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LIFE CYCLE ASSESSMENT OF THE FAIRPHONE 4

David Sánchez

Marina Proske

Sarah-Jane Baur

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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

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Abbreviations

ADP	Abiotic resource depletion
ADPe	Abiotic resource depletion elements
ADPf	Abiotic resource depletion fossil
AUO	AU Optronics Corporation, Taiwanese display manufacturer
BoM	Bill of materials
BtB	Board-to-board
CMOS	Complementary Metal Oxide Semiconductor
CO_2 eq.	Carbon dioxide equivalents
DRAM	Dynamic random access memory
ecoinvent	Life cycle inventory data base
Eco tox	Terrestrial Eco-toxicity
EoL	End of life
EPS	External Power Supply
Fab	Fabrication (used mostly for wafer fabrication)
FP3	Fairphone 3
FP4	Fairphone 4
GaBi	LCA software by thinkstep
GW	Global warming
Human tox	Human toxicity
IC	Integrated circuit
LCA	Life cycle assessment
LCD	Liquid crystal display
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
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
PMU	Power Management Unit
SB eq.	Antimony equivalents
SMD	Surface Mounted Device
SOx	Sulfur oxide
TPU	Thermoplastic polyurethane

TSS	Total suspended solids
TVS	Transient Voltage Supressor
USB	Universal Serial Bus
VOCs	Volatile organic compounds

1
Executive Summary

Fairphone 4 is the latest modular smartphone by Fairphone B.V.. This LCA study aims to identify the main environmental impacts of Fairphone 4 (6GB RAM 128 GB internal storage) and to analyse various repair scenarios in order to see which repair strategies are environmentally beneficial.

This study uses a baseline scenario to calculate the main impacts and a scenario-based analysis to account for the repair opportunities that the modular design of Fairphone 4 allows for. Furthermore, this study also conducts an analysis of the following accessories:

- Fairphone charger (including external power supply and two possible cables, USB 2.0 to 2.0 and USB 2.0 to 3.2)
- Wireless earbuds
- Screwdriver
- Protective cases (a TPU based case and a biobased plastic case)

The following impact categories are analysed in the study:

- Global Warming (GW)
- Abiotic resource depletion – elements (ADPe)
- Abiotic resource depletion – fossil resources (ADPf)
- Human toxicity (Human tox)
- Ecotoxicity (Eco tox)

The inventory for this study is based on the bill of materials provided by Fairphone B.V., as well as on the material declarations by its suppliers. Those were cross-checked with a teardown of a Fairphone 4 performed by Fraunhofer IZM.

Results

The total impact on Global Warming for the Fairphone 4 is estimated to be 43 kg CO2 eq. The relative values for all impact categories are shown in Figure 1. Compared to the FP3, this is 4 kg CO2 eq. higher, mostly due to the increased functionalities and transport. However, modularity overhead has been reduced as well as the enviornmental impacts related to repair, thereby making repair activities even more environmentally beneficial.

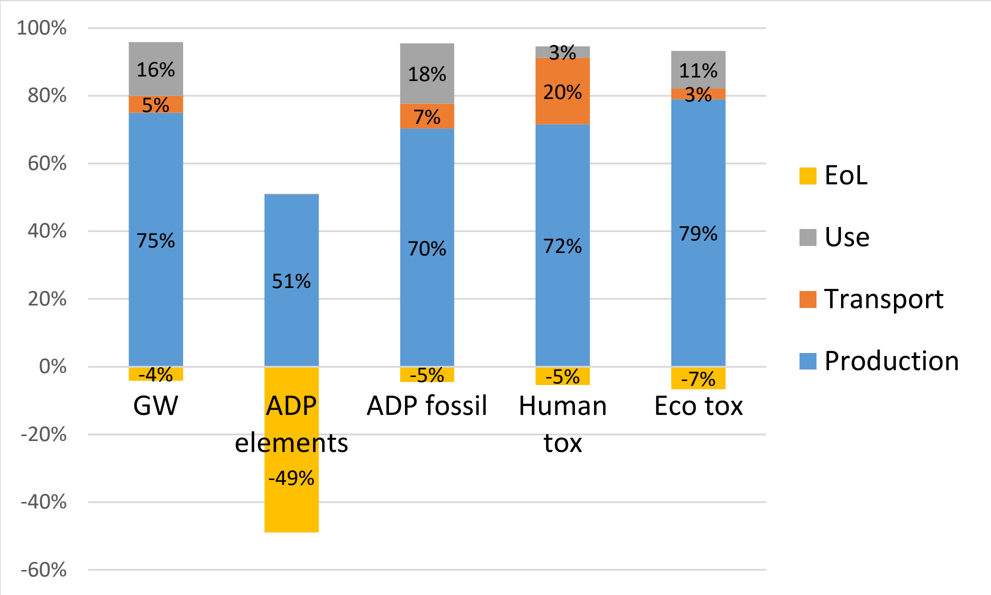

Figure 1 - Relative impacts of Fairphone 4 per life cycle phase

The life cycle stage production (incl. raw material acquisiton) shows the biggest contribution to all impact categories. For human toxicity (Human tox), transport is the second most impactful life cycle phase. End of life processes show a benefit in all impact categories, with the strongest contribution to abiotic resource depletion of elements (ADPe) due to material recovery.

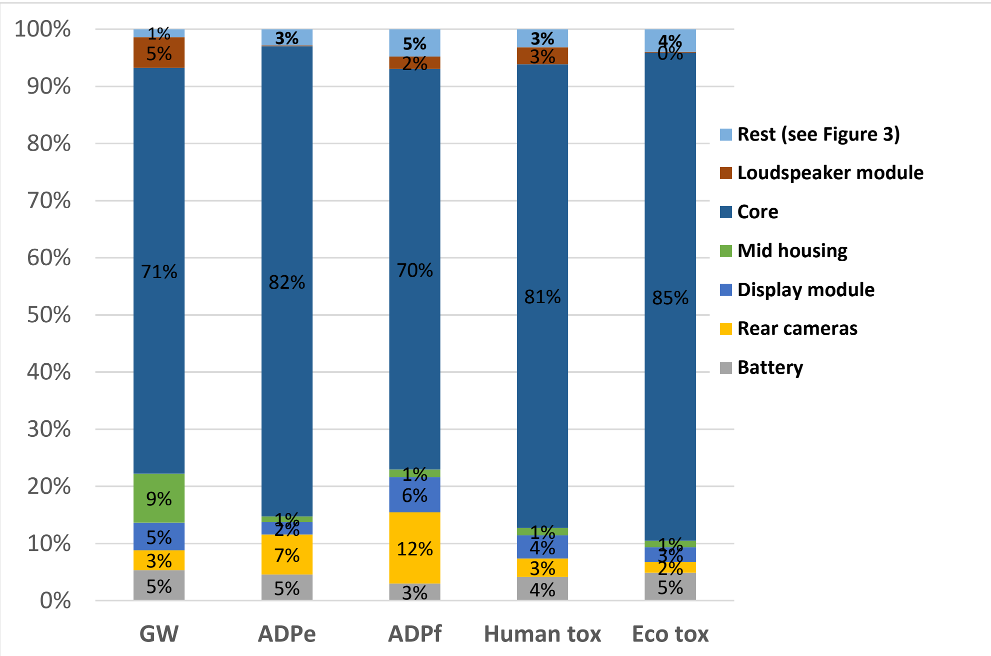

Figure 2 - Relative impacts of Fairphone 4 production per component type

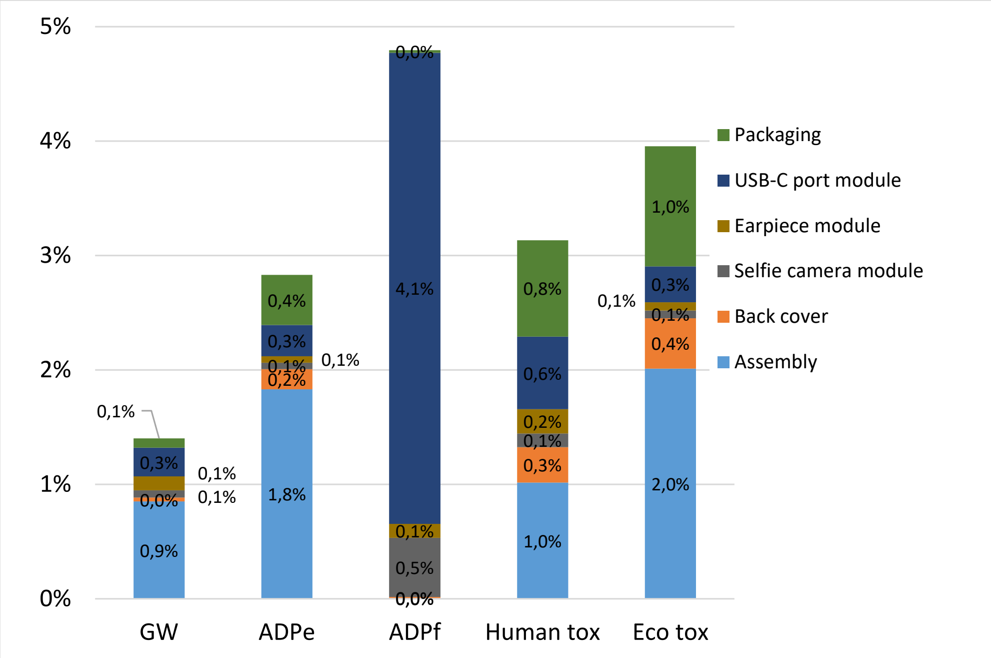

Figure 3 - Relative impacts of Fairphone 4 production per component type (rest of the modules)

Figure 2 and Figure 3 show the relative impacts within production. In the first figure the biggest contributors are shown, while the second one shows the contribution of the rest. The core is the main driver for all impact categories, because it contains the main PCB and most ICs and other electronic components.

In the comparison of the three baseline scenarios it can be seen that extending the lifespan of the device helps reduce the yearly impacts. This reduction is shown in Figure 4 for the Global Warming impact category. Extending the lifetime to 5 years helps reduce the yearly emissions on GW by 31%, while a further extension to 7 years of use helps reduce the yearly impact by 44%.

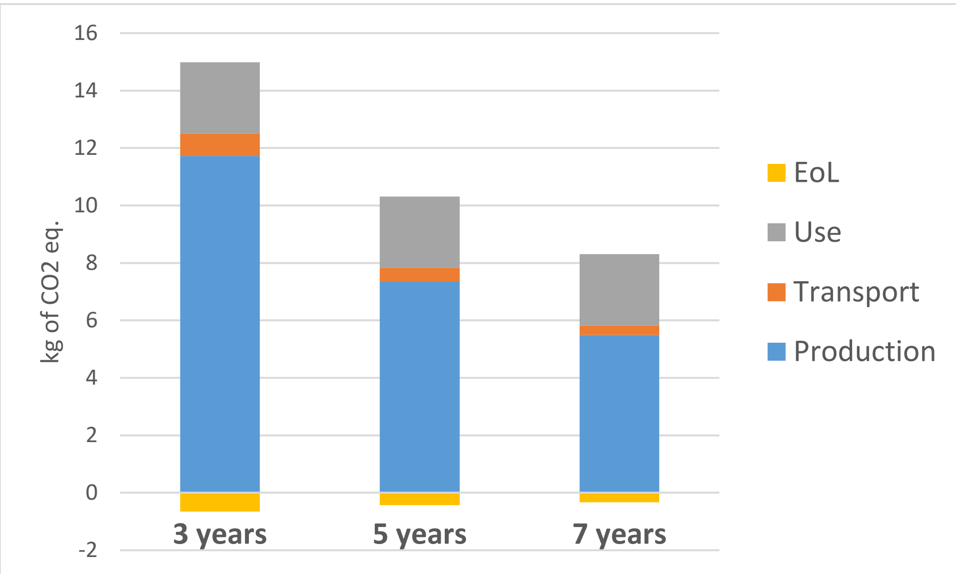

Figure 4 - Comparative of yearly emissions per baseline scenario

The absolute GW value of the wireless earbuds is of 3.49 kg CO2 eq. Figure 5 shows the relative impacts of the wireless earbuds. Production is the main contributor to most impact categories, while transport shows to be the main driver of the Human tox category.

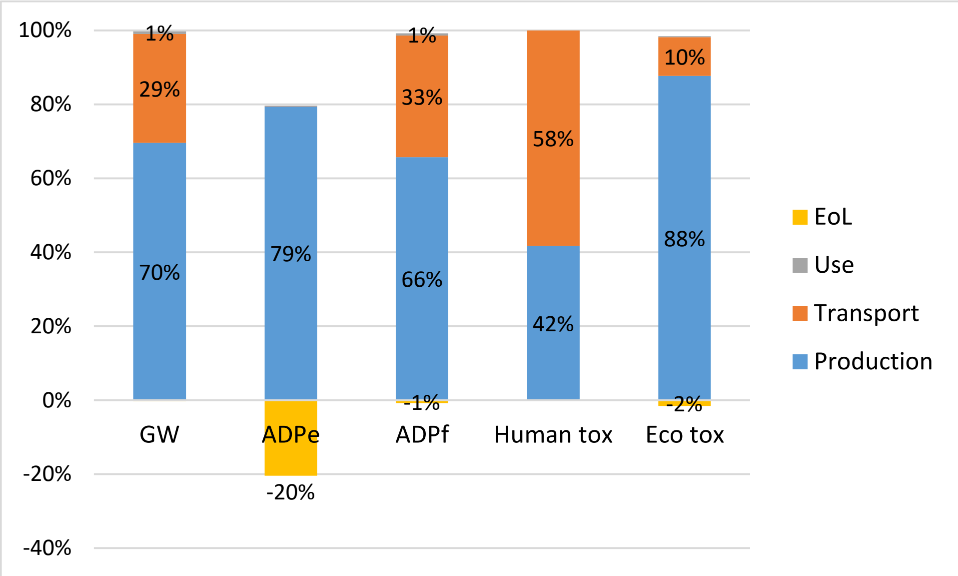

Figure 5 - Relative impacts of wireless earbuds per life cycle phase

The absolute GW value for the charger is 2.81 kg CO2 eq. Figure 6 shows the relative impacts per life cycle phase for all impact categories. The results refer to the configuration using the USB 2.0 to 2.0 cable. The production phase is the main driver for most impacts except for Human tox, where transport contributes the most.

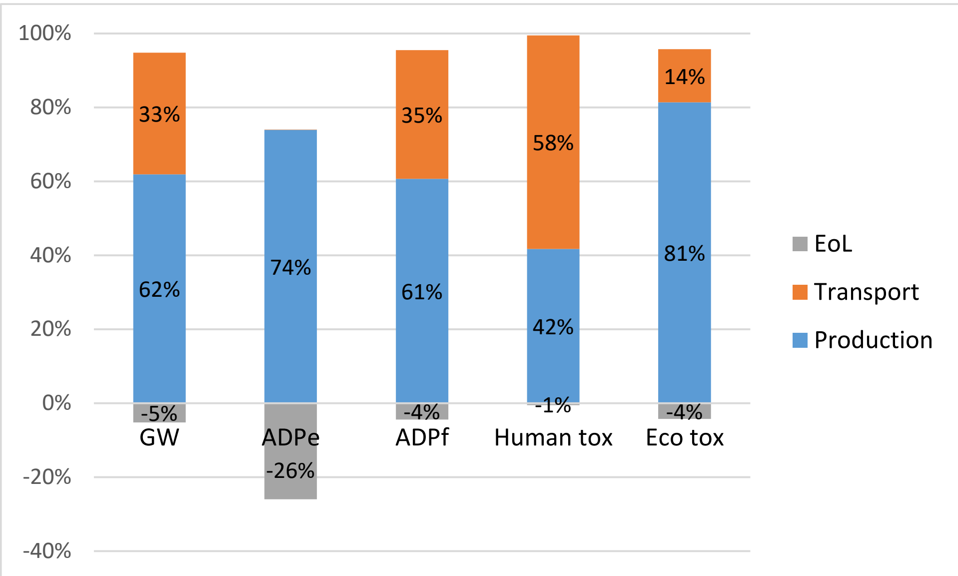

Figure 6 - Relative impacts of charger per life cycle phase (with USB 2.0 to 2.0 cable)

The absolute GW value for the screwdriver is 0.56 kg CO2 eq. Figure 7 shows the relative impacts for all impact categories per life cycle phase. Production is dominant for ADPe, Human tox and Eco tox. The transport phase is the main driver for GW and ADPf.

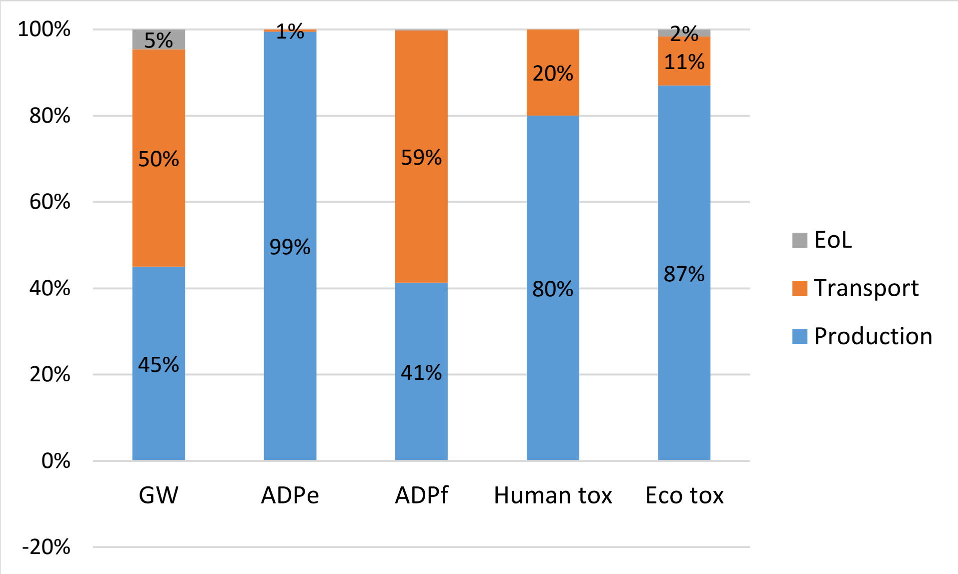

Figure 7 - Relative impacts of screwdriver per life cycle phase

The protective covers under analysis show GW impact values of 0.46 kg CO_2 eq. for the TPU case and of 0.36 kg CO2 eq. for the biobased case.

Modularity and repair

Additional fasteners (screws), pieces of housing for the modules, flex boards and press-fit board to board connctors which are needed to enable modularity in Fairphone 4 are called 'modularity overhead'. The GW value of this modularity overhead is estimated to be 0.25 kg CO2 eq. and it is driven mostly by the additional housing necessary. This represents only 1 % of the total GW value of the entire device. For ADPe the share is 2%, and it is mostly driven by additional flexboards and connectors used to connect the modules and the mainboard. This can be seen in Figure 8 below, which shows the relative contributions of the different components to the modularity overhead. Table 1 shows the absolute values per impact category.

Table 1 - Absolute impacts of modularity

	GW	ADPe	ADPf	Human tox	Eco tox
	kg CO_2e	**kg Sb eq.**	**MJ**	**kg DCB eq.**	**kg DCB eq.**
Totals	2.47E-01	2.92E-05	2.69E+00	6.51E-02	1.08E-03
Connectors	6.82E-03	6.13E-06	7.07E-02	9.07E-04	1.95E-05
Flex	4.01E-02	2.26E-05	4.23E-01	5.91E-03	1.25E-04
Fasteners	7.93E-04	3.15E-08	9.15E-03	1.92E-02	4.86E-06
Housing	2.00E-01	4.12E-07	2.18E+00	3.91E-02	9.34E-04
% of production	1 %	2 %	1 %	1 %	2 %

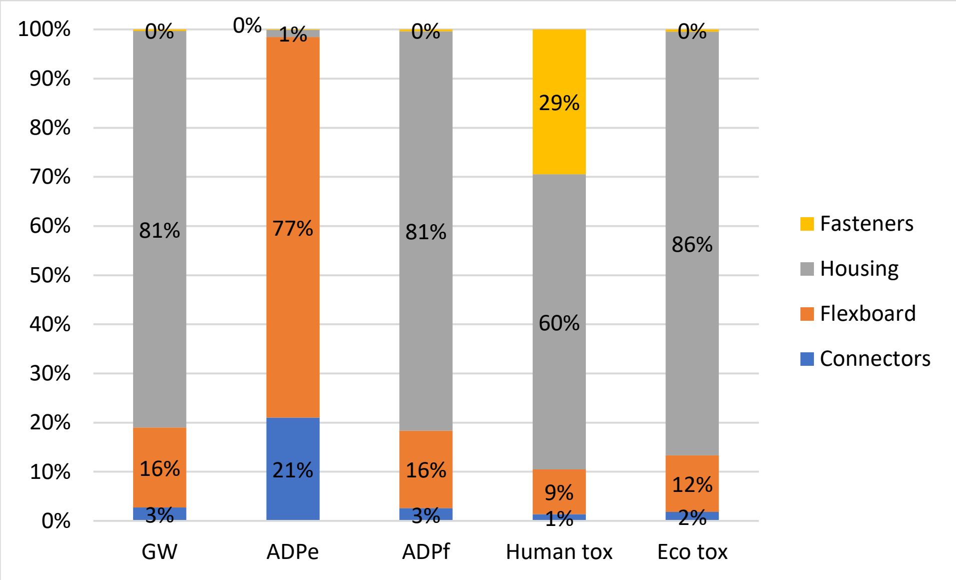

Figure 8 - Relative impacts of modularity

Figure 9 shows a comparison between the yearly GW impact of the device for two baseline scenarios (use of Fairphone 4 for 3 years and for 5 years, including battery replacement). Additionally, three further 5 year scenarios are shown, based on different repair strategies:

- Scenario A: the entire device is sent by the user to Fairphone's repair center in Brittany (France), where the faulty module is substituted by a new one.
- Scenario B: the entire device is sent to the repair center by the user, but board level repair is performed substituting only the faulty components and keeping the rest of the module in use. 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)
- Scenario C: Fairphone B.V. sends a new module to the user, who then sends the faulty module back. The rest of the device stays therefore with the user and the entirety of the faulty module is replaced.

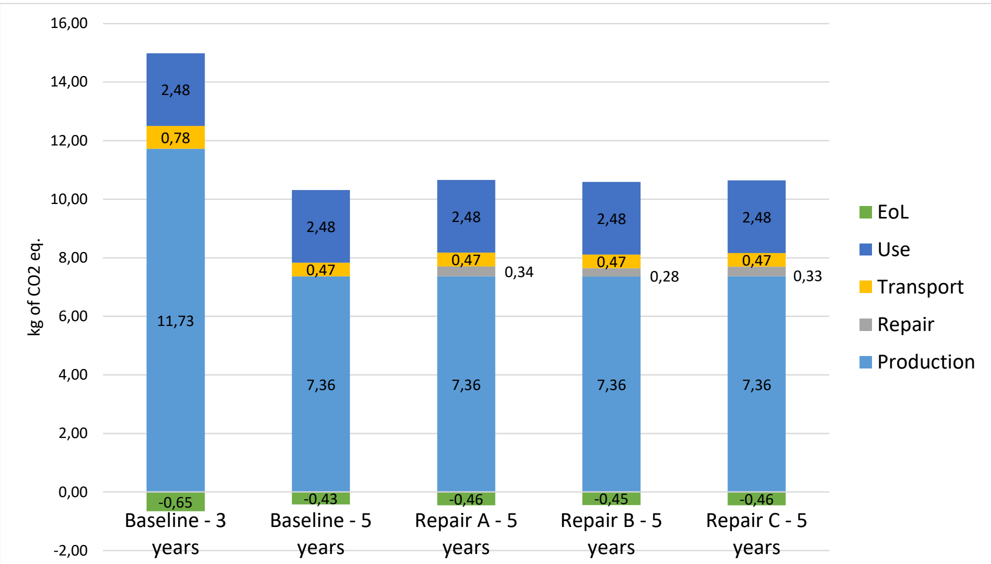

Figure 9 - Comparison of yearly Global Warming impact for baseline and repair scenarios

As can be seen in the figure above, the yearly impact decreases when extending lifetime (around 31% less GHG emissions per year when extending the lifetime by 2 years). Yearly emissions increase slightly for the repair scenarios due to the additional repair activities (i.e. module replacement/repair, additional transport, additional packaging). However, all three repair scenarios still show lower impacts than the 3 year use case due to the lifetime extension. Amongst the three scenarios, scenario B (board level repair of the module) shows the lowest impact.

Conclusions

The results of this study show that environmental impacts are mostly production-driven for the the Fairphone 4 and most impact categories of the accessories. Within production, electronics (e.g. integrated circuits, PCBs, etc.) are the most impactful components of the devices.

As production is the main driver for Fairphone 4 impacts, extension of use is a strong measure to reduce the impacts per year of use. Based on the analysis, it is estimated that the GW impact per year of use can be reduced by around 45% if prolonging use from 3 to 7 years. The analysis of varying repair scenarios also shows that lifetime extension through repair is beneficial, with the module repair approach (repair scenario B) being the best option of the three.

Additional impacts of the modular design have been reduced for Fairphone 4 when comparing it to Fairphone 3. Fairphone 4 uses mostly press-fit board to board connectors, this time also for the display. Additionally, the board structure has been redesigned compared to Fairphone 3, reducing the use of PCBs in most modules and concentrating most SMD electronics on the mainboard. This makes replacement of these modules even more environmentally beneficial.

Material recovery during EoL phase still shows to be beneficial, mostly for ADPe. All accessories analysed cause smaller impacts compared to the main device (Fairphone 4).

2
Goal and Scope Definition

2.1
Goal

This life cycle assessment has the following goals:

- Assessing the environmental impact of the Fairphone 4 model and identify environmental hotspots throughout the entire life cycle.
- Deriving improvement recommendations based on the results.
- Comparing different use and repair case studies in order to better assess environmental risks and opportunities of the device's modularity, using a scenario approach.
- Additionally, this life cycle assessment will also analyze the environmental impacts of accessories of the FP4.

To estimate the main impacts of this device a baseline scenario is set, representing the device as it is sold to consumers. Additional scenarios with extended lifetime are used to account for the devices increased reparability. This analysis is complemented with further repair scenarios accounting for repair overheads.

The intended applications of the study are:

- Using the results to make informed decisions for future upgrades and product designs,
- Analyzing whether after sales processes such as board level repair for modules make sense from an environmental point of view
- Inform users and consumers of specific environmental impacts of modules and use choices and
- General stakeholder communication

2.2
Scope

The study covers the entire life cycle of the Fairphone 4: raw material extraction, manufacturing, transports, use and end-of-life.

The study also covers the following accessories of the device:

- Proprietary External Power Supply (EPS) unit
- Cables
    - USB-C 2.0 cable reinforced with braided, 100% recycled polyester
    - USB-C 3.2 cable reinforced with braided kevlar and nylon, strain made of bio TPU with Velcro-organizer attached (incl. USB-C to USB-A adapter)
- Screwdriver
- Wireless earbuds
- Protective cases

For all devices the entire life cycle is considered, unless for the non-energy using devices where the use phase is not accounted for. Table 2 shows a summary of the devices and the considered stages.

Table 2 - LCA scope summary

	Production	Transport	Use	EoL
Fairphone 4	X	X	X	X
Proprietary EPS unit	X	X	*(included in FP4)*	X
Cables	X	X	*(included in FP4)*	X
Screwdriver	X	X		X
Earbuds	X	X	X	X
Protective covers	X	X		X

The functional unit for the baseline scenario is an intensive smartphone use over three years. The product system refers to the device as delivered to the consumer including sales packaging, manual and the phone itself. All main functionalities of the device are covered indistinctly. The additional scenarios cover:

- Baseline scenarios
    - 3 years of use with no battery replacement.
    - 5 years of use with one battery replacement.
    - 7 years of use with two battery replacements.
- Repair scenarios (all with one battery replacement)
    - 5 years of use with Fairphone B.V. replacing the faulty modules
    - 5 years of use with Fairphone B.V. replacing faulty modules and performing board level repair
    - 5 years of use with the user replacing faulty modules
- Packaging options
    - Smartphone and commercial package
    - Smartphone, screwdriver and commercial package
    - Smartphone, charger (EPS and cable) and commercial package

For more detailed information on the scenarios please refer to section 3.5. Figure 10 below gives an overview of all the different scenarios and devices considered throughout the life cycle.

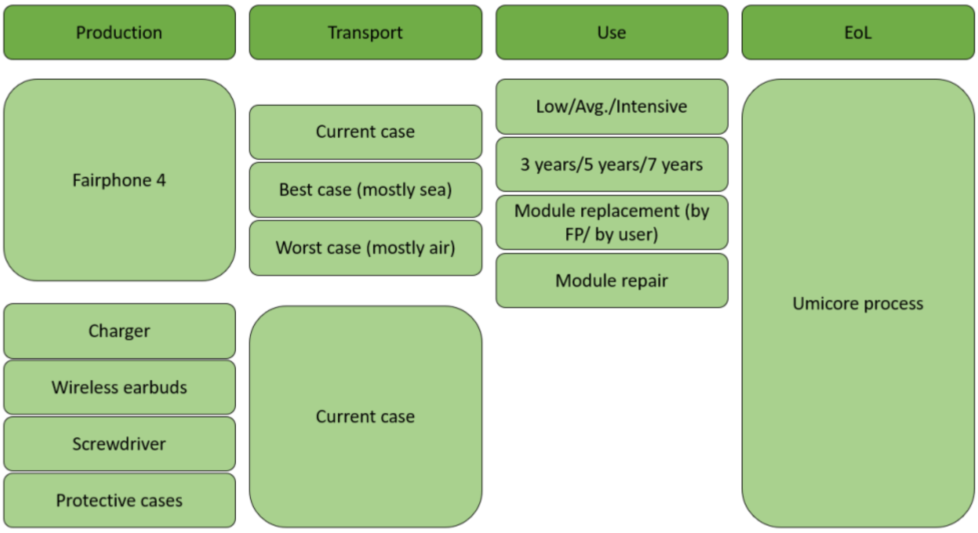

Figure 10 - Overall scheme of study

The inventory data is based on the Bill of Materials (BoM) of the devices under study, a teardown of those and material declarations for subparts from suppliers. The final assembly process is based on data received from Fairphone B.V. and modelled analoguely to the study of the Fairphone 3 (Proske, Sánchez, Clemm, & Baur, 2020).

The following impact categories are covered in the LCIA section (for further explanation on each of the categories and the rationale behind their selection, please refer to section 4.1):

- Global Warming (GW)
- Abiotic resource depletion – elements (ADPe)
- Abiotic resource depletion – fossil resources (ADPf)
- Human toxicity (Human tox)
- Ecotoxicity (Eco tox)

The transport phase covers all transport steps of parts and components to final assembly, final assembly to distribution hub in Europe and the transport to customers, based on Fairphone's sales splits.

Use phase impacts are related to the electricity consumption of the phone during its lifetime. Impact of the mobile network (availability and data transfer) are not part of this study. Consumables are considered for the repair scenarios (spare parts and package). This study will cover three different use scenarios modelled based on the charging cycles per year (more in section 3.2).

The Life Cycle Inventory (LCI) is modelled with Sphera's GaBi software and the latest version of its database, including the electronics extension. This has been supplemented with ecoinvent datasets v3.7 whenever necessary and primary inventory data whenever possible. More detailed information on the sources for LCI data can be found in section 3.

No specific cut-off criteria has been applied to the present study and instead all available data has been included insofar an appropriate dataset was found in the modelling software. Therefore the components and materials for which no suitable dataset nor a reasonable proxy was found have been left aside.

3
Life Cycle Inventory

In this section, the modelling of the Fairphone 4 device is explained. For each life cycle phase, the different unit processes are explained in detail. Relevant aspects presented here include: sources of the data (both for primary and generic data), calculation procedures, necessary assumptions and remaining data gaps (where applicable). For a full disclosure of the datasets used for each component, please refer to sections **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**.

3.1
Raw material acquisition and manufacturing

This life cycle stage represents the production of the Fairphone 4, from the acquisition of the raw materials to the assembly of the entire phone. Whenever available, a suitable dataset for an entire component from GaBi has been used. Wherever this was not the case, the modelling of the part or component has been conducted based on the material composition provided by Fairphone B.V. and using generic GaBi datasets. An explanation on the module level follows in the following sub-sections.

3.1.1 Core

The core includes most of the electronic components of the device, hosting the populated mainboard. The main parts are:

- Mainboard of the device with most of the ICs (e.g. CPU, memory, storage, etc.) and passive components of the Fairphone 4. Unlike the previous model's design, most of the electronic components (e.g. passive components, ICs…) related to peripheric modules (display, speaker etc) are situated on the mainboard.
- Metallic shields of the circuitry.
- Some protective plastic housing.
- SIM and Micro SD card connectors.
- Board to board (BtB) connectors for modules.
- Flexcables.

For more detailed data on how the electronics, connectors and PCB have been modelled please refer to 3.1.11.

3.1.2 Battery

The Fairphone 4 contains a removable and rechargeable lithium ion battery with the following specifications:

- Weight: 64.2 g
- Capacity: 3905 mAh

The battery has been modelled based on the following sources. Material data has been retrieved from the supplier by Fairphone B.V. Battery manufacturing energy, as well as the Battery Management System (BMS) circuits, have been taken from the model built for Fairphone 3 (see (Proske, Sánchez, Clemm, & Baur, 2020)).

3.1.3 Rear cameras module

The Fairphone 4 rear cameras module contains:

- Triple 48M camera with sensor

- Plastic housing of the module
- Flexboard with a BtB connector

The whole rear cameras module has been modelled based on the data provided by Fairphone B.V. The camera and the connector have been modelled on a material basis, while the flexboard has been modelled using a 1-layer PCB data set. The CMOS sensor, in turn, has been modelled as a CMOS logic IC using Fraunhofer IZM own datasets, more on those in section 3.1.11.3.

3.1.4 Bottom module

The bottom module includes the following main parts:

- Bottom speaker
- Vibration motor
- Plastic housing
- Connectors to mainboard

Although the USB-C port is physically included in this unit, it can easily be further separated and accounts as its own module for the purposes of this analysis (see section 3.1.7). All elements were modelled on a material basis.

3.1.5 Earpiece module

The earpiece module is composed of the speaker and a small flexboard with a connector to attach it to the mainboard. They were modelled based on the material data provided by Fairphone B.V, except the flexboard, modelled as 1-layer PCB.

3.1.6 Display Module

The display was modelled based on industry data, as no suitable dataset was available neither in the GaBi database nor ecoinvent. The only available dataset from ecoinvent compiles inventory data for a different technology from 2001, not suitable to be used for a smartphone display.

Therefore, the inventory data has been retrieved from the Corporate Social Responsibility Report of the manufacturer AUO (AUO Innovating Life, 2019) published in 2019. Table 3 lists the inventory data, part of which has been included in the present study. This approach has been chosen in order to make it coherent with the one taken for the rest of the modules and to adress further impact categories beside GW.

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. The data covers the panel manufacturing without backlight and electronics (display board).

Table 3 – Display inventory data by AUO (AUO Innovating Life, 2019)

Input / Output	Total		Per m2	
Material				
Glass substrate	9.15E+04	Tonnes	1.39E+00	Kg
Liquid crystal	8.90E+01	Tonnes	1.35E+00	Kg
Photoresist	2.95E+03	Tonnes	4.49E-02	Kg
Array Process Stripper	6.65E+04	Tonnes	1.01E+00	Kg

CF process thinner	1.50E+03	Tonnes	2.28E-02	Kg
Developer	1.20E+04	Tonnes	1.82E-01	Kg
Aluminium etchant	8.82E+02	Tonnes	1.34E-02	Kg
PFCs usage amount	9.13E+02	Tonnes	1.39E-02	Kg
Energy				
Total energy consumed	1.93E+07	GJ	2.94E-01	GJ
Purchased electricity	1.86E+07	GJ	2.83E-01	GJ
Natural gas	6.21E+05	GJ	9.44E-03	GJ
LPG	1.35E+04	GJ	2.05E-04	GJ
Diesel	6.86E+04	GJ	1.04E-03	GJ
Self generated and used solar power	1.93E+04	Gj	2.93E-04	GJ
Water				
Total water used	2.80E+04	Megaliters	4.25E+02	L
Emissions				
Scope 1	9.86E+00	Tonnes	1.50E-04	Kg
Scope 2	3.05E+02	Tonnes	4.63E-03	Kg
Scope 3	1.52E+03	Tonnes	2.31E-02	Kg
ODS emissions	1.10E-01	Tonnes	1.67E-06	Kg
Sulfur oxides	5.01E+01	Tonnes	7.61E-04	Kg
Nitrogen oxide	7.46E+01	Tonnes	1.13E-03	Kg
Fluorides	1.30E+00	Tonnes	1.98E-05	Kg
HCl	1.80E+00	Tonnes	2.74E-05	Kg
Volatile Organic Compounds (VOCs)	1.32E+02	Tonnes	2.00E-03	kg

Other elements like the display frame, the front glass and the flexboard with the connector have been modelled on a material basis via data provided by Fairphone B.V.

The backlight LEDs have been modelled based on (Deubzer, Jordan, Marwede, & Chancerel, 2012), rescaling from a comparable display, as described in (Proske, Sánchez, Clemm, & Baur, 2020).

3.1.7 USB-C port module

The USB-C port module is composed of the connector and the flexboard. The USB-C port has been modelled on the material basis provided by Fairphone B.V.

3.1.8 Back cover

The back cover (or battery cover) is modelled as 16.4 g of Polycarbonate (PC) plastic.

3.1.9 Selfie camera module

The selfie camera consists of a 24M camera and the connector to join it to the rest of the device. Both have been modelled based on the material composition provided by Fairphone B.V. The CMOS sensor has been modelled using datasets built by Fraunhofer IZM (more in section 3.1.11.3).

3.1.10 Middle frame

The middle frame is composed of two main elements:

- Aluminium frame
- Side keys flexboard

The frame is modelled as 34.34 g of aluminium while the side keys flexboard is modelled on a material basis with data provided by Fairphone B.V.

3.1.11 Cross-module approaches

In this sub-section, the approach for modelling certain components that appear in several modules is explained.

3.1.11.1 Connectors

Connectors are modelled according to the material composition provided by their manufacturers.

The press-fit BtB connectors in the Fairphone 4, which are used to join the modules to the mainboard consist mainly of:

- Copper for the contacts
- Nickel or tin for the plating
- Liquid Crystal Polymer plastic for the housing

Most modules are connected to the mainboard by flexcables, which have been modelled separately as one layer PCBs. Battery and bottom module are connected directly to the mainboard without any flexcable.

Unlike in the previous model, where the connection between display and mainboard was achieved through bigger, gold intensive pogo pins; Fairphone 4's display is connected with a press-fit BtB connector instead, like the other modules.

3.1.11.2 PCBs

Conventionally, printed circuit boards are modelled according to the number of layers and the smallest rectangular outer dimension. Based on the layout panel dimensions, the allocatable area is calculated, as to better estimate the actual PCB area. A comparison with the measured dimensions can be seen in Table 4.

Table 4 - Motherboard PCB dimensions

Board	Boards per panel	Length	Width	Area	Allocated area
		cm	cm	cm^2	cm^2
Motherboard panel	2	17.5	10.3	180.3	90.2
Motherboard		15.3	6.7	102.5	

As no generic dataset is available in GaBi for flexboards, they have been modelled as 1-layer PCBs, according to their outer dimensions.

3.1.11.3 Integrated circuits

The main environmental impacts of integrated circuits are driven by the size (area) of the processed semiconductor die within the package. In order to determine the die-size, x-ray imaging is used to identify the inner structure of the chip. For the present study, Fairphone B.V. has provided the results of said analysis to Fraunhofer IZM for all ICs on the mainboard bigger than 12 pins.

The biggest die sizes were measured in the main Power Management Unit circuit, the DRAM memory and the CPU (Central Processor Unit). The largest of the three is the memory chip, which includes several non-stacked dies within the same package.

The impact of the ICs is modelled according to figures by (Boyd, 2012) and (Prakash, Liu, Schischke, Stobbe, & Gensch, 2013). (Boyd, 2012) refers to CMOS logic, the numbers from (Prakash, Liu, Schischke, Stobbe, & Gensch, 2013) are based on a DRAM chip by Samsung. Therefore, the DRAM and storage of the Fairphone 4 are modelled according to (Prakash, Liu, Schischke, Stobbe, & Gensch, 2013) (see Table 7), all other ICs listed in (Deubzer, Jordan, Marwede, & Chancerel, 2012) are based on the figures for logic chips (see Table 6). As the wafer manufacturing is similar for all ICs, the more detailed wafer data set from (Prakash, Liu, Schischke, Stobbe, & Gensch, 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 5).

Table 5 - Gold, silver and palladium per module board

	Gold	Silver	Palladium
	[g]	[g]	[g]
Motherboard	4.73E-04	1.96E-03	1.99E-04

Table 6 - Environmental impacts according to (Boyd, 2012) per cm^2 of die for the technology 32 nm logic chips

Process	Energy	GW	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 7 - Environmental impacts according to (Prakash, Liu, Schischke, Stobbe, & Gensch, 2013) of storage chips

Process		**Wafer**	**Good die out**		**Packaged die**	
Reference	cm^2	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
Natural gas	kWh		1.60E-01	1.60E-01	7.09E-02	2.31E-01
Silicon dioxide	kg	4.87E-03		6.72E-03	1.10E-04	6.83E-03
Wood pallets (as energy material)	kg	1.83E-03		2.53E-03		2.53E-03
Lignite	kg	3.98E-03		5.49E-03		5.49E-03
Petroleum coke	kg	5.97E-04		8.24E-04		8.24E-04
Electrode material	kg	1.63E-04		2.25E-04		2.25E-04
HCl	kg	6.75E-03		9.32E-03		9.32E-03
Water	kg		7.88E+00	7.88E+00		7.88E+00
N2 (high purity)[1]	kg		6.06E-01	6.06E-01		6.06E-01
O2 (high purity)	kg		4.13E-03	4.13E-03		4.13E-03
Ar (high purity)	kg		2.34E-03	2.34E-03		2.34E-03
H2 (high purity)	kg		6.34E-05	6.34E-05		6.34E-05
Sulphuric acid (high purity)	kg		7.33E-03	7.33E-03		7.33E-03
Hydrogen peroxide (high purity)	kg		2.04E-03	2.04E-03		2.04E-03
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
2-Propanol (C3H8O)/ isopropyl alcohol (IPA) (high purity)	kg		2.78E-03	2.78E-03		2.78E-03
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
NF3	kg		3.02E-04	3.02E-04		3.02E-04
C2F6	kg		6.89E-05	6.89E-05		6.89E-05
SF6	kg		8.96E-06	8.96E-06		8.96E-06
NaOH (for wastewater treatment)	kg		2.04E-03	2.04E-03		2.04E-03
Polymer	kg				2.47E-05	2.47E-05
Au	kg				4.65E-07	4.65E-07
Carbon Black	kg				4.65E-07	4.65E-07
Ag	kg				1.62E-06	1.62E-06
Cu	kg				2.33E-07	2.33E-07
Sn	kg				5.49E-05	5.49E-05

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

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
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

3.1.11.4 Passive components

Passive components were modelled using suitable generic datasets available in the GaBi database, rescaled based on size when necessary.

3.1.12 Packaging

The packaging consists of a sales and distribution packaging. The sales packaging is modelled based on material data and weight information provided by Fairphone B.V. while the transport packaging is modelled proportionally in the transport phase.

3.1.13 Final assembly

For the final assembly, both material and electricity consumption during the process are included for the modelling. The electricity use is based on data provided directly by Fairphone B.V. Since no data on the material expenditure was available, data from Fairphone 3 has been used as a proxy, rescaled by weight. This consists in ethyl alcohol and cloths from cleaning processes in the packaging and nitrogen gas used in the reflow oven. See Table 8 for a summary of the assembly process inputs.

Table 8 - Final assembly

Energy use	
Electricity. from grid	0.8 kWh
Process material	
Ethyl alcohol (95% purity)	0.46 g
Nitrogen (gas. >95% purity)	0.59 g
Cloth (lint free)	0.15 g

3.1.14 Accessories' production

The following accessories have been analysed additionally: the charger (EPS and cable), the wireless earbuds, the protective covers and the screw driver.

3.1.14.1 Charger

The Fairphone 4 charger is composed of the following parts:

- External Power Supply (EPS) with a USB-A connection
- Cable (including two options)
  - USB-C 2.0 cable reinforced with braided, 100% recycled polyester
  - USB-C 3.2 cable reinforced with braided Kevlar and nylon, strain made of bio TPU with Velcro-organizer attached
- USB-C to USB-A adapter

All elements have been modelled based on the bill of materials provided by Fairphone B.V. as well as the weights obtained through on-site teardown of units in Fraunhofer IZM. Cables are modelled as three single core cables with different lengths, proportionately considering the differences in mass between both. Due to the lack of specific datasets for the materials (i.e. bio-based TPU and recycled polyester) generic datasets for cables have been used.

3.1.14.2 Wireless earbuds

The wireless earbuds consist of the following elements:

- Charging case
- Two (R+L) earbuds as separated pieces

As in the case of the charger, the modelling has been done following a combination of the BoM provided by Fairphone B.V. and data directly retrieved from disassembly.

A key element for impact categories like GW and ADP elements are the gold contacts that the earbuds use to connect to the base. Since no material data was directly retrievable from the supplier, an estimated amount of 12 mg per square inch[1] (for a 1 micron thickness plate) has been applied and rescaled based on the contact area. The estimate of a total contact area of around 40 mm^2 (for all four contacts) resulted in an estimated amount of 0,8 mg gold.

3.1.14.3 Screwdriver

The screwdriver has been modelled based on material data provided by Fairphone B.V. and is made of:

- Aluminium
- Brass
- Steel
- Synthetic rubber

3.1.14.4 Protective covers

Three versions of the protective cover are considered for the study as well, namely:

- TPU (100% preconsumer waste recycled)
- Linseed (100% biobased)
- TPU (~40% biobased)

Those specific materials were unfortunately not found in the GaBi database. As proxys, the following protective covers have been modelled:

- Option 1: Primary TPU (dataset from Sphera database)

[1] https://www.goldplating.com/pages/the-fundamentals-of-plating

- Option 2: Starch based PE biopolymer (dataset from Ecoinvent database)

3.2 Use Phase

3.2.1 Fairphone 4 use phase

Different cases for the use pattern have been analysed; setting different amounts of daily charges in three user profiles: low use, average use and intensive use.

No specific analysis of the energy use of specific apps and functionalities have been looked at, limiting the use phase modelling to the energy drawn from the grid while charging.

The user profiles assume the following charging cycles:

- Low use: 0.5 charging cycles per day (one full charge every two days).
- Average use: 230 cycles per year.
- Intensive use: a full charging cycle per day.

The energy use per charging cycle are based on tests conducted by Fairphone B.V. A full charge has been measured to require 18,4 Wh. The energy mix is based on a combination of mixes from different countries in proportion to the sales data by Fairphone B.V. From ageing tests performed in the previous study (Proske, Sánchez, Clemm, & Baur, 2020). We know that a battery lasts around 1,000 cycles and stays then at 80% of its original capacity.

- Baseline scenario A: the device is used during three years, no additional battery is necessary.
- Baseline scenario B: the device is used for five years, one battery replacement is needed.
- Baseline scenario C: the device is used for seven years and two battery replacement are necessary.

No other inputs are considered during the use phase.

3.2.2 Accessories' use phase

Only the wireless earbuds are considered to have a contribution to the energy use, since they have their own batteries. In the teardown, a LiPo battery of 3.7 V and 50 mAh has been identified in the charging case, and two smaller ones in the earbuds. The former is used as reference, as it stores the same energy that is then used to power the individual earbuds. Assuming a typical lifespan of 15-20 h for the charging case and of around 4-5 h for the earbuds, it can be estimated that each full charge of the case powers 3-4 complete discharge cycles of the earbuds' battery (or 3-4 usage cycles), each roughly corresponding to one day of use. Therefore, it is assumed a full charging cycle of the case every 3 days, which equals 122 charging cycles per year.

3.3 Transport

3.3.1 Transport of Fairphone 4

The transport of Fairphone 4 covers three phases:

- Transport of components and pieces to final assembly
- Transport of the assembled device to the distribution hub in The Netherlands
- Transport of the devices to final consumer.

Transport after end of use is included directly in end of life.

3.3.1.1 Transport to final assembly

The transport to final assembly is assumed to be done by truck for intracontinental transport and by plane for international shipping.

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 3 LCA):

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

The transport performance estimated is of 0.008 tkm by air and 0.057 tkm by truck.

3.3.1.2 Transport to distribution hub

The transport to the distribution hub is currently done both by air and by sea. In the future, however, Fairphone B.V. plans extend shipment by sea further, accounted for in the 'best case' scenario. Furthermore, in order to show the impact of those changes further, a third case has been added where most of the shipping is done by air, called 'worst case'. The three scenarios are modelled as follows:

- Current case: 50% by plane and 50% by ship.
- Best case: 30% by plane and 70% by ship.
- Worst case: 90% by plane and 10% by ship.

The transport efforts estimated per scenario are the following:

- Current case: 1.361 tkm for each
- Best case: 0.816 tkm by plane and 1.91 tkm by ship.
- Worst case: 2.45 tkm by plane and 0.272 tkm by ship.

3.3.1.3 Transport to consumer

All transport to customers is done by truck. The travelling distances are weighted based on the sales split as declared by Fairphone B.V., resulting in 0.14 tkm average truck transport.

3.3.2 Transport of accessories

All accessories have been modelled according to the following approach:

- Transport to final assembly has been neglected since specific information on the origin of each component and part was not available.
- Transport to distribution hub is assumed to be performed 50% by air and 50% by sea, according to data facilitated by Fairphone B.V.
- Transport to customers is assumed to be carried out by land (truck) and average distance is assumed to follow the same proportion as the main device (which is in turn based on the sales split).

Table 9 shows a summary of the estimated transport efforts for all accessories.

Table 9 - Estimated transport effort for accessories

	To distribution hub	**To customers**
Wireless earbuds	0.604 tkm plane 0.604 tkm ship	0.0685 tkm truck
Charger (USB 2.0 to 2.0)	0.604 tkm plane	0.0685 tkm truck

	0.604 tkm ship	
Charger (USB 2.0 to 3.2)	1.37 tkm plane 1.37 tkm ship	0.155 tkm truck
Screwdriver	0.166 tkm plane 0.166 tkm ship	0.0189 tkm truck
Protective cases	0.178 tkm plane 0.178 tkm ship	0.020 tkm truck

3.4 End-of-Life

3.4.1 Fairphone 4 end-of-life

In this study, the same conservative approach taken in the Fairphone 3 study has been taken i.e. that the Fairphone 4 device is assumed to be discarded as a regular phone and joins the wider WEEE recycling stream. This approach relies on the assumption that this is the most usual route for smartphones to follow at their end of life.

Due to a lack of specific data on smartphone recycling, several assumptions needed to be made, which will be explained in this section. 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 3 and Fairphone 2 (Proske, Clemm, & Richter, Life Cycle Assessment of the Fairphone 2, 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 truck (75 % of distance) and by train (25 % of distance).

Following the Umicore recycling process (Hagelüken C. , 2016), the device is set to have the battery removed first (depollution). 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 & Marwede, 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. Additionally, a disassembly of a Fairphone 3 device carried out at Fraunhofer IZM has been used as backup for completing weights and material data. All burdens as well as credits of the material recovery have been allocated to the device under study. This has been decided in order not to hinder comparability with the Fairphone 3. For the credits' estimation, direct correspondence has been assumed between recovered secondary material and avoided primary material production.

3.4.2 Accessories' end-of-life

In the modelling of the wireless earbuds and both versions of the charger, end of life has been considered to follow the same stream as Fairphone 4, assuming that those devices are also part of the electronics waste stream. Therefore, same processeses and material recovery rates are applied.

The screwdriver is no electronic device and therefore it has been assumed not to undergo the same recovery processes as the electronics scrap stream. Instead, EoL is modelled as landfilling. Similarly, as plastic fraction of WEEE, the protective cases have been assumed to be incinerated.

3.5 Scenarios

Apart for the aforementioned baseline scenarios studied, further scenario analyses was carried out. Those revolve around repair cases and different sales package options.

3.5.1 Repair scenarios

In order to analyse the benefits and limitations of the repair potential of the Fairphone 4, different scenarios are built. In all repair scenarios the lifetime is extended from the baseline 3 years to 5 years. In all cases, the baseline package and a replacement battery are assumed. For all cases, the faulty modules are based on the most typical failures in smartphones[1] as assessed by Wertgarantie (Wertgarantie, 2020). Based on those statistics, the following distribution has been chosen:

- 63% display module
- 16% USB connector module
- 10% rear cameras module
- 5% loudspeaker module
- 3% back cover
- 3% core

The repairing approach, however varies in each of the scenarios. For more on the differences between them, please see section 4.4.

Repair A

Repair scenario A assumes that users send the entire device to the repair center in Dinan (Bretagne, France) and get it back with a new module, so the module replacement takes place at Fairphone's repair center.

Repair B

In repair scenario B, the user sends the entire device to Fairphone B.V.'s repair center, but the faulty module is not replaced in its entirety. Instead, Fairphone B.V. performs a board-level repair and replaces the specific faulty component. In order to account for that, the following components are assumed to be faulty in each module:

- Display module: display (excluding therefore control IC and flexcable which are not replaced)
- USB connector module: USB-C port

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

- Rear cameras module: the two CMOs of the camera
- Loudspeaker module: entire module
- Back cover: entire back cover
- Core: PMU chip

As to account for inefficiencies in the process, different user bahviours and different levels of damages not a 100% rate of module repair is assumed. 75% of all faulty modules are assument to be returned to Fairphone B.V. Out of those, only 50% are assumed to be reparable. For the rest, direct replacement is assumed.

Repair C

Repair scenario C is very similar to scenario A. The only difference is that in this case, the new module is sent to the user who sends the faulty module back. Therefore, the replacement as such is done directly by the user.

3.5.2 Packaging options

As described earlier in 3.1.14, in this study not only the Fairphone 4, but also a number of accessories were assessed. Those accessories are part of different packaging options that Fairphone B.V. is considering as options for customers to buy several products together. Therefore, the impacts of said packs will be assessed separately as additional scenarios. Those comprise the following:

- Baseline pack: includes the main device and commercial packaging.
- Screwdriver pack: includes the main device and the official Fairphone screwdriver.
- Charger pack: includes the main device, the official Fairphone EPS, the USB-C to USB-A adapter and a cable (which in turn can be either USB 2.0 to 3.2 or USB 2.0 to 2.0).

4 Life Cycle Impact Assessment

In this section, the impact categories under analysis are explained. Afterwards, the results of the main and additional scenarios are presented and analysed.

4.1 Definition of impact categories

The CML methodology was put forward by the Leiden University in 2002 and focuses on midpoint indicators, following the ISO 14040 standards. It has a global geographical coverage, an infinite time horizon (except for global warming potential where a 100 year horizon is set) and it covers around 800 different substances (JRC, 2010). Although it models 12 different midpoint impact categories, 5 have been chosen:

- Global Warming (GW) 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 GW for greenhouse gases is expressed as CO2-equivalents, i.e. the effects are expressed relatively to the effect of CO2." (Stranddorf, Hoffmann, & Schmidt, 2005)
- Resource depletion: It 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)." (van Oers & Guinée, 2016)
    - Abiotic resource depletion elements (ADPe): "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)." (van Oers & Guinée, 2016)
    - ADP fossil (ADPf): "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)." (van Oers & Guinée, 2016)
- Human Toxicity (Human tox): "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, Hoffmann, & Schmidt, 2005)

- Terrestrial Ecotoxicity (Eco tox): "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, Hoffmann, & Schmidt, 2005)

The impact categories presented in this study have been chosen following the previous study (Proske, Sánchez, Clemm, & Baur, 2020). In that study, the selection was made in agreement with Fairphone B.V. with the goal of not only focusing on GW, allowing for the identification of trade-offs between impact categories and communicating a wider range of impacts. All the aforementioned impact categories are calculated by GaBi following the CML method. The rest of the impact categories within this method however, have not been included, since the present study uses many external sources for the inventory data (e.g. display, ICs, etc.) in order to fill in the data gaps in the GaBi library. In many cases, those sources mainly cover GHG data instead of other environmental impacts. Therefore, it has been considered that presenting all impact categories from CML is not as representative. Focusing on some key impact categories also makes communication more feasible.

4.2 Results

All results presented in the following sections relate to the functional unit presented above and are limited to the defined system boundaries. These results reflect midpoint indicators and do not predict impacts on category endpoints.

The absolute GW result is 43.0 kg CO_2 eq (see Table 10 for more details). The main contributor, as shown in Figure 11, is the production phase for all impact categories. Transport and use cause smaller impacts, although the former has noticeable relevance for human toxicity. The end of life (EoL) phase shows a positive effect in all impact categories but mostly in the ADP elements category, mainly driven by gold recovery.

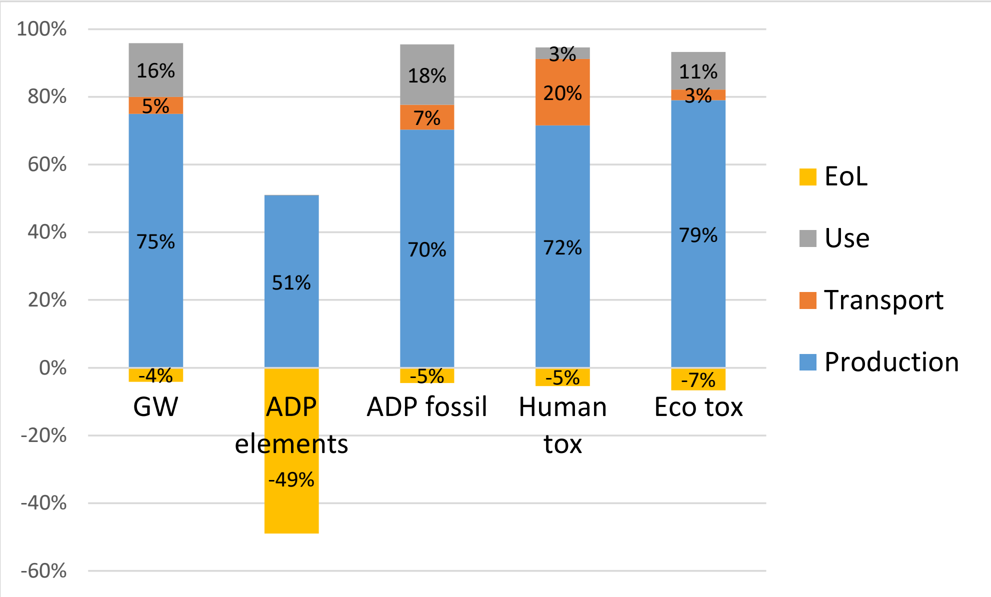

Figure 11 - Relative impact per life cycle phase (3 years scenario)

Table 10 - Absolute impacts of the whole life cycle (3, 5 and 7 years scenario)

	GW	ADPe	ADPf	Human tox	Eco tox
	kg CO2 eq.	**kg Sb eq.**	**MJ**	**kg DCB eq.**	**kg DCB eq.**
			3 years		
Totals	4.30E+01	9.92E-05	4.47E+02	1.00E+01	7.10E-02
Production	3.52E+01	1.69E-03	3.21E+02	6.77E+00	6.11E-02
Use Phase	7.44E+00	3.25E-06	8.15E+01	3.18E-01	8.64E-03
Transport	2.34E+00	3.71E-07	3.35E+01	1.86E+00	2.44E-03
EoL	-1.96E+00	-1.63E-03	-2.06E+01	-5.14E-01	-5.19E-03
			5 years		
Totals	4.99E+01	1.31E-04	4.89E+02	8.87E+00	7.78E-02
Production	3.68E+01	1.74E-03	3.37E+02	7.17E+00	6.60E-02
Use Phase	1.24E+01	5.42E-06	1.36E+02	5.29E-01	1.44E-02
Transport	2.35E+00	3.95E-07	3.36E+01	1.86E+00	2.47E-03
EoL	-2.14E+00	-1.65E-03	-2.26E+01	-7.76E-01	-7.07E-03
			7 years		
Totals	5.63E+01	1.63E-04	5.58E+02	9.21E+00	8.67E-02
Production	3.84E+01	1.79E-03	3.53E+02	7.55E+00	7.09E-02
Use Phase	1.74E+01	7.59E-06	1.90E+02	7.41E-01	2.02E-02
Transport	2.36E+00	4.18E-07	3.37E+01	1.87E+00	2.49E-03
EoL	-2.31E+00	-1.67E-03	-2.46E+01	-1.04E+00	-8.96E-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.

As said, with the extension of use time, more energy is consumed in the use phase resulting in a higher absolute impact. However, when looking at the impact per year of use in Figure 12, it can be seen how extended use reduces the contribution per year. The graph below shows a decrease of up to 31% for GW when extending the lifetime to 5 years and a reduction of 45% when extending the phone use to 7 years.

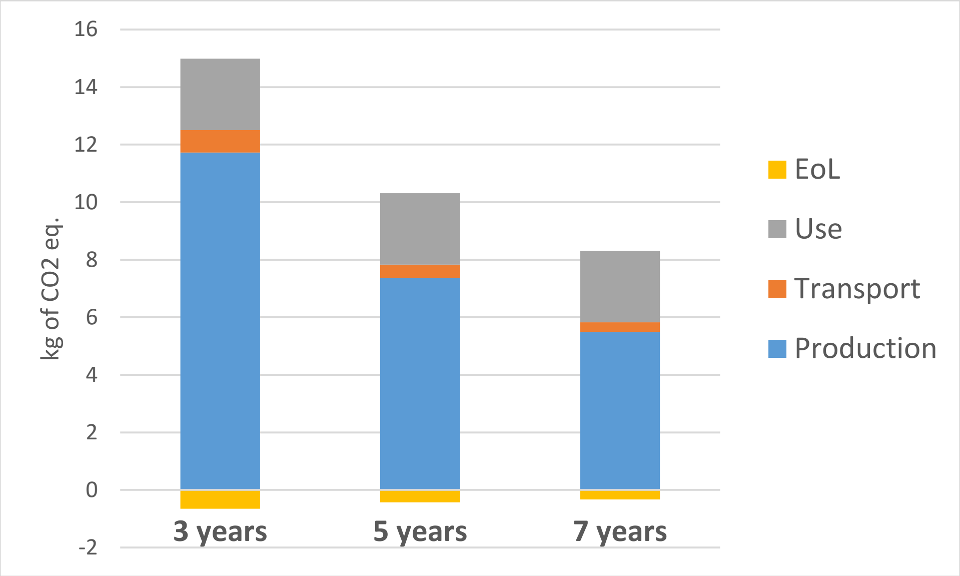

Figure 12 - Impact per year of use (baseline scenarios) for the impact category GW

4.3 Contribution Analysis

The following figures and numbers are based on the main baseline scenario (Baseline A).

4.3.1 Production

For the production phase, Figure 13 shows that the core is the most relevant element, followed at a distance by the battery and the camera (except for GW where the aluminium metal frame also contributes notably). This is due to the fact that all electronics are placed on the mainboard, which is part of the core.

For all impact categories the relative contribution of the core ranges between 71% and 86%. The rear camera module shows its highest contribution in human toxicity with a 12% (around

5% in the other categories). The battery shows a contribution of around 5% in all impact categories. For the absolute values, please see Table 11.

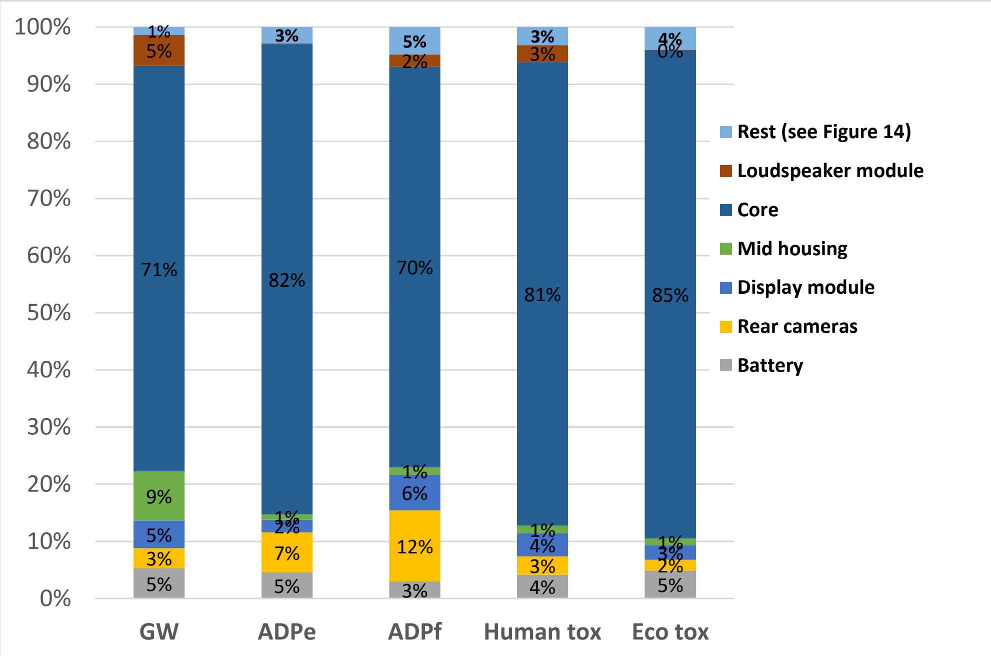

Figure 13 - Relative impacts of the production phase per impact category (3 year scenario)

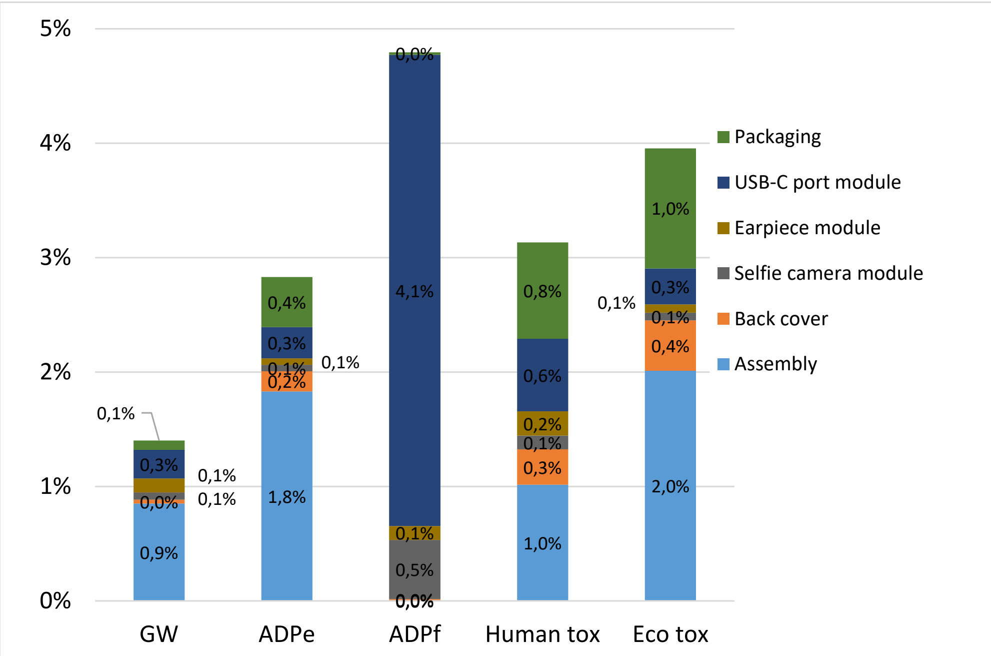

Figure 14 - Relative impacts of the production phase per impact category (rest of modules)

Table 11 - Absolute impacts of the production phase (3 year scenario)

	GW	ADPe	ADPf	Human tox	Eco tox
	kg CO2 eq.	kg Sb eq.	MJ	kg DCB eq.	kg DCB eq.
Production	3.52E+01	1.69E-03	3.21E+02	6.77E+00	6.11E-02
Assembly	6.44E-01	5.92E-08	6.45E+00	5.76E-02	6.20E-04
Back cover	6.20E-02	2.11E-07	1.41E+00	2.20E-03	1.88E-04

Battery	1.60E+00	5.04E-05	1.56E+01	3.61E-01	2.53E-03
Rear cameras module	2.46E+00	2.11E-04	6.20E+00	2.35E-01	1.98E-03
Display module	7.89E-01	1.05E-04	8.19E+00	3.28E-01	2.46E-03
Mid housing	3.24E-01	2.18E-05	3.61E+00	5.80E-01	8.18E-04
Core	2.90E+01	1.19E-03	2.74E+02	4.81E+00	4.95E-02
Loudspeaker module	4.96E-02	3.64E-05	5.33E-01	3.64E-01	1.82E-03
Selfie camera	1.98E-02	8.75E-06	2.15E-01	4.31E-03	7.39E-05
Earpiece	1.97E-02	2.05E-06	2.31E-01	8.29E-03	1.29E-04
USB-C port module	9.56E-02	6.97E-05	1.01E+00	1.70E-02	3.88E-04
Packaging	1.54E-01	3.97E-07	3.37E+00	5.47E-03	5.14E-04

The presentation by type of component shows the dominant effect of the ICs (see Figure 15). In the impact category GW, the second largerst contributors are the PCBs and the passive components. All three types of components are mainly found in the core.

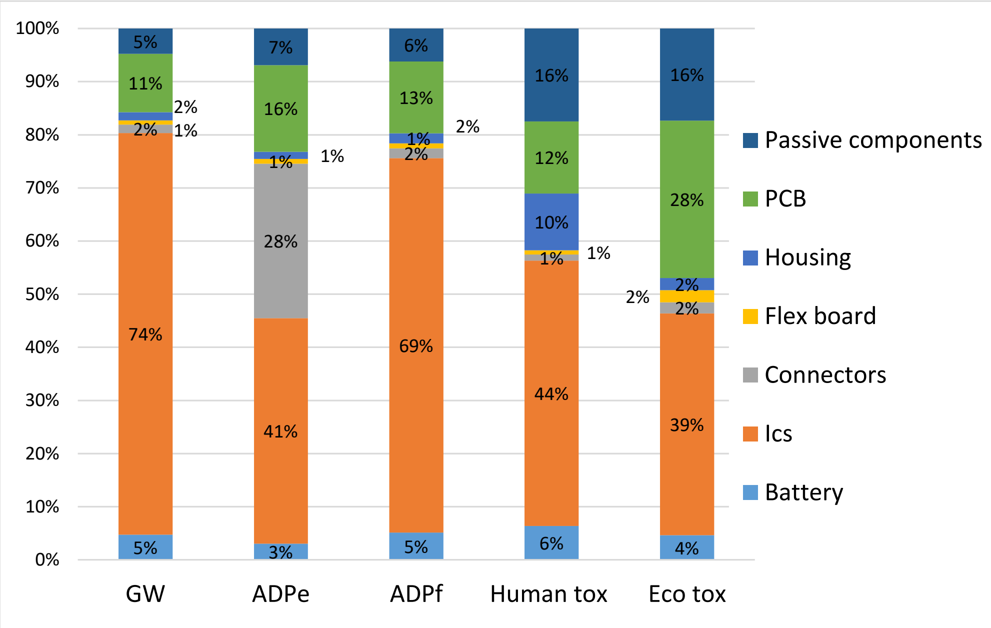

Figure 15 - Relative impact per component type (without packaging and assembly)

Table 12 - Absolute impact of components

	GW	ADP elements	ADP fossil	Human tox	Eco tox
	kg CO2 eq.	**kg Sb eq.**	**MJ**	**kg DCB eq.**	**kg DCB eq.**
Battery	1.60E+00	5.04E-05	1.56E+01	3.61E-01	2.53E-03
ICS	2.55E+01	7.00E-04	2.13E+02	2.82E+00	2.28E-02
Connectors	5.36E-01	4.80E-04	5.55E+00	6.36E-02	1.14E-03
Flex boards	2.68E-01	1.51E-05	2.89E+00	4.67E-02	1.25E-03
PCBs	5.18E-01	2.21E-05	5.72E+00	6.02E-01	1.26E-03
Electronic components	3.71E+00	2.69E-04	4.09E+01	7.65E-01	1.62E-02
Others	1.60E+00	1.14E-04	1.88E+01	9.88E-01	9.47E-03

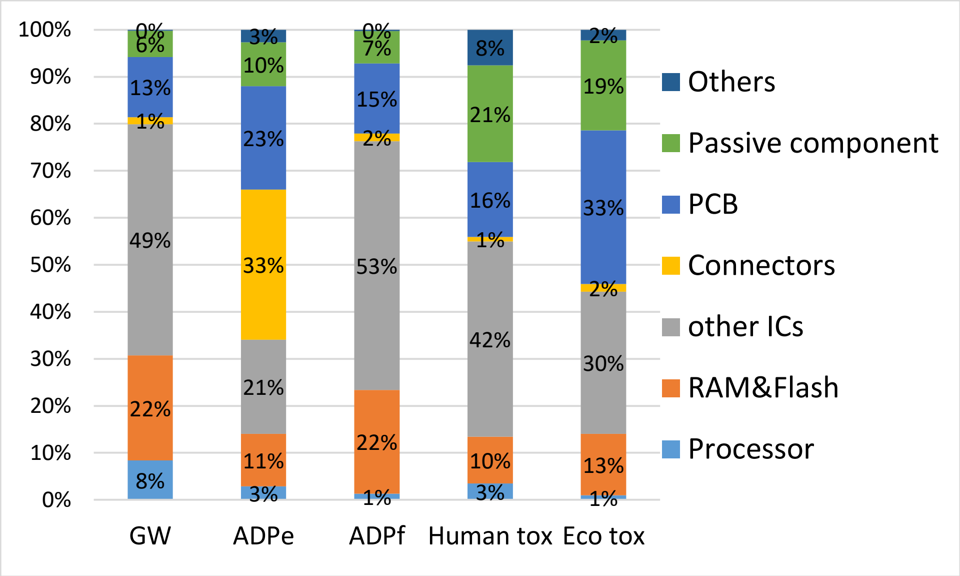

Figure 16 - Relative impact of the core per component type

As Figure 16 above shows, within the core, the ICs drive the impact in most impact categories. In ADP elements however, connectors are the main contributors due to the usage of precious metals e.g. gold or silver. When compared to the previous model (Proske, Sánchez, Clemm, & Baur, 2020), reduced die area for the current RAM & Flash chip reduces also the combined impact of the main chips, the processor and the memory.

4.3.2 Use phase

Within the use phase, the German energy mix is the main driver with above 60% of the impact for all categories, while representing around 44% of the total sales. This difference is due to the varying energy mixes of different countries.

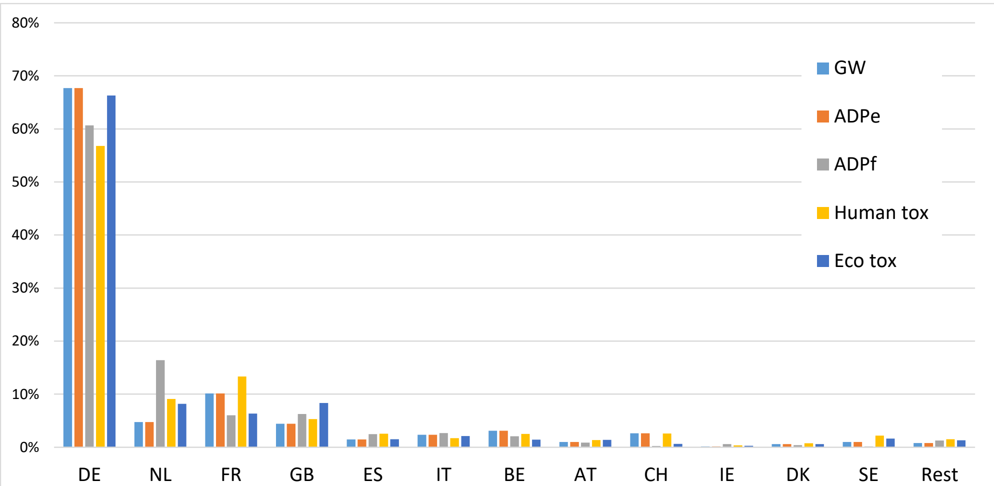

Figure 17 - Relative impact of the use phase per country and impact category

4.3.3 Transport

For the Fairphone 4, due to changes in the logistics approach by Fairphone B.V., greatly motivated by the COVID-19 pandemic taking place, the absolute impact of the transport has increased (see (Proske, Sánchez, Clemm, & Baur, 2020)).

As Figure 18 shows, the transport from assembly to the distribution hub has the highest impact in all categories (less so in ADP elements). This is caused by the share of air transport in this phase (see section 3.3). Air transport has a comparatively higher impact across all categories as opposed to land and sea transport as can also be seen in Figure 19, where the impacts are sorted by means of transport.

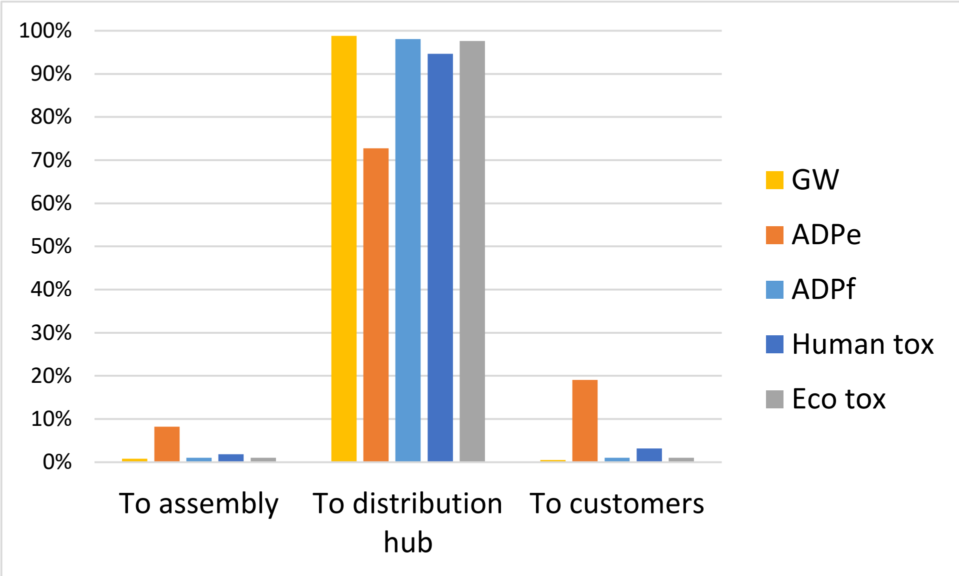

Figure 18 - Relative impact of transportation phases 'to assembly', 'to distribution' and 'to customer' (3 year scenario)

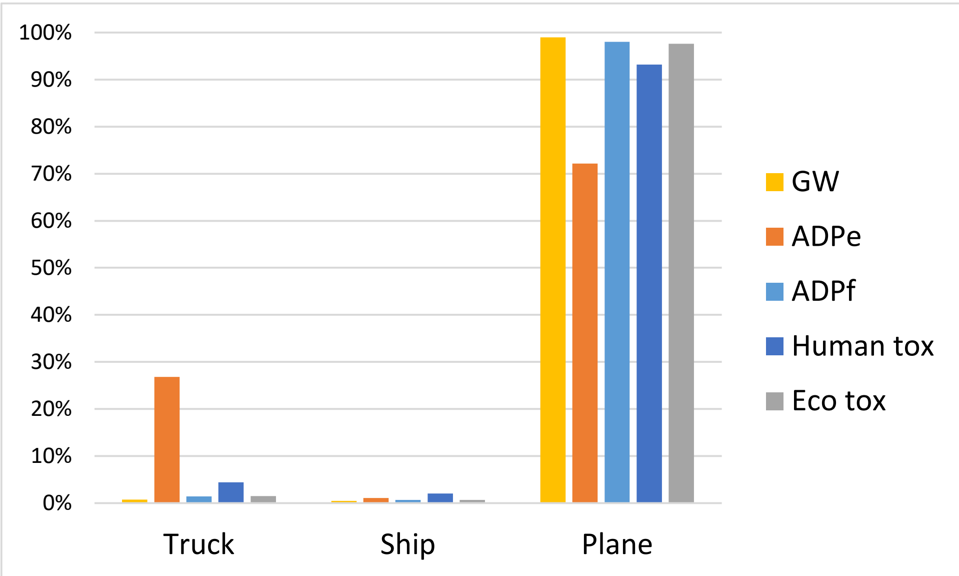

Figure 19 - Relative impact of transportation phase between modes of transportation 'air', 'train' and 'truck'

Table 13 - Results of the transport phase

Impact category		to assembly	to customer	to distribution hub
GW	**kg CO2 eq.**	2,34E-02	2.31E-02	2,30E+00
ADPe	**kg Sb eq.**	3,05E-08	7.06E-08	2,70E-07
ADPf	**MJ**	3,43E-01	3.53E-01	3,27E+01
Human tox	**kg DCB eq.**	1,51E-02	9.51E-03	1,84E+00
Eco tox	**kg DCB eq.**	4,53E-05	2.24E-03	2,31E-03

4.3.4 End-of-Life

Figure 20 shows the relative contributions of the different stages of the EoL phase. It shows that the precious metals recovery phase brings the biggest benefit mostly driven by the recovery of gold from the electronics scrap. The electronics refining and battery recycling also contribute positively (negative value, positive effect) due to the copper recovered in those steps. Both the copper smelting step and the transport to the EoL facility imply an environmental burden which is nonetheless outweighted by the credits of the recovered materials. In Table 14 the absolute values are shown.

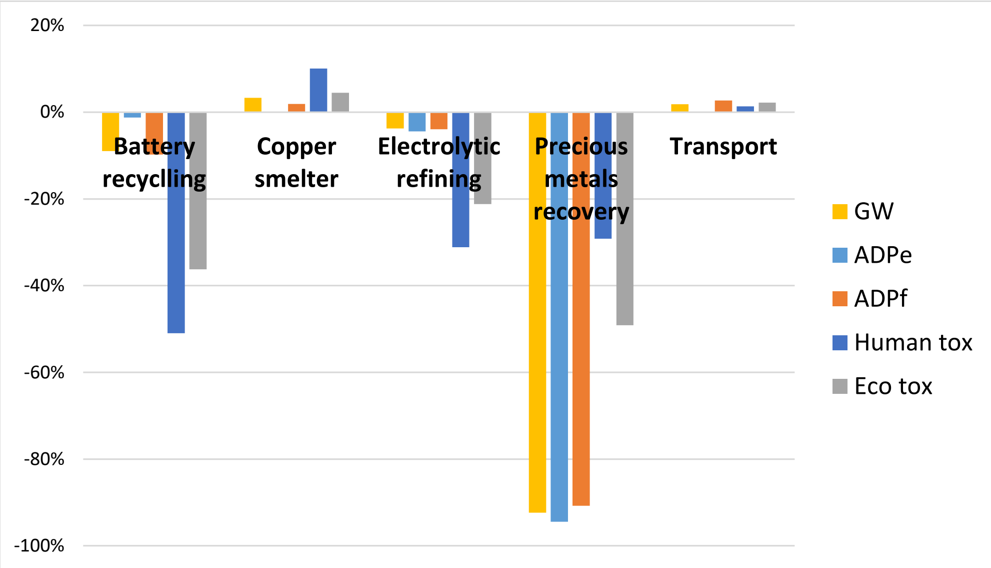

Figure 20 - Relative impact of EoL phase

Table 14 - Results of the EoL phase

Impact category		Battery recycling	Copper Smelter	Electrolytic refining	Precious metals recovery	Transport
GW	**kg CO_2eq.**	-2.06E-05	8.48E-09	-7.22E-05	-1.54E-03	8.57E-08
ADPe	**kg Sb eq.**	-2.01E+00	3.91E-01	-8.11E-01	-1.87E+01	5.53E-01
ADPf	**MJ**	-1.88E-03	2.32E-04	-1.10E-03	-2.55E-03	1.14E-04
Human tox	**kg DCB eq.**	-1.76E-01	6.54E-02	-7.37E-02	-1.81E+00	3.64E-02
Eco tox	**kg DCB eq.**	-2.62E-01	5.17E-02	-1.60E-01	-1.50E-01	6.91E-03

4.3.5 Modularity

Following the trend of the previous models (Proske, Clemm, & Richter, Life Cycle Assessment of the Fairphone 2, 2016), the Fairphone 4 has optimized further the elements enabling modularity. The modularity overhead is considered to be any additional connector, flexboard, fastener, piece of housing or any other kind of component that is needed to allow for easy separation (and connection) of the various modules. As Table 15 and Figure 21 show, the burden of modularity is very small in absolute terms for most impact categories, representing 1% of the production impacts of each.

Table 15 - Absolute impacts of modularity

	GW	ADPe	ADPf	Human tox	Eco tox
	kg CO_2eq.	**kg Sb eq.**	**MJ**	**kg DCB eq.**	**kg DCB eq.**
Totals	2.47E-01	2.92E-05	2.69E+00	6.51E-02	1.08E-03
Connectors	6.82E-03	6.13E-06	7.07E-02	9.07E-04	1.95E-05
Flex	4.01E-02	2.26E-05	4.23E-01	5.91E-03	1.25E-04
Fasteners	7.93E-04	3.15E-08	9.15E-03	1.92E-02	4.86E-06
Housing	2.00E-01	4.12E-07	2.18E+00	3.91E-02	9.34E-04
% of production	1 %	2 %	1 %	1 %	2 %

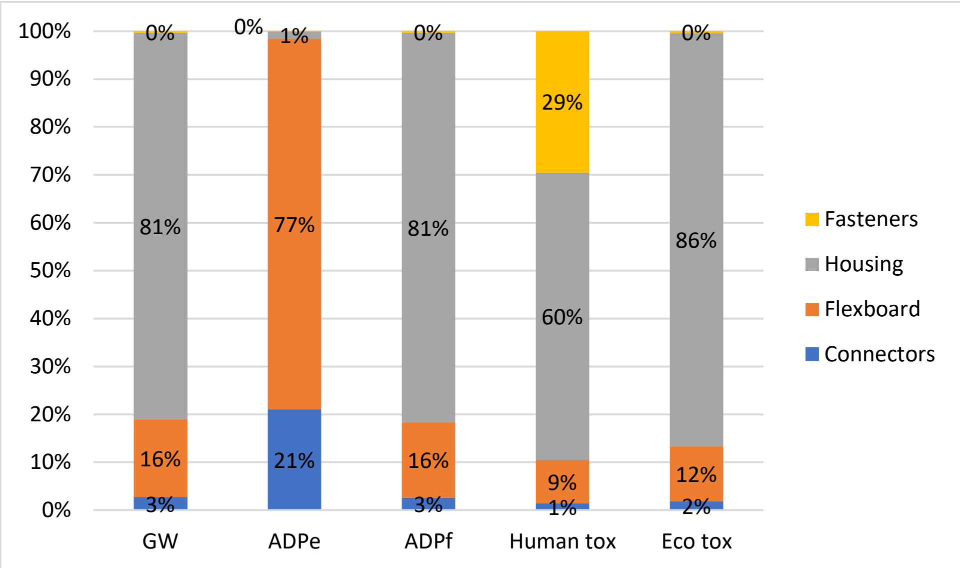

Figure 21 - Relative impacts of modularity

This figures mean a reduction from previous models, as presented in Table 16, consolidating a trend of less environmentally harmful integration of modular design.

Table 16 – Trend of contribution of modularity to imapct categories

		Fairphone 2	Fairphone 3	Fairphone 4
GW	**kg CO_2eq.**	5%	2%	1%
ADPe	**kg Sb eq.**	56%	17%	2%
ADPf	**MJ**	12%	3%	1%
Human tox	**kg DCB eq.**	4%	7%	1%
Eco tox	**kg DCB eq.**	7%	7%	2%

4.3.6 Accessories

In this section, the results for the accessories mentioned above are presented. In section 4.5.4 the effects of the different packaging options are discussed briefly.

4.3.6.1 Earbuds

Table 17 shows the absolute impacts for the entire life cycle of the wireless earbuds (including: the charging case, the earbuds and the packaging), while Figure 22 displays the relative contributions. The Production phase shows to be the main driver for most impact categories. EoL processes show very little impact except for the ADP elements category, where the recovery of precious metals shows a net environmental benefit.

Table 17 - Absolute values for the entire life cycle of the wireless earbuds

		Totals	Production	Transport	Use	EoL
GW	**kg CO2 eq.**	3.49E+00	2.44E+00	1.03E+00	2.49E-02	-7.26E-03
ADPe	**kg Sb eq.**	1.15E-04	1.54E-04	1.54E-07	1.09E-08	-3.96E-05
ADPf	**kg Sb eq.**	4.40E+01	2.94E+01	1.47E+01	2.73E-01	-3.27E-01
Human tox	**kg DCB eq.**	1.41E+00	5.85E-01	8.18E-01	1.06E-03	2.49E-03
Eco tox	**kg DCB eq.**	9.85E-03	8.91E-03	1.06E-03	2.89E-05	-1.53E-04

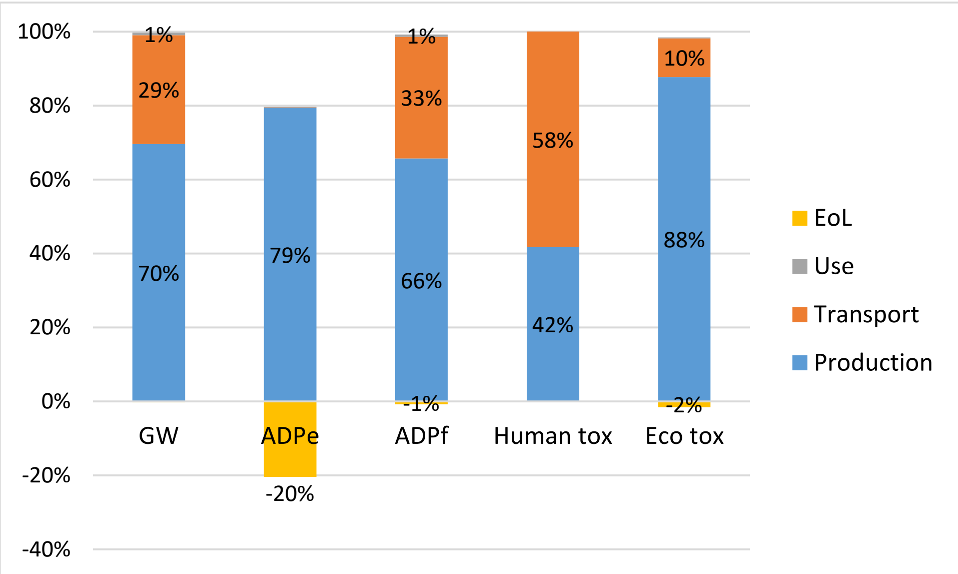

Figure 22 - Relative impacts of wireless earbuds per life cycle phase

Table 18 shows the absolute impacts of the production phase of the wireless earbuds and Figure 23 the contributions of each of its parts.

Table 18 - Absolute impacts of wireless earbuds production

		Totals	Charging case	Earbuds (R+L)	Packaging
GW	**kg CO2 eq.**	2.44E+00	9.22E-01	1.51E+00	8.68E-03
ADPe	**kg Sb eq.**	1.54E-04	5.66E-05	9.70E-05	8.49E-09
ADPf	**kg Sb eq.**	2.94E+01	1.13E+01	1.77E+01	3.56E-01
Human tox	**kg DCB eq.**	5.85E-01	2.70E-01	2.92E-01	2.30E-02

Eco tox	**kg DCB eq.**	8.91E-03	2.28E-03	4.13E-03	2.50E-03

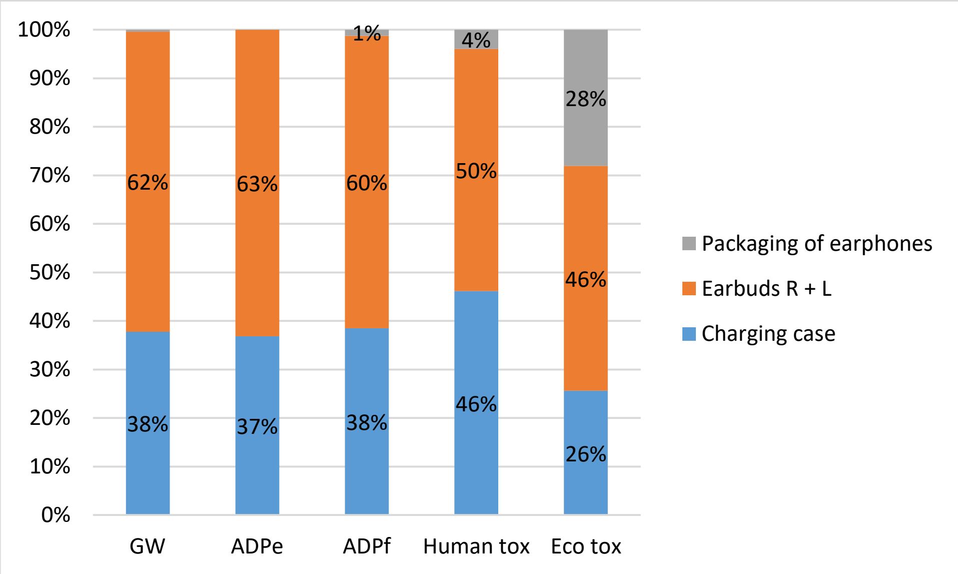

Figure 23 - Relative impacts of wireless earbuds

Figure 24 shows the distribution of impact on GW across the entire product but divided by component categories. As it can be seen, passive components and ICs contribute the most to its impacts, followed by the batteries (of which the earbuds have three in total) and category 'Others' (including small mechanical parts e.g. the rubber in the ear-in part). Figure 25 shows the relative ADP elements impact per component type. In this case, ICs show the highest contribution with over 40% of the total.

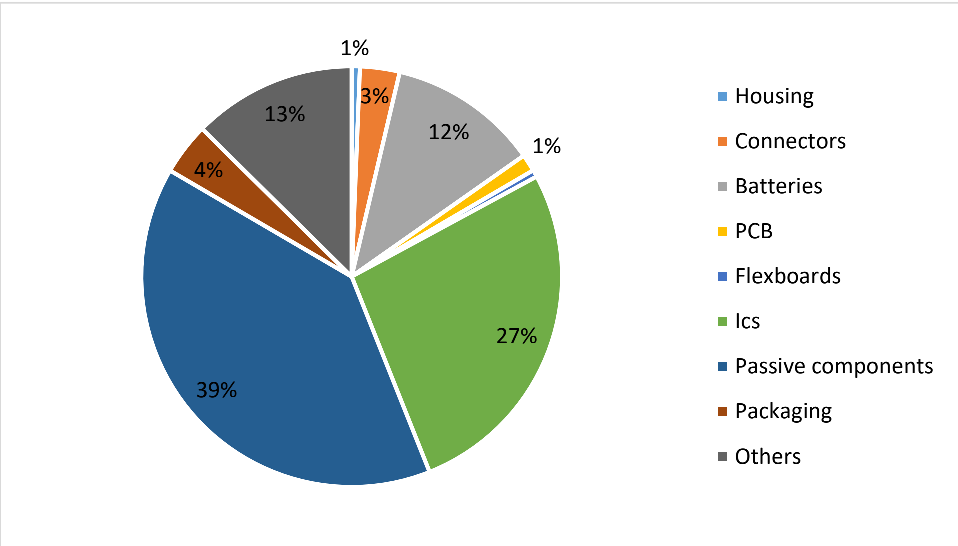

Figure 24 – Contributions to GW during the production phase of the earbuds

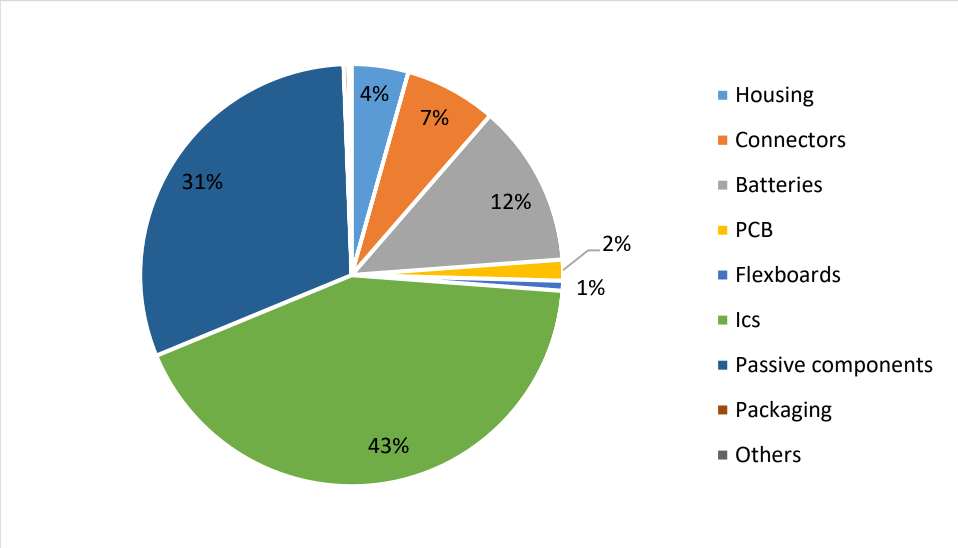

Figure 25 - Contributions to ADPe impact during the production phase of the earbuds

4.3.6.2 Chargers

Table 19 shows the absolute impacts of the entire life cycle for the USB 2.0 to 2.0 charger and Figure 26 shows the relative impacts. The production phase is the main contributor for most impact categories.

Table 19 - Absolute impacts of USB 2.0 to 2.0 charger per life cycle phase

		Totals	Production	Transport	EoL
GW	**kg CO2 eq.**	2.81E+00	1.94E+00	1.03E+00	-1.63E-01
ADPe	**kg Sb eq.**	3.28E-04	5.06E-04	1.54E-07	-1.78E-04
ADPf	**kg Sb eq.**	3.84E+01	2.56E+01	1.47E+01	-1.89E+00
Human tox	**kg DCB eq.**	1.40E+00	5.90E-01	8.18E-01	-7.59E-03
Eco tox	**kg DCB eq.**	6.74E-03	5.99E-03	1.06E-03	-3.13E-04

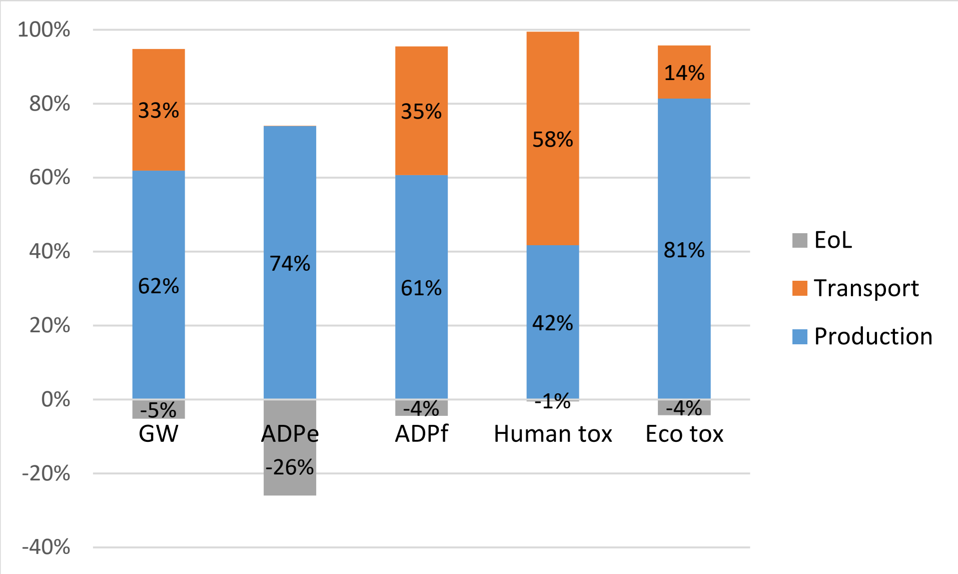

Figure 26 - Relative impacts of USB 2.0 to 2.0 charger per life cycle phase

Figure 27 shows the contributions of the different parts of the charger to the total impacts of the production phase. For all impact categories the EPS seems to be the main driver, while the cable and the adapter show lower impacts. In the case of ADP elements however, the impact distribution seems more even. Absolute values can be seen in Table 20.

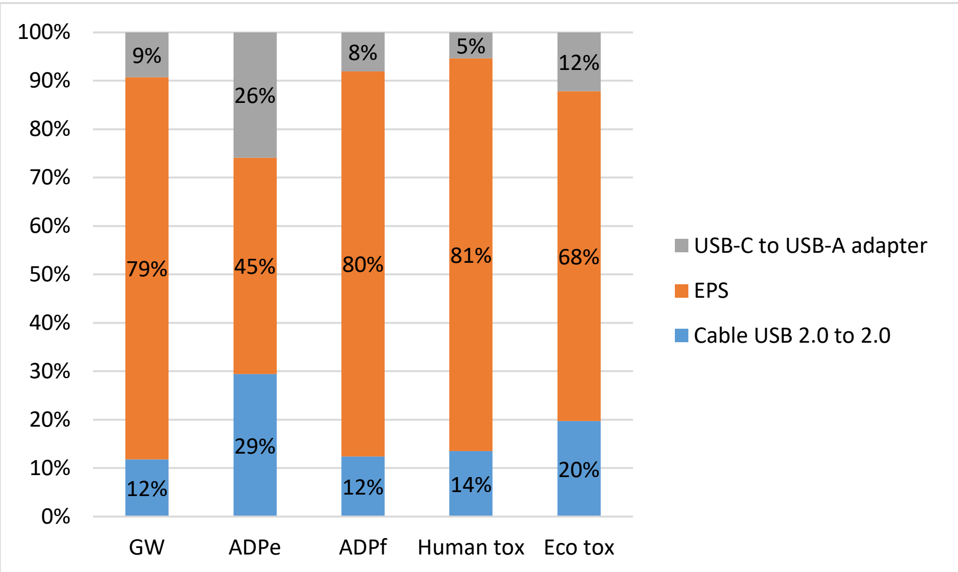

Figure 27 - Relative impacts of USB 2.0 to 2.0 charger production

Table 20 - Absolute impacts of USB 2.0 to 2.0 charger production

		Totals	Cable (USB 2.0 – 2.0)	EPS	USB-C to USB-A adapter
GW	**kg CO2 eq.**	1.94E+00	2.29E-01	1.53E+00	1.79E-01
ADPe	**kg Sb eq.**	5.06E-04	1.49E-04	2.26E-04	1.31E-04
ADPf	**kg Sb eq.**	2.57E+01	3.19E+00	2.04E+01	2.07E+00
Human tox	**kg DCB eq.**	5.91E-01	7.99E-02	4.79E-01	3.17E-02

Eco tox	**kg DCB eq.**	5.99E-03	1.18E-03	4.08E-03	7.28E-04

The other charger options has a USB 2.0 to 3.2 cable instead of a 2.0 to 2.0 one. It is worth noting that the specific recycled plastics could not be modelled and therefore the results presented here do not reflect its effects. Absolute and relative values for the entire life cycle of this are shown in Table 21 and Figure 28 respectively. The impact distribution is mostly the same as in the other version of the charger. When looking at Table 22, it can be seen that the production of the cable for this version of the charger shows higher impacts, mostly due to the bigger size and weight of it in comparison to the 2.0 to 2.0 cable. Impact distribution for production phase (Figure 29) remains similar to the previous case.

Table 21 - Absolute impacts of USB 2.0 to 3.2 charger per life cycle phase

		Totals	Production	Transport	EoL
GW	**kg CO2 eq.**	4.18E+00	2.00E+00	2.34E+00	-1.63E-01
ADPe	**kg Sb eq.**	3.41E-04	5.19E-04	3.50E-07	-1.78E-04
ADPf	**kg Sb eq.**	5.86E+01	2.72E+01	3.33E+01	-1.89E+00
Human tox	**kg DCB eq.**	2.47E+00	6.26E-01	1.85E+00	-7.59E-03
Eco tox	**kg DCB eq.**	8.51E-03	6.41E-03	2.41E-03	-3.13E-04

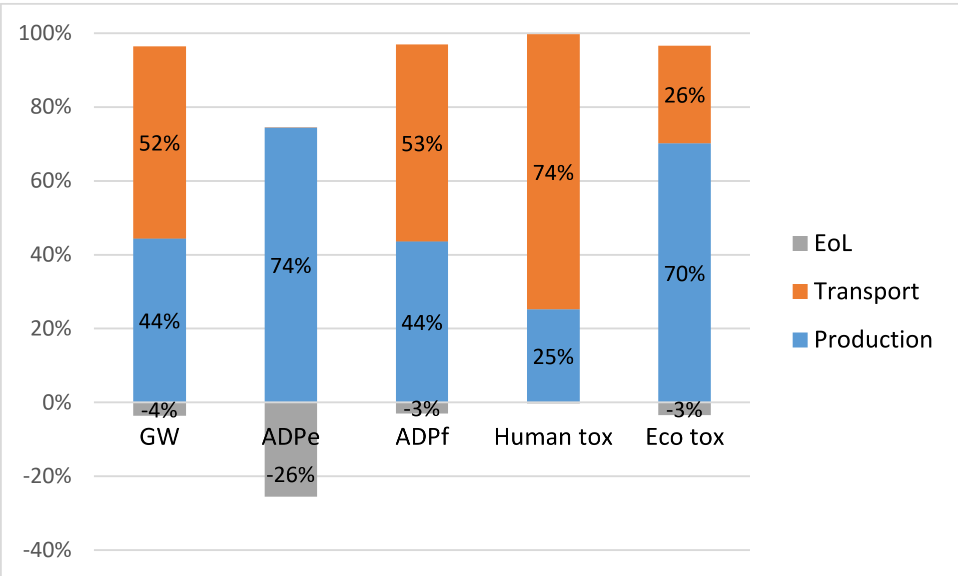

Figure 28 - Relative impacts of USB 2.0 to 3.2 charger per life cycle phase

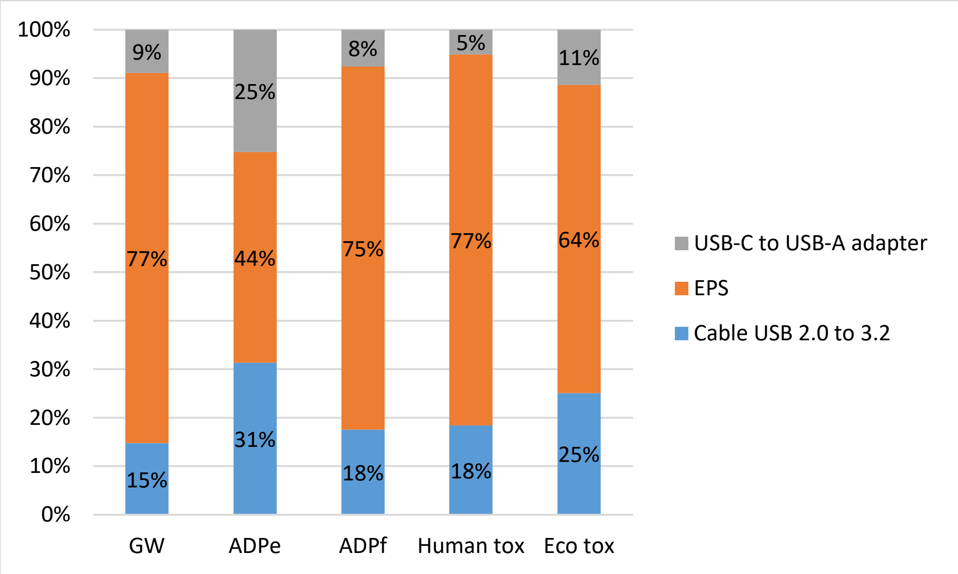

Figure 29 - Relative impacts of USB 2.0 to 3.2 charger production

Table 22 - Absolute impacts of USB 2.0 to 3.2 charger production

		Totals	Cable (USB 2.0 to USB 3.2)	EPS	USB-C to USB-A adapter
GW	**kg CO2 eq.**	2.00E+00	2.96E-01	1.53E+00	1.79E-01
ADPe	**kg Sb eq.**	5.19E-04	1.63E-04	2.26E-04	1.31E-04
ADPf	**kg Sb eq.**	2.72E+01	4.79E+00	2.04E+01	2.07E+00
Human tox	**kg DCB eq.**	6.26E-01	1.15E-01	4.79E-01	3.17E-02
Eco tox	**kg DCB eq.**	6.41E-03	1.61E-03	4.08E-03	7.28E-04

Passive components, ICs and the PCBs show the highest contribution to the Global Warming impact category. As it can be seen in Figure 30, passive components are the main driver in this category, due to the fact that the EPS' board uses more passives (e.g. the transformer, capacitors, resistors…) than ICs and considerably bigger passive components for electricity conversion compared to passive components within the smartphone. Figure 31 shows the same effect for ADPe with a similar distribution.

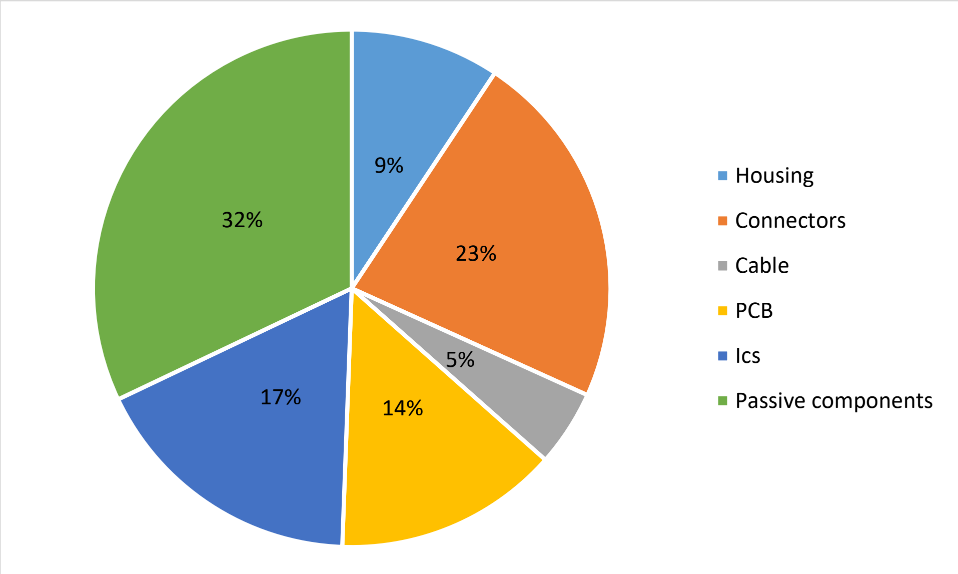

Figure 30 - GW distribution for USB 2.0 to 3.2 charger (EPS + cable + adapter)

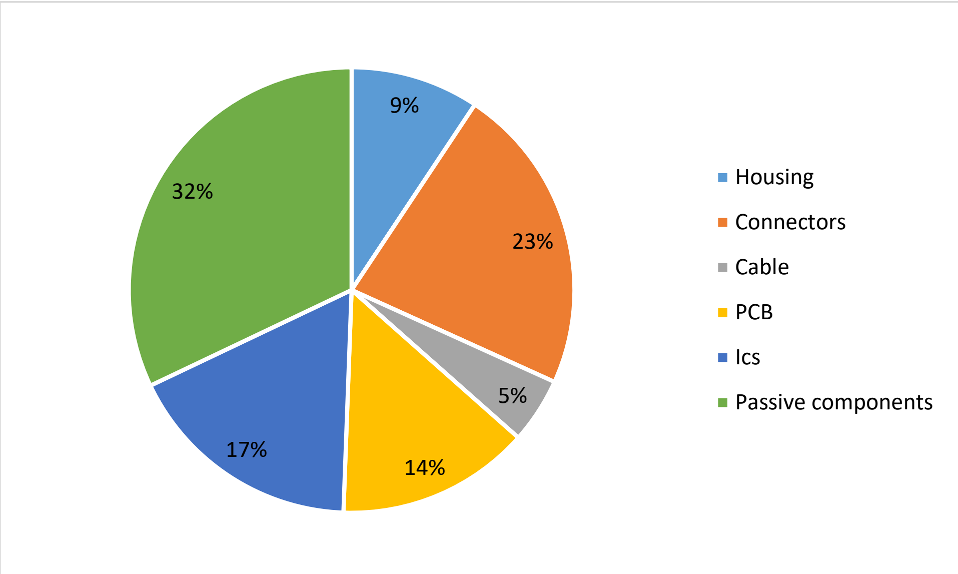

Figure 31 - ADPe distribution for USB 2.0 to 3.2 charger (EPS + cable + adapter)

4.3.6.3 Screwdriver

When compared to the other accessories, the screwdriver shows significantly lower impacts (see Table 23). When looking at the distribution of impacts in Figure 32, we see that both production and transport are the main contributors depending on the impact category. EoL plays a little role since no material recovery has been assumed for this one (nor does it contain any particularly polluting material).

Table 23 - Absolute impacts of the screwdriver per life cycle phase

		Totals	**Production**	**Transport**	**EoL**
GW	**kg CO2 eq.**	5.64E-01	2.54E-01	2.84E-01	2.57E-02
ADPe	**kg Sb eq.**	8.37E-06	8.33E-06	4.25E-08	-2.79E-11
ADPf	**kg Sb eq.**	6.92E+00	2.86E+00	4.05E+00	1.20E-02

Human tox	**kg DCB eq.**	1.13E+00	9.02E-01	2.25E-01	1.47E-05
Eco tox	**kg DCB eq.**	2.59E-03	2.25E-03	2.93E-04	4.20E-05

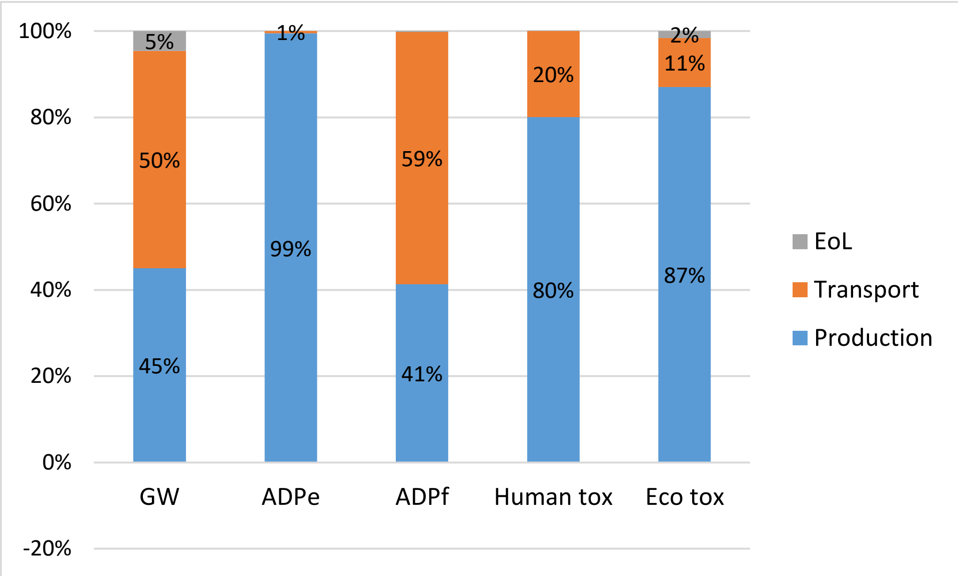

Figure 32 - Relative impacts of screwdriver per life cycle phase

Table 24 shows the absolute impacts of the screwdriver. The metallic screwdriver's head shows to be more impactful than the plastic handle for all categories.

Table 24 - Absolute impacts of screwdriver

		Total	Head	Handle
GW	**kg CO2 eq.**	2.54E-01	2.54E-01	1.72E-05
ADPe	**kg Sb eq.**	8.33E-06	8.33E-06	6.46E-10
ADPf	**kg Sb eq.**	2.86E+00	2.86E+00	5.37E-04
Human tox	**kg DCB eq.**	9.02E-01	9.02E-01	1.12E-05
Eco tox	**kg DCB eq.**	2.25E-03	2.25E-03	1.19E-07

4.3.6.4 Protective cases

Table 25 shows the absolute impacts of both versions of the protective covers per life cycle phase. The main driver of GW, ADPe and Human tox is transport while production of the covers seems to be the driver for ADPf and Eco tox.

Table 25 - Absolute impacts of protective covers

		Total	Production	Transport	EoL
			Primary TPU		
GW	**kg CO2 eq.**	4.64E-01	1.33E-01	3.04E-01	2.71E-02
ADPe	**kg Sb eq.**	4.16E-07	4.08E-07	4.55E-08	-3.71E-08
ADPf	**kg Sb eq.**	6.87E+00	3.07E+00	4.34E+00	-5.37E-01
Human tox	**kg DCB eq.**	2.40E-01	4.56E-03	2.41E-01	-6.07E-03

Eco tox	**kg DCB eq.**	6.96E-04	4.30E-04	3.14E-04	-4.80E-05
			Biopolymer		
GW	**kg CO2 eq.**	3.60E-01	2.86E-02	3.04E-01	2.71E-02
ADPe	**kg Sb eq.**	2.89E-07	2.81E-07	4.55E-08	-3.71E-08
ADPf	**kg Sb eq.**	5.28E+00	1.48E+00	4.34E+00	-5.37E-01
Human tox	**kg DCB eq.**	2.76E-01	4.04E-02	2.41E-01	-6.07E-03
Eco tox	**kg DCB eq.**	1.07E-03	8.06E-04	3.14E-04	-4.80E-05

4.4 Repair Scenarios

In this section, the results of the different repair scenarios are shown, compared and analysed for environmental impacts and benefits.

4.4.1 Repair scenario A

Table 26 shows the additional impact for the repair scenario A, not considering the battery replacement (since this is already part of the baseline scenarios described above).

Table 26 - Additional impact through repair (scenario A). without battery replacement

Impact category		Total repair	Spare part	Packaging	Transport
GW	**kg CO2 eq.**	1.73E+00	1.65E+00	3.40E-02	5.43E-02
ADPe	**kg Sb eq.**	1.37E-04	1.37E-04	2.59E-08	1.66E-07
ADPf	**kg Sb eq.**	1.58E+01	1.44E+01	5.76E-01	8.29E-01
Human tox	**kg DCB eq.**	4.22E-01	3.98E-01	1.32E-03	2.24E-02
Eco tox	**kg DCB eq.**	3.76E-03	3.46E-03	1.23E-04	1.81E-04

Figure 33 shows a comparison between GW yearly impact for baseline scenarios A and B (3 and 5 years of use respectively and with no repair) and the three repair scenarios. It can be seen how extension of use time reduces the yearly impact of the device. All three repair scenarios show a higher yearly impact than the no repair scenario (5 years) because here additional activities, parts and packaging related to repair are included. The difference between the three repair scenarios is however small and in any case they still show lower yearly impact than the 3 year scenario. Scenarios A, B and C also assume a 5 year usage, including not only the battery replacement but the repair/replacement of other modules as well.

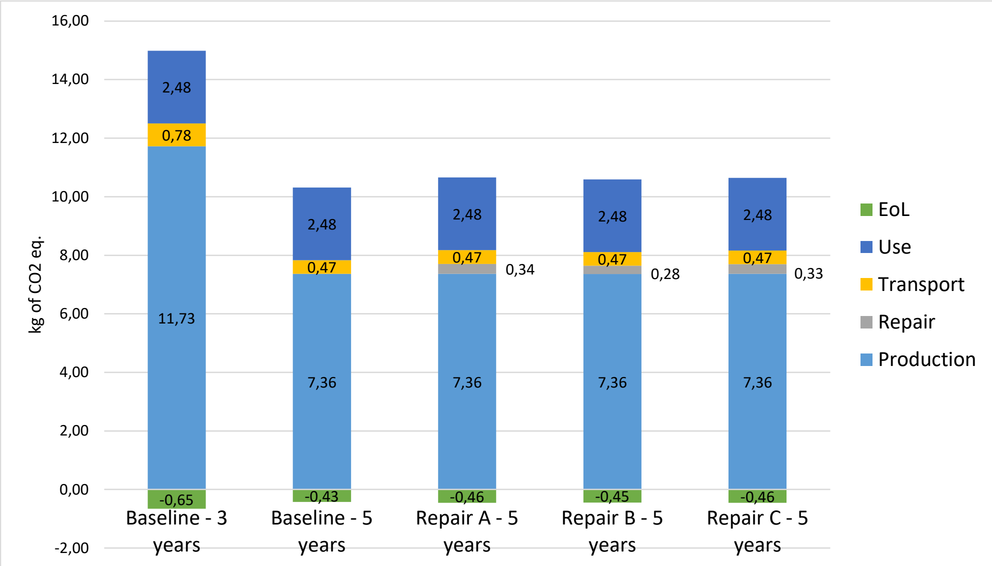

Figure 33 - Relative impact per year of use for the impact category GW

Figure 34 shows relative impacts of the repair overhead (i.e. the additional activities related to repair) for repair scenario A, which is based on substituting the entire faulty module for a new one. When looking into the repair overhead, production of the spare part is the most impactful activity, more than transport and the additional packaging.

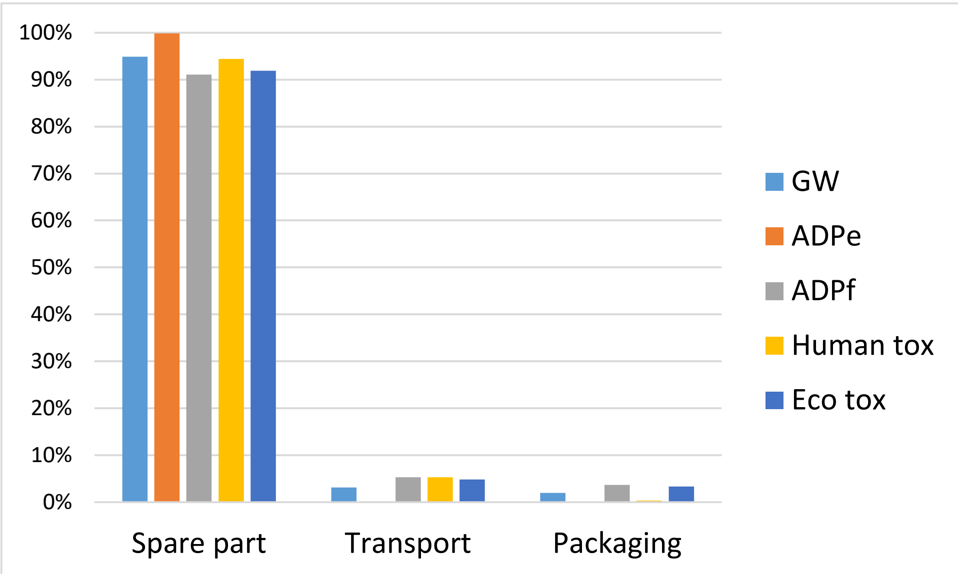

Figure 34 - Relative impact of repair (scenario A) due to spare part. additional packaging and additional transport

4.4.2 Repair scenario B

Table 27 shows absolute impacts for repair scenario B. In this case, instead of direct module replacement, modules are repaired at a board level whenever possible (to see which components are replaced within each module, please refer to section 3.5.1). The impact distribution for the different repair activities is shown in Figure 35, including in this case the electricity necessary for the component replacement.

Table 27 - Additional impact through repair (scenario B) without battery replacement

Impact category		Total repair	Spare part	Packaging	Transport	Module repair
GW	**kg CO2 eq.**	1.39E+00	1.29E+00	3.40E-02	5.43E-02	5.30E-03
ADPe	**kg Sb eq.**	9.66E-05	9.64E-05	2.59E-08	1.66E-07	1.01E-09
ADPf	**kg Sb eq.**	1.13E+01	9.85E+00	5.76E-01	8.29E-01	6.72E-02
Human tox	**kg DCB eq.**	3.28E-01	3.04E-01	1.32E-03	2.24E-02	1.57E-04
Eco tox	**kg DCB eq.**	2.76E-03	2.46E-03	1.23E-04	1.81E-04	3.98E-06

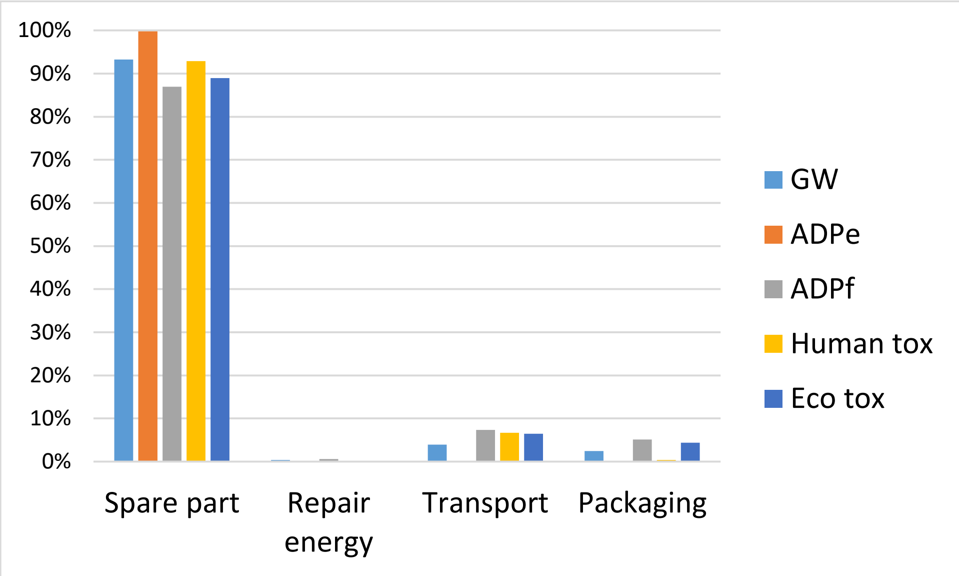

Figure 35 - Relative impact of repair (scenario B) due to spare part, additional packaging and additional transport

4.4.3 Repair scenario C

Table 28 and Figure 36 show the absolute and relative values for the repair overhead in repair scenario C. This scenario is similar to scenario A but with a different logistics strategy, namely in this case the new module is sent to the user who then sends the faulty module back to Fairphone B.V. (see section 3.5.1).

Table 28 - Additional impact through repair (scenario C), without battery replacement

Impact category		Total repair	Spare part	Packaging	Transport
GW	**kg CO2 eq.**	1.68E+00	1.65E+00	2.11E-02	9.34E-03
ADPe	**kg Sb eq.**	1.37E-04	1.37E-04	5.62E-09	2.86E-08
ADPf	**kg Sb eq.**	1.54E+01	1.44E+01	8.23E-01	1.43E-01
Human tox	**kg DCB eq.**	4.32E-01	3.98E-01	2.98E-02	3.86E-03
Eco tox	**kg DCB eq.**	6.36E-03	3.46E-03	2.87E-03	3.11E-05

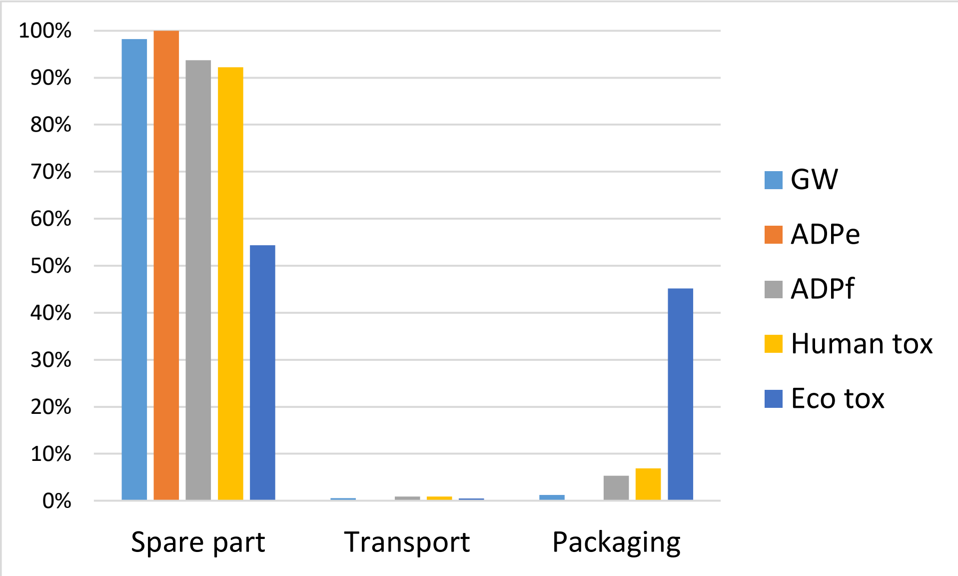

Figure 36 - Relative impact of repair (scenario C) due to spare part. additional packaging and additional transport

4.5 Sensitivity Analysis and Interpretation

Due to variations in the methodological approaches and data (e.g. assumptions, dataset choice, etc.), direct comparison between LCA results should be done with care. However, when looking at the extensive review of smartphone LCAs done by (Clément, Jacquemotte, & Hilty, 2020) it can be seen how both the absolute values for GW and the relative contributions of the different life cycle phases are consistent with the gathered results, even though values vary considerably depending on the model under study. There is not sufficient data available to perform a similar comparison for the other impact categories analysed in this study, since most LCAs published in this field report only on GW.

In the following subsection, alternative scenarios regarding some aspects of the model are presented and analysed, namely:

- Alternative approaches for transport
- User profiles
- Repair scenarios comparison
- Sales packs alternatives
- Comparison with Fairphone 3 results

4.5.1 Transport

Above (see section 3.3) the current approach for transport was presented. Fairphone B.V. intends to change to less air transport and more sea transport. In order to analyse the implications of the current logistics approach, two alternative scenarios have been studied. The second scenario serves as comparison on the effect of a worse case where air shipment represents the majority of shipments.

- Current scenario: 50% of transport to distribution hub done by plane, 50% by ship.
- Best case scenario: 30% of transport to distribution hub done by plane, 70% by ship.
- Worst case scenario: 90% of transport to distribution hub done by plane, 10% by ship.

Figure 37 shows how Future 2 scenario, where the least air transport is employed for shipping, halves the overall transport GW impact.

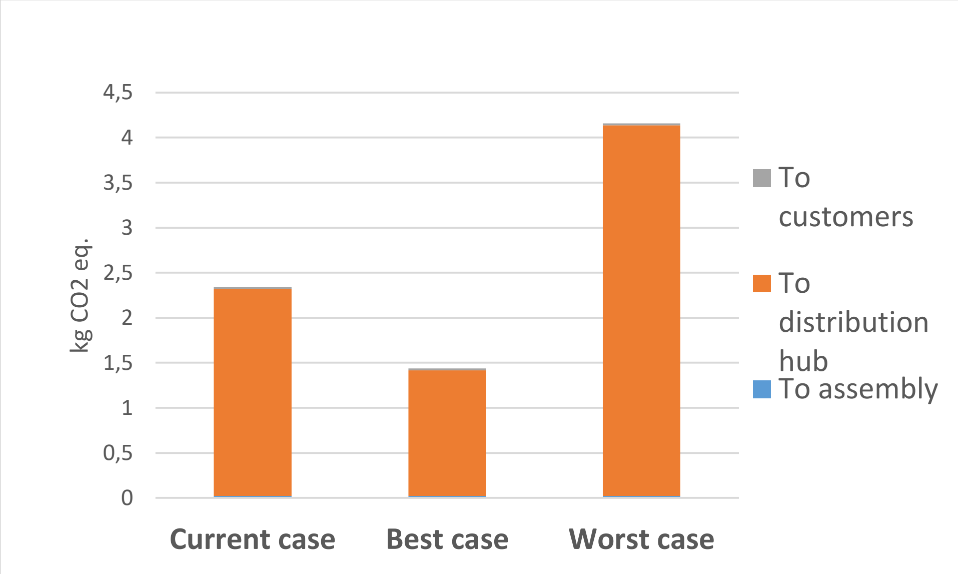

Figure 37 – Absolute GW impact per transport scenario

Additionally, Fairphone B.V. currently uses carbon offsetting for transports both within Europe and when shipping from Asia to Europe. Table 29 shows the total emissions considering this reduction and the total saved carbon emissions. This data does not include repair transport, although it is compensated for as well. It is seen that by offsetting the carbon of the transport from Asia, which is the main contributor to GW, the potential benefits are noticeable, representing almost the entire impacts related to transport.

Table 29 - Effect of decarbonisation in transport

	Current	Best case	Worst case
Total (original)	2.34E+00	1.44E+00	4.16E+00
Total offsetted	2.32E+00	1.41E+00	4.14E+00
Offsetted	99 %	98 %	99 %

4.5.2 User profiles

Figure 38 below shows the yearly GW value of each user profile (see section 3.2). The results are proportionate to the assumed charging cycles and it can be seen how the lowest intensity scenario can halve the GW impact of the most intensive one. However, the absolute difference amounts to less than 0.06 kg CO2 eq. per year.

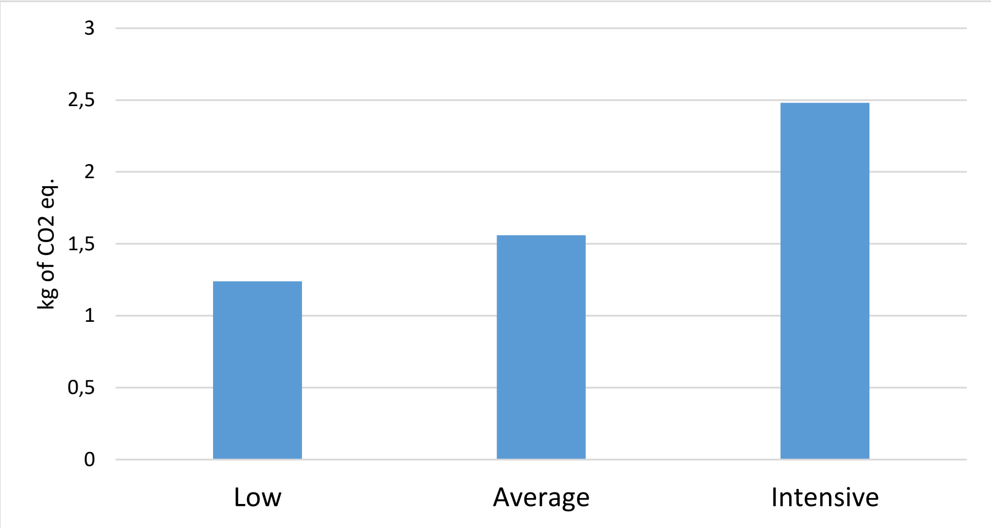

Figure 38 – Yearly absolute GW impact per use phase scenario

4.5.3 Phone and module repair scenario

Figure 39 shows the comparison of GW for repair strategies A and C. They both refer to module replacement and the difference is how it is performed: in scenario A the entire phone is sent to Fairphone B.V. while in scenario C the new module is sent to the user, who then sends the faulty module back. As seen in the figure below, changes in transport and additional packaging do not alter the final overhead much and the production of the spare module is still the main driver of GW.

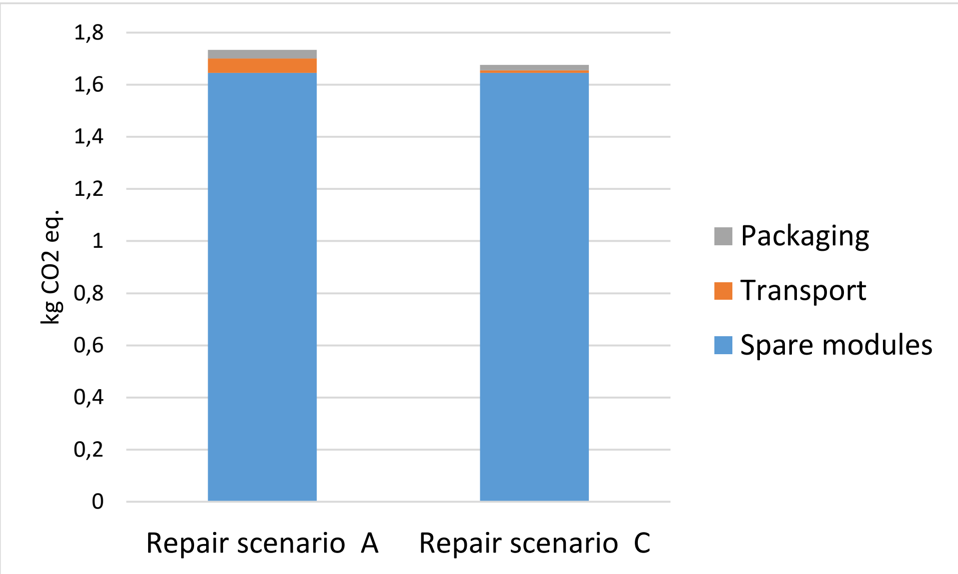

Figure 39 - Comparison of repair overhead for scenarios A and C (module replacement)

Figure 40 shows the comparison between scenarios B and C. Scenario B is based on board level repair i.e. faulty components are replaced by new ones and the rest of the module is used further. Scenario C is base on module replacement. For scenario B, transport efforts are allocated to the specific modules based on their weight. This comparison also includes the assumed repair yield (i.e. not all modules can actually be repaired on a board level and must be fully replaced). For a more detailed description of those assumptions, please see section 3.5.1. In Figure 40 it can be seen that the board level repair overhead is lower (around 0.3 kg CO_2 eq.).

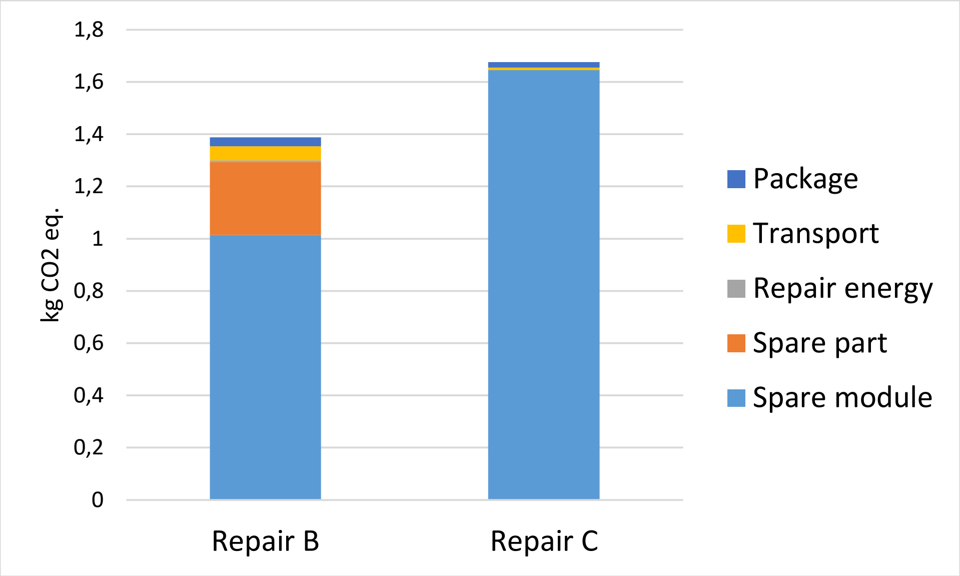

Figure 40 - Comparison of repair overhead for scenarios B and C (module repair and replacement. respectively)

In order to better understand the environmental difference between module repair and module replacement, the two approaches are compared per module in Figure 41. In this, no yield has been considered and a direct comparison between replacing the module entirely and board level repair is done. All figures include transport, additional package and electricity consumption during repair. For the core, the difference is significant because the most impactful components are in the mainboard and it is therefore beneficial to keep most of it in use. The rear cameras module seems to be the second most beneficial example, showing a difference higher than 1 kg CO2 eq between repair and replacement. For the rest of the modules, although repair is still an environmentally better strategy than replacement, the low absolute impact of both the modules and the components therein render the difference between the two approaches small.

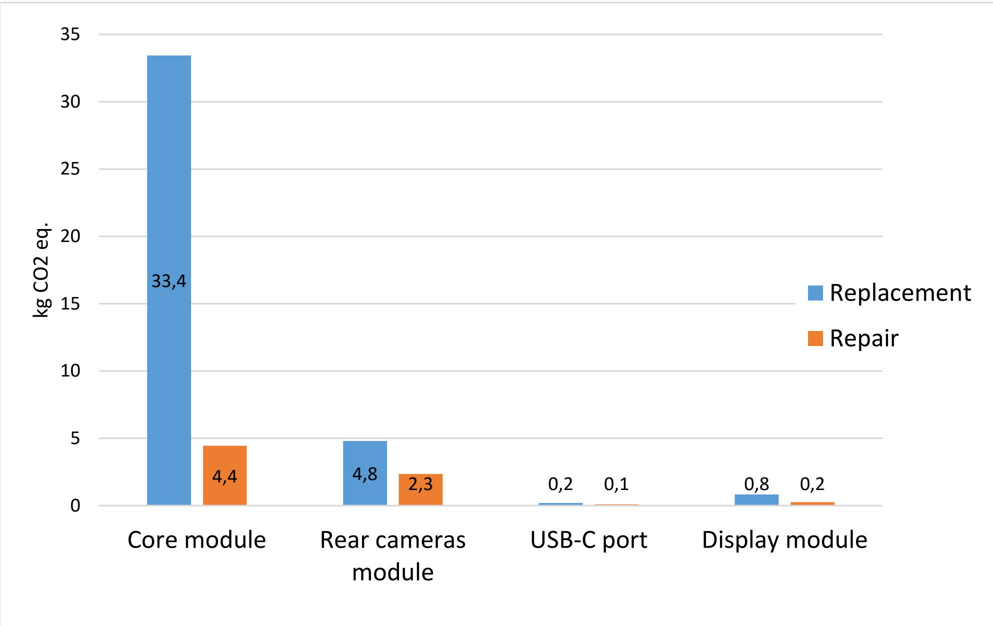

Figure 41 – Overview of replacement vs repair strategies

Another way of visualizing these differences is by estimating the environmental payback time of those repair strategies. This payback time is the theoretical value of how much longer the device should stay in use, so that the additional environmental burden of the repair effort is paid off by the reduction of the yearly emissions due to extended use. The assumptions are as follows:

- The reduction of the yearly savings per extended year of use are based on the results of the three baseline scenarios and intends to reflect the theoretical benefits of expanding service time.
- The repair overhead is based on the singled out results and includes therefore no successful repair yield. It does include all the efforts: spare parts/components. Transport, additional packaging and energy use in repair.
- The failure takes place in the 2nd year of use.
- It is important to note that this *benefit* is theoretical: most of the emissions come from the production phase and are therefore already caused at the beginning of the smartphones lifespan.

Figure 42 and Figure 43 show the curves for the yearly emissions over the years of use, for the module replacement and the module repair scenarios each. Each curve represents the scenario of each module being replaced/repaired (core scenario, loudspeaker scenario. etc.). The straight horizontal line represents the yearly emissions of the baseline case (end device only, no repair) for the two years mark, when the failure is assumed to happen. The intersection between the straight line and each of the curves represent the years of use in which the yearly emissions of the single replacement/repair scenarios are reduced back to baseline values and the repair overhead has therefore been compensated.

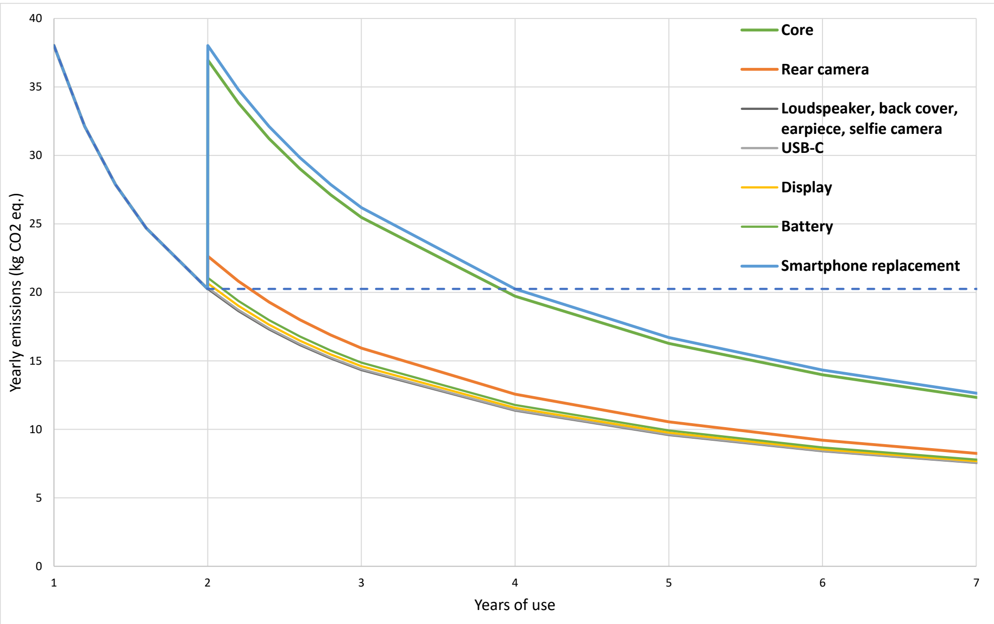

Figure 42 - Estimation of environmental payback period for module replacement, assuming failure at 2nd year of use

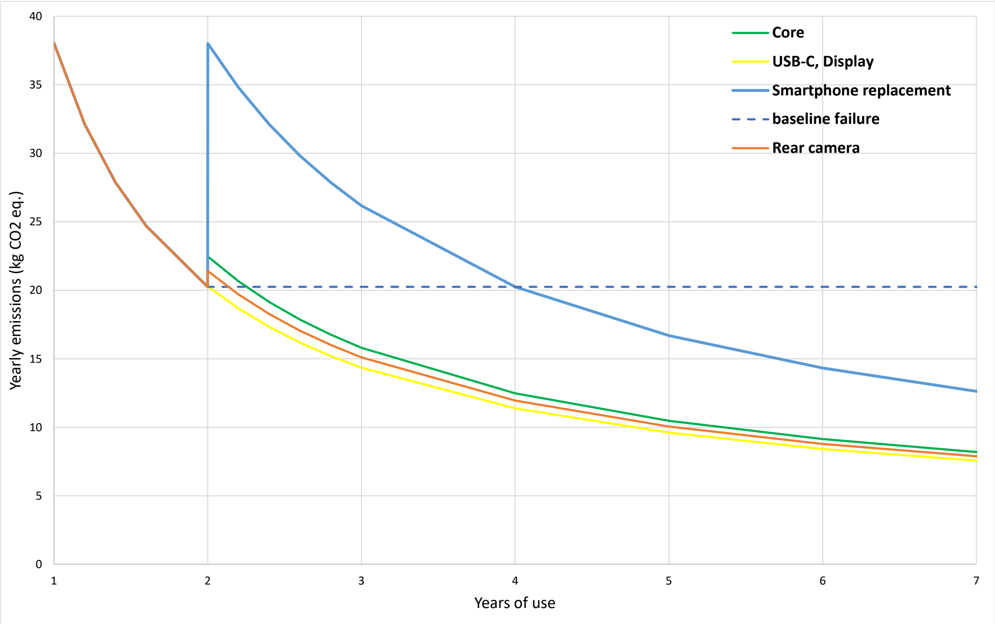

Figure 43 - Estimation of environmental payback period for module repair, assuming failure at 2nd year of use

Table 30 shows the final payback time estimates. In accordance with previous observations, the most noticeable one is the mainboard, due to its big absolute impact. Replacing the entire mainboard needs almost 2 years of extended use to pay off, while replacing only the faulty components (board level repair) requires less than a year. For the replacement of the rear cameras module the payback time seems to be of around 3 months (a third of a year). For the rest, the payback times are much lower due to the small absolute value of their GW emissions. It is to be noted however, that high estimated payback time should not be understood as a disencouragement to repair and extending the life of the phone since purchasing a new one and discarding the entirety of the device would of course always be more environmentally impactful.

Table 30 - Repair environmental payback time per module and repair strategy

	Replacement	Repair
Core	1.97 yr	0.32 yr
Rear cameras module	0.33 yr	0,19 yr
Loudspeaker module	0.05 yr	-
USB-C port	0.06 yr	0.06 yr
Display module	0.09 yr	0.07 yr
Back cover	0.05 yr	-
Battery	0.15 yr	-
Earpiece	0.05 yr	-
Selfie camera	0.05 yr	-

4.5.4 Package options

In this section, buidling upon the LCA data from accessories (see section 3.1.14), the different packaging options will be compared. This can be seen in Figure 44. The options of selling the device with the charger show to be the most impactful, mostly driven by the increase in production and transport impacts. For the option of selling the device with the screwdriver, the difference is small. In all three cases, the EoL is very similar to the baseline scenario because most recovered materials come from the main device.

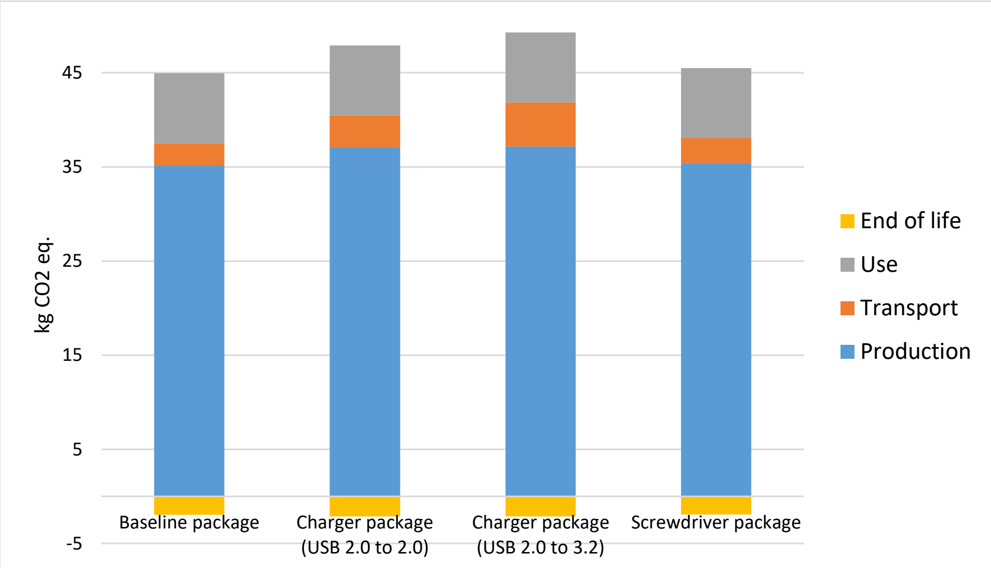

Figure 44 - Comparative GW for different packaging options

4.5.5 Comparison with Fairphone 3

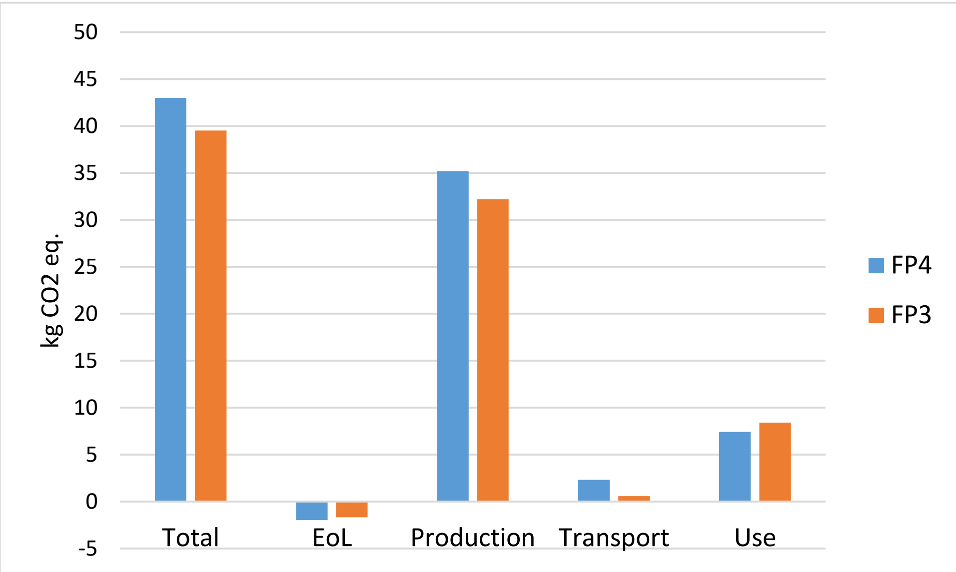

Figure 45 - Comparison with Fairphone 3 (GW)

As shown in Figure 45, the impact on GW of Fairphone 4 is higher than that of Fairphone 3. The production phase of Fairphone 4 has a higher impact, mostly due to the core, the rear cameras module and the battery. The material change for the middle frame (metal in Fairphone 4 as opposed to plastic in Fairphone 3) also entails a higher impact. The transport phase, which has a slight increase in air shipping when compared to FP3 (Proske, Sánchez, Clemm, & Baur, 2020) also shows a higher impact. Differences in use phase and EoL are lower.

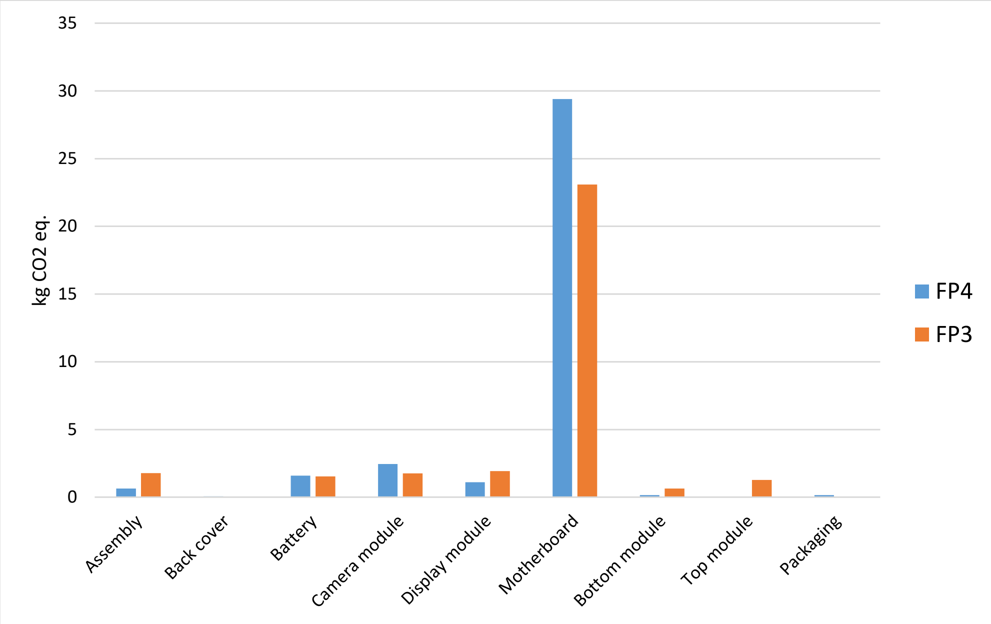

Figure 46 - Comparison of GW impact between FP4 and FP3. per module

Integrated circuits

Figure 47 shows the of GW values for ICs in both devices. Those are divided into three main groups:

- Main Central Processing Unit (CPU)
- Combined RAM and Flash memories
- Rest of ICs (e.g. power management units. WLAN. voltage regulators etc)

The processor in the Fairphone 4 shows a higher impact than the processor for Fairphone 3. The RAM&Flash memory, on the contrary, shows a significantly lower impact than its predecessor in Fairphone 3. This is most likely due to the fact that despite the memory capacity has been increased for the new model, the die size within the package is smaller (which in turn drives the related impacts down). The rest of the ICs show to have a higher impact than in the case of Fairphone 3. It is difficult to say why this is, since both are composed of different ICs altogether.

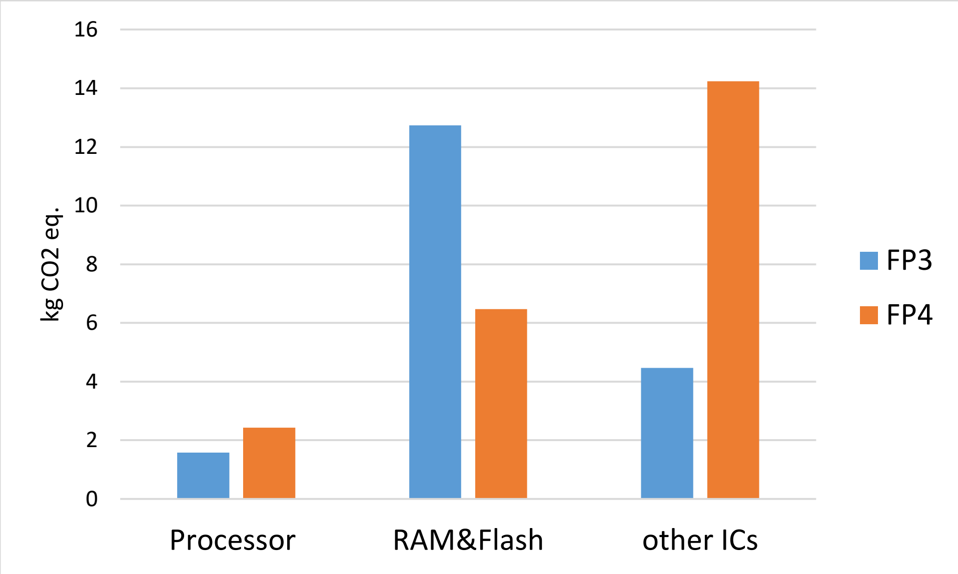

Figure 47 - GW values for ICs comparing Fairphone 3 and Fairphone 4

PCB area

One of the main design changes in this model when compared to FP3 are the PCBs. While Fairphone 3 had a small board per module apart from the mainboard (see Table 31). Fairphone 4 now gathers most of the electronics in just one PCB in the core, not needing smaller boards for each of the models which now only contain their main constituents.

Table 31 - Printed circuit board area modelled (Proske, Sánchez, Clemm, & Baur, 2020)

Module	Boards per panel	Length	Width	Area
		mm	mm	cm^2
Bottom		25.00	24.00	6.00
Camera		15.00	16.00	2.40
Display		49.00	13.00	6.37
Top		31.00	16.00	4.96
Mainboard		136.10	65.51	89.16
Fairphone 3 total PCB area	108.89 cm2			
Mainboard		15.30	6.70	102.51
Fairphone 4 total PCB area	102.51 cm^2 (90.2 cm^2 allocated based on layout)			

Although many factors influence the PCB size (layout design, circuitry design), the table above shows that the overall PCB area used has been reduced, suggesting that the new design approach might be more efficient in this regard.

Display

Table 32 - Comparison of displays for Fairphone 3 and Fairphone 4

Characteristic	Fairphone 3	Fairphone 4
Size (inch)	5.65	6.38

GW (kg CO2 eq.)	1.92	1.11[1]

Table 32 shows the comparison between both displays in Fairphone 3 and Fairphone 4. Following the trend from Fairphone 2, the increase in the size has been accompanied with a decrease of the emissions. In this case again, due to efficiency gains in display production, the scope 1 and 2 emissions declared by the used source (AUO Innovating Life, 2019) have decreased (specially scope 2) and this in turn outweighs the bigger area and increased material use.

[1] Value includes frame as to make it comparable with the Fairphone 3 modelling

5
Conclusions and Recommendations

PCBs

The design choice of using just one big PCB as mainboard and reducing the peripheric smaller boards reduces the environmental impacts of the peripheric modules, thus making their replacement environmentally more benefitting. However, it places now a greater burden on the core, making it even more important to be able to perform board level repair when a component in the mainboard fails.

Connectors

The design of Fairphone 4, learning from previous iterations, has reduced even further the amount of connectors. Currently the amount of board to board flexcables is comparable (when not identical) to most models of the latest generations (Schischke, Proske, Nissen, & Schneider-Ramelow, 2019), making the specific modularity overhead minimal in terms of materials and environmental impacts.

Mode of transportation

This study shows the impact of logistics for small ICT devices. Through a scenario analysis, the role that air transport plays in the emissions level has been shown, demonstrating how an increase in the porportion of the shipping done by sea can have noticeable environmental benefits, while doing the opposite quickly increases the environmental burden. Results also show the potential benefits of carbon offsetting, specially for the transport to the central distribution hub.

Data availability/acquisition

Up-to-date life cycle data for electronics is still not widely available and collection of primary data is a very demanding task. Therefore, many primary data points could not be derived for this study (e.g. production processes from component suppliers. LCI data for less common materials). Nevertheless, like in previous studies, extensive data on material composition, final assembly process and PCB layouts were available. Also data on die sizes of the main integrated circuits was provided for this study. Fairphone B.V. should keep pursuing this good work on transparency. Future further focus on primary data could also be put in parts and components with high impact contribution such as:

- Display manufacturing
- PCB manufacturing
- Battery manufacturing
- IC manufacturing

Focus of primary data collection could be on PCB and battery manufacturing as these processes are not as complex compared to display and IC manufacturing and contact to suppliers is likely to be easier. Nevertheless, up-to-date data for display and especially IC is needed. Here,a collective approach from regulation, industry associations and different buyers of ICs is likely to be more successful.

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 provides further insights on the specific production process of Fairphone.

Accessories

The overall impacts associated with the accessories is shown to be small in comparison with the entire device, for all life cycle phases affected. Due to a more limited access to material data, the modelling is less precise than in the case of the main device. Unlike the Fairphone 4 device, accessories are currently not designed to be modular (excluding the charger, where its three main parts are separable). Whether increased reparability would be benefitial would need to be studied separately.

Repair

The analysis of reparability shows that, due to the reduced embodied impacts of most modules (with exception of the mainboard), replacement pays off very fast. For this very reason, board level repair for peripheral modules is hardly worth it, as the most impactful components of the module would still need to be replaced. Additionally, if considering that not all modules will be reparable at that level, the overall difference between replacing or repairing faulty modules is limited. However, mainboard repair is crucial, as the mainboard concentrates most of the phone’s environmental impacts. Therefore, if failure is detected in the core, trying to replace the specific faulty components and avoiding to discard the rest has very clear environmental benefits. Thereby, the main focus is on keeping mainboards in use allowing for different ways to facilate such a repair. From environmental perspective, repairing a mainboard for a specific phone as well as replacing a mainboard (e.g. due to turn around times in repair) and repairing the replaced mainboard afterwards to be used as spare part in a different device, are both valid options.

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