)

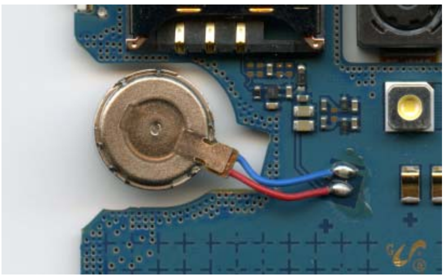
The vibration motor of the Nokia Lumia 830 is glued into a cavity of the plastic mid-frame and connected to the board with two golden or gold-coated spiral springs, which are attached to a rigid extension of the coin-shaped housing, see Figure 18.

Figure 18: Vibration motor with coin design, housing-extension with springs (Nokia Lumia 830)



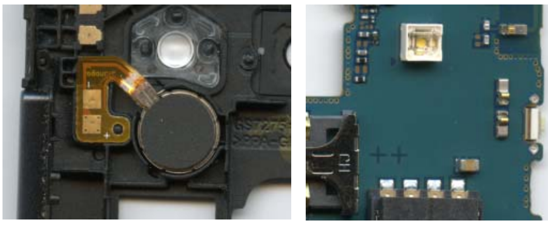
The Samsung Galaxy Ace 2 is an example of a smartphone, where the cables are soldered to the mainboard, see Figure 19.

Figure 19: Vibration motor with coin design, wires soldered to the board (Galaxy Ace 2)



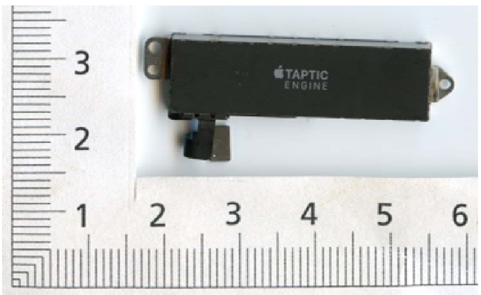
In the case of the Samsung Galaxy Ace 3 the vibration motor assembly (motor and flex connector) is inserted in the mid-frame (press-fit) and connected to the board with two spring contacts on the board, see Figure 20.

Figure 20: Vibration motor with coin design (left) and connected to the board through spring contacts (right), (Galaxy Ace 3)



Starting with the iPhone 6s Apple replaced the conventional vibration alarm with a feature to give a haptic response. For this purpose Apple developed the taptic engine (see Figure 21), which is an integrated assembly next to the home button. The taptic engine is actually made of coils and a vertically oscillating magnet core. There are no indications that tungsten is used for this design. A design similar to the taptic engine has been used already in the prior design of the iPhone 6, but not yet with the feature to give a touch response.

Figure 21: Taptic engine (iPhone 7)



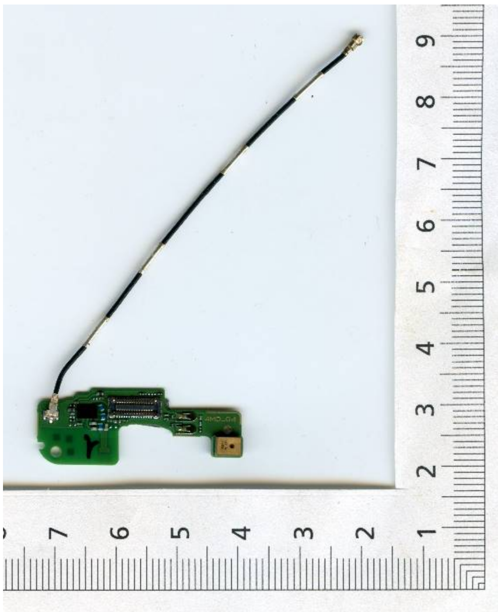
5.5 Antennas

A smartphone contains multiple antennas for WiFi, Bluetooth, 3G/4G/LTE etc. connectivity. Antennas are among the occasionally malfunctioning parts in smartphones and need to be replaced, which makes them an economically relevant spare part. The design of the antennas and the way they are integrated in the smartphone however frequently is a challenge for any repair of internal parts.
Three major antenna designs are used for smartphones:

- Cables
- Flex foils
- Molded antenna parts

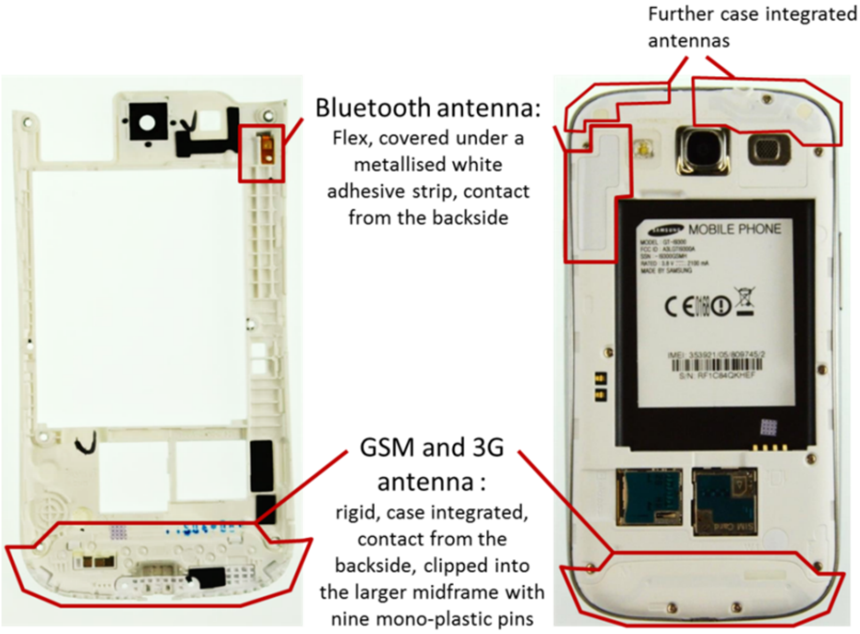
Cable antennas are a rather conventional design (see Figure 22). These antennas are usually either clipped in some cavities in the shell or midframe, or are just bended around other sub-assemblies within the phone. These antennas have to be handled with care not to be ripped off accidentally, but are otherwise a robust solution.

Figure 22: Cable antenna (Nokia Lumia 830)



Flex antennas are challenging for repair or reuse as there is a higher risk of ripping off the flex foil, cutting the foil unintentionally with any tool and as the frequently found complex geometry is not easy to handle when disassembling and reassembling a phone.
A specific antenna technology is used in many Samsung Galaxy models (Figure 23): Antennas are integrated in the plastic midframe as metallization on the surface (covered with a white coating as seen on the phots, the actual antennas shining through in a light grey) and connected on the backside. This way the antennas got a 3-dimensional design, following the shape of the midframe parts. In the Galaxy S3 these specific designs are integrated in a separate top part (in which in the backside also the loudspeaker is integrated) and in a bottom part. The latter is clipped into the main midframe part and can be separated easily. This design approach results in rigid antenna parts, which are less at risk to be damaged at product disassembly, but replacement might require the exchange of a larger part with additional integrated components.
Integrating metal into plastics in theory also hinders proper plastics sorting and recycling, but it has to be kept in mind, that these midframe parts weigh only few grams.

Figure 23: Case integrated antennas (Galaxy S3)

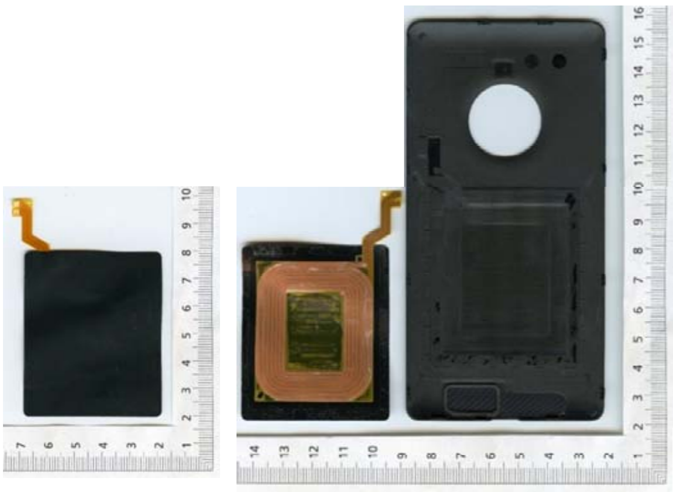


The same approach as in the Galaxy S3 is applied at least also in the Galaxy S3 mini and S4 mini.

5.6 Wireless charging

Wireless charging requires an additional large-scale coil for power transmission, being placed close to the backside of the phone to minimize the distance between coil and charging unit for higher transmission efficiency. Potentially this trend leads to a new composite assembly, which might hinder recycling.

Figure 24: Wireless charging coil attached to backcover (Nokia Lumia 830)



The Nokia Lumia 830 is such a device. Here the copper coil is attached to the plastic backcover with a strong adhesive (see Figure 24). Separating both leads to a mono-material plastics backcover and a larger coil foil, thus well recyclable parts. Also the Samsung Galaxy

S7 provides a wireless charging feature, but the design is different: The coil for the Qi-charging technology is embedded in a kind of mid-frame part.

Figure 25: Integrated Qi-charging coil (Samsung Galaxy S7)

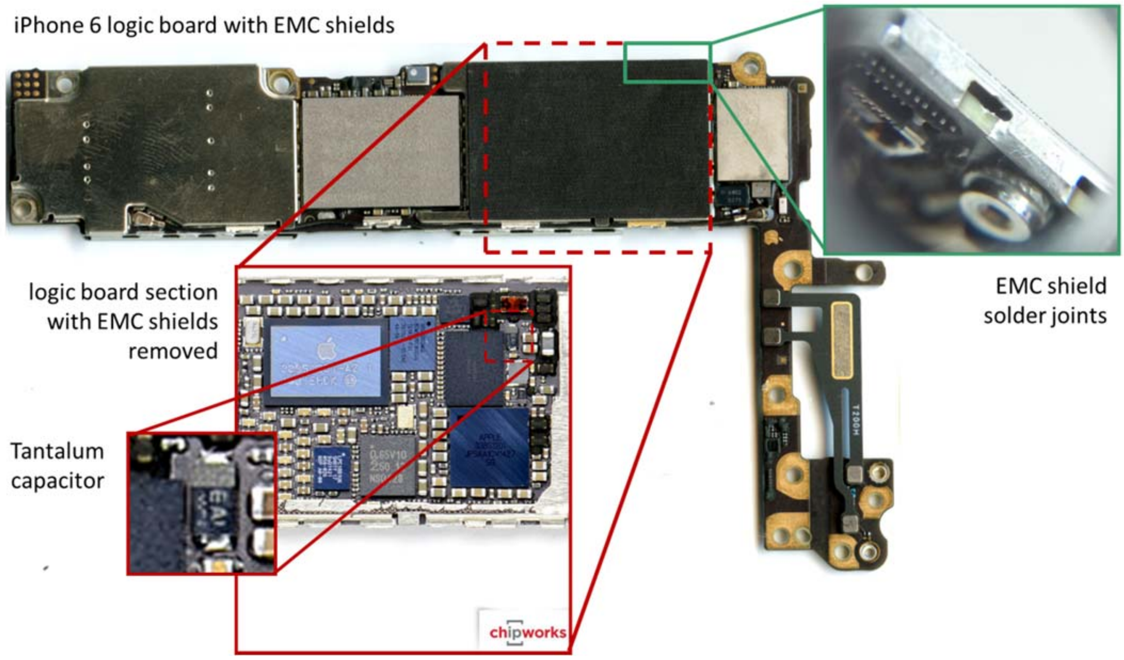
5.7 Mainboard

5.7.1 Tantalum capacitors

Those smartphones disassembled by Fraunhofer IZM feature only a very low number of clearly identifiable tantalum capacitors, except for the Fairphone 2, which for strategical reasons features 13 tantalum capacitors with tantalum from fair, non-conflict sources in D.R. Congo (Fairphone 2017).

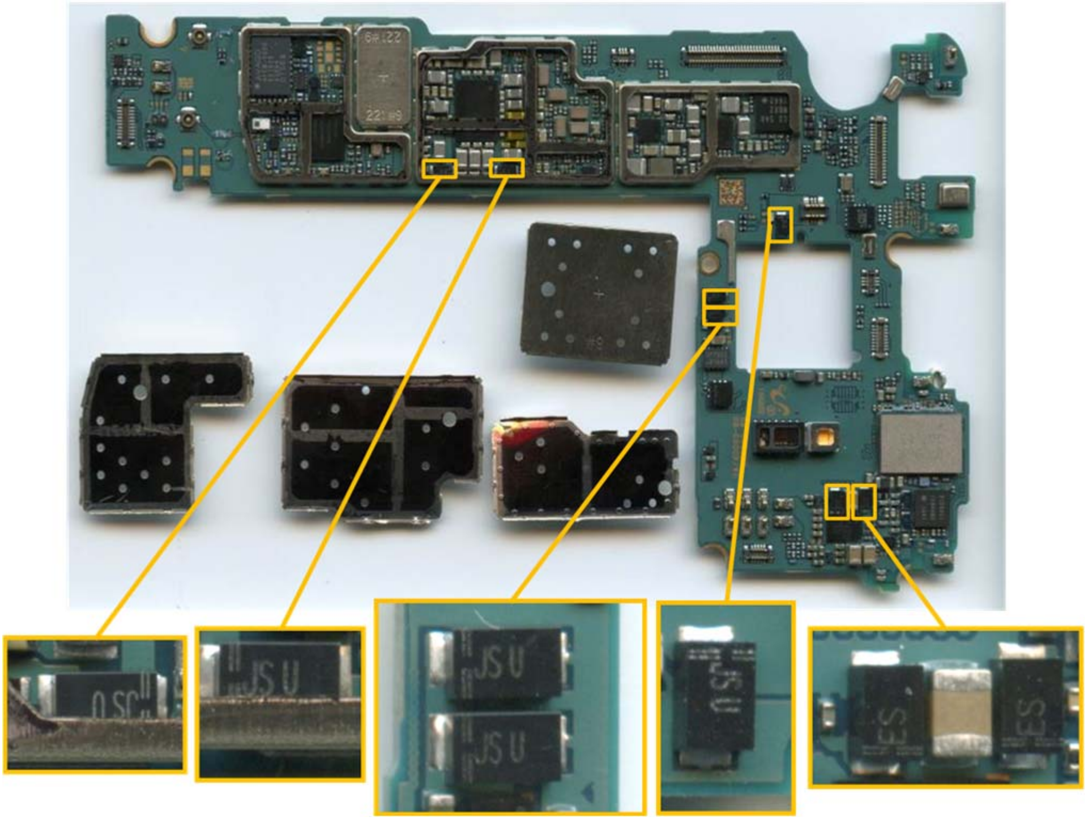
The iPhone 6 apparently contains 1 tantalum capacitor, which is accessible once a soldered EMC shield is removed (Figure 26, photo of logic board with EMC shields removed by Chipworks 2014, all other photos and graphical composition by Fraunhofer IZM).

Figure 26: Tantalum capacitor on logic board (iPhone 6)



Besides the Fairphone 2 all other investigated smartphones had a rather low number of tantalum capacitors. Not all potential tantalum capacitors could be identified unambiguously. In many models there seems to be only one tantalum capacitor. The Samsung Galaxy S7 actually contains 7 tantalum capacitors as depicted in Figure 27.

Figure 27: Tantalum capacitors on logic board (Samsung Galaxy S7)



5.7.2 Electromagnetic Shields

Electromagnetic shields are assembled on various parts of the mainboard to protect other parts from electromagnetic disturbances and resulting malfunction. These shields are made of steel covers.

In case repair on the board level is intended or desoldering of reusable components, any shields covering the components have to be removed first. This is logically easier with clipped-on shields. In case soldered shields have to be desoldered first, this might yield additional thermal stress for the components on the board.

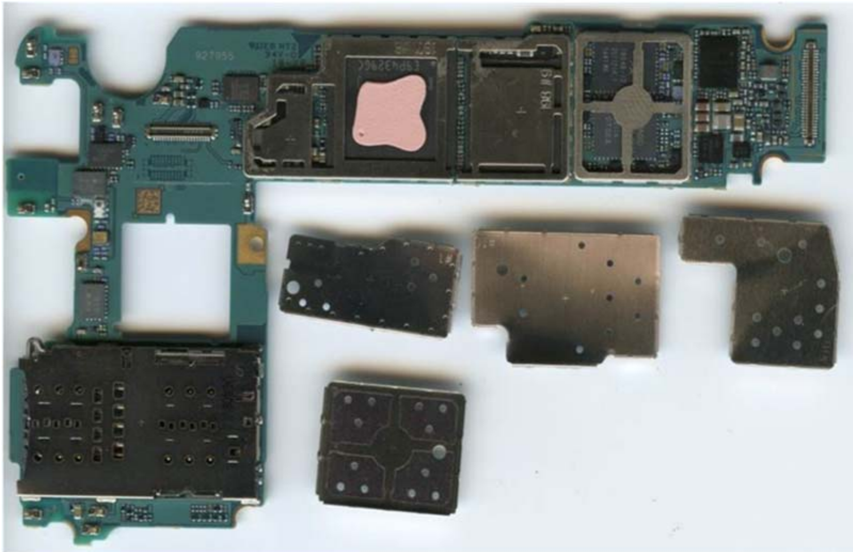
There are basically two different assembly designs of these shields on the board:

- Soldered shield
- Soldered frame with clipped-on shield

An example for a soldered shield is shown Figure 26.
Clipped-on shields are used e.g. in the Samsung Galaxy S7, as seen in the photo below. Although the EMC shield in this design can be easily removed, the larger semiconductors underneath, such as the processor and the flash memory, are still not directly accessible as

they are partly covered under remaining EMC shield frames. These frames are soldered to the board.

Figure 28: Clipped EMC shields removed (Samsung Galaxy S7)

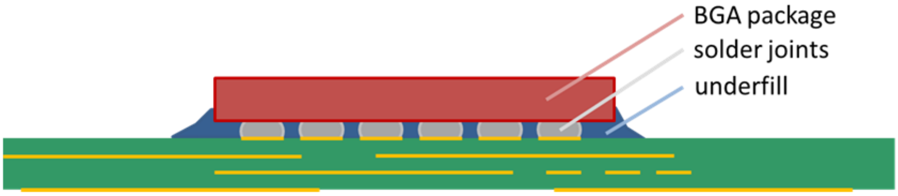


In some designs the larger semiconductors are not covered with a shield at all, which significantly eases access to components, see e.g. the Samsung Galaxy S4 mini board in Figure 31.

5.7.3 BGA Underfiller

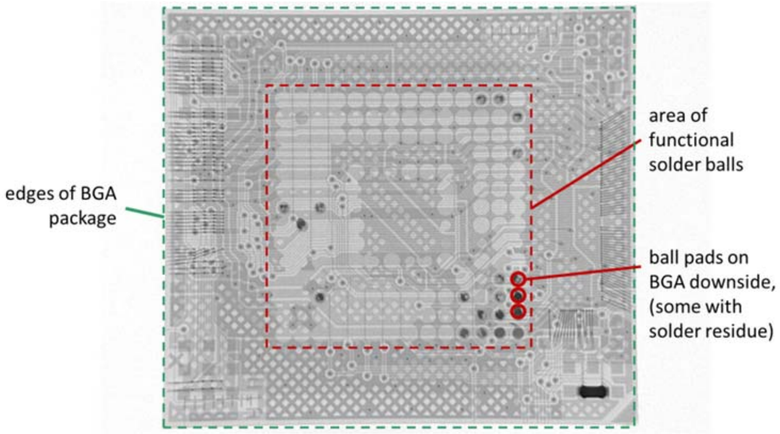
Several semiconductors in smartphones are packaged as Ball Grid Arrays, where solderable balls are placed as an array on the downside of the package. Flash memory packages are typically BGAs. Repair or reuse of such components requires a desoldering process. Increasingly BGAs are not only soldered on the board, but an epoxy underfiller is applied, which fills the gap between package and board. Such an underfiller enhances stability and reliability of the chip assembly. However, the desoldering and rework process is significantly hindered by an underfill as not only residues of the solder but also of the underfill remain on the downside of the package and need to be removed carefully.

Figure 29: Schematic drawing BGA package with underfill



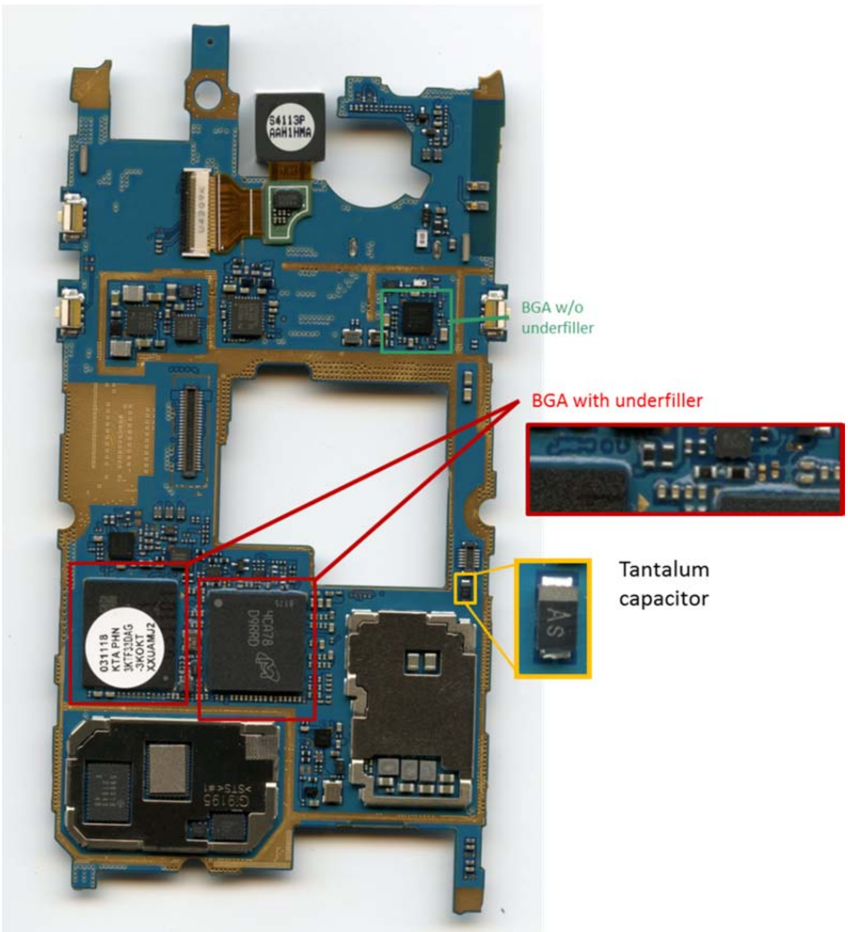
An x-ray image of the flash memory package used in the Fairphone 2 (Figure 30), which is a Samsung 32 GB eMMC NAND Flash Memory depicts the the solder ball pads in an array in the center of the chip package. The chip package as such is significantly larger than the ball array area. The x-ray also confirms the information from Samsung's product information (Samsung 2013), that memory chips (multiple dies) and the integrated memory controller chip are wirebonded (wire bonds visible as thin dark lines close to the left and right edges of the package), and no solders are used inside the package – which could otherwise be a major limiting factor for thermal stress at desoldering and resoldering such a package.

Figure 30: X-ray eMMC Flash memory BGA (Fairphone 2)



The underfiller is clearly visible as glossy meniscus under the two main BGAs of the Samsung Galaxy S4 mini shown below.

Figure 31: BGAs with underfiller on logic board (Samsung Galaxy S4 mini)



The status of flash memory underfill is summarized in Table 6. Usually underfiller is applied and if so for the memory chip, this is also the case typically for several other BGAs on the same board, such as the processor. Newer models have no visible underfiller, which does not necessarily mean, there is none. It might be the case that underfiller is applied before the chip is placed on the board (dip underfill), in which case the underfill does not flow beyond the edges. Such an approach might be required for process reasons as distances between chip and neighboring components become smaller and consequently space at the package edges is very limited for any dispensing process after assembly.

Table 6: Underfill usage for BGA flash memory packages

Smartphone model	Underfill flash memory (edge dispensed)[1]	Flash memory part number
Galaxy S3	yes	Samsung KMYTUOOOLM-B503
Galaxy S3 mini	yes	SanDisk SDIN7DU2 8G
Galaxy Ace 2	yes	Samsung K4P6G304EB
Galaxy Note 2	yes	Samsung KLMAG2GEAC
Galaxy S4 mini	yes	SanDisk SDIN7DU2 8G
Galaxy Ace 3	yes	SanDisk SDIN7DU2 8G
Fairphone 2	no	Samsung KLMBG4WEBC
Galaxy S5	yes	Elpida FA164A2PM
Sony Xperia M4 aqua	no	SK hynix H9TO64ABJTMC
Huawei P9	no	THGBMHG8C4LBAIR[2]

Some of the Samsung models actually share the same Flash memory component from SanDisk (Galaxy S3 mini, Galaxy S4 mini, Galaxy Ace 3)

6 Conclusions

Major lessons learnt from disassembly of numerous smartphone models have to be discussed on two levels: Product design and disassembly of components (repair, spare parts harvesting, reuse component harvesting, separation for recycling).

Product design:

- Larger plastics, aluminum and/or magnesium parts are frequently contained in current smartphones, but separability should be enhanced by design to facilitate a (nowadays hypothetical) better recycling of these fractions

- Fixing the cover glass to the LCD module with a full-area adhesive film complicates (low-cost) repairs and component harvesting, but fixing the LCD display with a strong adhesive in the midframe / LCD frame is neither an optimal solution; there are solutions, where the LCD module is fixed in the frame with adhesives, which can be

[1] Underfill dip might be applied (not visibile by non-destructive inspection) in those cases, which are marked “no”
[2] A teardown by iFixit found a Samsung memory package instead

separated without damaging the LCD unit – which seems to be the best option currently implemented

- Display edges and corners are similarly prone to accidental damage and thus should be protected against drop incidents by design as much as possible (frame with bumper properties, glass not elevated over device frame)
- Batteries, which can be removed are obviously the optimal solution in terms of easy replacement; for integrated batteries there are at least design options in place, where e.g. adhesives can be easily released
- Properly applied underfiller for major semiconductor packages is recommended for any product design, which is supposed to last explicitly long, - and where upgrade of such an underfilled component is not needed (e.g., by providing memory extension through microSD card slots); in case a product is – for whatever reasons – made to be in use only very few years, semiconductor packages should not be underfilled to facilitate desoldering and reuse
- Electromagnetic shields should be clipped only and frames of these shields should not hinder vertical access to key components

Disassembly of components:

- Separation of any material fraction beyond the current state of smartphone recycling (i.e., battery removal, all other parts for copper or precious metal smelter) should carefully consider not to direct recoverable materials (in particular precious metals with a large environmental footprint) into a recycling path, where they cannot be recovered
- Vibration motors and loudspeakers come in various designs, but are potentially of interest for separation as they contain moderate quantities of highly concentrated special metals (tungsten and neodymium)
- The amount and size of tantalum capacitors in smartphones seems to go down and the idea of separating these capacitors for a distinct tantalum recycling is becoming rather less relevant over time
- There is a range of Samsung Galaxy models (and the Fairphone 1), which feature a pretty similar basic design; disassembly processes can be effectively set up to disassemble these devices with the same sequence of processes; there are other “clusters” of similarly designed smartphones, which then could be disassembled in a similar way
- As long as no reversibly mounted modules are implemented in smartphones (see related research of sustainablySMART on sub-modules in embedding technology) at least high-value semiconductor packages without underfill should be the main focus of component desoldering and reuse (but see also the related research od sustainablySMART to rework BGA components)

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