Fraunhofer IZM

FRAUNHOFER-INSTITUT FÜR ZUVERLÄSSIGKEIT UND MIKROINTEGRATION IZM

LIFE CYCLE ASSESSMENT OF THE FAIRPHONE 3

Marina Proske
David Sánchez
Christian Clemm
Sarah-Jane Baur

Berlin, July 2020

Contact:
Fraunhofer IZM
Gustav-Meyer-Allee 25, 13355 Berlin, Germany
Phone: +49.30.46403-688
Fax: +49.30.46403-211
Email: marina.proske@izm.fraunhofer.de

Content

List of Tables

List of Figures

Abbreviations

ADP	Abiotic resource depletion
AUO	AU Optronics Corporation, Taiwanese display manufacturer
BOD	Biological oxygen demand
BoM	Bill of materials
CO_2e	Carbon dioxide equivalents
COD	Chemical oxygen demand
DRAM	Dynamic random access memory
ecoinvent	Life cycle inventory data base
EoL	End of life
FP2	Fairphone 2
FP3	Fairphone 3
GaBi	LCA software by thinkstep
GWP	Global warming potential
IC	Integrated circuit
LCA	Life cycle assessment
LCD	Liquid crystal display
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCO	Lithium cobalt oxide
LED	Light emitting diode
LPG	Liquefied petroleum gas
NOx	Generic term for the mono-nitrogen oxides nitric oxide (NO) and nitrogen dioxide (NO_2)
PC	Polycarbonate
PCB	Printed circuit board
PFC	Perfluorocarbons
SB-e	Antimony equivalents
SOx	Sulfur oxide
TPU	Thermoplastic polyurethane
TSS	Total suspended solids
VOCs	Volatile organic compounds

1
Executive Summary

Fairphone 3 is the new iteration of Fairphone's modular smartphone. The present LCA study aims to assess the environmental impact of the Fairphone 3 and identifies main drivers and hotspots in the life cycle. A special focus is put in the modular design of the device, which allows for easier repair. For that matter, a scenario-based approach is used, accounting for different lengths of the use phase and involving various repair strategies. The functional unit is set to be three years of intensive use of the Fairphone 3 as it is delivered to the customer.

The following impact categories are analysed in the study:

- Climate change (GWP)
- Abiotic resource depletion – elements (ADP elements)
- Abiotic resource depletion – fossil resources (ADP fossil)
- Human toxicity (Human tox)
- Ecotoxicity (Eco tox)

The data for this study is based on the bill of materials provided by Fairphone B.V., as well as on the material declarations provided by its suppliers. Those have been cross-checked with a teardown of a Fairphone 3 performed by Fraunhofer IZM.

Results

The total GWP for the Fairphone 3 is estimated to be 39.5 kg CO2e. The relative values for five impact categories are shown in Figure 1-1.

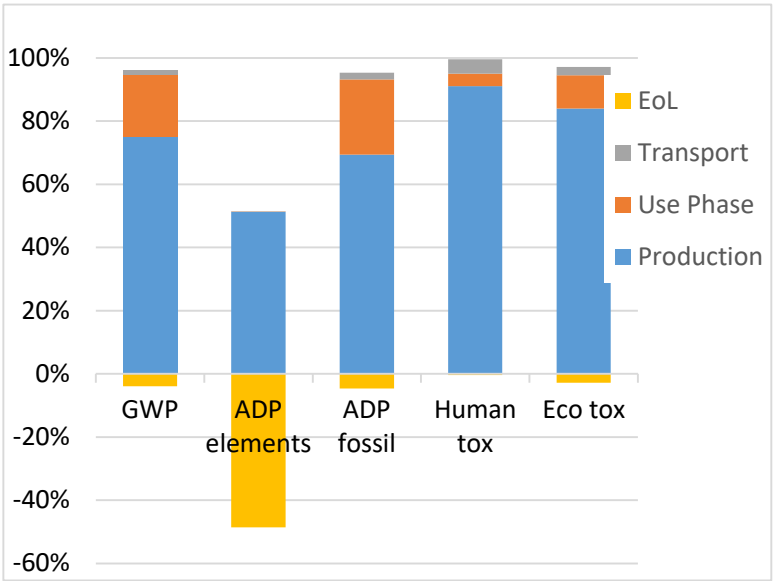

Figure 1-1: Relative impact per life cycle phase

Production is the main driver for all impact categories. A breakdown of the contributions of the different parts is shown in Figure 1-2 below. The second main contribution to the impact categories is the use phase while the role of transport is rather minor. The end-of-life (EoL) phase shows negative impacts, which means environmental benefits, most distinctly in the impact category ADP elements due to the recovery of gold.

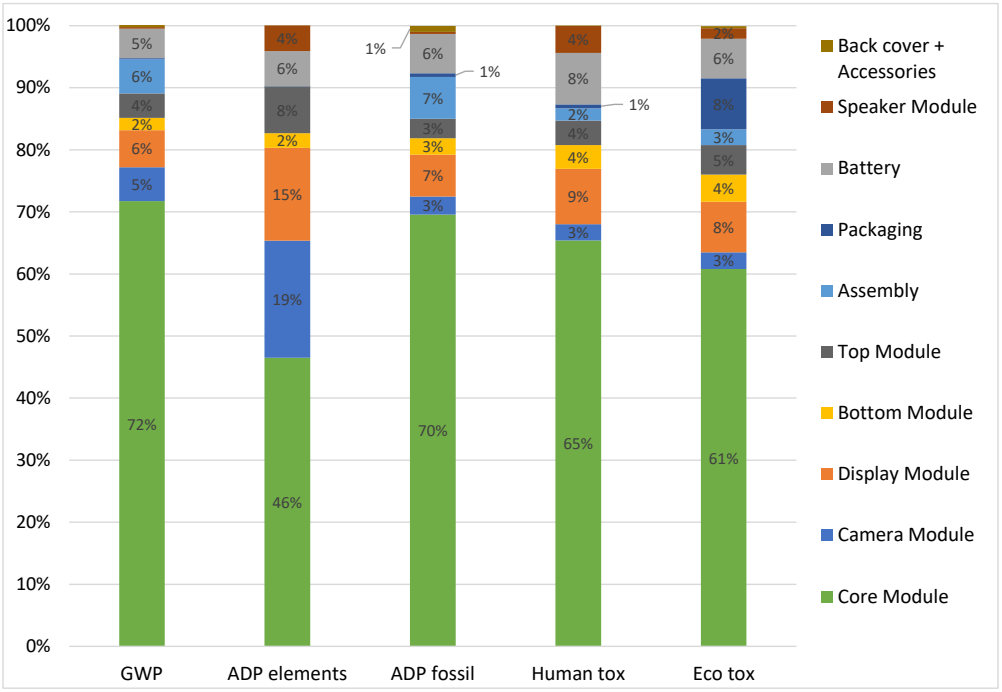

Figure 1-2: Relative impacts of the production phase per impact category

Within production, the core module is associated with the greatest contribution across all impact categories as it includes most of the PCB area, the main ICs and electronics.

Modularity and repair

Modularity has been modelled as being mainly related to extra housing and module connections. Those are made through flex cables and press-fit connectors. For GWP the modularity overhead is calculated to be 0.744 kg CO2e, which represents 2.3 % of all production impacts. For ADP elements the share is bigger at around 17.2 %, due to the gold plating of the connector contacts. Figure 1-3 expands on that.

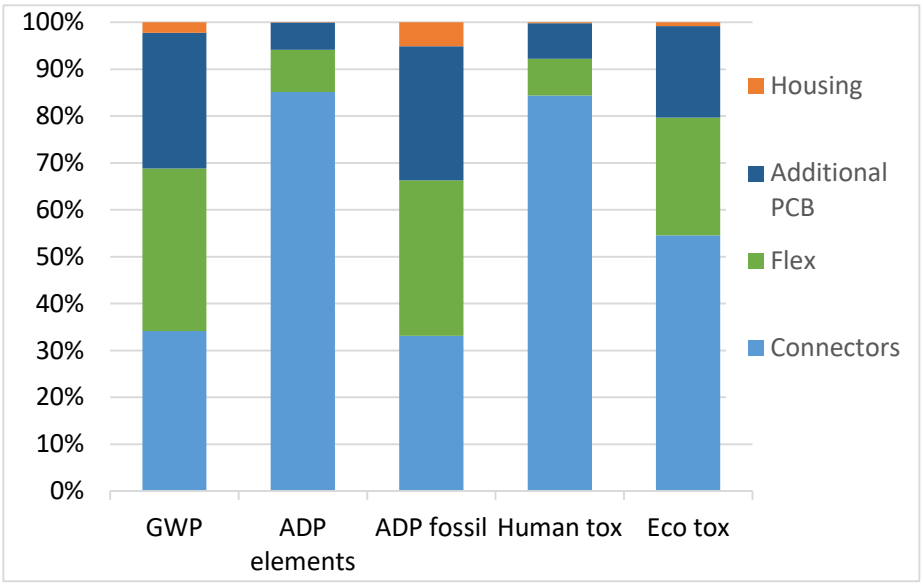

Figure 1-3: Relative impacts connected to modularity

As for repair, two main repair scenarios have been assumed. In repair scenario A, faulty modules are assumed to be replaced by new ones, taking advantage of Fairphone's

modular design. In repair scenario B, it is assumed that part of the faulty modules are actually repaired at board-level, allowing for replacement of specific components. A per-year comparison of the results are shown in Figure 1-4. It is clear that the benefits from both repair scenarios are highly dependent on the related use phase extension.

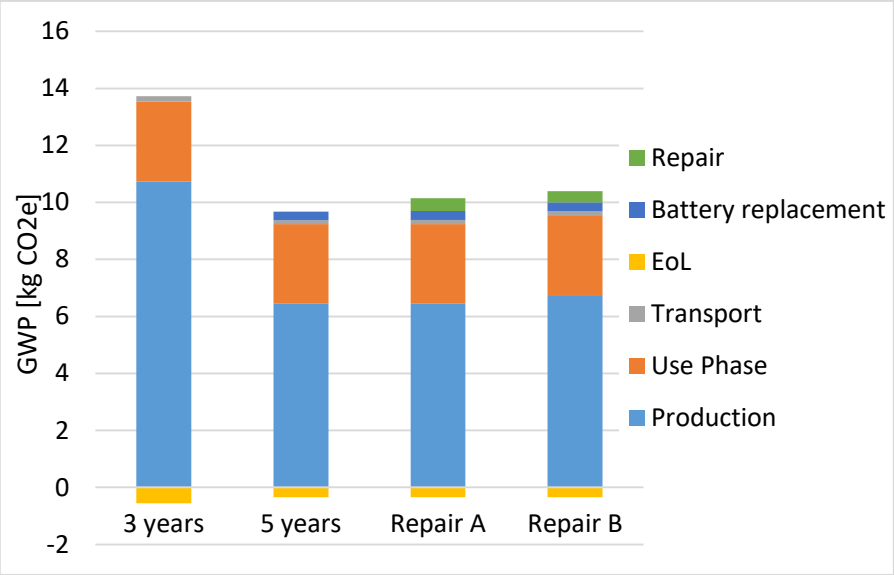

Figure 1-4: Relative impact per year use for the impact category GWP

Figure 1-5 provides a more detailed look at the differences between both repair scenarios which are too small to be seen in the per-year results. The benefits of on-board repair are tightly connected to the burden that transport poses and the components that can be effectively replaced. The study considered a conservative scenario in which only 37 % of modules are effectively repaired (75 % used modules are collected and only 50 % of those can be repaired).

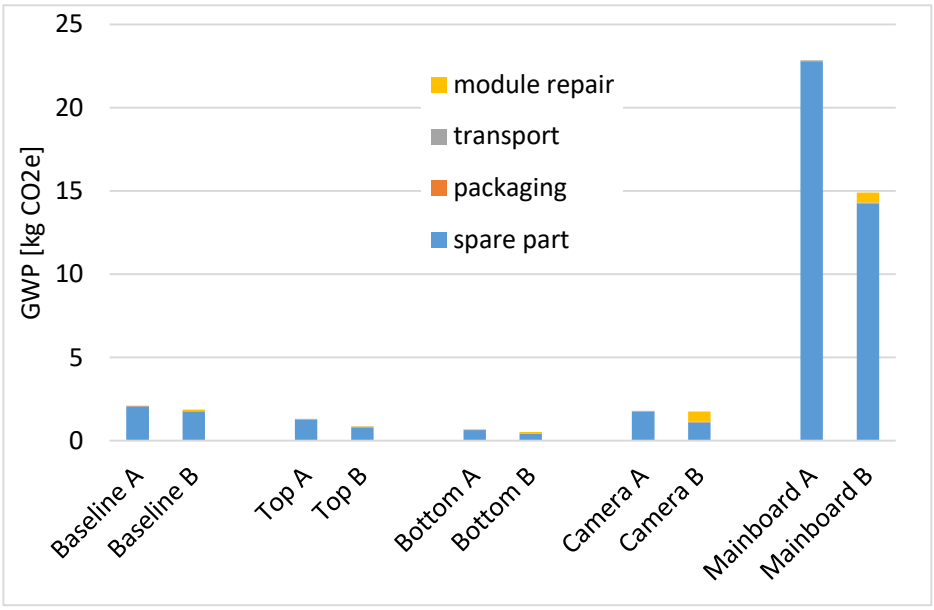

Figure 1-5: Variation between different repairs

Conclusions

The results of the Fairphone 3 LCA show that environmental impacts are largely production driven, with the electronic components causing the main impact. Housing and structural parts play a minor role in the overall impact. Design aspects, such as form factor, indirectly influence the entire LCA of the device, mainly through the display and battery size, but not through the impact of housing material itself.

As the main impact is caused by production, prolonging the use phase is still a strong measure to influence the overall environmental impact for all impact categories except ADP elements, which can be reduced through efficient precious metal recycling. The comparison of 3, 5 and 7 years of use shows that the impact per year of use drops significantly with longer lifetime (up to 42 % GWP drop per year for a 7 years use phase). This is still the case if repair is needed, as shown in the repair scenarios. This is, however, dependent on the effective lifetime extension that is achieved in reality.

The impact of the additional hardware required to enable modularity has been reduced in comparison with Fairphone 2. This is due to the new connectors which, unlike the previous pogo pin connectors, use less gold in their contacts. Furthermore, the small press-fit connectors are not a unique feature of the Fairphone, as they can also be found in more conventionally designed smartphones. Therefore, the "modularity overhead" is now much smaller when compared to the previous model.

The change in transport to the distribution hub, which now takes place by train rather than by air, is translated into a notable reduction on transport-related impacts of around 87 % reduction in GWP. The use phase, on the contrary, results in an increased environmental impact in all categories when compared to the Fairphone 2, mainly due to the bigger battery of the Fairphone 3 and the assumption of one full charge/ discharge cycle per day.

2
Goal and Scope Definition

2.1
Goal

The goal of this life cycle assessment is threefold:

- Assess the environmental impact of the Fairphone 3 and identify main drivers and hotspots in its life cycle.
- Compare different use phase assumptions, especially regarding repair.
- Assess the potential impact of using more recycled material for 8 focus materials (section 5).

To assess the environmental impact of the phone, a baseline scenario is assessed based on the product as sold to the users.

For the impact of repair and different use-times, additional scenarios with varying use-time (active years of use) and replacements of parts are being calculated.

The potential impact of a possible use of secondary materials for eight focus materials is assessed separately in section 5. Those are a selection of materials in which Fairphone is focusing efforts to tackle some environmental and social hotspots.

The intended applications of the study are:

- Use lessons-learned for possible future product designs,
- evaluate the effect of using more recycled materials in the production of the phone, and
- stakeholder communication

2.2
Scope

The scope of this study covers the entire life cycle of the Fairphone 3: raw material acquisition, manufacturing, transport, use and end-of-life.

The functional unit for the baseline scenario is an intensive smartphone use over three years. The corresponding reference flow is the Fairphone 3 as delivered to the customer including sales packaging, manual, screwdriver and protection bumper, but without charger, which is not part of the standard delivery. No parts' failures are assumed for the baseline scenario. The additional scenarios cover:

- Varying years of use:
  - 5 years of use with one additional replacement battery
  - 7 years of use with two additional replacement batteries
- Different repair scenarios:
  - Repair scenario A: 5 years use with replacement of several modules (see section 3.5.1)
  - Repair scenario B: similar to repair scenario A, but with additional repair of module (see section 3.5.2)

The data inventory is based on the bill-of-materials (BoM), a product tear-down, and material declarations for subparts from suppliers. The final assembly process is based on primary data from Arima comms in China (see section 3.1.13).

The following impact categories are covered for the life cycle assessment:

- Climate change (GWP)
- Abiotic resource depletion – elements (ADP elements)

- Abiotic resource depletion – fossil resources (ADP fossil)
- Human toxicity (Human tox)
- Ecotoxicity (Eco tox)

However, not all processes used in the assessment could cover all the listed impact categories. The effect will be described in the sensitivity analysis and interpretation of results (section 4.5). Additionally, the analysis of recycled materials covers mainly GWP and only partially other impact categories due to limited data availability (see section 5).

Transport processes cover the transport of parts to the final assembly, transport of the final product from final assembly in China to the distribution hub in Europe, and product delivery to the final customer within Europe.

Use phase impacts are related to electricity consumption of the phone and the charger, which is not delivered with the product. Impact of the mobile network (availability and data transfer) are not within the scope of this study. Consumables are considered for the scenarios with longer use (replacement batteries) and spare parts for the repair scenarios.

Processes are modelled with the LCA software GaBi and the corresponding data base, including the "Electronics" extension data base. This is supplemented with the ecoinvent data base v3.6 for processes where no suitable GaBi data set is available.

3
Life Cycle Inventory

The life cycle inventory covers the following sections:

- Raw material acquisition and manufacturing
- Use phase
- Transport
- End-of-life (EoL)

The raw material acquisition is indirectly covered using cradle-to-gate data sets for the manufacturing.

For the assessment, the life cycle assessment software GaBi with its own data base, the electronics extension as well as the ecoinvent 3.6 data base was used. If data is used from additional sources, this is specifically mentioned in the description. In many aspects, the modelling follows the same assumptions as the Fairphone 2 LCA [Proske et. al. 2016], which was also carried out by Fraunhofer IZM.

3.1
Raw material acquisition and manufacturing

The manufacturing phase was modelled according to the bill of materials (BoM) of the Fairphone 3 and the material compositions of several components provided by the suppliers. The analysis was supplemented with a teardown of the phone at Fraunhofer IZM.

Life cycle data sets were allocated to all parts based on weight (mechanical parts), number of pieces (electronic components) or size/area (e.g. printed circuit boards). The individual approach for each module and component group is described in the following. The modules of the phone with its main parts are shown in Table 3-1.

Table 3-1: Main parts per module

Module	Main parts	Weight [g]
Fairphone 3		190.4
Core module		
	Mainboard with • Main electronic components • Connectors to modules • Connectors to battery and display assembly	18.5
	Button assembly	
	Flex boards to module connectors	
	Fingerprint sensor	
	Frame and mid frame	
Top module		5.1
	Top module board	
	Front camera	
	Receiver (speaker)	
	Earphone jack	
Camera module		2.9
	Camera	
	Camera board	
Bottom module		4.3
	Bottom module board	
	Vibration motor	
	USB-C connector	

Module	Main parts	Weight [g]
Speaker module		3.1
	Speaker, microphone	
Display module		63.4
	Display frame	
	LCD display	
	Display board	
	Cover glass	
Battery module		50.4
	Battery	
Back cover		12.6

3.1.1 Core Module

The core module consists of the following parts:

- Mainboard with the majority of integrated circuits (ICs) of the phone, including the CPU, memory and storage, and other electronic components
- Metallic shielding on the board
- Connectors to the different modules, based on flexible printed circuit boards (flex boards)
- SIM card and MicroSD card connectors
- Mid-frame and screws
- Fingerprint sensor
- Buttons and printed circuit boards

The detailed modelling of the PCBs, ICs, passive components and connectors is described in subsection 3.1.9. The detailed BoM with the assigned weight and life cycle inventory data set for the core module can be found in the annex in Table 8-6.

3.1.2 Battery

The battery in the Fairphone 3 contains a lithium-ion cell with the following specifications:

- Capacity: 11.55 Wh / 3040 mAh
- Mass: 52 g

The following Table 8-1**Fehler! Verweisquelle konnte nicht gefunden werden.** in t he annex lists the material composition ranges provided by the manufacturer. The median values are used for modelling, which results in the mass of individual materials provided in the last column. A range of additional materials is included in the category "other".

The battery management system PCB and the cell packaging are assumed to be the same as in the FP2.

For replacement batteries (depending on the years of use, see section 3.2) additional packaging and transport is assumed.

3.1.3 Top module

The top module consists of the following parts:

- Module housing

- Module board with electronic components
- Front camera
- Receiver
- Connectors
- Earphone jack

The detailed modelling of the PCBs, ICs, passive components and connectors is described in subsection 3.1.9. The detailed BoM with the assigned weight and life cycle inventory data set for the top module can be found in the annex in Table 8-8.

3.1.4 Bottom module

The bottom module consists of the following parts.

- Module housing
- Module board with electronic components
- Connectors
- USB-C connector
- Vibration motor

The vibration motor is modelled based on the material composition. For the tungsten, no data set was available in GaBi or ecoinvent. Therefore, a data set from the German life cycle data base Probas was used [Probas 2020].

The detailed modelling of the PCBs, ICs, passive components and connectors is described in subsection 3.1.9. The detailed BoM with the assigned weight and life cycle inventory data set for the bottom module can be found in the annex in Table 8-8.

3.1.5 Speaker module

The speaker module consists of the following parts:

- Module housing
- Speaker
- Connectors

The detailed modelling of the connectors is described in subsection 3.1.9. The detailed BoM with the assigned weight and life cycle inventory data set for the speaker module can be found in the annex Table 8-9.

3.1.6 Display Module

GaBi does not contain an LCD data set. The data set from Ecoinvent for a display is from 2001 and therefore out-dated and has only limited applicability for a smartphone display. Therefore, the display is modelled according to the CSR report from the Taiwanese display manufacturer AUO [AUO 2019]. The same approach was used for the Fairphone 2 LCA, but with older data from 2015.

The data is scaled by panel size, which in the case of Fairphone 3 is of 81.9 cm^2.

AUO data covers scope 1 (direct emissions) and scope 2 (purchased energy). Scope 3 covers product use, business travel, and commuting but not the impact of upstream suppliers and is therefore not taken into account. Production of input materials is not covered. The data covers the panel manufacturing without backlight and electronics (display board).

The following data presented in Table 3-2 is given by the AUO CSR report and the data marked in blue is transferred to the LCA model.

The given values from AUO for scope 2 greenhouse gas (GHG) emissions (from purchased energy) are not directly transferred, but the energy consumption is included

via the corresponding processes (electricity production, gas, diesel) to also address other impact categories. Purchased electricity for the production process is included as electricity from Taiwan.

Table 3-2: Panel production data by AUO [2019]

Input	Total		per m^2	
Material				
Glass substrate	97,865.90	tonnes	1.42E+00	kg/m^2
liquid crystal	90.00	tonnes	1.31E-03	kg/m^2
Photoresist	31,290.00	kiloliters	4.55E-01	l/m^2
Array stripper Usage	80,862.30	tonnes	1.18E+00	kg/m^2
CF Thinner	1,774.00	tonnes	2.58E-02	kg/m^2
Developer	49,188.00	tonnes	7.15E-01	kg/m^2
Aluminium Etchant	10,493.00	kiloliters	1.53E-01	l/m^2
PFC Usage	900.40	tonnes	1.31E-02	kg/m^2
Energy				
total consumed	19,746,407.09	GJ	2.87E-01	GJ/m^2
Purchased Electricity	18,921,349.28	GJ	2.75E-01	GJ/m^2
Natural Gas	716,182.93	GJ	1.04E-02	GJ/m^2
LPG	12,511.37	GJ	1.82E-04	GJ/m^2
Diesel	96,363.50	GJ	1.40E-03	GJ/m^2
self-generated solar power	299.87	GJ	4.36E-06	GJ/m^2
Wind power	0.00	GJ	0.00E+00	GJ/m^2
Water				
total	33,735.21	megaliters	4.90E+02	l/m^2
Emissions				
scope 1	320,000.00	tonnes CO_2	4.65E+00	kg CO_2/m^2
scope 2	3,250,000.00	tonnes CO_2	4.73E+01	kg CO_2/m^2
scope 3	8,250,000.00	tonnes CO_2	1.20E+02	kg CO_2/m^2
ODS emissions	0.08	tonnes	1.16E-06	kg/m^2
SO_x	53.80	tonnes	7.82E-04	kg/m^2
NO_x	75.00	tonnes	1.09E-03	kg/m^2
Fluorides	3.60	tonnes	5.23E-05	kg/m^2
HCl_4	2.20	tonnes	3.20E-05	kg/m^2
Volatile organic compounds (VOC)	144.90	tonnes	2.11E-03	kg/m^2
Wastewater	25,995.10	megaliters	3.78E+02	l/m^2
COD	874.80	tonnes	1.27E-02	kg/m^2
Biochemical oxygen demand (BOD)	121.70	tonnes	1.77E-03	kg/m^2
total suspended solids	179.40	tonnes	2.61E-03	kg/m^2
hazardous waste	30,623.40	tonnes	4.45E-01	kg/m^2
non-hazardous waste	79,349.50	tonnes	1.15E+00	kg/m^2

Input	Total	per m²
Panel output		
large size	114.80	Mio pieces
small/medium size (<10inch)	166.60	Mio pieces
Total produced display area	68.78	Mio. m²

Backlight assembly:

Die size of LEDs per screen area is modelled (as for the FP2 LCA) based on Deubzer [2012] for a comparable tablet display (see Table 3-3). This results in a die area of 0.0077 cm² for the Fairphone 3 display. The LEDs are modelled per die area as CMOS logic according to Boyd [2012] as it is also described by Zgola [2011].

Table 3-3: Die area per display area [Deubzer 2012]

Backlight design (typical product)	Display diagonal	Brightness [cd/m²]	Total die area per display area [mm²/cm²]
Edge lit (tablet)	7"	350	0.0094

3.1.7 Camera Module

The camera module consists of

- Camera with camera sensor Sony IMX363
- Camera board
- Connector.

The sensor ICs are modelled according to the die size as described in section 3.1.9.3 and was determined via CT images.

The detailed modelling of the connectors is described in subsection 3.1.9. The detailed BoM with the assigned weight and life cycle inventory data set for the camera module can be found in the annex in Table 8-11.

3.1.8 Back cover

The back cover consists of 12.5 g polycarbonate.

3.1.9 Cross-module approaches

3.1.9.1 Connectors

Connectors are modelled according to their material composition provided by the manufacturers. The impacts of possible production overheads are analysed in the sensitivity analysis (see section 4.5.2).

The board-to-board connectors changed from pogo pin connectors in the Fairphone 2 to press-fit connectors in the FP3 and they mainly consist of the following materials:

- Copper, nickel and gold for the contacts
- Steel or bronze for metal fittings
- Glass fibre-supported plastic for the housing

A flex cable is used per module to connect it to the core, with a pair of male/female press-fit connectors on each end. The connectors are modelled based on the material composition from the manufacturer, while the flex cables are modelled as one-layer PCBs.

The detailed material breakdown can be found in the corresponding module table in the annex.

The connector between mainboard (core module) and display board is the only pogo pin connector with 32 pins on the mainboard and has contact areas on the PCB on the display side. The pogo pins are modelled as the press-fit connectors based on the material composition given by the supplier.

The contact area is modelled similarly to the Fairphone 2 LCA based on the additional amount of nickel and gold on the PCB. The amount of gold deposited on all module boards together is 2 mg (see also Figure 3-1). 80% of that gold is assumed to be connected to the contact area, resulting in 1.6 mg.

3.1.9.2 PCBs:

The conventional method to model printed circuit boards is according to the number of layers and outer dimension (smallest rectangular). This might over- or underestimate offcuts, depending on the specific form and production layout. For the Fairphone 3, the production layouts were available and therefore directly used for the modelling of the rigid PCBs.

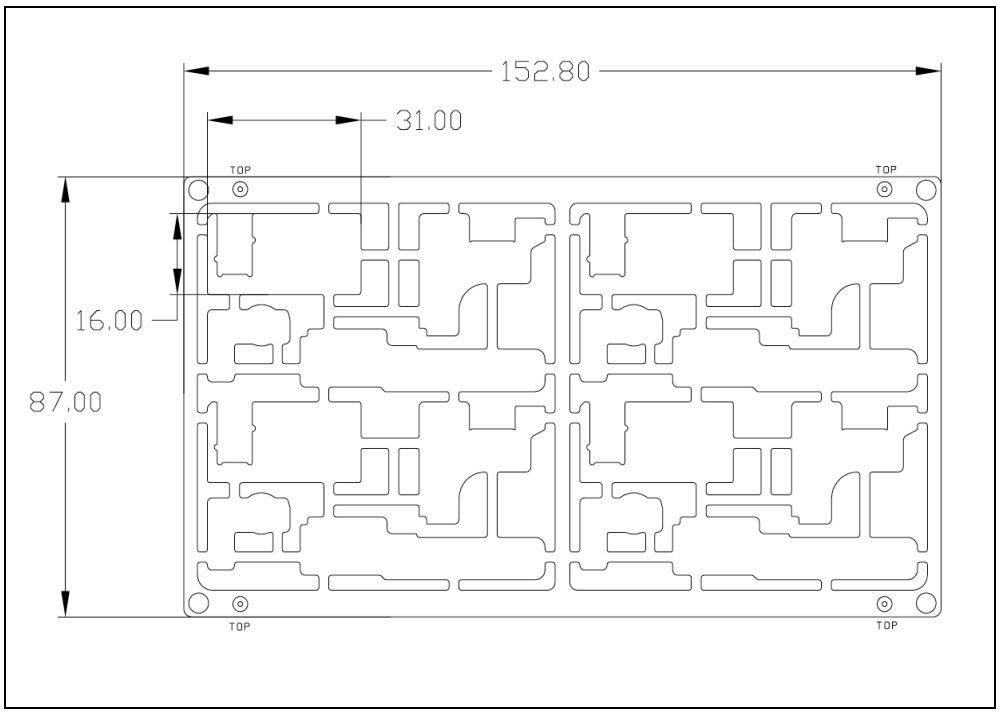

Figure 3-1: Module board production layout

The module PCBs are produced all on the same panel (Figure 3-1), with four module boards are arranged in each. The mainboard is modelled with two mainboards per panel. Table 3-4 shows the allocated area for the boards and the area based on the outer dimensions. The results show that the offcuts would have been underestimated for the module boards (in total by 13.5 cm^2) and overestimated for the mainboard (in total by 17.8 cm^2).

Table 3-4: Printed circuit board area modelled

Module	Boards per panel	Length	Width	Area	Allocated area
		mm	mm	cm^2	cm^2
Module panel	4 per module	152.8	87	132.94	
Bottom		25	24	6.00	10.11
Camera		15	16	2.40	4.04
Display		49	13	6.37	10.73

Top		31	16	4.96	8.35
Mainboard panel	2	166.0	86.0	142.76	71.38
Mainboard		136.1	65.51	89.16	

Flexible printed circuit boards are modelled as one-layer PCBs according to the outer dimensions as no data set for flex boards was available.

3.1.9.3 Integrated circuits

The environmental impact of ICs is determined mainly by the processed die area. For the Fairphone 3, die area was determined using CT images of the individual boards (Figure 3-2) and grinding of the ICs.

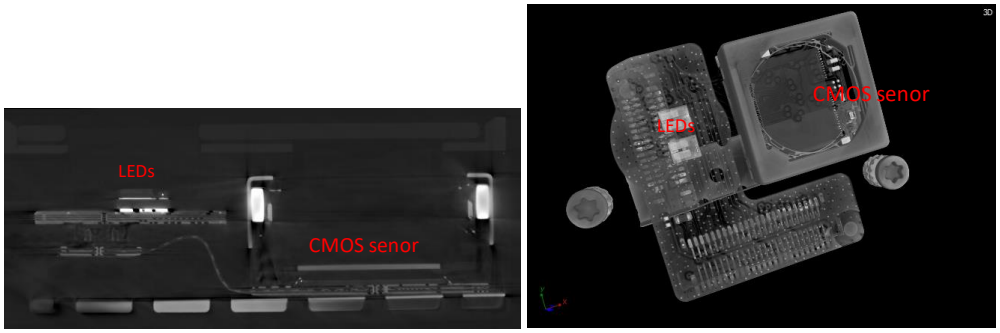

Figure 3-2: Exemplary pictures of CT images – camera module

For the main board, CT images were not enough to determine the die size. Therefore, additional x-rays from various dimensions and vertical grinding of the ICs was used.

Table 3-5 shows the identified and modelled die sizes per module. Additional ICs from the mainboard are modelled with existing data sets from GaBi.

Table 3-5: Die sizes

Module	IC description	Die area [mm²]
Bottom module	I.C analogue switch	0.847
Camera module	LED Flash	1.208
Camera module	LED Flash	1.222
Camera module	CMOS image sensor	35.714
Top module	Light sensor	0.8933
Top module	Light sensor	0.0814
Top module	LED Full Colour	0.2556
Top module	CMOS image sensor	18.0093
Mainboard (WLAN)	I.C WLAN	11.6
Mainboard (WLAN)	I.C WLAN	1.44
Mainboard	I.C audio power amplifier	12.96
Mainboard	I.C analogue switch	1.61
Mainboard (power management)	I.C power amplifier modules	6.28
Mainboard (power management)	I.C PMU	26.88

Module	IC description	Die area [mm²]
Mainboard (power management)	I.C PMU	0.77
Mainboard (power management)	I.C PMU	11.36
Mainboard	Sensor	7.2
Mainboard	NFC Microcontroller	8.69
Mainboard	I.C transceiver	11.44
Mainboard	I.C audio power amplifier	9.58
Mainboard (CPU)	Baseband processor	46.4
Mainboard (Flash/RAM)	Stacked memory	507.74

The integrated circuits with greater die size are the power management ICs, CPU and Flash/RAM stacked package. The latter having a higher die size than all other ICs together. Flash storage and RAM are contained within one stacked memory with 9 stacked dies. It was not possible to assign all of them to either RAM or Flash, so die area and results are presented for the whole package.

The impact of the ICs is modelled according to figures from Boyd [2012] and Prakash et al. 2013. Boyd [2012] refers to CMOS logic, the numbers from Prakash et al. [2013] are based on a DRAM chip by Samsung. Therefore, the DRAM and storage of the Fairphone 3 are modelled according to Prakash et al. [2013] (see Table 3-8), all other ICs listed in Table 3-3: Die area per display area [Deubzer 2012] and Table 3-5 are based on the figures for logic chips (see Table 3-7). As the wafer manufacturing is similar for all ICs, the more detailed wafer data set from Prakash et al. [2013] was used also for the wafer manufacturing of the CMOS logic ICs.

The impact category ADP elements is not covered by the data by Boyd [2012]. This impact category is driven by material use, specifically gold and other precious metals have a high impact. To reflect this, the ADP elements impact of gold, silver and palladium in the package is added to the individual ICs which are modelled with the CMOS logic based on the material composition given by the supplier (see Table 3-6).

Table 3-6: Gold, silver and palladium in IC packages per module board

	Gold	Silver	Palladium
	[g]	[g]	[g]
Mainboard	2,45E-04	1,83E-03	6,95E-06
Top module	8,55E-04	5,99E-05	3,10E-06
Camera module	0,00E+00	2,00E-07	0,00E+00
Bottom module	0,00E+00	1,70E-05	0,00E+00

The DRAM figures already include gold as an individual flow in the model. The material composition of the Samsung storage chip used by Prakash et al. [2013] therefore fits the amount of gold stated by the material composition of the Fairphone 3 storage IC very well when scaled by die size.

Table 3-7: Environmental impacts according to Boyd [2012] per cm² die for the technology 32 nm logic chips

Process	Energy	GWP	Photo-chemical smog	Acidification	Eco-toxicity	Human Health Cancer	Human Health non cancer
	[MJ]	[kg CO_2e]	[kg NOx]	[mol H+]	[kg 2,4-D]	[kg C6H6]	[kg C6H6]
Fab	33.6	0.9	0.006	0.356	0.030		2.444
Infrastructure (fab construction and equipment)	17.9	1.5	7.43E-03	3.86E-01	4.96E-05	7.36E-05	3.07E+00
Silicon	5.9	0.5	5.25E-03	3.03E-01	2.60E-02		2.08E+00
Chemicals	2.9	0.4					
Fab direct emissions and EoL			2.51E-04	2.00E-01	4.70E-04	1.89E-05	1.00E+00

Table 3-8: Environmental impacts according to Prakash et al. [2013] of storage chips

Process		Wafer	Good die out		Packaged die		GaBi process
Reference	cm²	1	1		1		
Inputs			process	incl. upstream	process	incl. upstream	
Wafer			1,38				
good die					1		
Electricity	kWh	3,85E-01	1,27	1,80E+00	5,72E-01	2,37E+00	CN: Electricity grid mix ts
Natural gas	kWh		1,60E-01	1,60E-01	7,09E-02	2,31E-01	US: Natural gas mix ts
Silicon dioxide	kg	4,87E-03		6,72E-03	1,10E-04	6,83E-03	GLO: Silicon mix (99%) ts
Wood pallets (as energy material)	kg	1,83E-03		2,53E-03		2,53E-03	EU-28: Wood pellets (6.2% moisture; 5.8% H2O content) (EN15804 B6) ts
Lignite	kg	3,98E-03		5,49E-03		5,49E-03	EU-28: Lignite mix ts
Petroleum coke	kg	5,97E-04		8,24E-04		8,24E-04	EU-28: Petroleum coke at refinery ts
Electrode material	kg	1,63E-04		2,25E-04		2,25E-04	
HCl	kg	6,75E-03		9,32E-03		9,32E-03	RER: Hydrogen chloride ELCD/PlasticsEurope <t-agg>

Process		Wafer	Good die out	Packaged die	GaBi process
Water	kg		7,88E+00	7,88E+00	7,88E+00 EU-28: Water (deionised) ts
N2 (high purity)[1]	kg		6,06E-01	6,06E-01	6,06E-01 EU-28: Nitrogen (gaseous) ts
O2 (high purity)	kg		4,13E-03	4,13E-03	4,13E-03 EU-28: Oxygen (gaseous) ts
Ar (high purity)	kg		2,34E-03	2,34E-03	2,34E-03 DE: Argon (gaseous) ts
H2 (high purity)	kg		6,34E-05	6,34E-05	6,34E-05 RER: Hydrogen (electrolysis) PlasticsEurope
Sulphuric acid (high purity)	kg		7,33E-03	7,33E-03	7,33E-03 EU-28: Sulphuric acid (96%) ts
Hydrogen peroxide (high purity)	kg		2,04E-03	2,04E-03	2,04E-03 DE: Hydrogen peroxide (100%; H2O2) (Hydrogen from steam cracker) ts
hydrofluoric acid (high purity)	kg		5,53E-04	5,53E-04	5,53E-04
Phosphoric acid (high purity)	kg		3,32E-03	3,32E-03	3,32E-03 EU-28: Phosphoric acid (H3PO4, 54% P2O5) Fertilizers Europe
2-Propanol (C3H8O)/ isopropyl alcohol (IPA) (high purity)	kg		2,78E-03	2,78E-03	2,78E-03 DE: Isopropanol ts
Ammonium hydroxide (high purity)	kg		1,09E-03	1,09E-03	1,09E-03
CF4	kg		5,94E-05	5,94E-05	5,94E-05
CHF3	kg		5,66E-06	5,66E-06	5,66E-06 GLO: trifluoromethane production ecoinvent 3.5
NF3	kg		3,02E-04	3,02E-04	3,02E-04
C2F6	kg		6,89E-05	6,89E-05	6,89E-05 GLO: hexafluoroethane production, from fluorination of tetrafluoroethane ecoinvent 3.5
SF6	kg		8,96E-06	8,96E-06	8,96E-06 RER: sulphur hexafluoride production, liquid ecoinvent 3.5

[1] For high-purity materials, adjustments factors according to Prakash et al. [2013] were applied.

Process		Wafer	Good die out		Packaged die		GaBi process
NaOH (for wastewater treatment)	kg		2,04E-03	2,04E-03		2,04E-03	EU-28: Sodium hydroxyde (caustic soda) mix (100%) ts
Polymer	kg				2,47E-05	2,47E-05	
Au	kg				4,65E-07	4,65E-07	GLO: Gold (primary) ts
Carbon Black	kg				4,65E-07	4,65E-07	DE: Carbon black (furnace black; general purpose) ts
Ag	kg				1,62E-06	1,62E-06	GLO: Silver mix ts
Cu	kg				2,33E-07	2,33E-07	GLO: Copper mix (99,999% from electrolysis) ts
Sn	kg				5,49E-05	5,49E-05	GLO: Tin ts
BT-Core (Bismaleimidetriazine)+ Cu+Au+Ni	kg				1,22E-04	1,22E-04	
Emissions							
CO2	kg	8,33E-03		1,15E-02		1,15E-02	
CO	kg	1,67E-04		2,30E-04		2,30E-04	
Nox	kg	1,38E-05		1,90E-05		1,90E-05	
Methanol	kg	8,51E-05		1,17E-04		1,17E-04	
Methane	kg	8,50E-05		1,17E-04		1,17E-04	
Ethan	kg	2,90E-05		4,00E-05		4,00E-05	
Particles	kg	2,01E-04		2,77E-04		2,77E-04	
H2O	kg	1,88E-03		2,59E-03		2,59E-03	
SO2	kg	3,44E-05		4,75E-05		4,75E-05	
Hydrogen	kg	1,25E-04		1,73E-04		1,73E-04	
HFC-23 (Trifluormethane)	kg		2,26E-06	2,26E-06		2,26E-06	modelled directly as CO2-emissions
Perfluorethane (C2F6)	kg		3,84E-06	3,84E-06		3,84E-06	
Tetrafluormethane (CF4)	kg		3,25E-06	3,25E-06		3,25E-06	
Perfluorpropane (C3F8)	kg		2,26E-06	2,26E-06		2,26E-06	
SF6	kg		2,26E-06	2,26E-06		2,26E-06	
NF3	kg		1,56E-05	1,56E-05		1,56E-05	

3.1.9.4 Passive components

Passive components were modelled with corresponding data sets from the GaBi electronics extension, scaled by number of pieces. If no corresponding data set was available in GaBi, an ecoinvent data set for unspecific passive components was used and scaled by weight.

3.1.10 Protection bumper

The Fairphone 3 is delivered with a protection bumper, therefore it is included in the reference flow. It consists of 13.7 g TPU from bio-based oil. As no life cycle data is available for this specific material it is modelled as conventional TPU.

3.1.11 Screwdriver

The screwdriver consists of a metal (~1.1 g stainless steel) and a plastic part (2.9 g polyamide) and was modelled by weight.

3.1.12 Packaging

The packaging consists of a sales and a distribution packaging. The distribution packaging is proportionality reflected in the modelling. The detailed parts and assigned GaBi data sets are listed in the annex in Table 8-12.

3.1.13 Final assembly

For the final assembly, electricity consumption of the final assembly process was considered using the Chinese energy grid mix. Additionally, the consumption of ethyl alcohol and cloths from cleaning processes in the packaging process and nitrogen gas used in the reflow oven are considered. This is based on primary data from the manufacturer Arima comms in China as shown in Table 3-9.

Table 3-9: Final assembly

Energy use		**GaBi dataset**
Electricity, from grid	2.186 kWh	CN: Electricity grid mix ts
Process material		
Ethyl alcohol (95% purity)	0.39 g	RoW: benzyl alcohol production ecoinvent 3.5
Nitrogen (gas, >95% purity)	0,50 g	EU 28 Nitrogen (gaseous)
Cloth (lint free)	0.15 g	GLO: Cotton fibre (bales after ginning) CottonInc

3.2 Use Phase

The following use pattern is assumed for the Fairphone 3 baseline scenario:

- Daily charging
- One charging cycle consumes 19.21 Wh, which results in 7.01 kWh/a

The energy per charging cycle is based on measurements carried out at Fraunhofer IZM with new and aged (state of health: 80 % capacity) batteries. As expected, aged batteries showed a lower efficiency. The average energy consumption was used to calculate the use phase consumption.

No repairs except battery replacements were assumed for the baseline scenario, but three different use-times were calculated:

- 3 years with one replacement battery
- 5 years with 2 replacement batteries

- 7 years with 3 replacement batteries

For the number of replacement batteries considered, laboratory cycle life testing of the battery was carried out. This resulted in the following insights: charging with the provided Quick Charge 3.0 enabled charger resulted in a charging rate of 0.67C (2A). The charging efficiency (power drawn from the grid relative to the battery capacity) with the above-mentioned charger was 60 %.

Battery cycle life testing at 0.67C in accordance with IEC 61960 showed that the batteries could, on average, withstand more than 850 cycles while retaining a capacity (SOH) of 80 %, and two out of three tested cells could even endure up to 1000 cycles.

Previous LCA studies of smartphones have worked with the conservative assumption that the battery is fully charged and discharged once every day, resulting in 365 charge/discharge cycles per year. Empirical data suggests that the actual number may be closer to 230 cycles on average annually [Clemm et al. 2016]. This study therefore works with the following assumptions: The battery durability is enough to last for 3 years of use, after which it needs to be replaced with a new battery. To calculate the use phase energy consumption, the study adopts the conservative assumption that the battery is fully charged once every day as explained above.

The electricity is assigned according to the distribution of sales within Europe (see Table 8-2 in the annex) assigning national electricity grid mixes.

3.3 Transport

The transport is separated in three main parts:

- Transport of parts from tier 2 suppliers to final assembly in China
- Transport of the final product to the distribution hub in Europe
- Transport to customer from distribution hub within Europe

The transportation is modelled as so-called tonne kilometres (tkm), considering transported weight and distance.

3.3.1 Transport to final assembly

For the transport to final assembly, the following modes of transportation are assumed:

- Truck delivery within China
- Air freight for international transportation

The transportation is scaled by distance and weight. For the components, a weight overhead is calculated to represent packaging. Therefore, the following factors are used (as for the Fairphone 2 LCA):

- 0.1 for components > 0.5 g
- 0.94 for components < 0.5 g

This results in the following distances:

- Air freight: 0.199 tkm
- Truck: 0.253 tkm

3.3.2 Transport to distribution hub

The phone is transported from the final assembly in China to the distribution hub in the Netherlands by train freight for regular orders, for which a distance of 1.632 tkm was modelled.

3.3.3
Transport to consumer

The phone is transported by truck within Europe. An average distance from the distribution hub to the different countries is assumed for this (Table 8-3 in the annex). These transport distances are weighted according to the distribution of sales.

3.4 End-of-Life

For the reference case scenario, a conservative approach has been taken i.e. that the Fairphone 3 device is assumed to be discarded as a regular phone and join the wider WEEE recycling stream. This approach relies on the assumption that this is the most usual route for smartphones to follow in their end of life. Additionally, this was also the modelling approach for the Fairphone 2 LCA and using alternative modelling options could therefore hinder comparability.

Due to a lack of specific data on smartphone recycling, several assumptions needed to be made, which will be explained in this section. To begin with, the device is assumed to be disposed of in its entirety, meaning that no mass losses take place between the disposal and the recycling plant. On the lines of the EoL scenario of Fairphone 2 [Proske et al. 2016], no specific point of disposal was assumed and instead a general transport to the plant was modelled as follows, in accordance with [Hischier, 2007].

- Total transportation distance from user to recycling plant: 1500 km
- Mode of transportation is by lorry (75 % of distance) and by train (25 % of distance).

Following the Umicore recycling process [Hagelüken 2006], the device is set to have the battery removed first (depollution) and then the rest is sent to the material recovery streamline as scrap. The main processes included in the model are:

- Copper smelting
- Electrowinning
- Precious metal recovery

In the depollution step, 95% of the batteries are assumed to be separated correctly [Sommer 2013] and a recovery rate of 95% for the copper and cobalt contained is estimated. In the electrowinning step copper is recovered with a rate of 95%. Finally, in the precious metal recovery step, three elements are yielded: gold, silver and palladium, all with a rate of 95%. All recovery rates are based on Chancerel et al. [2016]. The absolute amounts recovered are in turn based on the cross comparison of the bill of materials provided by Fairphone and the material declarations of the suppliers themselves. Additionally, a disassembly of a Fairphone 3 device carried out at Fraunhofer IZM has been used as backup for completing weights and material data. Table 3-10 below shows a summary of the materials considered in the EOL modelling, their recovery rates and the mass in the device.

Table 3-10: Recycling relevant material content in the device and recovery rate

Material	Recovery rate	Mass in device
Copper	95%	10,28 g
Cobalt	95%	11,25 g
Gold	95%	28,17 mg
Silver	95%	44,19 mg
Palladium	95%	7,5 mg

All burdens as well as credits of the material recovery have been allocated to the Fairphone 3 under study. This has been decided in order not to hinder comparability with the Fairphone 2 LCA study. For the credits' estimation, direct correspondence has

been assumed between recovered secondary material and avoided primary material production.

3.5 Scenarios

In addition to the baseline scenario with different years of use, two repair scenarios are calculated, which are described in the following.

3.5.1 Repair scenario A

Repair scenario A addresses the repair through module replacement:

- 5 years use
- 1 replacement battery
- And the repair of one module per phone based on repair and insurance statistics:
  - 63% display
  - 16% connectors resulting in
    - 9% top module (earphone jack)
    - 7% bottom module (USB-C connector)
  - 10% camera module
  - 5% speaker
  - 3% back cover and protection bumper
  - 3% mainboard

It is assumed that over the course of 5 years each phone is repaired once. The numbers are roughly based on numbers published by Clickrepair[1] with the following figures:

- 67.4% Display
  - 50.0% housings
  - 33.9% battery
  - 16.1% connectors
  - 7.9% camera

An older study from Clickrepair [click repair 2016] states a share of water damages of 5%. It is assumed that roughly half of these water damages lead to defects on the mainboard.

The battery is not included in the assumption of damages and replacement is based on degradation assumptions (see section 3.2). Additionally, it is assumed that broken housings are more frequent for phones with more fragile (glass) housings. Therefore, the number of replacement back covers is reduced compared to the statistics. The protection bumper is assumed to be replaced together with the back cover.

For the replacement batteries and spare part modules, additional transport and packaging is assumed. The changes in end-of-life are not assessed for the repair scenarios.

3.5.2 Repair scenario B

The repair scenario considers the same use phase and replacement rates of modules as repair scenario A. However, repair scenario B considers additional repair of the modules itself on board-level:

- Top module: earphone jack replaced

[1] https://www.clickrepair.de/images/presse/downloads/pdf/clickrepair-smartphone-repair-study-2019-en.pdf

- Bottom module: new microphone
- Camera module: new camera
- Mainboard: new power supply unit

For transport distances, a board-level repair in France is assumed. For the repair services, it is assumed that only the broken module and not the whole phone is transported.

It is assumed that 75% of broken modules (with the potential of repair, so no re-transport of e.g. displays) are sent back to Fairphone B.V. and 50% of these could be repaired. This results in 63% new modules still needed for top, bottom, camera module and mainboard plus individual components.

For the board-level repairs, energy consumption of de-soldering and re-soldering processes were measured at a rework station at Fraunhofer IZM to approximate board-level repair in professional environment.

Materials and methods

Standard activities involved in rework are as follows:

[1]Desoldering: Application of heat to the PCB and BGA up until the melting point of the solder balls, then picking up the component, commonly with a vacuum nozzle

[2]Residual solder removal: Application of heat to melt the residual solder on the PCB, and removal with a vacuum nozzle

[3]Soldering in: The new or repaired (and re-balled) component is placed on the PCB and soldered in using heat (application of heat to the PCB and the BGA component)

Professional board-level repair in practice may be performed using industrial rework stations offering precise pre-programmable temperature and air flow profiles, high placement accuracy and bottom heating of the PCB. This process is approximated in this project using a manual rework station. The power consumption of the rework station in different operational modes was measured using a laboratory power meter.

- Weller Multi-Digital Rework Station WMD 3 (with In-Built Pump)
  - Power Input: 310W
  - Temperature control soldering/desoldering 50-450°C; hot air pencil 50-550°C
  - Pump: max. low pressure 0.7 bar; max. conveyance 20 l/min; hot air max. 10 l/min
- Hameg Programmable Power Meter HM8115-2

Generic profiles were derived from rework training material and referring to standard IPC/JEDEC J-STD-020E. The air flow on the rework station can be set between 10 % and 100 %. The temperature indicates the settings of the machine, not the temperature of the PCB or sample component. The power consumption of each operational mode was measured for at least 30 seconds to obtain average values.

Results

The energy consumptions shown in Table 3-11 were measured, leading to simplified profile shown in Table 3-12.

Table 3-11: Desoldering/reflow (hot air flow from nozzle) – measurements from Fraunhofer IZM

Phase/device status	Air flow [%]	Temperature [°C]	Measured average power consumption [W]
Standby	n/a	n/a	3,38
Heating up	n/a	300	19,46
Operation	50	300	49,04

Phase/device status	Air flow [%]	Temperature [°C]	Measured average power consumption [W]
	50	350	49,39
	75	300	70,39
	75	350	70,39
	100	300	99,17
	100	350	109,43

Table 3-12: Simplified profile for desoldering/reflow energy consumption

Phase / device status	Time [s]	Power consumption [W]	Energy consumption [Ws]
Standby	180	3,4	612
Heating up / 300°C	30	19,5	585
Pre-heat / 300°C; 50%	60	49,0	2.940
Soak / 300°C; 75%	120	70,4	8.448
Reflow / 350°C; 100%	45	109,4	4.923
Total [Ws]			**17.508**
Total [Wh]			**4,86**

In a simplified scenario, the above process flow is assumed for both desoldering and soldering in, in addition to residual solder removal described below in Table 3-13.

Table 3-13: Residual solder removal

Phase / device status	Air flow [%]	Temperature [°C]	Measured average power consumption [W]
Standby	n/a	n/a	3,40
Heat up	n/a	300	89,12
Operation	10	300	56,86
	50	300	102,33
	75	300	143,95

The following simplified profile for residual solder removal energy consumption is considered, assuming this process takes place right after desoldering, therefore no standby or heating up is accounted for.

Table 3-14: Simplified profile for residual solder removal

Phase / device status	Time [s]	Power consumption [W]	Energy consumption [Ws]
Operation / 300°C; 75%	30	145	4.350
Total [Wh]			**1,21**

The energy consumption of the entire process is therefore:

$$4{,}86\ Wh + 1{,}21\ Wh + 4{,}86\ Wh = 10{,}93\ Wh$$

4
Impact Assessment

Based on material flows defined in the LCI, the life cycle impact assessment (LCIA) will be carried out according to the recognized CML methodology [CML 2001] using LCA software GaBi. For the following impact categories, the results will be displayed and discussed in detail:

- Climate change:
  - Global Warming Potential (GWP) 100 years in kg CO_2 equivalents
- Resource depletion:
  - Abiotic resource depletion (ADP) elements in kg Sb equivalents
  - ADP fossil in MJ
- Human toxicity:
  - Human Toxicity Potential in kg DCB equivalents
- Ecotoxicity:
  - Terrestrial Ecotoxicity Potential in kg DCB equivalents

Normalization, grouping, and weighting of the results (optional steps in the impact assessment of an LCA) will not be applied.

4.1
Definition of impact categories

For the impact categories covered in this LCA study, the following definitions from CML are used:

- Global Warming Potential (GWP) 100 years: "Global warming is considered as a global effect. Global warming - or the "greenhouse effect" - is the effect of increasing temperature in the lower atmosphere. The lower atmosphere is normally heated by incoming radiation from the outer atmosphere (from the sun). A part of the radiation is normally reflected from the surface of the earth (land or oceans). The content of carbon dioxide (CO2) and other "greenhouse" gasses (e.g. methane (CH4), nitrogen dioxide (NO2), chlorofluorocarbons etc.) in the atmosphere reflect the infrared (IR)-radiation, resulting in the greenhouse effect i.e. an increase of temperature in the lower atmosphere to a level above normal. […] The GWP for greenhouse gases is expressed as CO2-equivalents, i.e. the effects are expressed relatively to the effect of CO2." [Stranddorf 2005]
- Resource depletion: "The model of abiotic resource depletion […] is a function of the annual extraction rate and geological reserve of a resource. In the model as presently defined, the ultimate reserve is considered the best estimate of the ultimately extractable reserve and also the most stable parameter for the reserve parameter. However, data for this parameter will by definition never be available. As a proxy, we suggest the ultimate reserve (crustal content)." [Oers 2016]
  - Abiotic resource depletion (ADP) elements: "The impact category for elements is a heterogeneous group, consisting of elements and compounds with a variety of functions (all functions being considered of equal importance)." [Oers 2016]
  - ADP fossil: "The resources in the impact category of fossil fuels are fuels like oil, natural gas, and coal, which are all energy carriers and assumed to be mutually

substitutable. As a consequence, the stock of the fossil fuels is formed by the total amount of fossil fuels, expressed in Megajoules (MJ)." [Oers 2016]

- Human Toxicity Potential: "The normalisation references for human toxicity via the environment should reflect the total human toxic load in the reference area caused by human activity, i.e. the potential risk connected to exposure from the environment (via air, soil, provisions and drinking water) as a result of emissions to the environment from industrial production, traffic, power plants etc. Ideally, all emissions of substances potentially affecting human health should be quantified and assessed. However, the multitude of known substances (>100.000) and an even larger number of emission sources logically makes that approach unfeasible. The inventory used for calculating the normalisation references is therefore based on available emission registrations for substances, which are believed to contribute significantly to the overall load." [Stranddorf 2005]
- Terrestrial Ecotoxicity Potential: "The impact category ecotoxicity covers the possible effects of toxic substances released during the life cycle of a product to the environment. The sources of toxicants are quite different depending on the type of environment as well as the methods used in the assessment of the impact. Consequently, the impact on aquatic and terrestrial systems are usually considered separately. In principle, the normalisation reference for ecotoxicology includes all toxic substances emitted to the environment due to human activities, and it requires extensive data on all types of emissions. In general, however, only few data on environmental releases of toxic substances are available, and the normalisation there-fore relies on extrapolations from a relatively limited set of data.
  The normalisation reference includes the following emission types: […] Terrestrial environment: Pesticide use, Agricultural use of sewage sludge, Atmospheric deposition of metals and dioxins" [Stranddorf 2005]

4.2 Results

The assessment results in a GWP of 39.5 kg CO2e (see Table 4-1). The main impact for all impact categories is caused by the production phase. Transport and use phase have a smaller impact. EoL has a negative impact value, meaning a positive potential for the environment. This is especially relevant for the impact category ADP elements. Most of this impact could potentially be recovered through recycling (see Figure 4-1.)

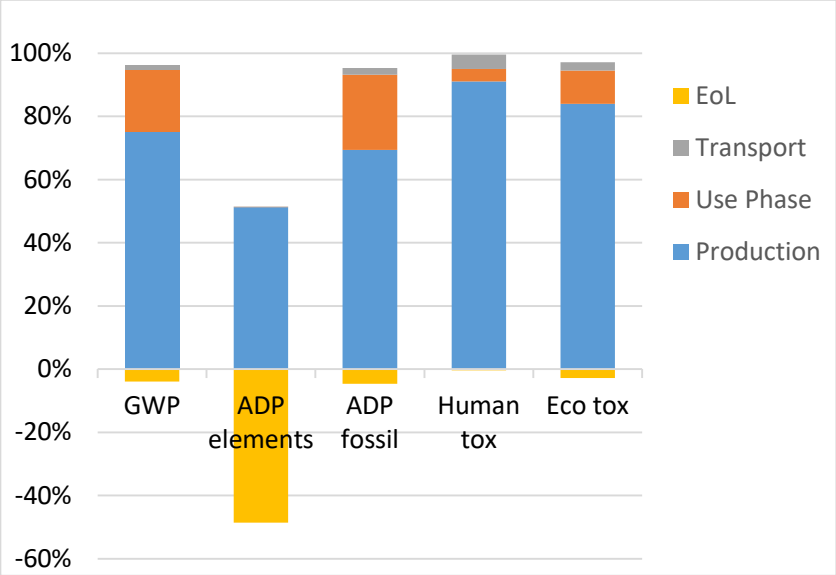

Figure 4-1: Relative impact per life cycle phase (3-year scenario)

Table 4-1: Absolute impacts of the whole life cycle (3-year scenario)

	GWP	ADP elements	ADP fossil	Human tox	Eco tox
	kg CO2e	kg Sb eq.	MJ	kg DCB eq.	kg DCB eq.
Totals	3,95E+01	8,40E-05	3,44E+02	8,63E+00	7,60E-02
Production	3,22E+01	1,51E-03	2,63E+02	7,92E+00	6,76E-02
Use Phase	8,40E+00	3,39E-06	9,03E+01	3,42E-01	8,49E-03
Transport	5,94E-01	5,79E-07	8,36E+00	3,98E-01	2,16E-03
EoL	-1,67E+00	-1,43E-03	-1,76E+01	-3,46E-02	-2,29E-03

The difference between the three baseline scenarios is the varying length of the phone's use-time. The use phase impacts therefore scale directly with number of years in use. Within the production phase, only the impact of the battery changes and, connected to it, a small increase of package and transport impact is caused by the additional transport of the replacement battery to the customer (see Table 8-4 in the annex).

The absolute impact increases with the length of the use phase. However, the impact per year of use decreases with longer use as the main product impact is distributed across a longer useful life (see Figure 4-2). The figure shows a decrease of 29% for the yearly GWP impact category when extending lifetime to 5 years and one of 42% when extended to 7 years.

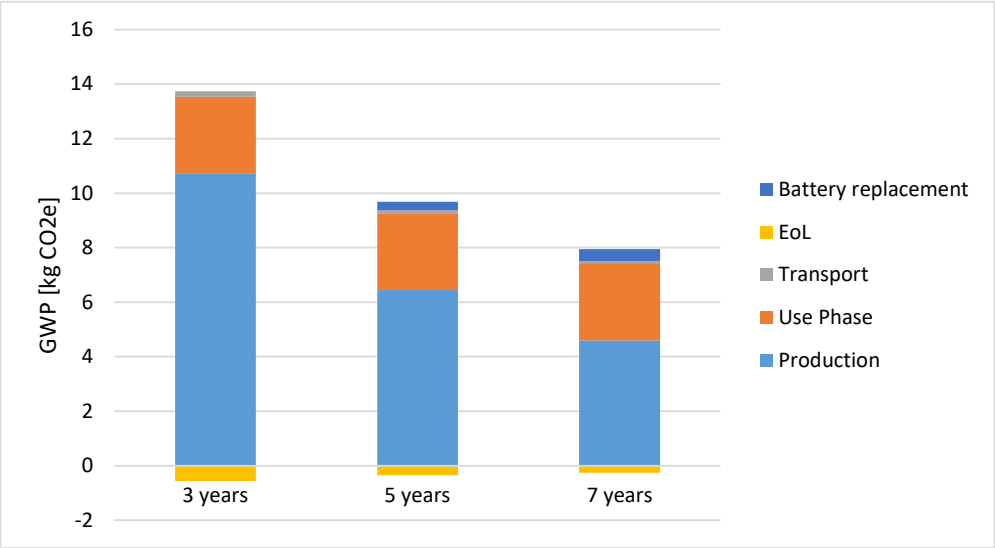

Figure 4-2: Impact per year of use (baseline scenarios)

4.3 Contribution Analysis

The following contribution analysis is focussed on the baseline scenario with 3 years of use. Additional numbers for packaging, transport and production of the replacement battery can be found in the annex in Table 8-4.

4.3.1 Production

Within the production phase, the production of the core module and therein specifically the mainboard causes the highest impact for all impact categories (see Figure 4-3 and Table 4-2). For the 5 and 7 years scenario, the impact of 1, respectively 2, batteries needs to be added accordingly, changing the relative impact of the modules only slightly.

The final assembly has an impact between 0.01 % (ADP elements) and 6.8% (GWP) of the total production impact, the display module between 7% (GWP) and 15% (ADP elements). Back cover, protection bumper and screwdriver cause a combined impact of less than 1%. Packaging is only relevant for the impact category eco toxicity (8.2%) due to paper and cardboard production.

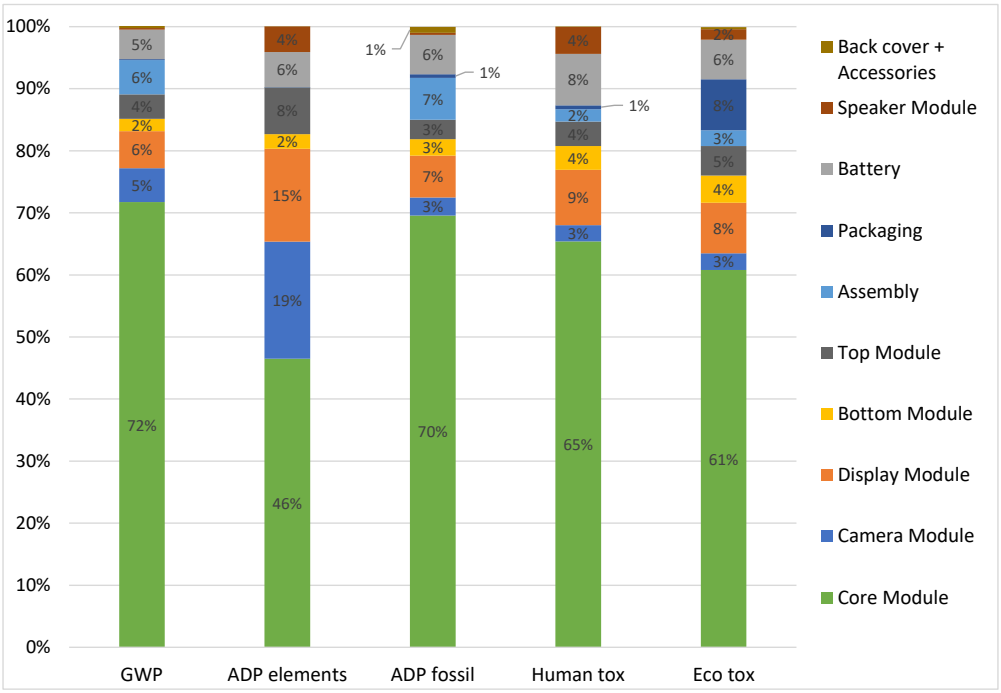

Figure 4-3: Relative impacts of the production phase per impact category (3-year scenario)

Table 4-2: Absolute impacts of the production phase (3-year scenario)

	GWP	**ADP elements**	**ADP fossil**	**Human tox**	**Eco tox**
	kg CO_2e	kg Sb-e	MJ	kg DCB-e	kg DCB-e
Production	3,22E+01	1,51E-03	2,63E+02	7,92E+00	6,76E-02
Assembly	1,78E+00	1,48E-07	1,78E+01	1,59E-01	1,70E-03
Back cover	4,24E-02	1,12E-07	1,08E+00	2,36E-03	7,39E-05
Battery	1,54E+00	8,55E-05	1,66E+01	6,57E-01	4,32E-03
Bottom Module	6,35E-01	3,55E-05	7,03E+00	3,06E-01	2,95E-03
Camera Module	1,76E+00	2,85E-04	7,61E+00	2,06E-01	1,83E-03
Core Module	2,31E+01	7,02E-04	1,83E+02	5,18E+00	4,11E-02
Display Module	1,92E+00	2,26E-04	1,77E+01	7,06E-01	5,50E-03
Packaging	4,55E-02	1,07E-07	1,56E+00	4,91E-02	5,55E-03
Speaker Module	7,84E-02	6,23E-05	8,58E-01	3,45E-01	1,14E-03
Top Module	1,27E+00	1,14E-04	8,19E+00	3,10E-01	3,23E-03
Screwdriver	1,26E-02	2,73E-08	2,81E-01	9,25E-04	1,89E-05
Protection bumper	5,58E-02	1,70E-07	1,23E+00	1,76E-03	1,48E-04

Broken down per type of component, the major share is caused by the production impact of the ICs, followed by the PCBs. Connectors have the highest relative impact in

the category ADP elements (14.7%) due to the amount of gold used (see Figure 4-4 and Table 4-3).

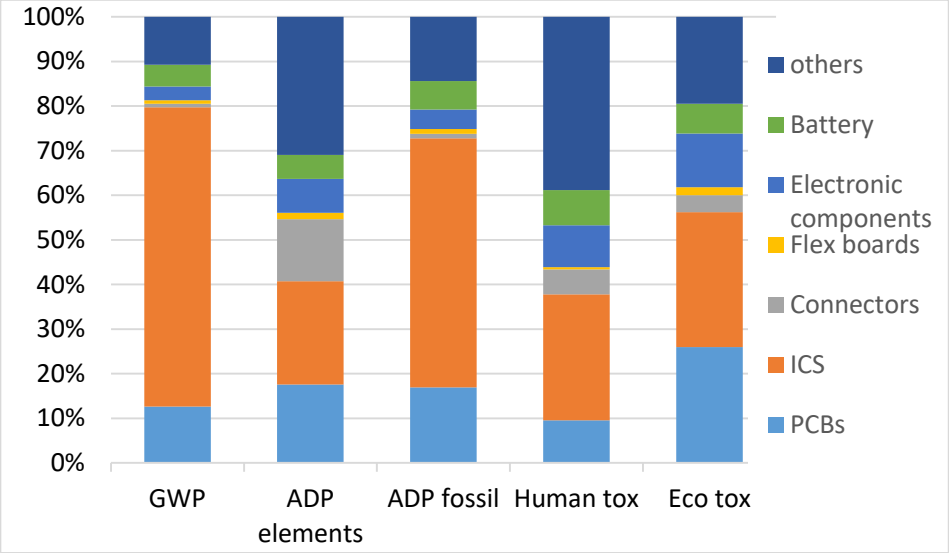

Figure 4-4: Relative impact per component type of the phone (without packaging, assembly, accessories)

Table 4-3: Absolute impact of components

	GWP	**ADP elements**	**ADP fossil**	**Human tox**	**Eco tox**
	kg CO_2e	kg Sb e	MJ	kg DCB e	kg DCB e
ICS	2,14E+01	3,70E-04	1,44E+02	2,37E+00	1,95E-02
Connectors	2,54E-01	2,21E-04	2,71E+00	4,68E-01	2,47E-03
Flex boards	2,58E-01	2,34E-05	2,72E+00	4,35E-02	1,14E-03
PCBs	4,03E+00	2,81E-04	4,38E+01	7,98E-01	1,67E-02
Electronic components	9,88E-01	1,21E-04	1,13E+01	7,86E-01	7,75E-03
others	3,43E+00	4,94E-04	3,71E+01	3,25E+00	1,25E-02

The core module causes more than half of the total production impact and is therefore analysed in detail in the following. The mainboard's ICs cause more than 80% of the related GWP impact. Within them, the combined RAM/Flash package causes the major share. The 8-layer rigid PCB has a share between 12% and 31%, whereas the flex boards of the connectors only have a share of 0.3% to 1.1% (see Figure 4-5).

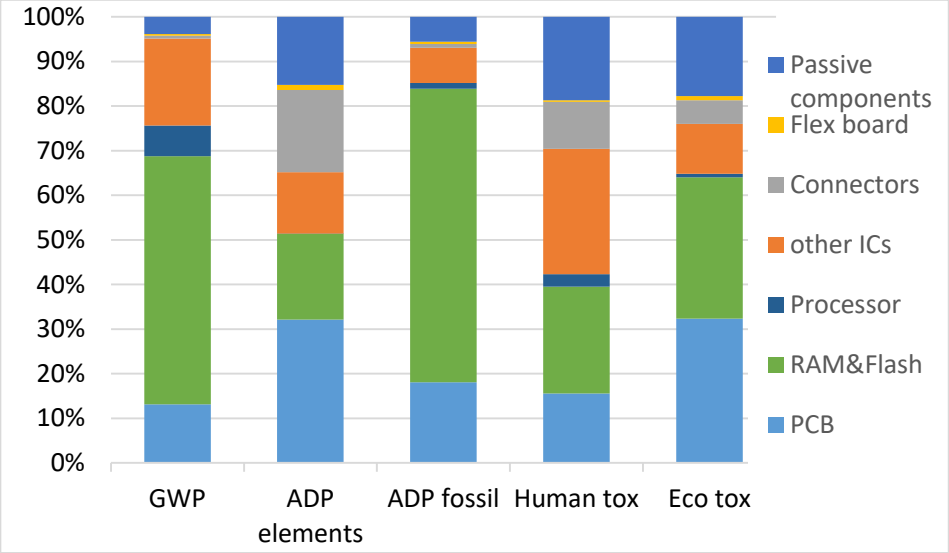

Figure 4-5: Relative impact of the core module per component type

4.3.2 Use phase

The use phase emissions cause a smaller share of the life cycle emissions of the Fairphone 3. Within the use phase, emissions caused by Germany's electricity mix have a share of 50 to 60% while making up 44 % of the sales (see Figure 8-1 in the annex).

The effect that the relative environmental impact differs from the share of sales is caused by the different energy grid mixes which exist in the countries across Europe. For instance, the German energy mix causes more emissions than the European average. Therefore, the relative environmental impact is higher than the share of sales. In contrast, the French energy grid mix has low GHG emissions leading to a significantly lower share in the environmental impact than the share of sales.

There are no major differences regarding the impact per country between the different impact categories (see Figure 4-6 and Table 8-5 in the annex).

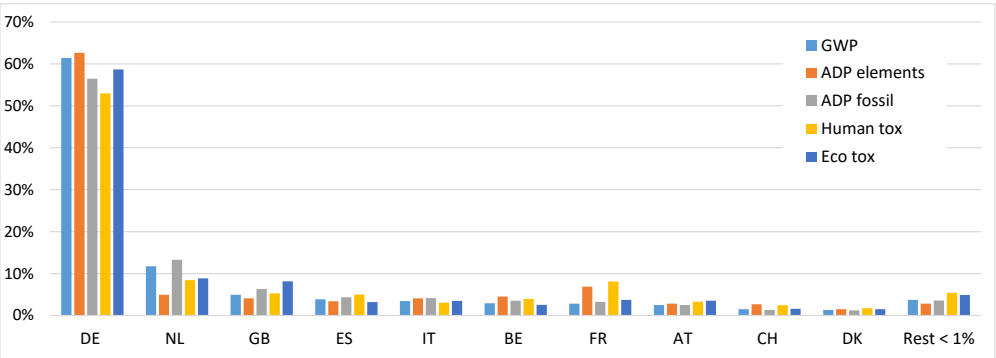

Figure 4-6: Relative impacts of the use phase per country and impact category

4.3.3 Transport

The transportation phase emissions cause a smaller share of the overall life cycle impact. The highest influence of the transportation phase can be seen for the impact category human toxicity.

The main influence from the transport processes is caused by the air freight transport which is mainly located in the transport to some pieces to final assembly (see Figure 4-7).

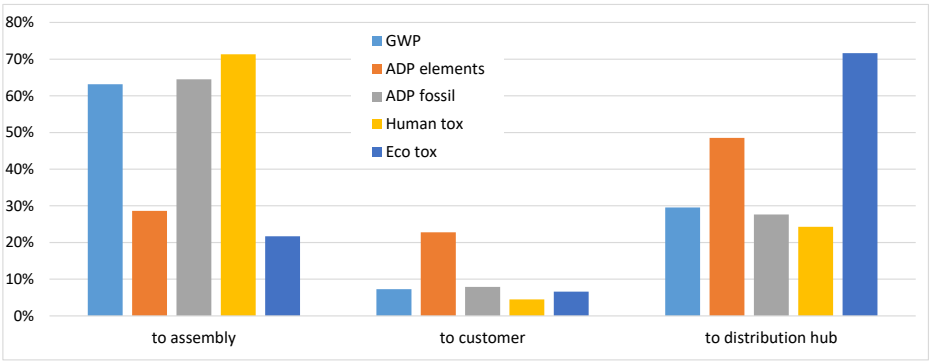

Figure 4-7: Relative impact of transportation phases "to assembly", "to distribution", and "to customer" (3-year scenario)

There are no major differences between the impact categories, except for the impact category Ecotoxicity, which is more influenced by train transport (see Figure 4-8).

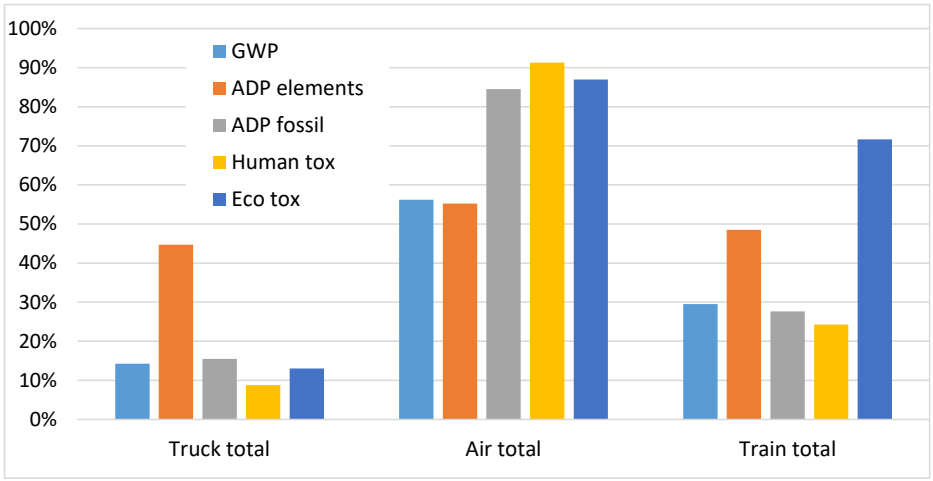

Figure 4-8: Relative impact of transportation phase between modes of transportation "air", "train" and "truck" (3 year scenario)

The absolute values for the 3-year use scenario can be found in Table 4-4. For the 5-year and 7-year scenario additional transport for one/two batteries is added to this according to Table 8-4 in the annex. The transport to the distribution hub by train is a recent change implemented by Fairphone, which previously took place by air freight. This reduces drastically its related impacts (around 87% lower GWP).

Table 4-4: Results of the transport phase (3 years scenario)

Impact category		to assembly	to customer	to distribution hub
GWP	kg CO_2e	3,75E-01	4,31E-02	1,75E-01
ADP elements	kg Sb-e	1,66E-07	1,32E-07	2,81E-07
ADP fossil	MJ	5,39E+00	6,58E-01	2,31E+00
Human tox	kg DCB-e	2,84E-01	1,78E-02	9,66E-02
Eco tox	kg DCB-e	4,69E-04	1,43E-04	1,55E-03

4.3.4 End-of-Life

The impact values for the end-of-life phase are negative for all impact categories, meaning that they have a positive impact for the environment. The positive effect stems from the precious metal recycling (see Figure 4-9) and thereby mainly from the gold recycling. Battery recycling and copper smelter have a positive value for the toxicity impact categories, but this is outweighed by the impact of precious metal recycling. Human toxicity shows the strongest differences between the processes. The absolute values compared to whole life cycle small are still small for all impact categories except ADP elements (Table 4-5: Results of the EoL phase (3-year scenario).

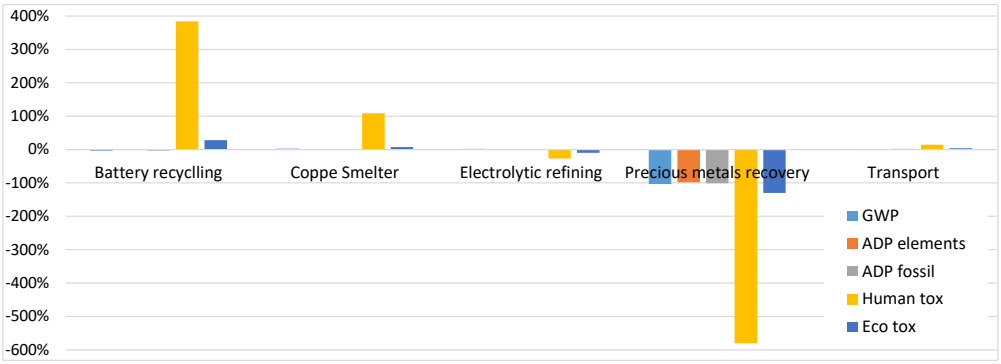

Figure 4-9: Relative impact of EoL phase between battery recycling, copper smelter, electrolytic refining, precious metals recovery and transport (3-year scenario)

Table 4-5: Results of the EoL phase (3-year scenario)

Impact category		Battery recycling	Copper Smelter	Electrolytic refining	Precious metals recovery	Transport
GWP	kg CO_2e	-6,06E-02	4,84E-02	3,64E-02	-1,72E+00	2,67E-02
ADP elements	kg Sb-e	-7,59E-06	6,40E-09	-2,04E-05	-1,40E-03	6,28E-08
ADP fossil	MJ	-5,53E-01	3,09E-01	9,90E-02	-1,78E+01	4,05E-01
Human tox	kg DCB-e	1,33E-01	3,76E-02	-9,27E-03	-2,01E-01	5,07E-03
Eco tox	kg DCB-e	6,51E-04	1,69E-04	-2,19E-04	-2,98E-03	8,38E-05

4.3.5 Modularity

The impact of the modularity overhead (as it was shown also for the Fairphone 2) is connected to additional module housing, module connectors and the connecting flex boards as well as the additional PCB area for the board-to-board connector between Display and mainboard. The impact is shown in Table 4-6 and Figure 4-10.

Table 4-6: Impacts connected to the modularity

	GWP	ADP elements	ADP fossil	Human tox	Eco tox
	kg CO_2e	kg Sb eq.	MJ	kg DCB eq.	kg DCB eq.
Totals	7,44E-01	2,60E-04	8,19E+00	5,54E-01	4,53E-03
Connectors	2,54E-01	2,21E-04	2,71E+00	4,68E-01	2,47E-03
Flex	2,58E-01	2,34E-05	2,72E+00	4,35E-02	1,14E-03
Additional PCB	2,16E-01	1,51E-05	2,34E+00	4,21E-02	8,84E-04
Housing	1,64E-02	4,43E-08	4,17E-01	9,18E-04	3,59E-05

For GWP, ADP fossil and Eco tox, additional PCB area, flex cables and connectors cause each about one third of the modularity overhead. ADP elements and Human tox are

driven more strongly by gold, leading to the connectors causing a stronger impact. Module housing causes a minor relative impact.

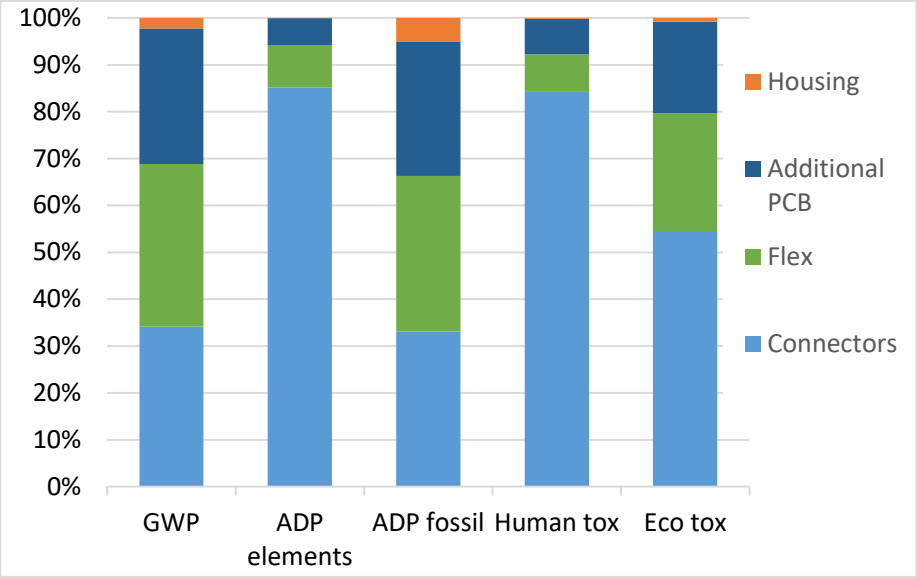

Figure 4-10: Relative impacts connected to modularity

The modularity overhead causes between 2.3 % (GWP) and 17.2% (ADP elements) of the total production impact.

4.4 Repair Scenarios

The results of the two different repair scenarios are presented in the following.

4.4.1 Repair Scenario A

Table 4-7 shows the additional impact through repair for repair scenario A without battery replacement.

Table 4-7: Additional impact through repair (scenario A), without battery replacement

Impact category	Total repair	Spare part	Packaging	Transport
GWP	2,33E+00	2,23E+00	2,28E-02	7,11E-02
ADP elements	2,05E-04	2,05E-04	1,06E-08	1,33E-07
ADP fossil	2,04E+01	1,86E+01	8,49E-01	9,66E-01
Human tox	7,12E-01	6,45E-01	2,99E-02	3,73E-02
Eco tox	8,88E-03	5,45E-03	2,87E-03	5,55E-04

Figure 4-11 shows the results per year of use for the 3-year and 5-year use scenario with and without repair. The impact of the repair itself is rather small and pays off when it leads to longer use. The difference between module replacement (scenario A) and module repair (scenario B) is too small to be visible per year of use. This is mainly caused by the very conservative assumptions of scenario b. Furthermore, the additional benefit of module repair differs significantly between the repaired modules (see discussion in the sensitivity analysis section 4.5).

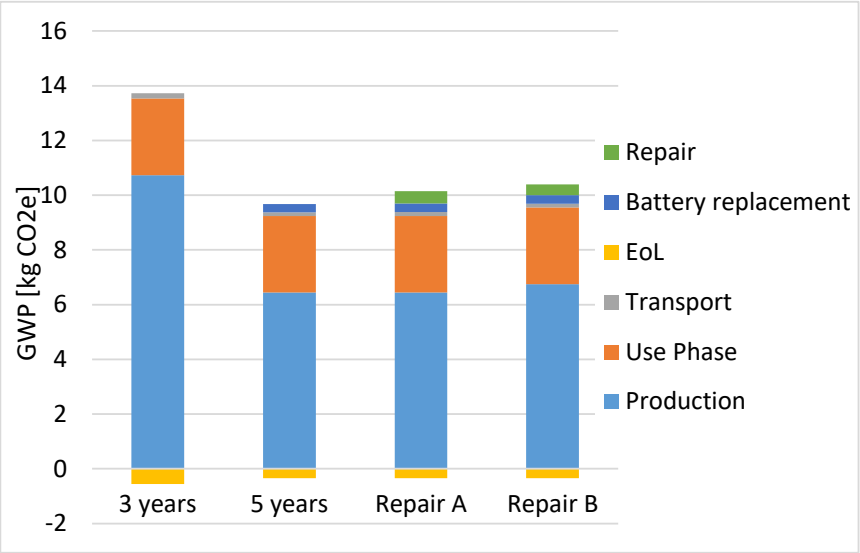

Figure 4-11: Relative impact per year use for the impact category GWP

The recent change in transport done by Fairphone removes a part of the burden associated with repair, namely the air freight emissions. This can be seen in Figure 4-12, where the main drivers in the repair overhead impacts are the spare parts themselves.

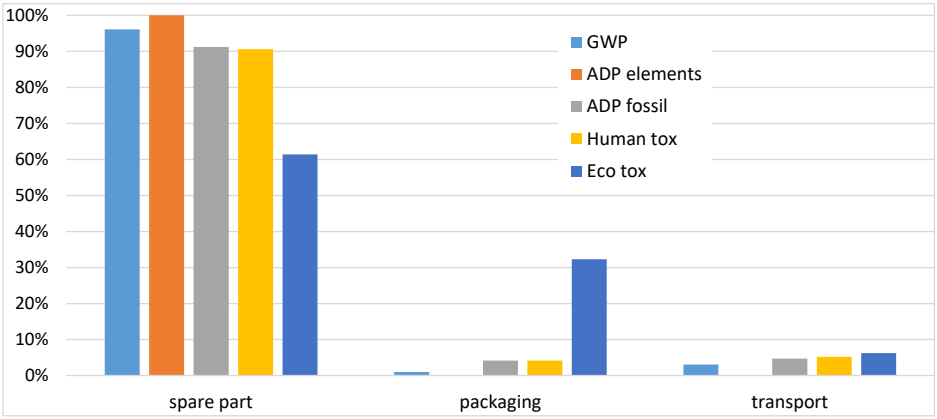

Figure 4-12: Relative impact of repair (scenario A) due to spare part, additional packaging and additional transport

4.4.2 Repair Scenario B

The absolute impact overhead of repairing is reduced due to module-level repair in scenario B. However, the effect is rather low for the assumed share of repairs (see Table 4-8 and Figure 4-13).

Table 4-8: Additional impact through repair (scenario B), without battery replacement

Impact category	Total repair	Spare part	Packaging	Transport	Module repair
GWP	2,03E+00	1,85E+00	2,62E-02	7,02E-02	8,57E-02
ADP elements	1,97E-04	1,83E-04	1,15E-08	1,33E-07	1,39E-05
ADP fossil	1,81E+01	1,59E+01	9,82E-01	9,57E-01	3,73E-01
Human tox	6,59E-01	5,77E-01	3,48E-02	3,66E-02	1,09E-02

Impact category	Total repair	Spare part	Packaging	Transport	Module repair
Eco tox	8,73E-03	4,77E-03	3,33E-03	5,40E-04	8,54E-05

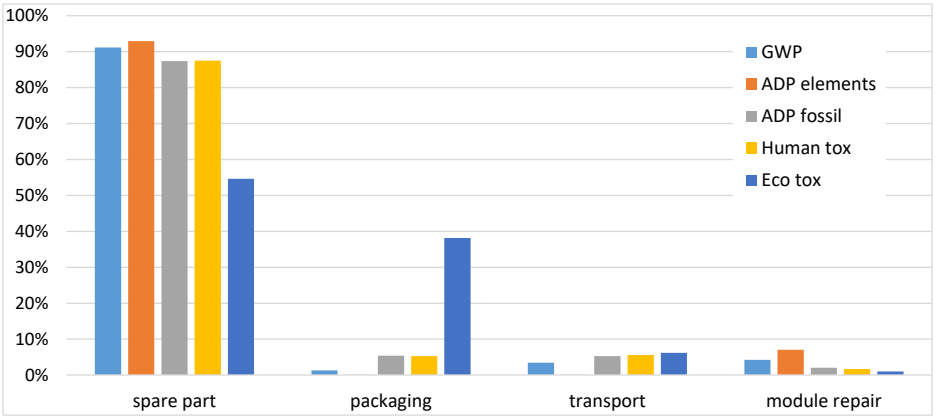

Figure 4-13: Relative impact of repair (scenario B) due to spare part, additional packaging and additional transport

4.5 Sensitivity Analysis and Interpretation

The absolute impact of 39.5 kg CO2e as well as the distribution across life cycles are comparable with other smartphone LCAs, which differ in detail but have several similarities as shown by Clément et al.[2020]. Other impact categories are harder to compare as they are not addressed in most of the other studies.

The results and contribution analysis show that the main environmental impact is caused by the mainboard, which includes the ICs and more specifically, the RAM/Flash package. This is in line with other smartphone LCAs, although the relative impact of the RAM/Flash package are higher, which might be caused by the very high die size identified in the IC analysis.

4.5.1 Display

The FP3 display was – similar to the FP2 display – modelled based on AUO environmental data as no data set was available in GaBi. The 2018 AUO material and energy consumption per produced panel area was smaller than in 2016 leading to lower relative emissions. Additionally, the IC data set used to model the ICs for the backlight had lower impacts. Although the display size increased from FP2 to FP3, the calculated impact decreased due to the new IC data set. This reduces the impact of the backlight LCDs as well as the display controller ICs. The FP3 has one display controller IC compared to two of the FP2. The overall impact of the display unit is influenced more strongly by the IC data set than by the display panel.

Compared with other smartphone LCAs, the result for the display is quite low. Ercan et al. (2016) state a value for 3.6 kg CO_2e for a 74 cm^2 display compared to 1.9 kg CO_2e for 81.9 cm^2 for the FP3 display. Ercan et al. (2016) state a higher electricity consumption for display manufacturing at about 0.1 kWh/cm^2, compared to 0.008 kWh/cm^2 from AUO (2019). However, the electricity value from AUO does not include the production of upstream materials or display electronics.

4.5.2 Connectors

Connectors in the Fairphone 3 are modelled based on the material declaration provided by Fairphone B.V. and their suppliers, therefore neglecting possible losses in the manufacturing processes. For sensitivity reasons, a further analysis was done to assess the possible overhead.

To model the connector manufacturing processes, the following choices were made:

- The functional unit was set to be a female BtB connector and in terms of weight and materials, all connectors are assumed as equal.
- The processes include housing fabrication through injection moulding, the contact fabrication (modelled as sheet rolling of copper) and the contact plating.
- For the process modelling, pre-existing databases from Ecoinvent and Thinkstep were used.

The final individual GWP impact related to the production of a connector was then calculated to be 7.11E-05 kg of CO_2e. For the sensitivity analysis the focus will be in the board to board connectors, from which Fairphone 3 has 6 in total. A pair each for connecting the top, bottom and camera modules to the mainboard. The overhead modelling does not apply to the pogo pins connector attaching the display and core modules. The total process related overhead would then be 4,266e-4 kg of CO_2e. Table 4-9 shows that the total share of the connector production alongside the material related impacts is low for the connectors themselves and negligible on a broader scope. It should be borne in mind that the process modelling has a limited scope (not all steps involved in the actual process could be included in the model due to lack of data availability) and that a number of assumptions were done.

Table 4-9: Connectors manufacturing overhead

Process impacts	Material impacts	Connectors totals (materials + processes)	Share
[kg CO_2e]	[kg CO_2e]	[kg CO_2e]	
4,266E-4	2,54E-01	2,544E-01	0,17 %

4.5.3 Integrated Circuits

ICs have a very strong impact on the overall result. At the same time, it is a topic where up-to-date life cycle data is scarce and technology advances fast. Therefore, these results are connected with higher uncertainties than other aspects of the phone.

All ICs are modelled based on silicon die data, although at least one chip (WiFi) in the Fairphone three contains a Gallium-Arsenide die. However, no life cycle data is available for that material.

Data is scaled by the die size as the area is linked to the production processes more strongly than to the weight of the dies or total chip packages. External data sources were used as described in section 3.1.9.3 as GaBi data on ICs can only be scaled per piece of packaged chip without detailed information on the die size. Thereby the die to package ratio can vary significantly. Ecoinvent data on the other hand is scaled per weight, which is not deemed a reliable factor as especially stacked dies are thinned leading to lower silicon mass but increased production impact. The FP2 LCA contains a comparison with ecoinvent IC data [Proske et al. 2016].

The impact of 3.4 kg CO_2e/cm^2 for logic chips and 2.5 for DRAM/Flash used in the study are within the range of 2.2 to 4.3 k CO_2e/cm^2 as used by Andrae et al [214] and Ercan et al. [2016] according to Clément et al. [2020]. The absolute results for the ICs

of the Fairphone 3 as well as the resulting share are within the range as reported by Clément et al. [2020] for other smartphone LCAs.

4.5.4 Final assembly

Final assembly causes an impact of 1.7 kg CO_2e per device or a share of 5.5 % of the GWP impact. This is caused mainly by the electricity consumption of 2.2 kWh per phone. There is not much data on energy consumption of assembly processes of smartphones available, but the number is considerably lower than for the Fairphone 2, for which the manufacturer stated an electricity consumption of 4.7 kWh per phone.

Huawei publishes carbon footprints for their smartphones [Huawei 2018]. The short reports do not state the energy consumption of the final assembly, but the corresponding GWP impact. They range between 2.1 and 3.2 kg CO_2e per Huawei smartphone, thereby being a little higher but in the same range as the Fairphone assembly.

4.5.5 Phone and module repair scenario

The results for the repair scenarios A and B showed little difference between simple module replacement and module repair. This is due to the assumed share of repairs with more than 63% being display replacements, where the display modules themselves cannot be repaired. For the repairable modules, the variations between scenario A and B differ as shown in Figure 4-14). The absolute benefit of module repair is significant for the repair of the mainboard, which also causes the major share of the initial production impact. Keeping as many parts of the ICs in use as possible is therefore beneficial from an environmental perspective. For the camera module, the repair of the module only leads to a reduction of 10% as the submodule with the highest environmental impact (the camera itself) has to be replaced during the process.

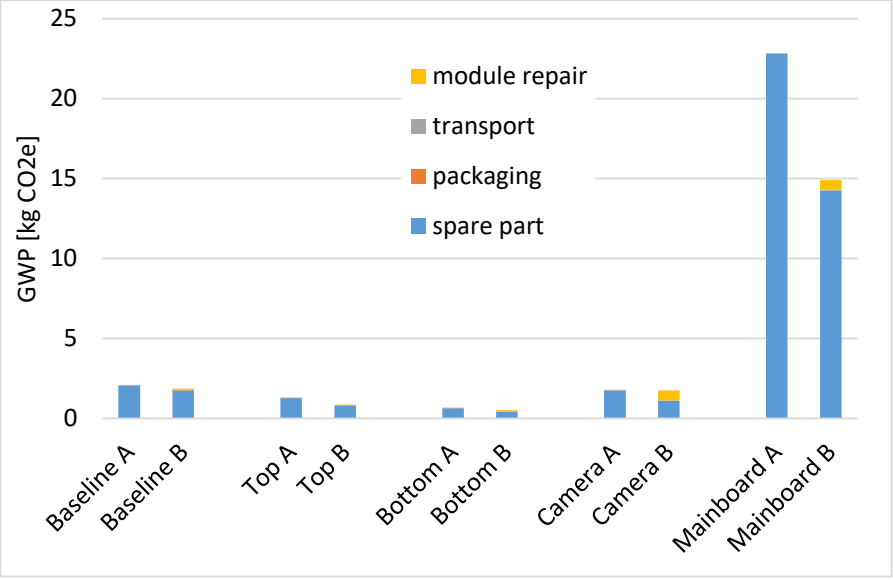

Figure 4-14: Variation between different repairs

Looking at the whole life cycle and the pay-off of smartphone repair, the results show that the environmental impact strongly depends on the module which is replaced. As shown in Figure 4-15, repair leads to reduced emissions per year of use for all parts except the main board. As the main board causes the major share of the absolute impact, replacing it to extend the time of active use by 2 years is not beneficial. However, if this is connected to on-board repair, it is beneficial – even if this still needs

a share of 62.5 % new mainboards (as only 37.5% modules can be re-used based on the assumed return and repair rates).

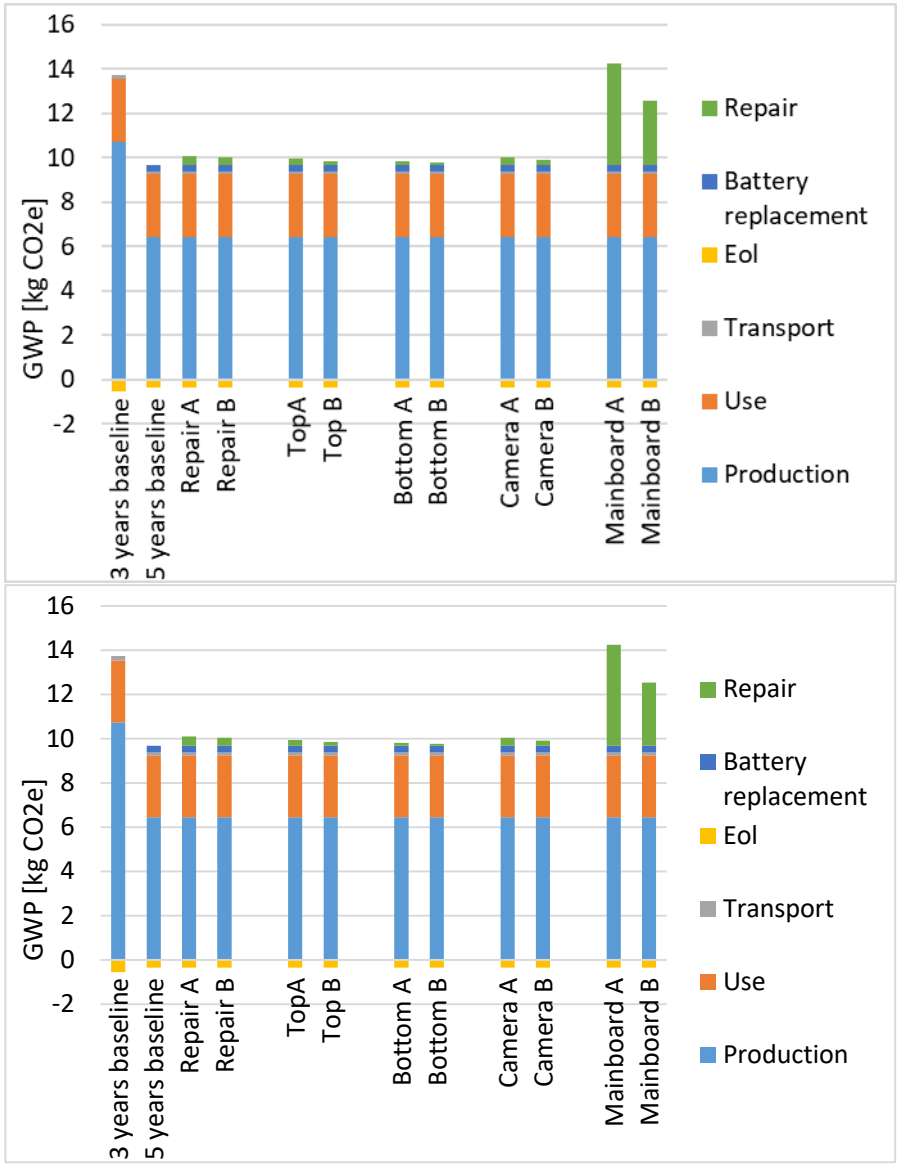

Figure 4-15: Variation of different repairs – per year of use compared to baseline scenarios

It is nonetheless important to point out that those results are heavily influenced by the assumptions made in terms of the share of effectively repaired modules. For instance, as seen above the main driver in repair overhead is the production of new modules or parts, which under the assumptions of this study goes from replacing an entire module to replacing 63% (see 3.5.2). Figures below show the potential benefits of module level repair itself, accounting only for the new parts in the production of the B scenario. Module repair in those diagrams refers to the energy use of the reworking machine modelled as explained in 3.5.2.

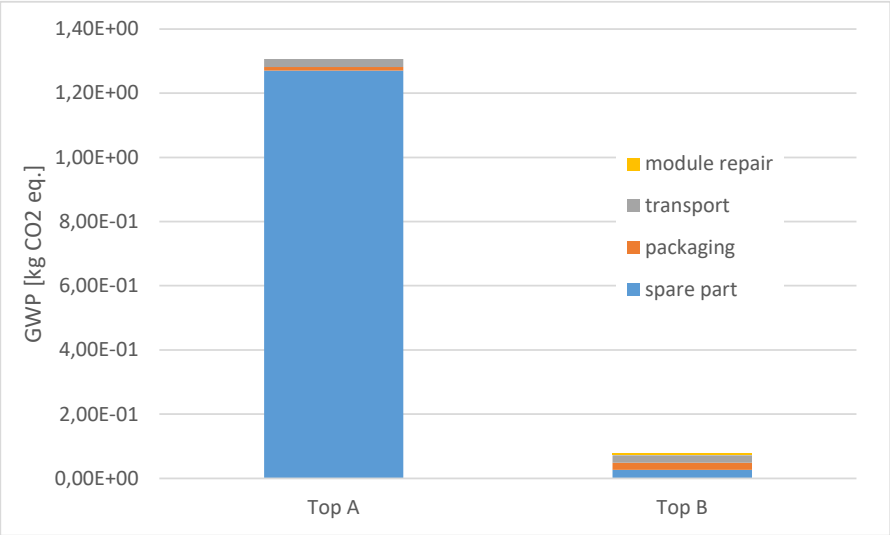

Figure 4-16: Module level repair overhead comparison for top module

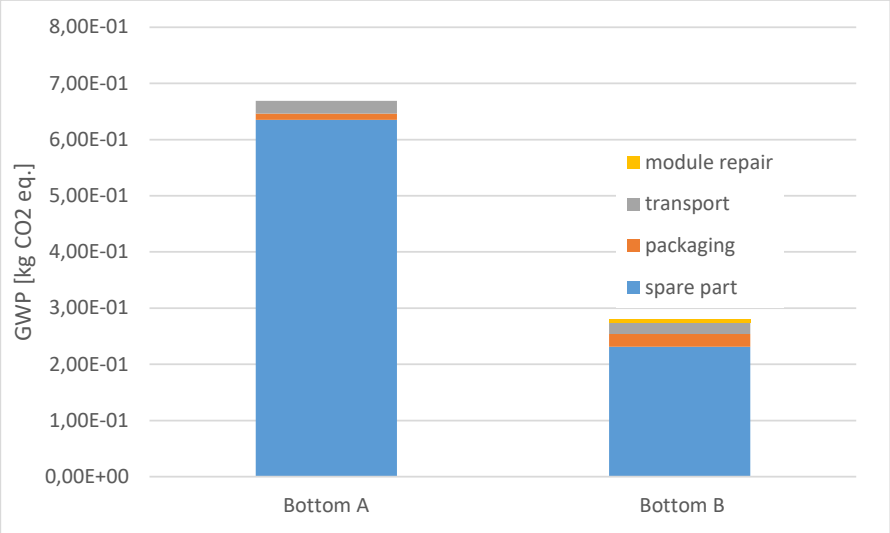

Figure 4-17: Module level repair overhead comparison for bottom module

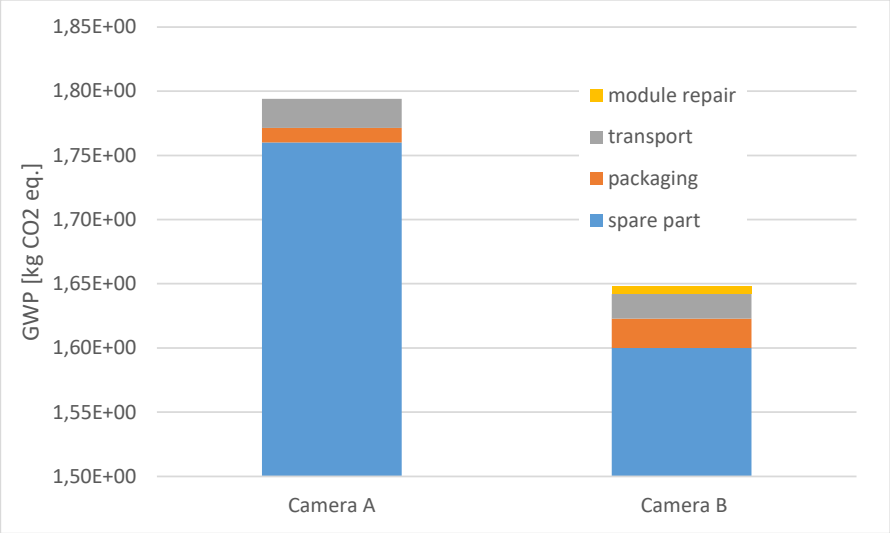

Figure 4-18: Module level repair overhead comparison for camera module

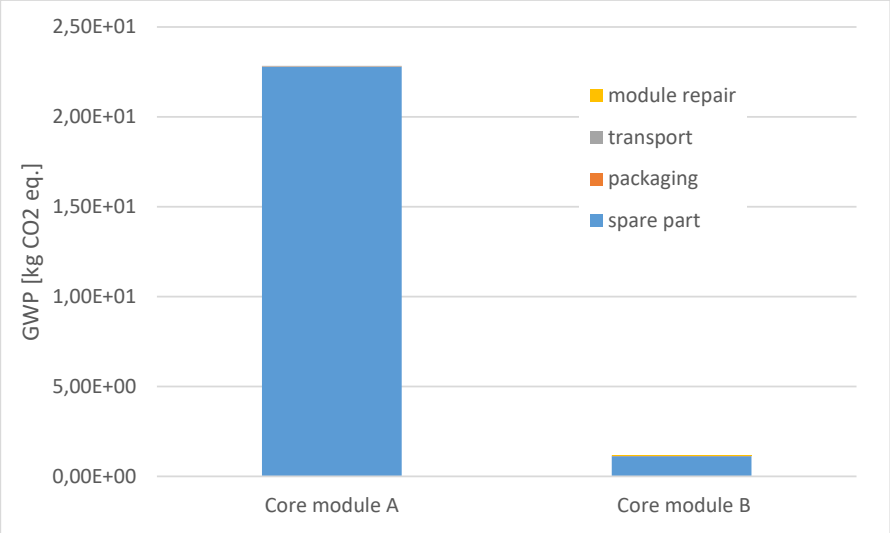

Figure 4-19: Module level repair overhead comparison for core module

As seen here, the top and core modules show the highest benefit opportunities since they have the largest production related impacts. The camera module shows the smallest benefit due to the fact that the camera itself it's being replaced within the module, which is the main driver for its production impacts. It is therefore seen that, while the potential benefits of enabling module level repair are noticeable, they are also highly dependent on the replaced pieces and parts as well as the means of transport used for the modules (as commented earlier).

4.5.6 Modularity

The "impact of modularity" is calculated in section 4.3.5 to make a comparison with the Fairphone 2 and show the effect of the new connectors. However, to assign these connectors to the module boards solely to the feature "modularity" is not truly correct, as it neglects that conventional smartphones have more and more connectors on the mainboard, as well, leading flex cables to sub-parts and sub-boards (see Schischke et al. 2019). So, the real hardware differences to achieve modularity are lower than the

impact shown there. The only parts really differing from conventional smartphones are the display connector (but even this became smaller compared to the Fairphone 2) and the module housing which have no significant impact on the overall phone.

It can be discussed whether the modular design leads to higher PCB area (not due to the connectors which is calculated in section 4.3.5). The individual module boards do not exist in many other smartphone designs. The impact of the module boards together makes up one third of the mainboard PCB (Table 4-10) due to lower PCB area and less PCB layers.

Table 4-10: Impact of PCBs

	GWP	ADP elements	ADP fossil	Human tox	Eco tox
	kg CO_2e	kg Sb eq.	MJ	kg DCB eq.	kg DCB eq.
PCB totals	4,03E+00	2,81E-04	4,38E+01	7,98E-01	1,67E-02
Mainboard	3,01E+00	2,15E-04	3,27E+01	6,10E-01	1,28E-02
Top module	2,54E-01	1,44E-05	2,76E+00	4,72E-02	9,96E-04
Camera module	1,25E-01	8,47E-06	1,35E+00	2,30E-02	4,84E-04
Bottom module	3,12E-01	2,12E-05	3,38E+00	5,75E-02	1,21E-03
Display module	3,31E-01	2,25E-05	3,59E+00	6,10E-02	1,29E-03

However, the manufactured PCB areas differ across smartphone designs and the total Fairphone 3 PCB area is within the range of conventional smartphone designs and depends strongly on the shape of the PCB. L- and especially U-shaped PCBs lead to more produced PCB area compared to rectangular PCBs. PCB layout placing on the production panel by the PCB manufacturer also has an impact as the comparison of Fairphone 2 and Fairphone 3 PCB production shows. FP2 PCBs were more strongly nested and closer arranged on the production panel leading to less cut-off area.

4.5.7 Comparison with Fairphone 2

In this section, a comparison with the prior Fairphone model will be carried out in order to identify environmental trends with the new design. The Fairphone 2 results were re-calculated using the newest life cycle inventory database updates in order to foster comparability between the two models (see Figure 4-20 and Figure 4-21).

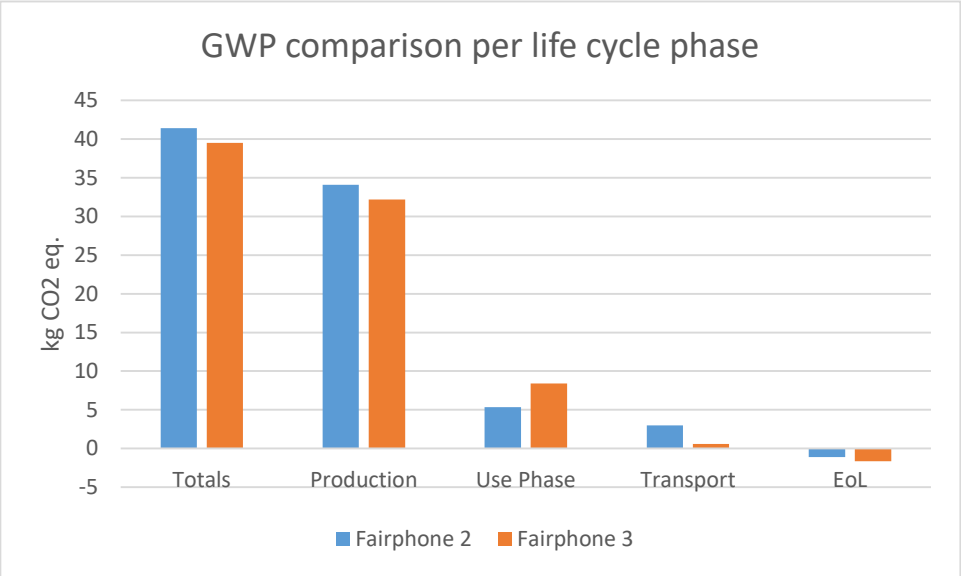

Figure 4-20: GWP comparison per life cycle phase

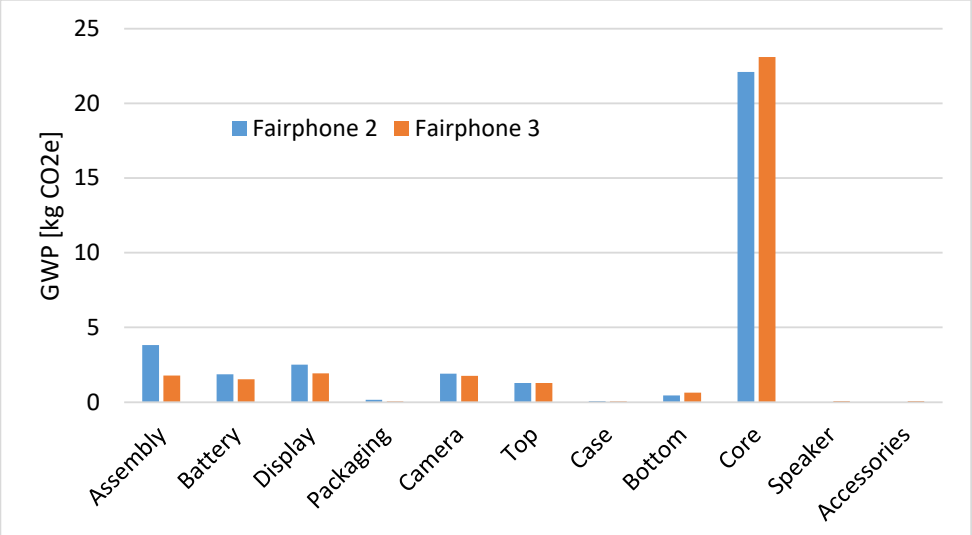

Figure 4-21: GWP comparison at production level

The overall values are quite similar, as seen in Figure 4-20, although the overall relative impacts of the Fairphone 3 are a bit lower. Transport shows the greatest decrease due to the replacing of air freight by train transport from final assembly to the distribution hub. Use phase-related impact has, on the contrary, increased for the newer model due to the higher battery capacity. End of life and production phases seem to be in the same range as the previous model, although production shows to have a smaller impact in comparison.

In Figure 4-21 the decomposition of the production phase into its constituents can be seen. While the core module shows higher impacts the assembly related impacts and the display ones are lower.

The end-of-Life results show a slight relative increase on environmental benefits, which are tied to a higher amount of recovered gold. This can be attributed mainly due to the improed data availability for the Fairphone 3, where for the majority of components a full material declaration was available.

Use phase

The base case use phase results show a noticeable divergence between Fairphone 2 and Fairphone 3. Table 4-11 below shows a summary of the main aspects of the use phase modelling for both devices.

Table 4-11: Use phase comparison

Characteristic	Fairphone 2	Fairphone 3
Use period (yr.)	3	3
Charging frequency assumed	Daily	Daily
Battery size (Wh)	9,196	11,628
Capacity and efficiency	Constant	Average (with ageing)
GWP (kg CO2 eq.)	5,6	8,4

The two main differences are the following: battery size and charging efficiency. The Fairphone 3 has a bigger battery (3060 mAh compared to 2420 mAh) which, based on

the assumption of one complete charging cycle per day increases consequently the amount of energy used by the phone. The other main cause of the difference is the chosen efficiency. The batteries tested in-house at Fraunhofer IZM (see section 3.2) showed a drop on capacity and efficiency. This has in turn been reflected and an average value has been chosen as a proxy. Additionally, in order to estimate the energy use of the phone for one charging cycle in-house testing has been carried out, giving away a higher value as compared to the estimation done based on the charger nominal efficiency and the battery size, which was the approach in the previous model's LCA (Proske et al. 2016).

Integrated circuits

Integrated circuits are a component where modelling differs between Fairphone 2 and Fairphone 3. Figure 4-22 shows the difference in the impact category of GWP in the ICs of both models, distributed by parts.

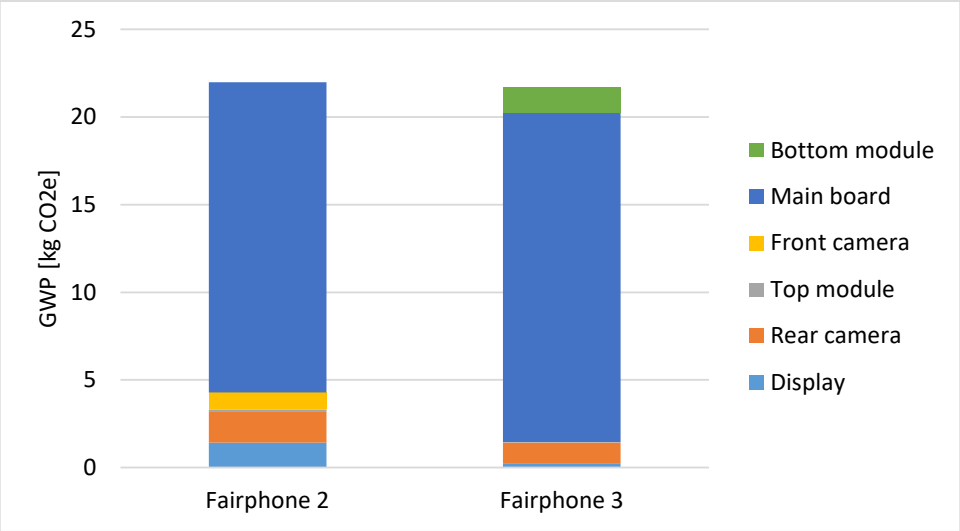

Figure 4-22: GWP impact of IC per module

CT imaging, x-rays and grinding have been used in order to measure the die size of the main ICs of the main board, due to their central role in the most relevant impact categories related to electronics (namely GWP and ADP). Figure 4-23 below shows the difference in the measured areas. Although for the Fairphone 2 LCA, grinding and x-rays were used as well, FP2 ICs were grinded horizontally and FP3 ICs vertically, leading to a better differentiation of stacked dies, which proved to be specially relevant in the Flash memory IC. The rest of the differences in die areas are most likely due to differences in the IC technology of the phone.

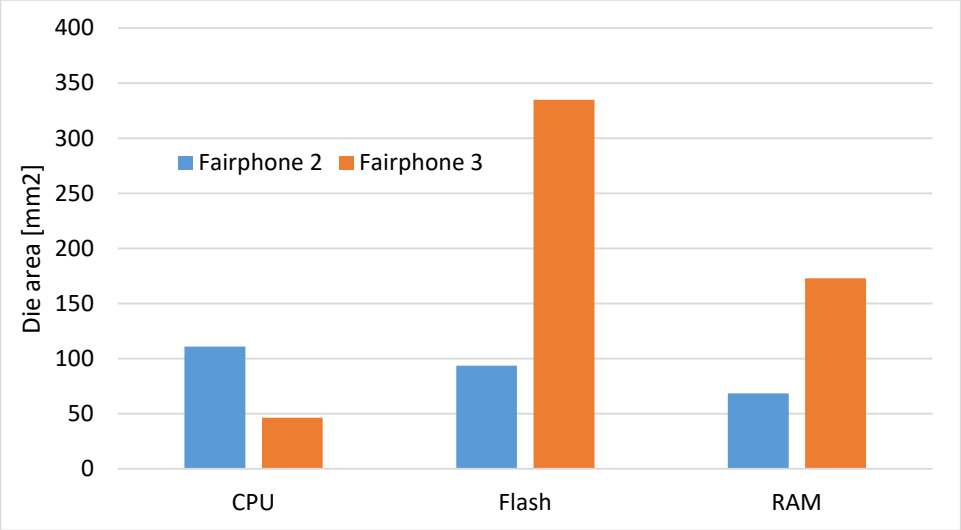

Figure 4-23: Measured die area for the main ICs

When comparing the figure above with Figure 4-22 it can be seen that the main differences in die area for the main ICs in Fairphone 3 and Fairphone 2 models are not directly correspondent in their GHG emissions impact, which are only slightly higher for the FP3 model in the main board and actually a bit smaller as a whole due to a different data source used for the storage and memory chip as explained in section 3.1.9.3.

Connectors

One of the main design changes following Fairphone 2 were the connectors. Table 4-12 shows the comparison between the GWP and ADP elements impact for Fairphone 2 and Fairphone 3.

Table 4-12: Connectors comparative impact summary

Model	Impact	Unit	BtB connectors	Flex cables	Sub-housing	Extra PCB (connector related)
Fairphone 2	GWP	kg CO_2 e	0,94	-	4,21E-02	0,66
	ADP elements	kg Sb e.	7,92E-04	-	9,72E-07	4,02E-05
Fairphone 3	GWP	kg CO_2 e	0,25	0,26	1,64E-02	0,22
	ADP elements	kg Sb e	2,21E-04	2,34E-05	4,43E-08	1,51E-05

As the numbers point out, a noticeable reduction has been achieved in this regard, that is central to the modularity overhead. The main reason for this reduction is a change in the connectors used to bring the modules and the main board together. In the FP2 case pogo pin connectors were used, which are bigger and contain more gold. They were identified as a hotspot regarding the modularity in the FP2 LCA [Proske et al. 2016] and were substituted by flex cables and press-point male female connector pairs in the Fairphone 3. Since those connectors are smaller than the previous pogo pins, the additional PCB area is also reduced and thus the related impacts.

Table 4-12 shows that although Fairphone 3 ends up having more connectors (two pairs of male/female connectors per each flex cable) and a higher flex board use (which was not present in the FP2), the overall impacts are still favourable to the Fairphone 3

design since the pogo pins had more gold and the rigid PCB has greater impacts than flex cable.

Display

Table 4-13 below shows the comparison between the GWP impact of the display for both FP2 and FP3 as well as their size.

Table 4-13: Display comparison

Characteristic	Fairphone 2	Fairphone 3
Size (inch)	5	5,65
GWP (kg CO2 eq.)	2.67	1.92

Despite the screen being now bigger for the Fairphone 3 the related impact is nonetheless lower. This is due to two main reasons: firstly, as commented above, the corrected IC modelling amounts to a lower impact compared to the modelling used for FP2. On the other hand, the GHG emissions reported by the AUO Environmental Report [AUO 2016, 2019] used as reference show a decrease of around 30 % on the impact per produced area from 2015 to the latest data in 2018. Those therefore outweigh the added impact due to the larger display. Additionally, the FP3 display unit has only one display control IC compared to two display control ICs for the FP2.

Extra module

Another main difference between the Fairphone 3 and Fairphone 2 models is the extra module: the separate speaker module in the FP3. The impact on the total results is rather low. The speaker module only includes the speaker itself, the housing and the connector and represents only 0.24 % of the GWP impact for production. Table 4-14 below shows the comparison for the relative contribution in GWP for each module in both models.

Table 4-14: Module GWP contribution comparison

Module	Fairphone 2	Fairphone 3
	%	%
Core	62.5	71.6
Battery	5.4	4.8
Display	7.5	6.0
Camera	5.4	5.5
Top	3.6	4.0
Bottom	1.5	2.0
Speaker		0.2
Back cover	0.2	0.1
Assembly	13.4	5.5
Packaging	0.6	0.1
Accessories		0.2

5
Potential impact of recycled content as input material

Fairphone B.V. developed a list of focus materials in order to invest effort in tackling some environmental and social hotspots:

- Gold
- Copper
- Tin
- Tungsten
- Lithium
- Cobalt
- Neodymium
- Plastics

A separate analysis was carried out to assess the environmental impact of these materials within the phone and to determine a potential reduction of such impact through using recycled materials instead. The analysis is performed for each material individually and may vary between the materials due to different technical possibilities of material retraction and recycling, life cycle data for primary and secondary material and market forces (is the recycling market already established, are there differences in cost and quality, etc.). Due to limited data availability, the environmental impact is limited to global warming potential (GWP) for most materials and also differences in the GWP between different sources will be shown. It should therefore be kept in mind that the presented values for GWP might differ from the values used in the aforementioned LCA. The LCA is mainly calculated with datasets from GaBi whose terms of use do not allow to cite individual impacts of data sets.

The amount of material within the phone is determined in a similar way for all focus materials. The BoM was combined with the material composition as stated by the supplier to calculate the total amount per material, taking into account not only homogenous materials (e.g. copper foils for copper or gold-plated connector pins for gold), but also material within electronic components. If a component is supplied by different suppliers, only the first supplier in the material list is considered.

5.1
Gold

Gold	**0,143 g**
Main contributor	Battery, PCBs
Estimated benefit	Increase of 3,146 kg CO2 eq. in GWP (decrease in all other relevant impact categories)

Impact of primary production

The GWP impact of primary gold production varies between 11,500 and 55,000 kg CO_2e/kg gold according to different studies [Giegrich et al. 2012, Nuss & Eckelman 2014, Mudd 2007, Norgate & Haque 2012, Hagelüken & Meskers 2010, Chen et al. 2018, Dell 2017]. The differences stem mainly from different electricity production (e.g. coal or hydro power) and declining ore grade (Mudd 2007). The majority of sources state values around 15,000 kg CO_2e/kg gold.

Impact for secondary production

The data on the environmental impact of recycled gold is much more limited than on primary gold. According to Dell [2017], the impact is significantly lower for most environmental impact categories. However, for GWP the environmental impact is about 2.5 times higher – about 37,000 kg CO_2e/kg gold – due to higher energy consumption in hydrometallurgical processes [Dell 2017]. Calculations with the software GaBi present benefits through recycling, however the numerical results cannot be presented in the public report.

Potential impact of recycled content as input material

Recycling processes and qualities

The processes for gold recycling are well established and available on a large scale. The environmental impact and technology used depend on the sources of the gold scrap (e.g. jewellery or electronic scrap).

Market

Markets for gold recycling are well established. Recycled gold accounted for approximately a third of the total gold supply from 1995 through 2014. Most of this, roughly 90%, is high-value recycled gold, mostly jewellery, gold bars and coins. The other 10% are industrial recycled gold, for example from e-waste. This value has doubled from 2004 to 2014. However, gold content in WEEE is decreasing, meaning that recyclers will have to process larger amounts of scrap to extract the same amount of gold. Gold made up 90% of bonding wires in 2008, for example, a value which had fallen to 50% in 2015 already [Hewitt 2015].

As is the case with many other recycling industries, gold recycling fluctuates in accordance to fluctuations in gold price and economic conditions. Interestingly, economic crisis boost gold recycling as gold is often used as a liquid asset to raise cash. An increase in gold price leads to an increase in gold recycling, as well [Hewitt 2015].

Conclusion

Based on the well-established market and technologies for gold recycling even from WEEE and no quality differences between primary and secondary material, recycled gold is widely available on the market. Recycling methods are so well established, in fact, that buyers might not even be able to distinguish, whether they purchased primary or secondary gold. So, there is no additional market stimulation achieved through purchasing recycled gold specifically and rates are mainly influenced by the gold price. Therefore, it is recommended to calculate with a market average for the input material within environmental assessments and focus efforts on good EoL collection and treatment to increase the amounts of devices which enter the correct recycling stream.

5.2 Copper

Copper	**8,145 g**
Main contributor	PCBs
Estimated benefits	Decrease of between 41,38 g and 19,22 g CO2 eq. in GWP

Impact of primary production

The impact of primary copper production varies between 2.8 and 5.4 kg CO_2e/kg copper [Giegrich et al. 2007/2012, Farjana et al. 2019, Nuss & Eckman 2014, BIR 2008].

Impact for secondary production

Values given for life cycle data and GWP of recycled Copper vary. Jingjing et al. conducted an LCA on secondary copper production in China and calculated a GWP value of 0.32 kg CO_2e/kg recycled copper. In comparison, their LCA yields a GWP value of 3.4 kg CO_2e/kg copper for virgin copper. The GWP of recycled Copper is, in this case, therefore 90% smaller than that of virgin copper [Jingjing, 2019]. Similarly, the BIR cites 0.44 kg CO_2e/kg copper recycled from copper scrap [BIR, 2008]. Giegrich et al. conducted an LCA for copper recycling based on industry data and concluded that the recycling of copper scrap containing 60% copper has a GWP of 1.24kgCO_2/kg recycled copper product [Giegrich, 2007].

Potential impact of recycled content as input material

Recycling processes and qualities

Copper is fully recyclable without any loss in quality or quantity [Bonnin 2015 and van Beers 2007]. It was estimated in 2012 that 85% of copper in use could be recovered through recycling [SCF, 2012]. Additionally, recycling methods for copper are well established. Pyrometallurgical recycling is the prevalent method, but an established hydrometallurgical process also exists [Bonnin, 2015].

PCB scrap presents a high concentration of copper, but its recycling suffers from low collection rates, just like other e-waste recycling methods [Veit, 2005].

Market

Markets for the recycling of copper are well established. In 2008, approximately 37% of copper used worldwide was recycled copper [Bonnin, 2015] while figures for Europe today are up to 50% [ECI, 2018]. Because of its high economic value and comparably large availability in e-waste, recycling copper is economically feasible [Hagelüken, 2006].

Conclusion

Similarly to gold, recycling technologies and markets for copper recycling are well established. Margins are a lot lower for copper, nickel, and tin than for precious metals. If WEEE recycling is considered, gold, copper and tin will be recycled from the same stream. Therefore, the same approach for considering environmental impact is considered: calculate LCA impacts with a market average for the input material and focus efforts on good EoL collection and treatment to increase the amount of devices which enter the correct recycling stream.

5.3 Tin

Tin	**2,48 g**
Main contributor	Solder paste
Estimated benefit	Decrease of 42,1 g CO2 eq. in GWP

Impact of primary production

The stated impact of primary tin production varies between 2.18 and 17.1 kg CO_2e/kg tin with two of the three sources citing values around 17 kg CO_2e/kg tin [BIR 2008, Giegrich et al. 2007, Nuss & Eckman 2014].

Impact for secondary production

Life cycle data on the recycling of tin could only be found in a report from the Bureau of International Recycling [BIR, 2008]. Here, they state the GWP of recycled tin to be 0.024 kgCO_2e/kg recovered tin. Seeing as their initial values for primary tin were much

lower than the ones from other sources, however, this number should be considered in comparison to the BIR GWP value for primary tin rather than in comparison to the other sources' values. But even when comparing the value to the BIR GWP value for virgin tin the recycled material's GWP is 99% smaller.

Potential impact of recycled content as input material

Recycling processes and qualities

Tin can be recovered through pyro- and hydrometallurgical processes [BIR, 2008]. Metals such as tin are highly recyclable due to their intrinsic properties and relatively high economic value [ITA, 2020]. Approximately 44% of refined tin is being used in PCBs. Recycling of electronic waste is therefore an important factor in securing the tin supply for the upcoming years. One of the main problems of recovering tin from e-waste is, as mentioned above for other materials already, the low collection rate for recycling, with take-back numbers being as low as 12% in some developed countries. As there are also more valuable metals in e-waste, tin has not been a priority in the recovery [Yang, 2017].

Market

According to the International Tin Association (ITA), the contribution of secondary tin towards the total tin consumption was 31% in 2018. 13% of this was re-refined tin with the remainder being reused or reformulated alloys. According to the ITA the contribution of recycled tin towards the total tin use was steady around 30-35% over the last decade, with dips roughly corresponding to periods of low tin prices [ITA, 2020]. In general, tin is highly used in the electronics industry. Yang et al. assumed in 2017 that at this rate, tin reserves would be depleted 16 years from then – in 2033. Improving the waste collection and recycling processes and increasing the amount of recycled materials is therefore very important. In 2014, for example, the amount of tin in e-waste reached 35% of the mined material in the same year, thus making it a great option to slow down tin depletion [Yang, 2017].

Conclusion

Tin is highly recyclable. Large amounts of tin mined annually are used within the electronics industry. However, collection and recycling rates of electronic waste leave much to be desired. It is crucial to further stimulate the collection and recycling of electronic waste with a focus on tin, amongst other materials, to secure the tin supply for the upcoming decades.

5.4 Tungsten

Tungsten	**0,013 g**
Main contributor	Vibration motor
Estimated benefit	Not enough data

Impact of primary production

The life cycle data for tungsten is very scarce. According to Giegrich et al. [2012] the GWP of tungsten is about 2.9 kg CO_2e/kg tungsten. Nuss & Eckman [2014], on the other hand, state a value of 12.6 kg CO_2e/kg tungsten. For the LCA of the Fairphone 3, figures from Giegrich et al. [2012] for tungsten are used, as even the commercial data bases of GaBi and ecoinvent do not contain life cycle data on tungsten.

Impact for secondary production

Potential impact of recycled content as input material

No figures on the environmental impact of recycled tungsten are available in literature or commercial data bases, even though significant parts of the world's tungsten supply are covered through recycled tungsten, as suggested by the International Tungsten Industry Association (ITIA) [ITIA, 2016].

Recycling processes and qualities

Methods for the recycling of tungsten are well established and there are a variety of such available. The level of quality of recovered tungsten differs depending on the process used and input scrap material, but many of the processes are well established and tested [ITIA, 2016].

Market

The ITIA suggests that 35% of tungsten used for producing intermediate products in 2016 was recycled [ITIA, 2018]. Tungsten is therefore in the top third of metals when it comes to recycling [UNEP, 2013].

Conclusion

Tungsten recycling is well established with recycled tungsten making up a significant amount of total tungsten used for production. However, life cycle data is not readily available, thereby making it difficult to estimate the effects of using recycled tungsten. Tungsten is one of the materials with a comparatively high recycling rate, yet there is still room for improvement [ITIA, 2018].

5.5 Lithium

Lithium	**5,2 g**
Main contributor	Battery
Estimated benefit	Not enough data

Impact of primary production

Life cycle data for lithium is very scarce. Nuss & Eckman [2014], the only publicly available source found, state a value of 7.1 kg CO_2e/kg lithium as GWP.

Impact for secondary production

No lifecycle data on secondary lithium was found, probably because lithium recycling has not been of great interest in the past.

Recycling processes and qualities

Different types of lithium batteries, such as li-Ion batteries, have been recycled for several decades now. Up until a few years ago, however, the focus was the recovery of scarce metals such as cobalt and nickel [Georgi-Maschler, 2012]. It was not economic to recover lithium, as there was an abundance of natural lithium and demand and prices were comparatively low [Buchert, 2018]. With the increase in demand and in price for lithium, however, mainly due to the increasing production of electronic vehicles, the recovery of lithium from scrap materials is becoming a topic of interest [Buchert, 2018].

It has been stated by some sources, though, that the most prominent recycling technologies for lithium are not yet cost-effective on a large scale [Kushnir, 2015].

Many new research projects on the topic of lithium battery recycling have emerged in the last few years. Most of them, however, heavily focusing on electric vehicle

batteries, many proposing a closed-loop approach, thereby not creating secondary lithium for other market segments. Batteries for electric vehicles are much larger than smartphone batteries and their disposal is easier to control, which makes research into the field of recycling them more appealing.

Potential impact of recycled content as input material

Market

At the moment, there is no real market for secondary lithium for smartphone batteries with only few companies recovering lithium from scrap materials.

Conclusion

Recovery methods for lithium are not well established. Much research is conducted and funded in this area mainly focusing, however, on lithium batteries for electric vehicles. It is therefore unlikely to be possible to substitute primary lithium with secondary lithium in smartphone batteries any time soon. An alternative might be using batteries that substitute other materials and combine them with primary lithium (see section on cobalt).

5.6 Cobalt

Cobalt	**11,24 g**
Main contributor	Battery
Estimated benefits	Not enough data

Impact of primary production

Few sources are available on the GWP of cobalt mining and production. Determined GWP values for cobalt vary between 8.3 and 11.73 kg CO_2e/kg cobalt, depending on the source [Nuss & Eckman 2014, Farjana 2019]. The variation in values cited by the sources is much smaller than for some of the other materials.

Impact for secondary production

No lifecycle data on secondary cobalt was found. It was, however, possible to find data on recycled lithium-cobalt-oxide (LiCoO2). The only part of the FP3 that contains larger amounts of cobalt is the phone's battery. Recycling information on LiCoO2 is therefore also valuable [Umicore, 2011].

Umicore lists the GWP value of primary LiCoO2 as 10.1 kg Co_2e/kg LiCoO2. In comparison, the GWP value of secondary LiCoO2 is stated to be 2.8 kg CO_2e/kg LiCoO2, leading to a significant reduction in CO2-emission. Umicore combines secondary cobalt with newly sourced lithium to produce LiCoO2, any reduction in the LiCoO2's GWP value is therefore due to a reduction in the GWP value of cobalt [Georgi-Maschler, 2012].

Recycling processes and qualities

Methods for recycling cobalt from a range of applications, such as li-Ion batteries or catalytic converters, exist [Buchert, 2012]. Recovery quotes for cobalt in professional recycling plants are already very good, with some plants recovering up to 95% of materials [Buchert, 2018]. Pyro-metallurgical recovery processes to recover cobalt from smartphone and notebook batteries are also already established. Because of their high cobalt content, li-ion batteries are an attractive end-of-life product [Buchert, 2012]

Market

The end-of-life recycling rate for cobalt in the EU was estimated to be around 35% in 2016. The old scrap ratio is calculated at 50% [UNEP, 2011]. Recycling cobalt is currently not profitable on a big scale. The number of recycling plants is therefore limited and recycling mainly occurs together with primary production [Kotnis, 2018]. The market for cobalt recycling is not well developed.

Potential impact of recycled content as input material

Umicore is the biggest recycling company for cobalt from li-ion batteries with an input capacity of 7 000 tons of li-ion and nickel metal hydride batteries in 2011 [Umicore, 2011]. Demand for cobalt is likely going to increase further with an increase in electric vehicles, thus probably also increasing the demand for recycled cobalt. It is, however, likely that most research into this field will concentrate on batteries of electric vehicles.

Conclusion

Because demand for cobalt is likely going to increase further in the upcoming years, recycling will gain further importance and methods for recycling cobalt from different applications are already established. It is also already possible to recover cobalt from li-ion batteries on an industrial level. One of the biggest challenges, as with many recycling products, is once again the comprehensive collection and thorough separation of the batteries in preparation for shredding [Buchert, 2012].

5.7 Rare earth (neodymium)

Neodymium	**0,17 g**
Main contributor	Vibration motor (magnet)
Estimated benefits	Not enough data

Impact of primary production

Nuss & Eckman [2014] were, again, the only publicly available source found on life cycle data of neodymium. They state the GWP value of neodymium to be 17.6 kg CO_2e/kg neodymium.

Impact for secondary production

No life cycle data on the recycling of neodymium could be found, which is likely due to neodymium recycling being an absolute niche market.

It was, however, possible to find life cycle data on the recycling of neodymium-iron-boron magnets (NdFeB), which is a common type of neodymium magnet. Jin et al. conducted an LCA for a closed-loop-approach to NdFeB-magnet-recycling and concluded that the GWP value for recycled NdFeB magnets was 12.5 kg Co_2e/kg produced NdFeB-magnet, while it was 27.6 kg Co_2e/kg for virgin NdFeB magnets. Recycling thereby halves the GWP of NdFeB magnets [Jin, 2016]. These values should, however, be taken with caution as the recycling process used in this study is only effective if the magnet is already separated from other parts. Due to the nature of the application this would not be the case for the FP3, requiring further pre-processing steps and thereby probably increasing the GWP.

Recycling processes and qualities

Ciacci, as well as others, states that the recycling rate for neodymium is below 1%. The often very small amount of neodymium in products makes recovery difficult and not economically feasible. For this reason, recycling processes are not well developed [Ciacci, 2019]. Schebek even goes as far as considering none of the currently available recycling methods for neodymium to be on an industrial scale level [Schebek, 2019]. Currently used recycling methods are very energy-intensive and use large amounts of

acid to recover the rare earth materials, but less environmentally impactful recycling methods are already being researched [Schebek, 2019.]

Market

The market for neodymium recycling is small and not well developed [Ciacci, 2019]. With an increase in electronic vehicles, research into recycling possibilities for neodymium and rare earth elements in general might become more prominent [Schebek, 2019].

Conclusion

The market of neodymium recycling is not well developed. Recycling methods are lacking and often not economically feasible. As of right now, it does not seem possible to substitute the neodymium in the FP3's magnets with recycled neodymium.

5.8 Plastics

Plastic is different from the other "focus materials" as it does not describe a specific material, but rather a material group, which is present in many different parts of the phone. One way to differentiate between the different types of plastic could be to separate them into plastics for structural parts (midframe, housings, etc.) and functional parts (e.g. plastics within PCBs, connectors, etc.) In this analysis on recycled content, we chose to focus on structural plastics used for mechanical parts.

For the Fairphone 3, the module housing, midframe and back cover are made of polycarbonate (PC). Additionally, the protection bumper is made from a single material: TPU.

Impact of primary production

TPU

Data on TPU is very limited in literature as well as in LCA data bases (incl. GaBi and ecoinvent). According to Biron 2018, primary TPU has a GWP of 4.1 kg CO_2e/kg TPU. This is in line with the value given for rigid PU according to PlasticsEurope [2005] with 4.2 kg CO_2e/kg PU. However, the production process of TPU can also be compared to other thermoplastics. ABS has – in comparison – a fusion temperature similar to TPU and a GWP of 3.1 kg CO_2e/kg ABS according to PlasticsEurope [2015]. PA with a higher fusion temperature than TPU has a GWP of 6.4 kg CO_2e/kg PA [PlasticsEurope 2014 -b].

There are also new material inventions being launched by companies trying to lessen the carbon footprint of TPU. One attempt is, for example, to use CO_2, which was already created in the production phase, thereby lessening the impact of the virgin TPU produced [Covestro, 2020]. However, these methods are rather new and there is next to no life cycle data publicly available.

PC

Life cycle data on polycarbonate is widely unavailable. PlasticsEurope [2019], the only source found, cites the GWP value for PC to be 3.4 kg CO_2e/kg PC.

Impact for secondary production

No life cycle data was found on the impact of secondary production of TPU and PC.

Wäger and Hischier performed a life cycle analysis on the recycling of mixed plastics-rich WEEE and found the GWP for the production of post-consumer-recycled plastics to

be only a fifth of that for the production of virgin plastics [Wäger & Hischier, 2015]. They consider a mix of plastics (ABS, PP and HIPS) and do not give absolute numbers, but the tendency is clear.

Potential impact of recycled content as input material

Garraín et al. conducted an LCA on HDPE recycling with data from the Italian recycling industry and compared it to other sources [2007]. Reversing their normalisation of values, the secondary HDPE has a GWP value of 0.86 kg CO_2e/kg HDPE. The values they cite from econinvent, Buwal and Plasticseurope for the GWP value of virgin HDPE are around 5.8 to 6.63 kg CO_2e/kg HDPE, thus reducing the GWP of HDPE by almost 90% through using secondary HDPE. Newer data from Plasticseurope, however, lists the GWP of virgin HDPE at 1.8 kg CO_2e/kg material [Plasticseurope, 2014 -a]. Unfortunately, no newer data on the GWP for secondary HDPE was found.

While these types of plastics are not used within the FP3 they clearly indicate a tendency: using secondary plastics reduces the GWP of the parts in question significantly when compared to using virgin plastics.

Recycling processes and qualities

Plastics are, in difference to metals, not recyclable without quality losses. The number of recycling cycles, which are possible, depend on the plastic type and the needed quality. Each cycle leads to down-cycling.

Additionally, certain additives and especially glass fibres used to enhance strengthening of materials such as PC lead to materials, which are not recyclable.

Coherent information on TPU recycling is hard to find. Only few companies seem to be recycling TPU with often highly individualized methods, depending on the type of input [sikoplast, 2015]. Some companies mix secondary and primary TPU granulate to compensate for potential losses in quality during the recycling process [malz-polytec, n.d.]. According to BASF a maximum of 30% of TPU regenerate can be mixed into primary TPU [BASF, n.d.].

As for PC, the typical recycling process is to shred the parts and turn them into PC granulate. There are, however, also other recycling methods available [plastic expert, n.d.]. Little information on the quality of recycled PC was found. Recycled PC may show a reduced impact resistance and resilience in general. It is possible to reduce this effect through additives [AZoM, 2012].

Market

There is a market for recycled plastics. However, currently the market is under-utilized, and potential production volumes exceed purchase volumes. Problems are varying quality and colour variations. Therefore, design for recycling and design from recycling should be considered. To enable the use of recycled content, it should be analysed which material qualities are really necessary from a design perspective and which are requested just out of routine.

Conclusion

As the market is still growing and needs stimulation, the use of recycled input material does actually enhance the market. Therefore, it is also arguable that LCAs calculated with recycled input materials and using recycled plastics should be a focus strategy in design for environment.

6
Conclusions and Recommendations

The results of the Fairphone 3 LCA show that environmental impacts are production driven, with the electronic components causing the main impact. Housing and structural parts play a minor role on the overall impact. Design aspects such as form factor influence the whole LCA of the device, mainly through impacts on the display and battery size, but not through the impact of housing material.

As the main impact is caused by production, prolonging the use phase is still a strong measure to influence the overall environmental impact for all impact categories except ADP elements, which can be reduced through efficient precious metal recycling. The comparison of 3, 5 and 7 years of use shows that the impact per year of use drops significantly with longer lifetime. This is still the case if repair is needed, as shown by the repair scenarios. However, as analysed in the sensitivity analysis, replacing the core module/mainboard with new modules is only beneficial if the additional time of use is as long as the use-time before the repair, because the mainboard causes the major share of environmental impact. With board-level repair, repair again becomes beneficial in case of mainboard replacement, being nonetheless dependent on the replaced parts and pieces and the extent to which said reparations can actually take place.

The "modularity overhead", which is caused by the design features allowing for repair, causes a lower impact than for the Fairphone 2 due to smaller connectors with less material usage. Additionally, comparison with conventional smartphones shows that small press-point connectors with flex cables are no stand-alone feature of the Fairphone anymore, so the additional impact through the feature of modularity would be even lower.

As described in the inventory and in the interpretation, the availability of specific and up-to-date life cycle data on electronics is still not sufficient and discrepancies between different data bases and sources is high. Nevertheless, the overall results are deemed reliable.

ICs

ICs cause the major share of environmental impact and are at the same time directly enabling the functional spectrum of the device. Limiting or reducing ICs is therefore not a sensible option to improve the impact of the device as it would be done for material-driven parts. ICs production impact decreases over time when technology advances as it is shown by e.g. Boyd [2012].

Nevertheless, balance between designing an up-to-date product which can keep up with on-going trends and avoiding over-dimensioning is needed at the same time.

PCBs

PCB area is directly connected to environmental impact. Area and number of layers should therefore be reduced where possible, including efficient production and reduced cut-offs. Reducing the needed area through different connector design was already a good development from Fairphone 2 to Fairphone 3.

Connectors

The new Fairphone 3 connectors are a progress from environmental perspective as they need less material and less PCB area. Possible further reduction of material should be carefully aligned with reliability considerations as the main the active years of use of the phone as an important parameter for the overall impact. Material reduction should therefore not limit reliability. However, in that context, the new connectors are expected to be more reliable despite their lower material footprint.

Display

Display size is directly connected to the environmental impact of the display panel and the housing. However, both of them have only a small overall impact. Display impact is more strongly electronics- than panel-driven. Nevertheless, the display size also impacts the energy consumption of the phone leading to a need for a bigger battery and/or more charging cycles. Reducing the display size would therefore be favourable from environmental perspective but has to be considered carefully with market trends as it is directly linked to purchasing decisions.

Mode of transportation

Fairphone has recently changed the transportation from the production sites to its distribution hub via train for most of its shipments. This has shown to reduce notably the transport related environmental impacts as well as reducing the repair overhead, although delays compared to air shipping are also to be expected.

Additionally, reduced packaging for spare modules has the potential to reduce associated transport emissions as these parts have a high relative weight of packaging.

Data availability/acquisition

Up-to-date and specific life cycle data for electronics is scarce. Collecting primary data from component manufacturers is time consuming and difficult, as e.g. confidentially problems occur. Therefore, it was not possible to derive primary data on production processes from component suppliers within this study. Nevertheless, data on the final assembly, PCB production layouts as well as the majority of full material declarations were available for the LCA. Fairphone B.V. should pursue this good work to derive primary data. Focus on the primary data collection should be on parts and components with a high production impact:

- ICs, especially CPU and memory
- Display
- PCBs
- Battery

Such primary data has the potential to improve the quality of the LCA and enhance accurate fitting to the specific Fairphone characteristics. It also builds the foundation for an individual hotspot analysis in the Fairphone manufacturing process.

The effect of an increased share of primary data on the numeric LCA results is difficult to predict. More detailed analyses often result in higher estimated environmental impacts as more processes and materials are covered. This should, however, not be seen as a drawback, as it still helps to improve the overall quality of the assessment and increase the knowledge about the product's manufacturing processes.

7 Literature

Andrae et al. 2014 Andrae, A.S.G., Vaija, M.S.: 2014. To which degree does sector specific standardization make life cycle assessments comparable? - the case of global warming potential of smartphones. Challenges 5 (2), 409–429, 2014, https://doi.org/10.3390/challe5020409, online: http://www.mdpi.com/2078-1547/5/2/409

AUO 2016 AUO: Corporate Social Responsibility Report 2015, AU Optronics Corporation, 2016

AUO 2019 AUO: Corporate Social Responsibility Report 2018, AU Optronics Corporation, 2019

AZoM, 2012 Azo Materials 2012: Polycarbonate (PC) (C15H16O2) Plastic Recycling. Retrieved on 13.05.2020. Retrieved from: https://www.azom.com/article.aspx?ArticleID=7963

BASF, n.d. BASF SE: Think, Create, Elastollan: Thermoplastische Polyurethan-Elastomere (TPU). Retrieved on 13.05.2020. Retrieved from: http://www.polyurethanes.basf.de/pu/solutions/elastollan/en/function/conversions:/publish/content/group/Arbeitsgebiete_und_Produkte/Thermoplastische_Spezialelastomere/Infomaterial/Thermoplastische-Polyurethan-Elastomere_DE.pdf

Biron 2018 Michel Biron: Thermoplastics and Thermoplastic Composites, 3rd Edition, ISBN: 9780081025017, William Andrew, 2018

BIR 2008 Bureau of International Recycling (BIR): Report on the Environmental Benefits of Recycling, 2008

Boyd 2012 Sarah B. Boyd: Life-Cycle Assessment of Semiconductors, 2012

Bonnin, 2015 Bonnin, M., Azzaro-Pantel, C., Domenech, S., Villeneuve, J., 2015. Multicriteria optimization of copper scrap management strategy. Resour. Conserv. Recycl. 99, 48–62. https://doi.org/10.1016/j.resconrec.2015.03.013.

Buchert, 2012 Buchert, M., Manhart, A., Bleher, D., Pingel, D.: Recycling Critical Raw Materials from Waste Electronic Equipment. Oeko-Institut e.V, Darmstadt, Germany, 2012

Buchert 2018 Buchert, M: Recycling von Kobalt und Lithium für die Energiewende. Öko-Institut e.V.; HIF Resource Talk, Freiberg 2018

Chancerel 2016 Perrine Chancerel, Max Marwede: Feasibility study for setting - up reference values to support the calculation of recyclability/recoverability rates of electr(on)ic products – DRAFT REPORT, JRC Technical Reports, 2016, online: http://eplca.jrc.ec.europa.eu/uploads/TUB-JRC_Feasibility-study_Final-report_Draft-for-stakeholder-consultation.pdf

Chen et al. 2018 Wei Chen, Yong Geng, Jinglan Hong, Huijuan Dong, Xiaowei Cui, Mingxing Sun, Qiang Zhang: Life cycle assessment of gold production in China, Journal of Cleaner Production 179 (2018) 143-150

Ciacci 2019 Ciacci, L.; Vassura, I.; Cao, Z.; Liu, G.; Passarini, F.: Recovering the "new twin": Analysis of secondary neodymium sources and recycling

potentials in Europe. Resources, Conservation & Recycling 142, p. 143–152. https://doi.org/10.1016/j.resconrec.2018.11.024 , 2019

Clément et al. 2020 Louis-Philippe P.-V.P. Clément, Quentin E.S. Jacquemotte, Lorenz M. Hilty: Sources of variation in life cycle assessments of smartphones and tablet computers, Environmental Impact Assessment Review 84 (2020) 106416

Clemm et al. 2016 Christian Clemm, Paul Mählitz, Alexander Schlösser, Vera Susanne Rotter, Klaus-Dieter Lang: Umweltwirkungen von wiederaufladbaren Lithium-Batterien für den Einsatz in mobilen Endgeräten der Informations- und Kommunikationstechnik (IKT), TU Berlin, Herausgeber: Umweltbundesamt, Dessau-Roßlau, 2016

Click repair 2016 click repair: Mehr Transparenz im Handymarkt, 2016

Covestro, 2020 Covestro Solution Center: TPU and material with CO2 raw ingredient merge for increased sustainability in tubing. Retrieved on 13.05.2020. Retrieved from: https://solutions.covestro.com/en/highlights/articles/stories/2019/tpu-profile-cardyon-tube

Dell 2017 Dell: Environmental Net Benefit of Gold Recycling, November 2017

Deubzer 2012 Deubzer, O.; Jordan, R.; Marwede, M.; Chancerel, P.: Categorization of LED products, Project cycLED - Cycling resources embedded in systems containing Light Emitting Diodes, Deliverable 2.1, Berlin, May 2012

ECI, 2018 European Copper Institute 2018: Europe's demand for copper is increasingly met by recycling. Retrieved on 13.05.2020. Retrieved from: https://copperalliance.eu/benefits-of-copper/recycling/

Ercan et al. 2016 Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E., Nilsson, E.: Life Cycle Assessment of a Smartphone. pp. 124–133. https://doi.org/10.2991/ict4s-16.2016, 2016, online: http://www.atlantis-press.com/php/download_paper.php?id=25860375

Farjana et al. 2019 Shahjadi Hisan Farjana, Nazmul Huda∗, M.A. Parvez Mahmud: Life cycle assessment of cobalt extraction process, Journal of Sustainable Mining 18 (2019) 150–161

Garraín, 2007 Garraín, D.; Martínez, P.; Vidal, R.; Bellés, M.: LCA of thermoplastics recycling. Conference Paper for LCM, Zurich, 2007.

Georgi-Maschler 2012 Georgi-Maschler, T.; Friedrich, B.; Weyhe, R.; Heegn, H.; Rutz, M.: Development of a recycling process for Li-ion batteries. Journal of Power Sources 207, p. 173–182. https://doi.org/10.1016/j.jpowsour.2012.01.152, 2012

Giegrich et al. 2007 Jürgen Giegrich, Axel Liebich, Horst Fehrenbach: Ableitung von Kriterien zur Beurteilung einer hochwertigen Verwertung gefährlicher Abfälle, Umweltbundesamt, 2007

Giegrich et al. 2012 Jürgen Giegrich, Axel Liebich, Christoph Lauwigi, Joachim Reinhardt: Indikatoren / Kennzahlen für den Rohstoffverbrauch im Rahmen der Nachhaltigkeitsdiskussion, Umweltbundesamtes, 2012

Hagelüken, 2006 Hagelüken, C.: Improving metal returns and eco-efficiency in electronics recycling - A holistic approach for interface optimization

between pre-processing and integrated metals smelting and refining. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, May 8-11, p. 218-223. San Francisco, 2016.

Hagelüken & Meskers 2010 Hagelüken, C., Meskers, C., 2010. Complex life cycles of precious and special metals. In: Graedel, T., van der Voet, E. (Eds.), Linkages of Sustainability/Ernst Strungmann, Forum. MIT Press, pp. 163e197.

Hewitt 2015 Hewitt, A.; Keel, T.; Tauber, M.; Le-Fiedler, T: The Ups and Downs of Gold Recycling. BCG, 2015. Retrieved on 13.05.2020. Retrieved from: https://www.bcg.com/de-de/publications/2015/metals-mining-cost-efficiency-ups-and-downs-of-gold-recycling.aspx

Hischier 2007 Roland Hischier: Life Cycle inventories of Packagings and Graphical Papers. Ecoinvent report nr. 11. Dübendorf.

Huawei 2018 Product Environmental Information, individual reports on smartphones, 2018, online: https://consumer.huawei.com/en/support/product-environmental-information/

ITA, 2020 International Tin Association 2020: Tin recycling. Retrieved on 13.05.2020. Retrieved from: https://www.internationaltin.org/recycling/

ITIA, 2018 International Tungsten Industry Association: Recycling of Tungsten – Current share, economic limitations and future potential. Association's newsletter, May 2018.

Jin 2016 Jin, H.; Afiuny, P.; McIntyre, T.; Yuehwern, Y.; Sutherland, J.: Comparative Life Cycle Assessment of NdFeB Magnets: Virgin Production versus Magnet-to-Magnet Recycling. 23rd CIRP Conference on Life Cycle Engineering. https://doi.org/10.1016/j.procir.2016.03.013, 2016

Jingjing, 2019 Jingjing, C.; Zhaohui, W.; Yufeng, W.; Liquan, L.; Bin, L.; De`an, P.; Tieyong, Z: Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. Resour. Conserv. Recycl. 146, 35–44. 2019. https://doi.org/10.1016/j.resconrec.2019.03.020

Kotnis, 2018 Kotnis, J.: CRITICAL RAW MATERIALS IN THE CITY: RECYCLING PERSPECTIVES FOR COBALT IN THE HAGUE. University of Leiden. Leiden 2018

Kushnir 2015 Kushnir, D: Lithium Ion Battery Recycling Technology 2015: Current State and Future Prospects. Environmental Systems Analysis. Chalmers University, Göteborg, Sweden. ESA REPORT # 2015:18

malz-polytec, n.d. malz-polytec GmbH& Co. KG: KUNSTSTOFF-RECYCLING: Wir helfen, Rohstoffkosten zu senken. Retrieved on 13.05.2020. Retrieved from: https://www.malz-polytec.de/Recycling-Polyurethan-Polyamid-Polyolefin-Polypropylen-Kunststoff.html

Mudd 2007 Gavin M. Mudd: Global trends in gold mining: Towards quantifying environmental and resource sustainability?, Resources Policy 32 (2007) 42–56, doi:10.1016/j.resourpol.2007.05.002

Norgate & Haque 2012 Terry Norgate, Nawshad Haque: Using life cycle assessment to evaluate some environmental impacts of gold production, Journal of Cleaner Production 29-30 (2012) 53e63

Nuss & Eckelman 2014 Philip Nuss, Matthew J. Eckelman: Life Cycle Assessment of Metals: A Scientific Synthesis. PLoS ONE 9(7): e101298. doi:10.1371/journal.pone.0101298, 2014

Oers 2016 Lauran van Oers, Jeroen Guinée: The Abiotic Depletion Potential: Background, Updates, and Future, Resources, 2016, online: http://www.mdpi.com/2079-9276/5/1/16 (checked: 10/24/2016)

Plastic expert, n.d. Plastic Expert Ltd.: How is polycarbonate recycled?. Retrieved on 13.05.2020. Retrieved from: https://www.plasticexpert.co.uk/plastic-recycling/polycarbonate-recycling/

PlasticsEurope 2005 PlasticsEurope: POLYURETHANE RIGID FOAM, 2005

PlasticsEurope 2014 -a PlasticsEurope: Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers - High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Linear Low-density Polyethylene (LLDPE), 2014

PlasticsEurope 2014 -b PlasticsEurope: Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers - Polyamide 6.6 (PA6.6), 2014

PlasticsEurope 2015 PlasticsEurope: Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers - Styrene Acrylonitrile (SAN) and Acrylonitrile Butadiene Styrene (ABS), 2015

PlasticsEurope 2019 PlasticsEurope: Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers – Polycarbonate (PC), 2019

Prakash et al. 2013 Siddharth Prakash, Ran Liu, Karsten Schischke, Lutz Stobbe, Carl-Otto Gensch: Schaffung einer Datenbasis zur Ermittlung ökologischer Wirkungen der Produkte der Informations- und Kommunikationstechnik (IKT) – Teilvorhaben C des Gesamtvorhabens Ressourcenschonung im Aktionsfeld Informations- und Kommunikationstechnik (IKT), Umweltbundesamt, 2013

Probas 2020 Description of the Tungsten data set in German: ProBas: Wolfram, online: http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={A4A89322-AC81-4FA2-BB1C-5EE0B77E9180} (checked: 18/02/2020)

Proske et al. 2016 Marina Proske, Christian Clemm, Nikolai Richter: Life Cycle Assessment of the Fairphone 2, Berlin, 2016

SCF, 2012 Société Chimique de France – Données sur le Cuivre. http://www.societechimiquedefrance.fr/. Retrieved on 13.05.2020. Retrieved from: http://www.societechimiquedefrance.fr/extras/Donnees/metaux/cu/texcu.htm

Schebek, 2019 Schebek, L.; Gutfleisch, O.; Gassmann, J.; Zimmermann, J.: Materialkreisläufe der Energiewende: Potentiale, Technologien, Nachhaltigkeit. Recycling und Rohstoffe Band 12, Thomé-Kozmiensky Verlag GmbH, Neuruppin 2019. ISBN 978-3-944310-46-6

Schischke et al. 2019 Schischke, K.; Proske, M.; Nissen, N.F.; Schneider-Ramelow, M.; Impact of modularity as a circular design strategy on materials use for smart mobile de-vices, Materials Research Society, Volume 6, 2019, https://doi.org/10.1557/mre.2019.17

sikoplast, 2015 Sikoplast 2015: Recycling von schwierigen technischen Kunststoffen, wie z.B. PVB. Retrieved on 13.05.2020. Retrieved from: http://www.sikoplast.de/aktuelles/newsdetails.html?tx_ttnews%5Bpointer%5D=2&tx_ttnews%5Btt_news%5D=36&tx_ttnews%5BbackPid%5D=7&cHash=a709d51abef913d0d0629b6afa67c960

Sommer 2013 Philipp Sommer: Recycling Potential of Rare Earth Elements and Cobalt in WEEE-Batteries. Diploma Thesis. Technische Universität Berlin, Fachge-biet Abfallwirtschaft. Berlin, 2013.

Stranddorf 2005 Heidi K. Stranddorf, Leif Hoffmann, Anders Schmidt: Update on Impact Categories, Normalisation and Weighting in LCA – Selected EDIP97-data, Environmental Project Nr. 995, 2005, online: http://www2.mst.dk/udgiv/publications/2005/87-7614-570-0/pdf/87-7614-571-9.pdf (checked: 10/24/2016)

Umicore 2011 Yazicioglu, B.; Tytgat, J.: Life Cycle Assessments involving Umicore's Battery Recycling process. Umicore N.V./S.A. . DG Environment – Stakeholder Meeting 2011

UNEP 2011 UNEP: Recycling Rates of Metals - A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. UNEP 2011

UNEP 2013 M. A. Reuter, C. Hudson, A. van Schaik, K. Heiskanen, C. Meskers, C. Hagelüken: Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel, 2013.

Van Beers, 2007 Van Beers, D., Kapur, A., Graedel, T.E., 2007. Copper and zinc recycling in Australia: potential quantities and policy options. J Clean Prod, 15, 8–9, 862–877.

Veit, 2005 Veit, H. M., Pereira, C. C., Bernardes, A.M., 2005. Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste Manage 25, 1, 67-74.

Wäger & Hischier 2015 Wäger, P. & Hischier, R.: Life cycle assessment of post-consumer plastics production from waste electrical and electronic equipment (WEEE) treatment residues in a Central European plastics recycling plant. Science of the Total Environment 529, p. 158–167. https://doi.org/10.1016/j.scitotenv.2015.05.043 , 2015

Yang, 2017 Yang, C.; Tan, Qu.; Liu, L.; Dong, Q.; Li, J.: Recycling Tin from Electronic Waste: A Problem That Needs More Attention. ACS Sustainable Chem. Eng. 2017, 5, 9586-9598. https://pubs.acs.org/doi/10.1021/acssuschemeng.7b02903

Zgola 2011 Melissa Lee Zgola: A Triage Approach to Streamline Environmental Foot-printing: A Case Study for Liquid Crystal Displays, MIT, 2011