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LIFE CYCLE ASSESSMENT OF THE FAIRPHONE FAIRBUDS XL

David Sánchez

Sarah-Jane Baur

Marina Proske

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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: david.sanchez@izm.fraunhofer.de

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Abbreviations

ABS	Acrylnitril Butadien Styrol Copolymer
ADPe	ADP elements
ADPf	ADP fossil
CN	China
CTUe	Comparative Toxic Units for the environment
DCB	1,4-Dichlorbenzol
Ecotox	Ecotoxicity
EF	Environmental Footprint
EoL	End of Life
EPD	Environmental Product Declaration
eq.	Equivalent
FMD	Full Material Declaration
g	Gram
GHG	Greenhouse Gas
GLO	Global
GW	Global Warming
Human tox	Human toxicity
IC	Integrated Circuit
IPCC	International Panel of Climate Change
ISO	International Standard Organisation
LCA	Life Cycle Assessment
mAh	Milliampere hour
MJ	Mega Joule
PC	Polycarbonate
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PET	Polyethylene Terephthalate
PM	Precious Metals
PU	Polyurethane
RoW	Rest of the World
tkm	Tonne kilometer
USB	Universal Serial Bus
WEEE	Waste Electrical and Electronic Equipment
Wh	Watt hour

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Executive Summary

The Fairphone FairBuds XL are the first iteration of over-ear headphones by Fairphone. The present LCA study aims to assess the environmental impact of the FairBuds XL and identifies main drivers and hotspots in their life cycle. As such, this LCA is cradle-to-grave, meaning that its scope covers the whole life cycle from raw material acquisition to end-of-life. This LCA has been performed following the principles outlined in ISO 14040/14044 and, for the Global Warming impact category, following the requirements of ISO 14067.

A special focus is put on the use of recycled materials in the manufacturing process of the FairBuds XL and a scenario-based approach is applied to analyse the calculated benefits of reusing material. A scenario-based approach is also used to account for the benefits of a longer lifespan (with or without repair).

The functional unit is set to be three years of intensive use of the FairBuds XL as it is delivered to the customer.

The following impact categories are analysed in the study:

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

The data for this study is based on the bill of materials provided by Fairphone B.V., as well as on the material declarations provided by its suppliers. Those have been cross-checked with a teardown of the Fairphone FairBuds XL performed by Fraunhofer IZM. For life cycle phases which are out of direct control of Fairphone B.V. (e.g. use phase, End-of-life) literature and scenario analysis have been used to build the model.

Results

The total carbon footprint of the FairBuds XL is 6,8 kg CO_2 eq. The overall values for all impact categories are shown in Table 1-1 and the distribution of the impacts alongside the life cycle phases are shown in Figure 1-1. For all impact categories analysed, the production phase shows to be the main driver, most significantly for abiotic resource depletion. Distribution and use phase show a lower contribution of around 10% for both GW and ADPf and of around 5% for ecotoxicity. For human toxicity, transport shows to be more relevant, causing around 20% of the total impact. End-of-life activities i.e. transport to disposal site, depollution and pre-treatment for recycling contribute only marginally for all impact categories.

Table 1-1: Summary of environmental impacts of FairBuds XL per life cycle phase

Impact category name	Total	Production	Distribution	Use	EoL
Total emissions [kg CO_2-eq.]	6,80E+00	5,61E+00	6,12E-01	4,88E-01	9,45E-02
Abiotic depletion elements [Kg Sb eq.]	7,43E-04	7,43E-04	1,77E-07	1,28E-07	1,60E-07
Abiotic depletion fossil [MJ]	8,17E+01	6,67E+01	8,75E+00	5,41E+00	8,96E-01
Freshwater ecotoxicity [CTUe]	5,73E+01	5,22E+01	2,32E+00	2,52E+00	2,88E-01
Human toxicity potential [kg DCB eq.]	2,24E+00	1,74E+00	4,59E-01	2,31E-02	1,78E-02

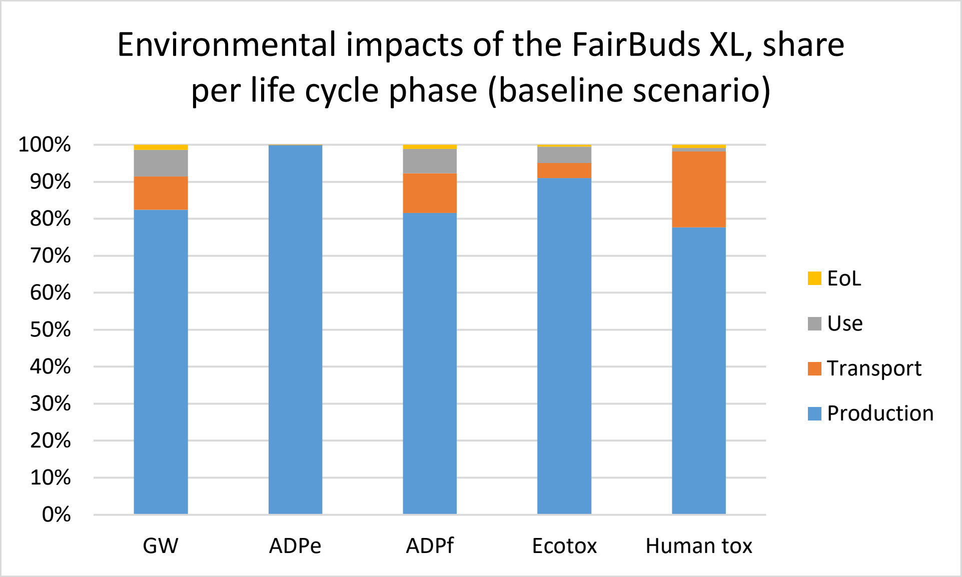

Figure 1-1: Environmental impact distribution per life cycle phase as % of the total for each category.

Figure 1-2 shows the contribution of the different component groups (e.g. electronics, housing, etc.) to the overall environmental impacts of production. For global warming and ADP fossil, the electronics (i.e. printed circuit boards (PCBs), integrated circuits (ICs), passive components, connectors and other semiconductors) and the speakers contribute most. These two impact categories are usually related to energy use along the supply chain and electronics are generally energy intensive due to their manufacturing process, very particularly PCBs and ICs. ADP elements is mostly related with the expenditure of precious metals like gold, silver and palladium and is in this case mostly driven by the electrical connectors used in the device to interconnect the different parts and modules. More precisely, these precious metals are commonly used for plating the contacts of said connectors. Ecotoxicity also shows a significant contribution of electronics, in this case related not only to the energy use during manufacturing but also the use of chemicals; also the battery's contribution is relevant for ecotoxicity. The chemicals needed for the production of the lithium-ion cells are in this case driving the toxicity. Finally, human toxicity is also connected to the electronics and also with the housing materials (and other mechanical elements) consisting of various metals and plastics.

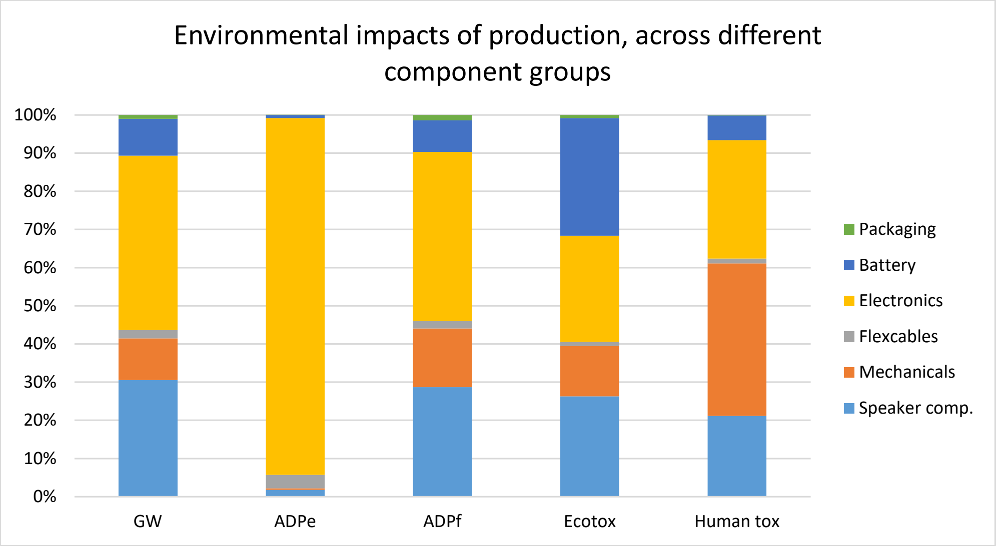

Figure 1-2: Impact distribution for production per component group. Bars show the contribution of different component types to each of the impact categories (in %). Mechanicals includes not only housing but also fasteners and other structural elements.

The potential benefits of extended use time can be seen below. In Figure 1-3 three lifespan scenarios are compared:

- 3 years with no part replacement
- 5 years with one battery replacement
- 7 years with two battery replacements

The columns below represent the estimated yearly emissions[1] for each use case. It can be seen that even considering the manufacturing of up to two additional batteries, extending the use of the device to 5 years can achieve a reduction of 28% of the yearly emissions (one additional battery) and up to 43% if the extension is to 7 years (2 additional batteries).

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[1] Here it is not meant real direct emissions caused by the device in the yearly use but rather the allocated impacts from the total to each year of use

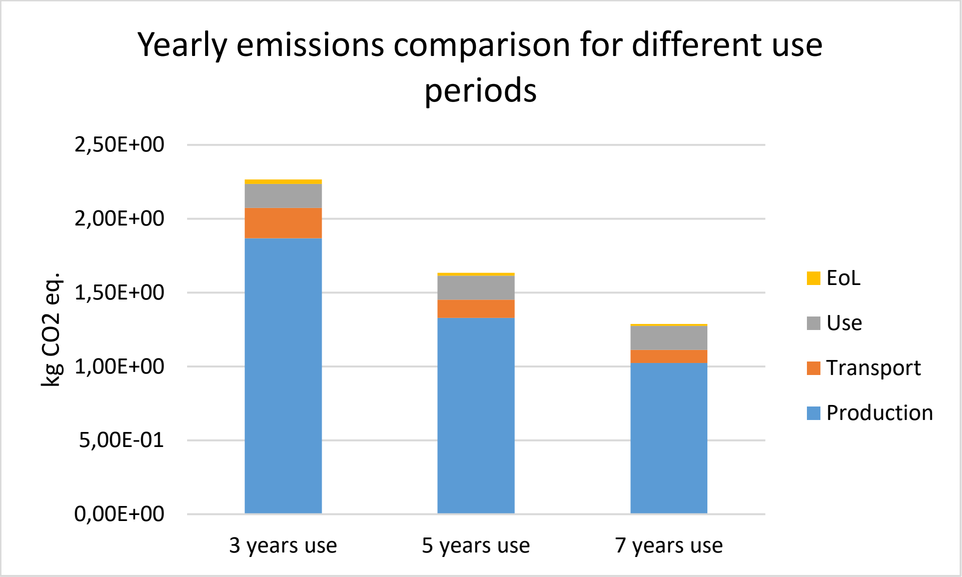

Figure 1-3: Estimated yearly emissions (GW100, CML) for the FairBuds XL, related to the baseline scenario. Each column represents a different use case with a longer useful life each. For the 5 years and 7 years use case, respectively one or two battery replacements are assumed (related impacts included in production).

Use of recycled materials

The FairBuds XL currently use 84% recycled PC, 100% recycled aluminium and 100% recycled tin (which could not be modelled in this LCA due to lack of data on recycled tin). In order to estimate the benefits of reusing material in the device, an alternative scenario of fully primary materials has been modelled and an overview can be seen in Figure 1-4. As it can be seen, an impact reduction is achieved in most impact categories except ADP elements. This impact category is mainly driven by metals like gold, copper, or silver and these are not included in the materials re-used in this product. For global warming and ADP fossil this reduction is calculated to be around 10% of the total life cycle impact whereas for toxicity related impacts i.e. ecotoxicity and human toxicity, this reduction is of around 30% and 20% respectively.

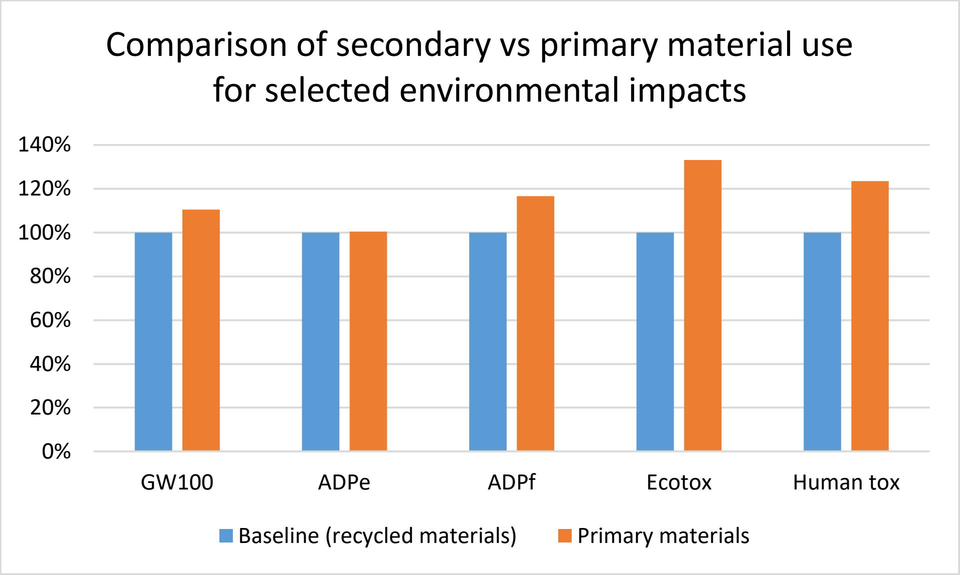

Figure 1-4: Recycled content vs primary content for the entire life cycle, various impact categories. Baseline scenario incl. secondary material is used as a reference and the primary materials scenario is then shown in relation to it.

Modularity and repair

In order to achieve a modular design that is easy to disassemble and repair by the user, several design changes are necessary. These include, most importantly: additional connector ports for the different modules, bigger mechanical elements to support the device structurally and its own enclosure for the battery. Table 1-2 shows the environmental impacts of the additional elements required for modularity and the % of the total impacts of the device they represent.

For most impact categories this is low but for ADP elements it is very significant. This is because many of the connectors that the device uses (mostly USB-C connector ports) serve the purpose of allowing easy separation of the different modules. ADP elements is mostly connected to the use of certain metals which, based on aspects like annual production and known reserves are given different weights. According to the latest update of the method (van Oers, Guinée, & Heijungs, 2020) gold contributes a 72,4% of the total, followed by copper (7,9%) and silver (3,8%). In the FairBuds XL, the USB-C connectors are the most gold-rich components and they play an important role in modularity, thus having the shown associated ADPe impact.

Table 1-2: Environmental impacts of modularity and their share in the total impacts

Impact category name	**Total modularity overhead**	**% of total**
Total emissions [kg CO_2-eq.]	2,30E-01	3%
Abiotic depletion elements [Kg Sb eq.]	3,63E-04	49%
Abiotic depletion fossil [MJ]	3,37E+00	4%
Freshwater ecotoxicity [CTUe]	2,45E+00	4%
Human toxicity potential [kg DCB eq.]	1,29E-01	6%

In order to analyze the effects of reparability and its benefits, a module to module comparison has been performed. In this, two repair strategies are compared:

- Replacement: the user is sent a new module, which they replace and send the faulty module back to Fairphone B.V. The considered activities here are the production of the new module and the transport of the module back and forth.
- Repair: the user sends the faulty module to Fairphone's repair centre in France. There, Fairphone B.V. removes the failing component, replaces it with a new one and keeps it in use for further replacements. The considered activities here are the production of the new component, the electricity needed for the desoldering of the malfunctioning piece and the soldering of the new one and the transport of the module.

In Figure 1-5 a comparison of both repair scenarios can be seen for the impact category global warming. For modules with high environmental impacts, like both speakers, the difference between both strategies is significant since they house the electronics and thus being able to reuse parts of them is always beneficial. For more mechanical modules like the ear cushion and the buttons the difference is negligible since their relative impacts are lower.

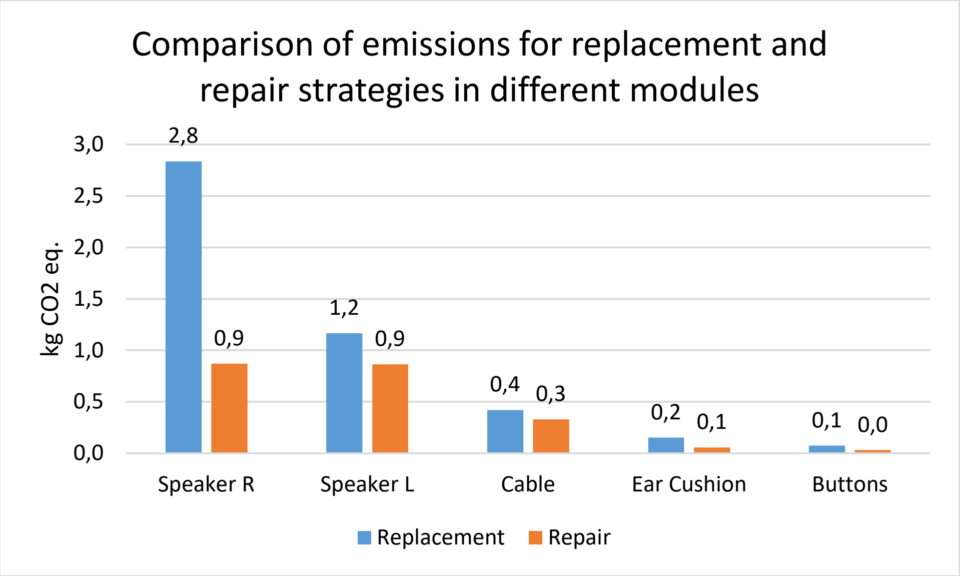

Figure 1-5: GW100 values per module repair strategy, replacement vs repair. Bars represent the total emissions for the repair scenario of each module, which includes additional packaging, necessary transport and the production of the spare part or spare component.

In all cases however, the additional environmental effort of replacement and repair is only a fraction of the environmental impacts of producing a new set of headphones. In order to better visualize this, an estimation of the *environmental payback times* has been carried out, presented in Table 1-3. These represent the theoretical time that it would take to compensate the additional emissions caused by the module replacement or repair with the achieved extension of lifetime and the subsequent reduction in yearly emissions (assuming failure at the second year). As seen, replacing the right speaker module would be the longest with 1 year for replacement and 3 months for repair. For other modules like the earcap covers, the replacement of the scratched or broken ones would almost pay off directly.

Table 1-3: Environmental payback times

	Replacement	*Repair*
Speaker right	~1 year	3 months
Speaker left	4 months	3 months
Speaker to speaker cable	1 month	1 month
Ear cushion	1 month	4 days
Earcap cover	~1 day	-
Headband	13 days	-
Headband base	3 days	-
Headband cover	15 days	-
Battery	2 months	-

Conclusions

The results of the LCA show that the environmental impacts of the FairBuds XL are production driven. For global warming and resource depletion (both elements and fossil) the electronics are the main contributors whereas for toxicity related impact categories both the battery and the housing materials show some significant contributions.

Although the modularity overhead for this device can be significant depending on the impact category, the potential of the enabled repair to bring about environmental benefits by keeping the device in use longer has been shown that it can significantly reduce yearly emissions. For the speaker modules, exploring the possibility of board-level repair and component reuse seems a possible way to make repair even more environmentally sensible.

Finally, the scenario analysis shows that the use of recycled materials brings about a reduction in total life cycle emissions and more significantly in toxicity related impacts. A wider selection of recycled materials could, however, further reduce other indicators as well and thus, could be a path to further explore.

2
Goal and Scope Definition

2.1
Goal

This LCA focuses on the current Fairphone headphones, the FairBuds XL, and their accessories. The current LCA succeeds previously done work on the LCAs for the Fairphone 2, Fairphone 3 and Fairphone 4 and therefore takes up some of the assumptions and research work done there. The goals of this life cycle assessment can be summarized in four main points:

- Assess the environmental impact of the FairBuds XL and identify main drivers and hotspots in their life cycle.
- Assess the effects of product-specific use of recycled materials, with special focus on GHG emissions.
- Compare different use phase assumptions, regarding usage time and repair.
- Inform consumers and stakeholders transparently of environmental effects of the device and certain usage options.

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

As opposed to the earlier life cycle assessments, however, a stronger focus is now laid on the use of recycled materials as a replacement for primary materials in the manufacturing process, which will affect mostly the allocation rules chosen.

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

The intended applications of the study are:

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

2.2
Scope

The scope of this study covers the entire life cycle of the FairBuds XL: raw material extraction, manufacturing, transport, use and end-of-life. This LCA follows the principles outlined in ISO 14040/44 and follows the requirements of ISO 14067 when it comes to Global Warming.

The functional unit for the baseline scenario is three years of average use of the headphones. The corresponding reference flow is the FairBuds XL as delivered to the customer including sales packaging and manual, but without charger, which is not part of the standard delivery. Furthermore, accessories not shipped with the headphones are also assessed i.e. a USB-C to audio jack adapter and a travel pouch. No part failures are assumed for the baseline scenario. Due to the lack of technical reports or studies on the lifetime of consumer headphones, informal sources have been consulted to estimate the useful life of headphones and base additional scenarios on this[2]. The additional scenarios cover:

- Varying effective lifespans:
  - 5 years of use, replacing the battery once.
  - 7 years of use, replacing the battery twice.
- Varying intensity of use:
  - 3 years of light use (one hour per day)
  - 3 years of heavy use (8 hours a day)

The data inventory is based on the bill-of-materials (BoM), a product tear-down, and material declarations for subparts from suppliers. The final assembly process is based on primary data from Honsenn Technology Co., Ltd. in China (for a more detailed explanation, please see section 3.1.13).

Additional attention was given to the use of recycled polycarbonate, aluminium and tin in the production of the headphones.

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

- Climate change (GW100) incl. sub-categories according to ISO 14067 and IPCC (all in kg CO_2 eq.)
- Abiotic resource depletion incl. elements (kg Sb eq.) and fossil (MJ)
- Human toxicity (Human tox) (kg DCB eq.)
- Ecotoxicity (Eco tox) for freshwater bodies (in CTUe)

However, not all processes used in the assessment could cover all the listed impact categories due to data availability issues. While GHG emissions are widely covered in literature, other impact categories are less studied and thus data is scarce. The effect will be described in the sensitivity analysis and interpretation of results (section 4.5).

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

Use phase impacts are related to electricity consumption of the headphones and the charger, which is not delivered with the product.

Processes are modelled with the LCA software Sphera LCA for Experts (Version 10.7.0.183) and the corresponding database, including the “Electronics” extension data base (both in their 2023.1 version). This is supplemented with the Ecoinvent database v3.9 for processes where no suitable Sphera data set is available.

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[2] As examples see, all consulted late 2022:

https://headphonesexpert.com/lifespan-of-bluetooth-headphones/

https://www.depreciationrates.net.au/headphones

https://headphoneuniversity.com/average-lifespan-of-headphones/

3
Life Cycle Inventory

The life cycle inventory covers the following sections:

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

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

For the assessment, the life cycle assessment software Sphera LCA for Experts with its own database (at its 2023.1 version), the electronics extension as well as the Ecoinvent 3.9 data base was used. If data is used from additional sources, this is specifically mentioned in the description. In some aspects, the modelling follows the same assumptions as the Fairphone 4 LCA (Sánchez, Proske, & Baur, 2022), which was also carried out by Fraunhofer IZM. Whenever any modelling choice is carried over from this, it is also explicitly mentioned in the report.

3.1
Raw material acquisition and manufacturing

The manufacturing phase was modelled according to the bill of materials (BoM) of the FairBuds XL and the material composition of several components provided by the suppliers. The analysis was supplemented with a teardown of the headphones at Fraunhofer IZM.

Life cycle data sets were allocated to all parts based on weight (mechanical parts), number of pieces (electronic components) or size/area (e.g. printed circuit boards). The individual approach for each module and component group is described in the following. The modules of the headphones with their main parts are shown in Table 3-1. The table below does not show minor elements such as screws.

Table 3-1: Main parts per module

Module	Main parts	Amount	Weight [g]
FairBuds XL		1	316[3]
Headband		1	34,67
	Head clamp		
	Further structural parts of the headband		
Headband Base		2	14,72
	Sliders that connect the head clamp with the speakers		
Headband Cover		1	24,66
	Faux-leather cover		
	Additional supporting structures		
Speaker L		1	58,31
	Speaker, microphone		
	One PCB		

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[3] Weight measured in-house by Fraunhofer IZM, may not be the same as the sold version of the FairBuds nor completely consistent with the FMD provided by Fairphone B.V., since the version of the device used for the in-house teardown differs slightly with the version associated with the FMD data, due to time constraints. This does not however affect the modelling in any crucial aspect.

Module	Main parts	Amount	Weight [g]
	USB-C connector		
Speaker R		1	73,4
	Speaker, microphone		
	Mainboard		
	Buttons		
	2 USB-C connectors		
	Several PCBs		
Earcap Covers		2	4,8
	Polycarbonate Cover		
Ear Cushions		2	26,2
	Cushion foam		
	Cushion cover		
Audio adapter		1	4
Battery		1	18,77
	Battery		
Speaker-to-Speaker cable		1	9,31
	2 USB-C connectors		
	Cable		

3.1.1
Recycled input materials

The FairBuds XL use the following recycled materials, as indicated by Fairphone B.V.:

- 84% recycled polycarbonate (PC), mostly in structural parts.
- 100% recycled aluminium, mostly in structural parts.
- 100% recycled tin.
- 100% post-consumer recycled polyester, in the travel pouch.

Due to the scarcity of available data, the modelling for the secondary manufacturing of those materials is based on different sources and entails some omissions and assumptions.

For PC and aluminium, generic datasets from the Sphera database have been used (in the case of PC, the dataset is for generic plastic rather than specifically PC).

For the modelling of recycled polyester, several sources provide some simplified inventory data of the production of secondary polyester e.g. (Hagoort, 2013) and (Patagonia, 2006). However, it was found that the review performed by (Munasinghe, Druckman, & Dissanayake, 2021) provides the most complete inventory data, covering energy and water use in different process steps. This has been completed with a generic dataset for injection moulding.

Data on secondary tin is rather scarce. The main sources found are (Bureau of International Recycling, 2011) and (Sphera, 2019). Both sources provide either very high-level LCIA data or, in the case of the latter report, mixed between primary and secondary sources. Since it is not feasible to properly incorporate this data to our model, it has been decided to model tin as primary in the baseline scenario.

3.1.2
Headband

The headband is mainly made from polypropylene. Structural parts are made from recycled polycarbonate. The headband was modelled according to the manufacturer’s FMD.

3.1.3
Headband Base

The base of the headband consists of two sliders that connect the headband clamp to the speaker modules. The sliders are made from polycarbonate while the rest of the mechanical elements that tie the module together are made of a mix of metals (copper, aluminium, chromium, iron…). They were modelled according to the FMD provided by the manufacturer and are mainly made from recycled polycarbonate and various other metals, such as iron and chrome.

3.1.4
Headband Cover

The headband cover consists of a faux-leather cushion, as well as supporting polymer structures and small magnetic buckles. The faux leather is made up of a combination of – mostly – PET and PU. The modelling of this module is based on the FMD provided by the suppliers.

3.1.5
Speaker Left

The left speaker module consists of the following parts:

- Module housing (mainly PC)
- Microphone(s)
- Speaker (component)
- PCBA with a USB-C connector and a battery connector

The detailed modelling of the PCBs, ICs, passive components and connectors is described in subsection 3.1.12. Datasets used are modelled based on weight data from the FMD provided by the suppliers and, when missing, the teardown performed in-house.

3.1.6
Speaker Right

The right speaker module consists of the following parts:

- Module housing (mainly PC)
- Mainboard with the majority of integrated circuits (ICs) of the headphones and other electronic components
- Microphone(s)
- Speaker (component)
- Charging PCBA including one USB-C connector
- One more USB-C connector
- Buttons

The detailed modelling of the PCBs, ICs, passive components, and connectors is described in subsection 3.1.12. Datasets used are modelled based on weight data from the FMD provided by the suppliers and, when missing, the teardown performed in-house.

3.1.7
Earcap Covers

The earcap covers consist of polycarbonate each, datasets scaled based on FMD weight data.

3.1.8
Ear Cushions

The ear cushions consist of a frame made from polycarbonate, as well as a soft cushion part. The cushion is made from PU covered in the same type of faux leather (with the material composition mentioned above) cover as the headband cover.

3.1.9
Battery

The battery in the FairBuds XL contains a lithium-ion cell with the following specifications:

- Capacity: 3,04 Wh / 800 mAh
- Mass: 18,77 g

Material modelling of the battery is based on the FMD provided by the supplier. As for the energy required for the battery's manufacturing, several sources have been consulted (Kurland, 2020), (Jinasena, Stokke Burheim, & Hammer Stroman, 2021), (Romare & Dahllöf, 2017) and (Wang, Yu, Huang, & Tang, 2019).

3.1.10
Speaker-to-Speaker cable

The speaker-to-speaker cable connects the two speakers with each other. It consists of two male USB-C connectors, which are tied by a flat cable. The flat cable has been modelled as a flexible printed circuit board, which was modelled as a one-layer PCB according to the outer dimensions as no data set for flex boards nor flat-cables were available. The USB-C male plugs are modelled based on material data.

The detailed modelling of the connectors is described in subsection 3.1.12.1.

3.1.11
Accessories

3.1.11.1
Audio Adapter

The audio adapter has been modelled based on different sources: the connectors, USB-C on the one side and audio jack on the other. The USB-C socket is based on material data from a similar component in Fairphone 4. The audio jack is, in turn, modelled using material data from a female audio jack connector from Fairphone 3 as a proxy, due to the lack of more suitable data. The cable is modelled based on the cable length, using a generic dataset.

3.1.11.2
Travel pouch

The travel pouch is made of 100% recycled polyester, with a weight of 24 g. The modelling approach is described in Section 3.1.1 above.

3.1.12
Cross-module approaches

3.1.12.1
Connectors

In this report, connectors are understood as both the male plugs and female sockets that serve as interfaces for different modules and parts, regardless of the type (press-fit, USB, etc.). Connectors are modelled according to their material composition provided by the manufacturers, since the current version of the database in use by Fraunhofer IZM does not include suitable models. The material composition of the connectors consists mainly of:

- Copper for the contacts
- Nickel or tin for the plating

- Liquid Crystal Polymer plastic for the housing

The microphones are placed on flexboards with a pair of male/female press-fit connectors on one end.

Three USB-C connectors are placed in the headphones, one for charging and two to connect the speaker modules to each other. These were modelled similarly to the corresponding part of Fairphone 4 in the Fairphone 4 LCA and based on the FMD.

3.1.12.2
PCBs:

The conventional method to model printed circuit boards is according to the number of layers and outer dimension (smallest rectangular). This might over- or underestimate offcuts, depending on the specific form and production layout. Table 3-2 shows the area based on the outer dimensions.

Table 3-2: Printed circuit board area modelled

Module	Length	Width	Area
	mm	mm	cm^2
Mainboard	55	36	19,8
Charging Board	17	16	2,72
Battery board	26	12	3,12
Multifunction Button board	15	9	1,35
ANC Button	17	6	1,02
Mic Boards (2)	6	5	0,3
Transfer Boards (2)	10	8	0,8

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

3.1.12.3
Integrated circuits

It is common practice to have processed die area as the main scaling factor for integrated circuits (Pirson, et al., 2020), mainly because the final die area correlates well with the energy use during front-end processing which in turn is the main driver of impacts (Boyd, 2012). In this LCA, die size has been estimated based on package size and package type, following the assumptions provided and documented by Sphera. All ICs were modelled by adapting existing data sets from Sphera LCA for Experts.

3.1.12.4
Passive components

Passive components were modelled with corresponding data sets from the Sphera LCA for Experts electronics extension, scaled by number of pieces. If no corresponding data set was available in Sphera LCA for Experts, the generic Ecoinvent dataset for passives was used, scaled by total mass.

3.1.13
Final assembly

For the final assembly, due to a lack of primary data specific to this product, data from smartphone production was provided as a proxy by Fairphone B.V. It is based on primary data from the manufacturer Arima comms in China as shown in Table 3-3. All background data updated to their latest versions.

Table 3-3: Final assembly

Energy use		GaBi dataset
Electricity, from grid	260,77 Wh	CN: Electricity grid mix

Process material		
Ethyl alcohol (95% purity)	0,04 g	RoW: benzyl alcohol production ecoinvent 3.5
Cloth (lint free)	0,08 g	GLO: Cotton fibre (bales after ginning) CottonInc

3.1.14
Modularity overhead

The modular design of Fairphone products pursue the increase of their use time by making repairs easier to users and reducing thus the disposal of products due to failures or aging of parts. However, modularity does have a clear impact in product design and on the environment (Schischke, Proske, & Nissen, 2019). In order to quantify this impact for the FairBuds XL, Fairphone B.V. provided a list of components in each module that can be allocated to the purpose of modularity. This allows then to estimate the impacts related to these design choices. Table 3-4 below summarises the modularity design feature in the different modules (please note that the modules missing are assumed to not change significantly or at all in comparison to non-modular design).

Table 3-4: Summary of design aspects of modularity

Module name	**Design aspects of modularity**
Headband cover	Springs Additional elastic mesh
Speaker to speaker cable	Connectors Increased copper amount More wire shielding
Left speaker	Total size bigger due to removable battery More complex PCBA (more connectors) Screws (instead of glued snap fits)
Battery	Own enclosure
Right speaker	Total size bigger due to more complex PCBA More complex PCBA (more connectors) Screws (instead of glued snap fits)

3.2
Use Phase

Although there is no reliable data on the amount of time people use their headphones, certain assumptions can be made. Based on those, three possible user cases can be built:

- Light user. According to the World Health Organisation, one hour a day is the maximum recommended usage time for earphones[4]. Thus, a light user could be understood as someone who only makes a scarce daily use of headphones (e.g. on the way to work).

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[4] https://www.popsci.com/limit-headphone-time-hour-day-says-who/

- Average user. The average user would be someone using headphones intensely on a free time context e.g. for gaming or watching movies. This is understood around 3 h per day for the purposes of this LCA.
- Heavy user. A heavy user is someone who needs to use earphones for work and possibly on their free time as well. We expect a maximum of 8 h per day.

The average user was defined as the baseline scenario.

The use phase of the headphones was modelled on the basis of the energy used to charge the phone during its entire lifetime. The battery life after a charging cycle is known to be 28 hours. This is coherent with existing references: according to extensive testing of similar devices performed by Rtings[5], the average duration is of around 29 h (with a maximum of 68 h and a minimum of 5 h within the sample, showing thus high variability). The resulting three scenarios are shown in Table 3-5 below.

Table 3-5: User profile summary

	Use h per day	*Charging cycles per year*
Light user	1	13
Average user	3	38
Heavy user	8	101

A lifetime of three years is assumed for each scenario. The electricity is assigned according to the distribution of sales within Europe assigning national electricity grid mixes. For the charging efficiency, assumptions of the Fairphone 3 (Proske, Sánchez, Clemm, & Baur, 2020) were used. The charging efficiency (power drawn from the grid relative to the battery capacity) was 60 %. This leads to the estimation that one charging cycle consumes 5,07 Wh.

3.3
Transport

The transport is separated into three main parts:

- Transport of parts from tier 2 suppliers to final assembly in China, by truck
- Transport of the final product to the distribution hub in Europe, by a combination of 90% ship and 10% air.
- Transport to customer from distribution hub within Europe, by truck.

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

3.3.1
Transport to final assembly

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

- Truck delivery within China

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 in (Proske, Clemm, & Richter, Life cycle assessment of the Fairphone 2, 2016)):

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

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[5] https://www.rtings.com/headphones/tests/active-features/battery-life

3.3.2
Transport to distribution hub

The headphones are transported from the final assembly in China to the distribution hub in the Netherlands mostly by ship. Only a small amount for the product launch is transported by air freight. This ratio was modelled proportionally.

3.3.3
Transport to consumer

The headphones are transported by truck within Europe. An average distance from the distribution hub to the different countries is assumed for this. These transport distances are weighted according to the distribution of sales. Due to a lack of sales data for the FairBuds XL, assumptions were based on the sales split of the Fairphone 4, shared by Fairphone B.V.

3.4
End-of-Life

Modelling the End-of-Life of products is complex because individual devices may ultimately follow different routes after disposal and it is difficult to reliably track what these are and capture them in a single model. For this LCA, a screening of available information sources and studies has been performed in order to identify the most common route. Therefore, the model has been built from several sources and it's generally presented in Figure *3-1*.

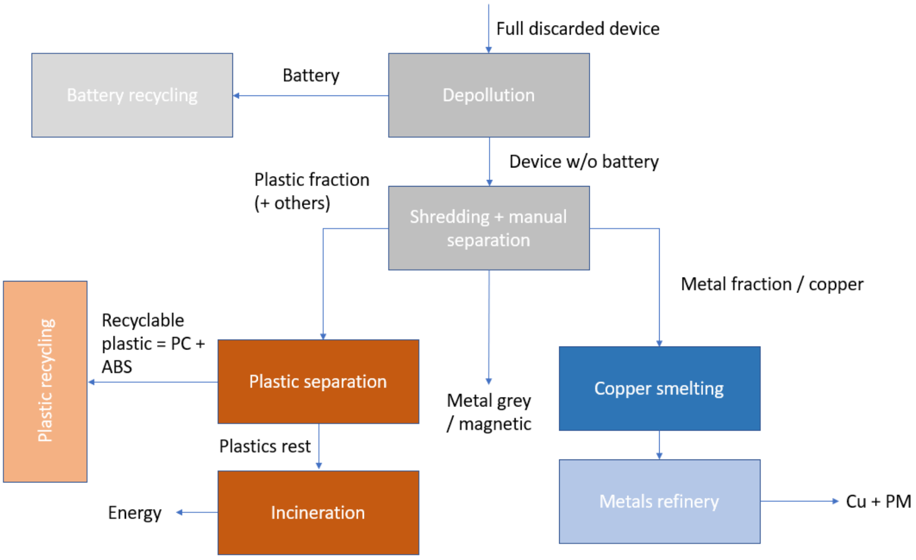

Figure 3-1: Overview of EoL routes for modelling

The EU reports[6] that in 2018 51% of the WEEE is reported as collected and recycled according to regulations while *only* 12% is unreported and estimated to be recycled under non-compliant conditions. From the remaining fraction the streams are estimated to diverge from being mixed with the household waste to being exported. Based on the figures above, it is considered that for the European market, WEEE treatment according to regulation is the most common route and therefore recycling at the end of life is deemed as representative enough.

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[6] https://environment.ec.europa.eu/news/improved-weee-data-give-better-picture-collection-and-recycling-rates-2022-12-07_en

The current WEEE Directive[7] requires that firstly all hazardous substances have to be removed from waste, which for this device means that a depollution step i.e. the removal of the battery is the first treatment undertaken.

A comprehensive review of the state of the art for end-of-life treatment of WEEE performed in 2019 (Ökopol, 2019) sheds some light as to what processing steps follow depollution. This report, also drawing from (Chancerel, Meskers, & Rotter, 2009) and (Sander, et al., 2019), suggests that more than half of the WEEE in Germany is pre-treated in facilities that can separate at least:

- Mixed plastics
- Ferrous metals
- Non-ferrous metals (excluding precious metals)
- Copper and precious metals
- Fine shredding material (mixed composition)

Therefore, in this LCA it is assumed that pre-treatment based on shredding and semi-manual separation leads to separation of mixed plastics, ferrous metals and fraction containing copper as well as precious metals (PM).

For the metal fraction, two-step shredding pre-treatment is able to recover up to 70% (Ökopol, 2019), which is the recovery rate applied thus in our model for the materials in this stream. For this recycling stream, the Umicore process already used for the Fairphone 4 LCA (Sánchez, Proske, & Baur, 2022) is followed once again. This stream includes copper smelting, electrolytic refining and precious metal refining yielding the recovery of part of the copper, gold, silver and palladium in the device.

As for the plastics, the same report (Ökopol, 2019) estimates that mechanical pre-treatment can separate up to 50% of the WEEE plastics successfully while the other half ends up mixed in the metal stream. According to the PolyCE deliverable No. 3.1. (Accili, et al., 2019), the plastic from WEEE under the group of Small Household Appliances (SHA) should follow these streams:

- 84,48% recycled
- 3,25% incineration
- 12,28% disposal

Based on these numbers, for the model of this LCA it is assumed that out of the successfully separated 50% of the plastic, 85% goes to the recycling stream while the remaining 15% is incinerated.

It is noteworthy however, that due to the allocation rules followed in this LCA, the baseline scenario EoL does not include the recycling efforts and thus models only the process steps highlighted in Figure *3-2*. For a more detailed explanation of the allocation approach applied, please refer to Section 3.6.

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[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02012L0019-20180704

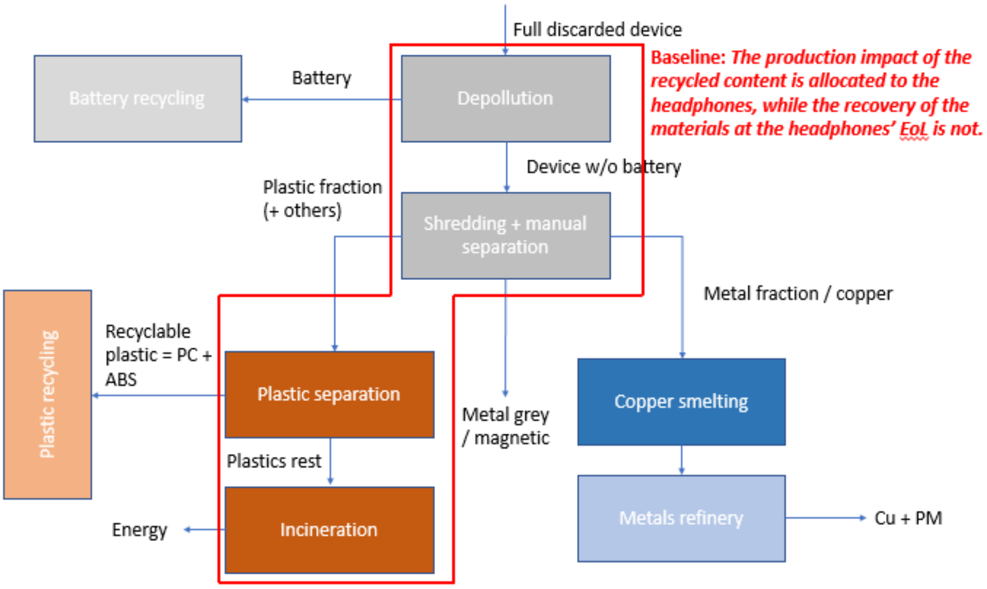

Figure 3-2: Overview of EoL scope, baseline case. Here the *production* of the recycled content is allocated to the FairBuds XL, while the recovery of material at the headphones' EoL is not. Thus, only EoL transport and pre-treatment processes are included.

3.5

Repair Scenarios

By the time of performing this LCA, no primary failure statistics of the headphones are available. Therefore, it has been decided to not include general repair scenarios like the ones studied in the Fairphone 4 LCA. In order to study reparability and its effects, a module per module approach is followed, comparing different repair strategies, namely replacement and repair.

- Replacement: the user is sent a new module, which they replace and send the faulty module back to Fairphone B.V. The considered activities here are the production of the new module and the transport of the module back and forth.
- Repair: the user sends the faulty module to Fairphone's repair centre in France. There, Fairphone B.V. removes the failing component, replaces it with a new one and keeps it in use for further replacements. The considered activities here are the production of the new component, the electricity needed for the desoldering of the malfunctioning piece and the soldering of the new one and the transport of the module.

Since not all modules can meaningfully be subdivided into smaller sub-groups, it only makes sense to compare both strategies for some of the modules, namely:

- Speaker right
- Speaker left
- Speaker to speaker cable
- Buttons

Apart from this, the theoretical environmental payback time is estimated for all modules replacement and repair (when applicable). In this, the evolution of the yearly impact based on extended longevity is plotted and failure is assumed to take place at the second year, where a new module/piece is required. Then, the amount of time required for the new impact to converge with the baseline (failure free) is estimated. For more on this, see Results.

A more in-depth explanation of this metric can be found in the Fairphone 4 LCA (Sánchez, Proske, & Baur, 2022).

3.6
Allocation Scenarios

The FairBuds XL are produced using recycled materials (see Section 3.1.1) and also allow for recyclability at their end of life. Therefore, the question of allocation becomes relevant, since it is important to set which impacts are considered as attributable to this product and which ones should belong to previous or upcoming products in the lifetime of different materials.

As a main reference for this LCA we use the overview of allocation methods performed by Ekvall (Ekvall, et al., 2020) as well as the framework and recommendations set by the ISOs 14040, 14044 and 14067. As a first consideration: the life cycle of this product is not a closed loop, since both the incoming secondary materials as well as the materials recovered at EoL are not directly reused for this same production line. Furthermore, while metals retain their properties once recovered and can, in a sense, be considered closed loop from a modelling point of view, plastics cannot. In the case of these headphones, plastics make up a significant part of the recycled content and thus an open loop approach is more representative.

For this LCA's baseline scenario a simple cut-off and, more specifically, 100/0 method has been chosen: the impacts related to the recovery of the secondary materials used in the headphones is understood to be allocatable to the headphones themselves. In coherence with this, the necessary efforts to extract secondary materials from the headphones at the end of their life is understood to be part of the next products' impacts, thus falling out of the scope. A simplified picture can be seen in Figure *3-3*.

An alternative interpretation of the cut-off approach could however be the opposite: the effort required to recycle materials from the headphones should be allocated to these and therefore, the efforts of extracting the recycled content are part of the previous product (thus coming into this product system *burden-free*). Since this product includes both recycled and recyclable content, in this LCA both approaches are compared as part of the sensitivity analysis (see Section 4.5.1).

Figure 3-3: *Allocation approach scheme*

This approach has been chosen mostly because it is consistent with both the attributional LCA principles and the existing ISOs mentioned above. Furthermore, it is a simple approach that avoids market-based (or otherwise) assumptions that add further uncertainty to the model. However, as pointed out by (Ekvall, et al., 2020), an issue with cut-off approaches in general is that they can obscure or ignore the benefits of recycling (in both ends): for example, in the case of metal recycling from the headphones, the environmental footprint of recycling is indeed higher than a worse scenario where electronics are sent to incineration (more on this in Section 4.5.1). In order to better analyse benefits, further allocation scenarios including credits for avoided disposal and production are also compared as part of the sensitivity analysis.

4
Impact Assessment

Based on material flows defined in the LCI, the life cycle impact assessment (LCIA) will be carried out according to several existing and recognised LCIA methodologies using LCA software Sphera LCA for Experts. For the following impact categories, the results will be displayed and discussed in detail:

- Climate change:
  - Global Warming, 100 years (GWP100) in kg CO_2-eq., including:
    - Air craft emissions
    - Biogenic GHG emissions
    - Biogenic GHG removal
    - Emissions from land use change (dLUC)
    - Fossil GHG emissions
- Resource depletion:
  - Abiotic resource depletion (ADP) elements in kg Sb equivalents
  - ADP fossil in MJ
- Human toxicity:
  - Human Toxicity Potential in kg DCB equivalents
- Ecotoxicity:
  - Freshwater Ecotoxicity Potential in kg DCB equivalents
  - Marine Aquatic Ecotoxicity Potential in kg DCB equivalents
  - Terrestrial Ecotoxicity Potential in kg DCB equivalents

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

4.1
Definition of impact categories

For the impact categories covered in this LCA study, the following definitions from CML are used, except for the impact category global warming where the IPCC methodology is applied[8]:

- Global Warming (GW): “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.

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[8] Definition from CML documentation, CML values however not used in this LCA. Excplanation see following page.

[…] The GWP 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: "The model of abiotic resource depletion […] is a function of the annual extraction rate and geological reserve of a resource. In the model as presently defined, the ultimate reserve is considered the best estimate of the ultimately extractable reserve and also the most stable parameter for the reserve parameter. However, data for this parameter will by definition never be available. As a proxy, we suggest the ultimate reserve (crustal content)." (van Oers & Guinée, The Abiotic Depletion Potential: Background, Updates and Future, 2016)
  - Abiotic resource depletion (ADP) elements: "The impact category for elements is a heterogeneous group, consisting of elements and compounds with a variety of functions (all functions being considered of equal importance)." (van Oers & Guinée, The Abiotic Depletion Potential: Background, Updates and Future, 2016)
  - ADP fossil: "The resources in the impact category of fossil fuels are fuels like oil, natural gas, and coal, which are all energy carriers and assumed to be mutually substitutable. As a consequence, the stock of the fossil fuels is formed by the total amount of fossil fuels, expressed in Megajoules (MJ)." (van Oers & Guinée, The Abiotic Depletion Potential: Background, Updates and Future, 2016)
- Human Toxicity Potential: "The normalisation references for human toxicity via the environment should reflect the total human toxic load in the reference area caused by human activity, i.e. the potential risk connected to exposure from the environment (via air, soil, provisions and drinking water) as a result of emissions to the environment from industrial production, traffic, power plants etc. Ideally, all emissions of substances potentially affecting human health should be quantified and assessed. However, the multitude of known substances (>100.000) and an even larger number of emission sources logically makes that approach unfeasible. The inventory used for calculating the normalisation references is therefore based on available emission registrations for substances, which are believed to contribute significantly to the overall load." (Stranddorf, Hoffmann, & Schmidt, 2005)
- Ecotoxicity Potential: "The impact category ecotoxicity covers the possible effects of toxic substances released during the life cycle of a product to the environment. The sources of toxicants are quite different depending on the type of environment as well as the methods used in the assessment of the impact. Consequently, the impact on aquatic and terrestrial systems are usually considered separately. In principle, the normalisation reference for ecotoxicology includes all toxic substances emitted to the environment due to human activities, and it requires extensive data on all types of emissions. In general, however, only few data on environmental releases of toxic substances are available, and the normalisation therefore relies on extrapolations from a relatively limited set of data." (Stranddorf, Hoffmann, & Schmidt, 2005)

Table 4-1 below summarises the LCIA methodologies used for the calculation of each of the impact categories. For global warming, the methodology proposed by the ISO 14067 (ISO, 2018) is used, based in turn in the conversion factors proposed in the latest IPCC report. This methodology breaks down the GHG emissions into different categories outlined by the ISO norm. Both ADP elements and ADP fossil are calculated employing the CML methodology in its 2016 iteration, as recommended by ILCD (International Reference Life Cyce Data System, 2011) and some authors like (Mikosch, Dettmer, Plaga, Gernuks, & Finkbeiner, 2022). For ecotoxicity, the latest update in the Environmental Footprint methodology (EF3.1) has been chosen, which utilizes the USEtox model (v2.0). In previous studies e.g. (Sánchez, Proske, & Baur, 2022) ecotoxicity had been calculated also using CML which is based on the model USES-LCA 1.0 (Mikosch, Dettmer, Plaga, Gernuks, & Finkbeiner, 2022) but as some sources note, (Gandhi & Diamond, 2018) and (Sala, Biganzoli, Sanye Mengual, & Saouter, 2022), older models like this seemingly overestimated the ecotoxic impacts of several metals due to a too simplified modelling that didn't account for some material specificities. Finally, for human toxicity CML is also used.

Table 4-1: Summary of analyzed environmental impact categories and the LCIA methodologies used for each

Impact category	**LCIA methodology**
GW, total	ISO 14067 (IPCC AR6)
GW, air craft emissions	ISO 14067 (IPCC AR6)
GW, biogenic GHG emissions	ISO 14067 (IPCC AR6)
GW, emissions from land use change	ISO 14067 (IPCC AR6)
GW, fossil GHG emissions	ISO 14067 (IPCC AR6)
Abiotic Depletion elements	CML2001 – Aug. 2016
Abiotic Depletion fossil	CML2001 – Aug. 2016
Freshwater ecotoxicity	EF 3.1
Human toxicity	CML2001 – Aug. 2016

4.2

Results

The LCIA shows that the final emissions for the entire life cycle of the headphones are 6,8 kg CO_2-eq. Of those, 5,61 kg CO_2-eq. are attributable to the production of the headphones, 0,61 kg CO_2-eq. to their distribution, 0,49 kg CO_2-eq. to their use and around 0,09 kg CO_2-eq. to the end-of-life phase (values based on the baseline scenario, more on this in Section 4.5). A complete table with the results for the impact categories under study is presented in the Table *4-2*.

Table 4-2: General results for baseline scenario

Impact category name	**Total**	**Production**	**Distribution**	**Use**	**EoL**
Total emissions global warming [kg CO_2-eq.]	6,80E+00	5,61E+00	6,12E-01	4,88E-01	9,45E-02
- Air craft emissions [kg CO_2-eq.]	1,50E-03	1,50E-03	0,00E+00	7,74E-07	1,82E-09
- Biogenic GHG emissions [kg CO_2-eq.]	5,16E-01	3,38E-01	1,03E-03	1,77E-01	7,30E-04
- Biogenic GHG removal [kg CO_2-eq.]	-5,07E-01	-3,34E-01	-8,77E-04	-1,71E-01	-8,07E-04
- Emissions from land use change [kg CO_2-eq.]	4,90E-03	4,74E-03	7,29E-05	6,97E-05	1,34E-05
- Fossil GHG emissions [kg CO_2-eq.]	6,78E+00	5,60E+00	6,12E-01	4,82E-01	9,45E-02
Abiotic depletion elements [Kg Sb eq.]	7,43E-04	7,43E-04	1,77E-07	1,28E-07	1,60E-07

Abiotic depletion fossil [MJ]	8,17E+01	6,67E+01	8,75E+00	5,41E+00	8,96E-01
Freshwater ecotoxicity [CTUe]	5,73E+01	5,22E+01	2,32E+00	2,52E+00	2,88E-01
Human toxicity potential [kg DCB eq.]	2,24E+00	1,74E+00	4,59E-01	2,31E-02	1,78E-02

As it can be seen both in the table above and in Figure *4-1*, for all impact categories the production is the main environmental hot spot. As the second to production, distribution seems to be also a relevant contributor, most notably for human toxicity where it represents around 20% of the final value (being around 10% in GW and ADP fossil). The use phase (under the assumption of an intensive user) lays in between 10% (for GW and ADPf) to less than 1 % (ADP elements). Finally, the EoL in the baseline scenario contributes only marginally to all environmental impacts.

The central role of production in the environmental impacts of the headphones is coherent with what is known about environmental issues of smaller electronic devices where the manufacturing and materials of the devices are at the core of their impacts. Regarding the EoL impacts, it is important to note that the current baseline scenario does not include the efforts required to extract and recover materials from the device and thus covers only transport and disposal, which considerably contributes to the low impact of EoL for some categories (for more on the EoL please refer to Section 3.4 and for a comparative analysis of different EoL models, see Section 4.5.1).

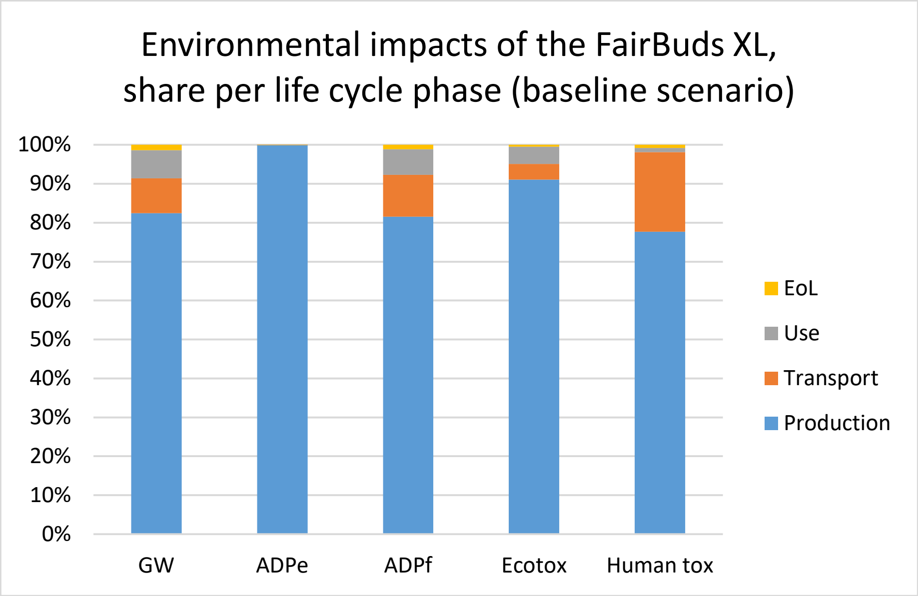

Figure 4-1: Selected environmental impacts for the entire life cycle of the FairBuds XL, referenced to the baseline scenario. Figure represents the relative contribution of the main life cycle phases in %, relative to the total value for each impact category shown.

4.3
Contribution Analysis

In this section, a closer look is taken at which components and activities contribute to the results presented above. The following subsections are dedicated to the main life cycle phases on the baseline scenario.

4.3.1

Production

Figure *4-2* shows an overview of the share of impacts that is attributed to each module. The bars in the graphic below show therefore the % of the impact of production that each module (including also final assembly and packaging) is responsible of.

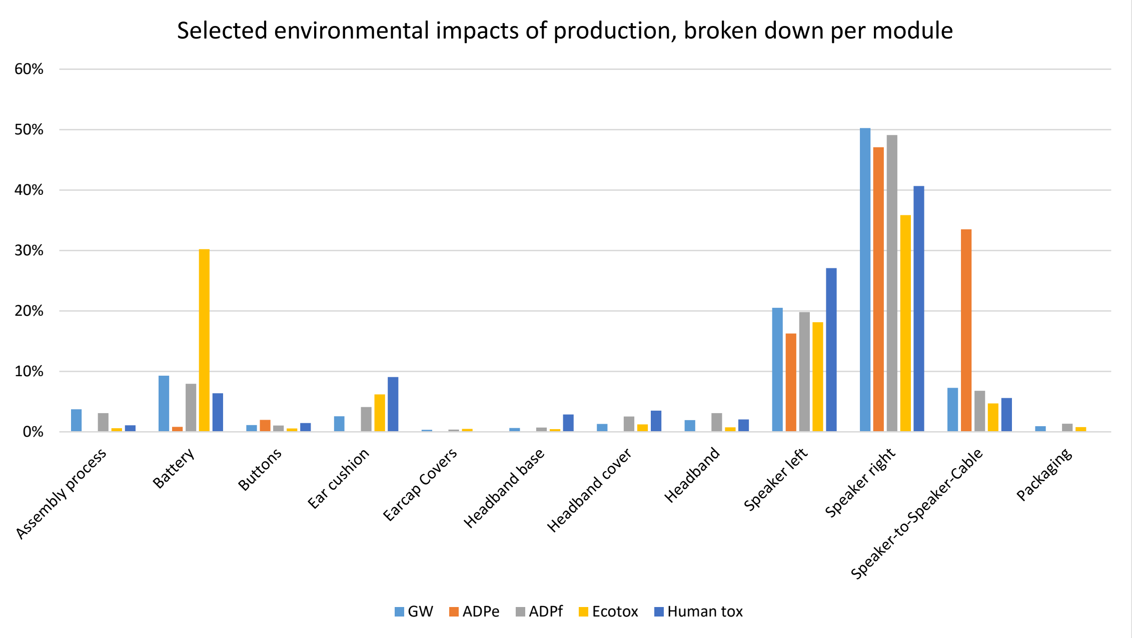

Figure 4-2: Environmental impacts of production organized by modules. Bars represent the contribution of each module to the total value of each impact category, given in %.

For Global Warming, the modules with the highest impact are both speakers (right and left), where all the electronics of the product are contained. These are followed by the battery and the assembly process. ADP fossil, being related mostly to energy use, shows a very similar distribution to GW. ADP elements, however, is mostly influenced by the expenditure of metals mainly in electronics and connectors. According to the latest update of the ADPe model (van Oers, Guinée, & Heijungs, 2020), the main contributors are gold, copper and silver. Therefore, while also peaking in both speaker modules, it also shows a relevant contribution in the speaker-to-speaker cable. For ecotoxicity, electronics also drive the impact due to the intensive use of chemicals in both silicon wafer manufacturing and PCB manufacturing. Consequently, both speaker modules and their electronics are also big contributors here. However, the battery shows a very significant contribution as well, due to the chemistry used for the cells manufacturing. Finally, human toxicity hotspots are found in both speaker modules as well although some minor contributions can be seen spread out in more structural modules mainly connected to plastics use.

Figure *4-3* shows the distribution of impacts within the right speaker module, where most of the electronics are housed. For all impact categories it can be seen that both the motherboard and the speaker component are the main hotspots. As previously mentioned, in the case of ADP elements the connectors play a key role (due to the expenditure of precious metals plating on the contacts) and thus the charge board which contains the USB-C connector of the charging cable.

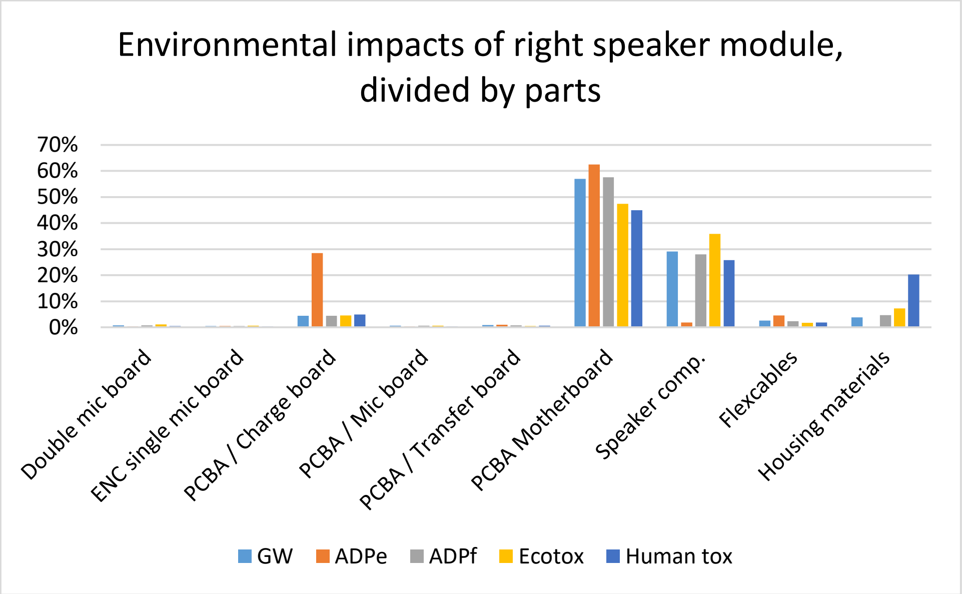

Figure 4-3: Impact distribution for the right speaker module. Bars represent the contribution of each part of the module to the total for each impact category, as a %.

Figure 4-4 below shows the impact distribution for the mainboard PCBA. For all impact categories, the PCB itself is responsible for almost half. The manufacturing of a PCB involves intensive use of energy and the use of chemicals for certain process steps e.g. etching of excess copper, washing etc. A good overview of the environmental impacts of PCB production can be seen in (Ozkan, Nilay, & Germirli Babuna, 2018). While global warming and ADP fossil are driven by energy use in several stages, other impacts are more localized: toxicity is mainly driven by the etching step (removal of excess copper via chemical bath) and human toxicity is mainly connected with printing. The ADP elements impact of the FairBuds XL is mostly attributable to the connectors, due to their material use (as comment already above). Both GW and ADP fossil however, have their hotspot in the integrated circuits, due to the energy intensity of their manufacturing; mostly in the front-end processes i.e. the wafer manufacturing and circuit printing, as shown by (Boyd, 2012). Human toxicity also has a major contribution from ICs and passive components connected once again with plastics and chemicals employed in their manufacturing.

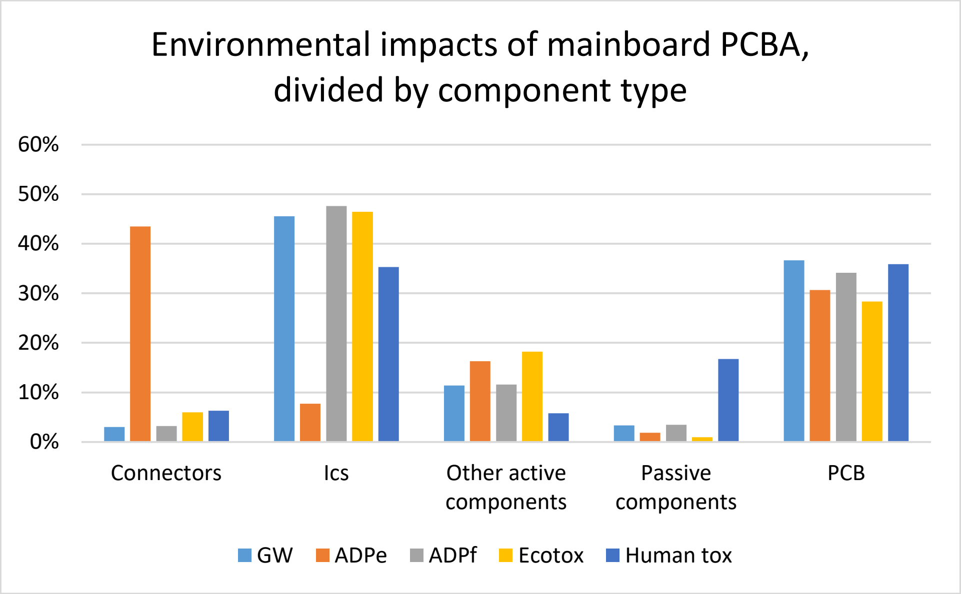

Figure 4-4: Impact distribution for mainboard PCBA, divided by component type. Bars represent the contribution of each group to the total value of each impact category for the entire assembly. Passive components include resistors, capacitors and inductors. Other active components include diodes and transistors.

Figure *4-5* shows a similar distribution of impacts but for the left speaker. The left speaker contains some smaller boards, most prominently the L board (PCBA which includes both the battery connector and a USB connector for the speaker-to-speaker cable), which makes it the major contributor to ADP elements in this module, due once again, to the material use in the connector ports. The rest of impacts peak at the left speaker component. Around half of its impacts are related to the production of some of the metals involved e.g. aluminium, cast iron… while the rest is likely related to its manufacturing process that includes some energy intensive steps like high pressure stamping and bending. Mechanicals and housing elements also show a significant contribution for human toxicity. The rest of the sub-assemblies in this module, although they include electronics, are very small in comparison and thus have a very minor contribution to the impacts of the left speaker module.

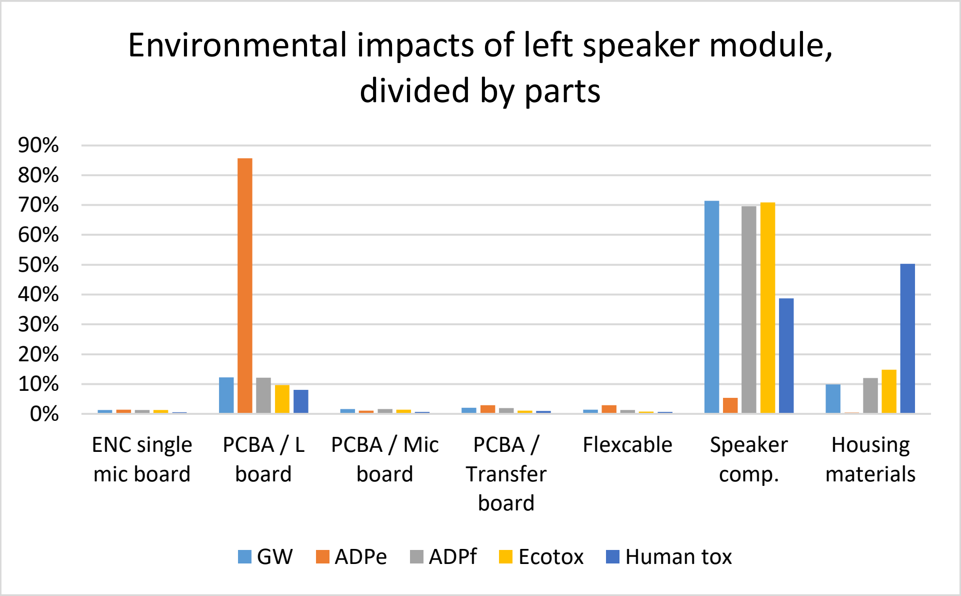

Figure 4-5: Impact distribution for left speaker module, divided by parts. Bars represent the contribution of each group to the total value of each impact category for the entire assembly. L board named after

BoM naming convention, refers to the battery board (includes the battery connector, amongst other components).

Finally, Figure *4-6* below shows the production impacts divided by component groups (where mechanicals refers to both housing bodies and other structural elements like fasteners). As commented earlier, both GW and ADP fossil are closely related to the energy use during production of the different parts and components. Therefore, electronics (including the speaker components) drive these impacts. For ADP elements the majority of the production impacts can be allocated to electronics, which in this case also includes connectors. Precious metals are used extensively in electronics, mostly for plating connector contacts and wiring chips (both within the package and to the PCB). Ecotoxicity is mostly driven by electronics manufacturing (which for ICs and PCBs is a process that intensively uses chemical washing and chemical solutions in several steps e.g. etching) and the battery, which also involves toxic chemicals in the cell manufacturing. Finally human toxicity is mostly distributed between electronics and mechanicals, in this case related with the plastics used in the manufacturing of the device.

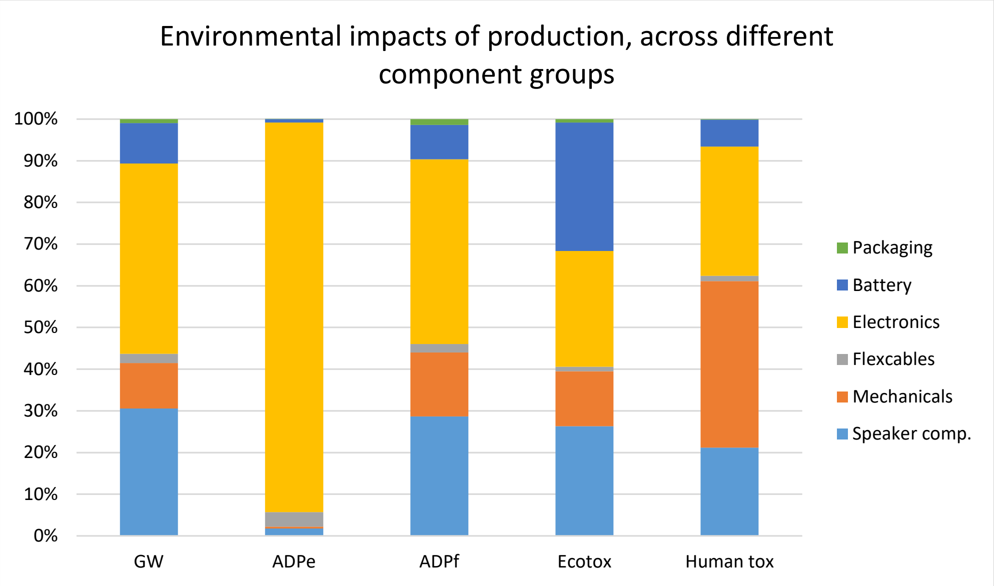

Figure 4-6: Impact distribution for production per component group. Bars show the contribution of different component types to each of the impact categories (in %). Mechanicals includes not only housing but also fasteners and other structural elements.

Table 4-3: Environmental impacts for production phase, baseline scenario

Impact category name	Total	Assembly process	Battery	Buttons module	Ear cushion	Earcap cover	Headband base	Headband cover	Headband	Speaker left module	Speaker right module	Speaker-to-speaker cable	Packaging
Total emissions [kg CO₂-eq.]	5,61E+00	2,08E-01	5,22E-01	6,34E-02	1,45E-01	1,85E-02	3,57E-02	7,45E-02	1,09E-01	1,15E+00	2,82E+00	4,09E-01	5,32E-02
Air craft emissions [kg CO₂-eq.]	1,50E-03	5,83E-08	8,13E-08	2,08E-08	3,51E-08	7,48E-09	1,19E-08	7,21E-09	1,62E-08	3,43E-07	1,50E-03	1,25E-07	1,39E-08
Biogenic GHG emissions [kg CO₂-eq.]	3,38E-01	7,03E-03	1,05E-02	4,73E-03	7,59E-03	1,45E-03	5,86E-03	3,69E-03	7,75E-03	6,28E-02	1,85E-01	3,44E-02	6,47E-03
Biogenic GHG removal [kg CO₂-eq.]	-3,34E-01	-7,25E-03	-1,09E-02	-4,29E-03	-7,34E-03	-1,39E-03	-5,74E-03	-3,33E-03	-7,49E-03	-6,03E-02	-1,78E-01	-3,13E-02	-1,61E-02
Emissions from land use change [kg CO₂-eq.]	4,74E-03	1,31E-04	2,55E-04	7,17E-05	6,42E-05	7,51E-06	4,16E-05	3,17E-05	2,28E-05	8,92E-04	2,26E-03	4,55E-04	5,13E-04
Fossil GHG emissions [kg CO₂-eq.]	5,60E+00	2,08E-01	5,22E-01	6,29E-02	1,45E-01	1,84E-02	3,55E-02	7,42E-02	1,09E-01	1,15E+00	2,81E+00	4,05E-01	6,23E-02
Abiotic depletion elements [Kg Sb eq.]	7,43E-04	1,27E-08	6,23E-06	1,46E-05	6,51E-07	2,33E-08	6,87E-07	4,09E-07	6,80E-07	1,21E-04	3,50E-04	2,49E-04	3,55E-08

Abiotic depletion fossil [MJ]	6,67E+01	2,08E+00	5,29E+00	6,97E-01	2,73E+00	2,61E-01	4,72E-01	1,68E+00	2,08E+00	1,32E+01	3,27E+01	4,54E+00	9,03E-01
Freshwater ecotoxicity [CTUe]	5,22E+01	3,22E-01	1,58E+01	2,97E-01	3,25E+00	2,49E-01	2,34E-01	6,52E-01	3,90E-01	9,47E+00	1,87E+01	2,46E+00	4,10E-01
Human toxicity potential [kg DCB eq.]	1,74E+00	1,87E-02	1,11E-01	2,53E-02	1,58E-01	1,41E-03	5,02E-02	6,09E-02	3,59E-02	4,71E-01	7,07E-01	9,71E-02	2,07E-03

4.3.2 Transport

In Figure 4-7, the distribution of environmental impacts across the utilized means of transport can be seen. For most impact categories except ADP elements air transport seems to be clearly the environmental hotspot. For ADP elements, instead, land transport plays a more important role. It is important to note that air shipping does not represent the biggest nor the main shipping choice (only 10% of the transport to the distribution hub is done by air). This however shows, how environmentally critical plane transport is.

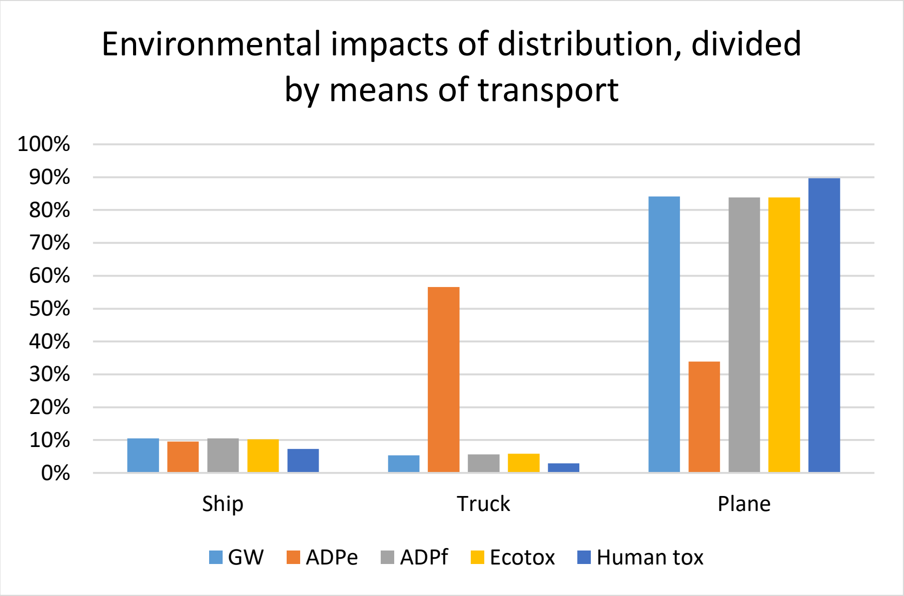

Figure 4-7: Distribution related impacts, per means of transportation. Bars represent the % of the total distribution impacts allocatable to each means of transport employed.

Table 4-4: Impact categories of distribution, by means of transportation

Impact category name	Ship	Truck	Plane
Total emissions [kg CO_2-eq.]	6,45E-02	3,27E-02	5,15E-01
Air craft emissions [kg CO_2-eq.]	0,00E+00	0,00E+00	0,00E+00
Biogenic GHG emissions [kg CO_2-eq.]	3,71E-04	1,55E-04	5,02E-04
Biogenic GHG removal [kg CO_2-eq.]	-3,14E-04	-1,48E-04	-4,15E-04
Emissions from land use change [kg CO_2-eq.]	3,42E-05	9,56E-06	2,91E-05
Fossil GHG emissions [kg CO_2-eq.]	6,44E-02	3,27E-02	5,15E-01
Abiotic depletion elements [Kg Sb eq.]	1,68E-08	9,99E-08	5,99E-08
Abiotic depletion fossil [MJ]	9,18E-01	4,99E-01	7,33E+00

Freshwater ecotoxicity [CTUe]	2,38E-01	1,36E-01	1,94E+00
Human toxicity potential [kg DCB eq.]	3,37E-02	1,35E-02	4,11E-01

In Figure 4-8 the same distribution is broken down per transport section or phase. Air transport takes place only when distributing the headphones from the assembly site in China to the hub in Europe, from which the final transport to customers happens by land. Furthermore, this is the longest distance in the whole distribution phase and is accordingly also the most relevant environmentally.

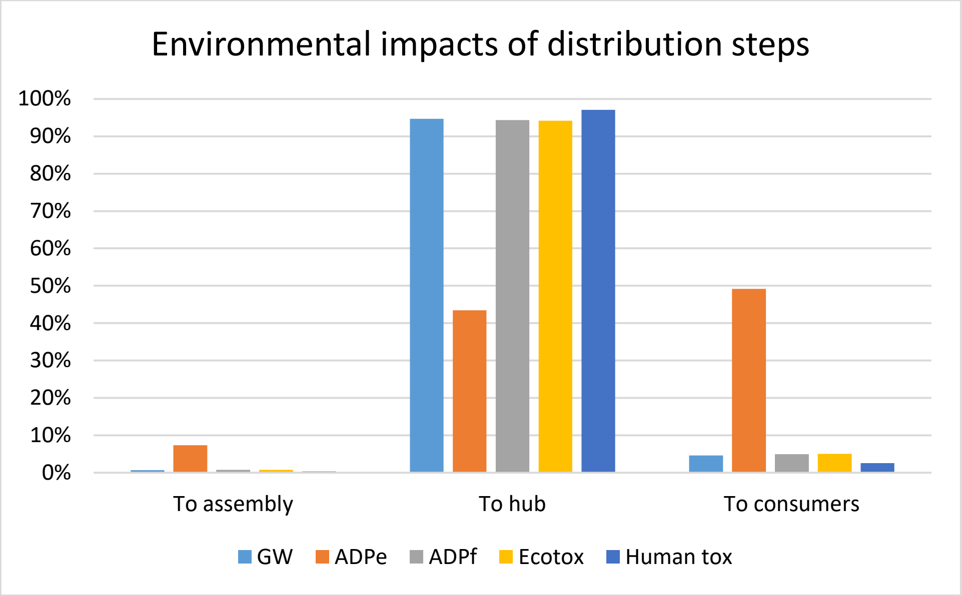

Figure 4-8: Distribution related impacts, per transport step. To assembly refers to the transport of components to the assembly site, to hub refers to the transport of the full device to the stock hub in Europe and lastly to consumers refers to the shipping of the device to the end user.

Table 4-5: Impact categories of distribution, by distribution step

Impact category name	**Transport to assembly**	**Transport to hub**	**Transport to consumers**
Total emissions [kg CO_2-eq.]	4,28E-03	5,79E-01	2,84E-02
Air craft emissions [kg CO_2-eq.]	0,00E+00	0,00E+00	0,00E+00
Biogenic GHG emissions [kg CO_2-eq.]	2,02E-05	8,73E-04	1,35E-04
Biogenic GHG removal [kg CO_2-eq.]	-1,93E-05	-7,29E-04	-1,28E-04
Emissions from land use change [kg CO_2-eq.]	1,25E-06	6,34E-05	8,31E-06
Fossil GHG emissions [kg CO_2-eq.]	4,27E-03	5,79E-01	2,84E-02
Abiotic depletion elements [Kg Sb eq.]	1,31E-08	7,68E-08	8,69E-08

Abiotic depletion fossil [MJ]	6,52E-02	8,25E+00	4,34E-01
Freshwater ecotoxicity [CTUe]	1,77E-02	2,18E+00	1,18E-01
Human toxicity potential [kg DCB eq.]	1,76E-03	4,45E-01	1,17E-02

4.3.3
Use phase

An estimation of the yearly impacts and the effects of increased longevity are shown in Figure 4-9. The *yearly emissions* for the assumed base case use of 3 years are of 2,27 kg CO_2-eq., while the emissions per year for a 5 year lifetime would decrease to 1,63 kg CO_2-eq.; and to 1,29 kg CO_2-eq. for a 7 year lifetime. That is a reduction of up to 43 % for a usage extension of 4 years. This estimation includes additional impacts with increased use time i.e. additional battery production (one battery for the 5 years use scenario and 2 batteries for the 7 years use scenario) and the increase in use phase related impacts.

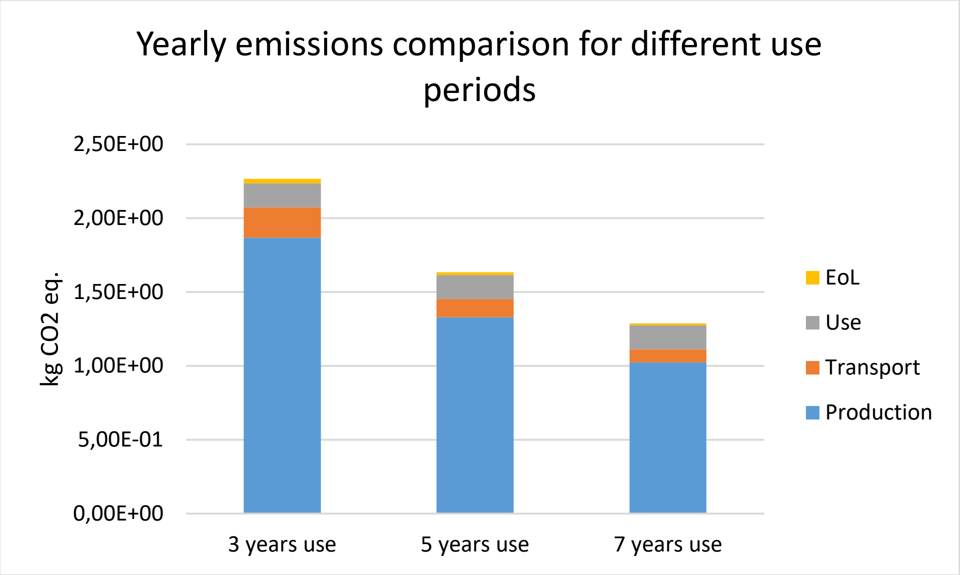

Figure 4-9: Estimated yearly emissions (GW100, CML) for the FairBuds XL, related to the baseline scenario. Each column represents a different use case with a longer useful life each. For the 5 years use case, an additional battery replacement is assumed (related impacts included in production). For the 7 years use case two replacement batteries are assumed. No further repair assumed for any case.

Table 4-6: Estimated yearly impacts for the 3 years of use scenario

Impact category name	Total	Production	Distribution	Use	EoL
Total emissions [kg CO_2-eq.]	2,27E+00	1,87E+00	2,04E-01	1,63E-01	3,15E-02
Air craft emissions [kg CO_2-eq.]	5,01E-04	5,01E-04	0,00E+00	2,58E-07	6,08E-10
Biogenic GHG emissions [kg CO_2-eq.]	1,72E-01	1,13E-01	3,43E-04	5,90E-02	2,43E-04

Biogenic GHG removal [kg CO_2-eq.]	-1,69E-01	-1,11E-01	-2,92E-04	-5,70E-02	-2,69E-04
Emissions from land use change [kg CO_2-eq.]	1,63E-03	1,58E-03	2,43E-05	2,32E-05	4,46E-06
Fossil GHG emissions [kg CO_2-eq.]	2,26E+00	1,87E+00	2,04E-01	1,61E-01	3,15E-02
Abiotic depletion elements [Kg Sb eq.]	2,48E-04	2,48E-04	5,89E-08	4,27E-08	5,32E-08
Abiotic depletion fossil [MJ]	2,72E+01	2,22E+01	2,92E+00	1,80E+00	2,99E-01
Freshwater ecotoxicity [CTUe]	1,91E+01	1,74E+01	7,72E-01	8,39E-01	9,61E-02
Human toxicity potential [kg DCB eq.]	7,46E-01	5,80E-01	1,53E-01	7,71E-03	5,93E-03

Table 4-7: Estimated yearly impacts for the 5 years of use scenario

Impact category name	**Total**	**Production**	**Distribution**	**Use**	**EoL**
Total emissions [kg CO_2-eq.]	1,63E+00	1,33E+00	1,22E-01	1,63E-01	1,89E-02
Air craft emissions [kg CO_2-eq.]	3,01E-04	3,01E-04	0,00E+00	2,58E-07	3,65E-10
Biogenic GHG emissions [kg CO_2-eq.]	1,29E-01	6,96E-02	2,06E-04	5,90E-02	1,46E-04
Biogenic GHG removal [kg CO_2-eq.]	-1,26E-01	-6,90E-02	-1,75E-04	-5,70E-02	-1,61E-04
Emissions from land use change [kg CO_2-eq.]	1,04E-03	9,99E-04	1,46E-05	2,32E-05	2,68E-06
Fossil GHG emissions [kg CO_2-eq.]	1,63E+00	1,33E+00	1,22E-01	1,61E-01	1,89E-02
Abiotic depletion elements [Kg Sb eq.]	1,50E-04	1,50E-04	3,53E-08	4,27E-08	3,19E-08
Abiotic depletion fossil [MJ]	1,81E+01	1,44E+01	1,75E+00	1,80E+00	1,79E-01

Freshwater ecotoxicity [CTUe]	1,81E+01	1,68E+01	4,63E-01	8,39E-01	5,77E-02
Human toxicity potential [kg DCB eq.]	4,73E-01	3,70E-01	9,17E-02	7,71E-03	3,56E-03

Table 4-8: Estimated yearly impacts for the 7 years of use scenario

Impact category name	**Total**	**Production**	**Distribution**	**Use**	**EoL**
Total emissions [kg CO_2-eq.]	1,29E+00	1,02E+00	8,74E-02	1,63E-01	1,35E-02
Air craft emissions [kg CO_2-eq.]	2,15E-04	2,15E-04	0,00E+00	2,58E-07	2,60E-10
Biogenic GHG emissions [kg CO_2-eq.]	1,09E-01	4,97E-02	1,47E-04	5,90E-02	1,04E-04
Biogenic GHG removal [kg CO_2-eq.]	-1,07E-01	-4,93E-02	-1,25E-04	-5,70E-02	-1,15E-04
Emissions from land use change [kg CO_2-eq.]	7,49E-04	7,14E-04	1,04E-05	2,32E-05	1,91E-06
Fossil GHG emissions [kg CO_2-eq.]	1,28E+00	1,02E+00	8,74E-02	1,61E-01	1,35E-02
Abiotic depletion elements [Kg Sb eq.]	1,07E-04	1,07E-04	2,52E-08	4,27E-08	2,28E-08
Abiotic depletion fossil [MJ]	1,35E+01	1,03E+01	1,25E+00	1,80E+00	1,28E-01
Freshwater ecotoxicity [CTUe]	1,54E+01	1,42E+01	3,31E-01	8,39E-01	4,12E-02
Human toxicity potential [kg DCB eq.]	3,40E-01	2,64E-01	6,55E-02	7,71E-03	2,54E-03

Figure 4-10 below presents a comparison of the different user profiles. It can be seen that use patterns do have a visible effect in contribution of the use phase to the impacts. Global warming and fossil depletion are most significant with an increase from being around 1% of the total to around 7%. Less relevant for toxicity related impacts that range below 5% at all times. Element depletion (ADPe) stays below 1% in all cases.

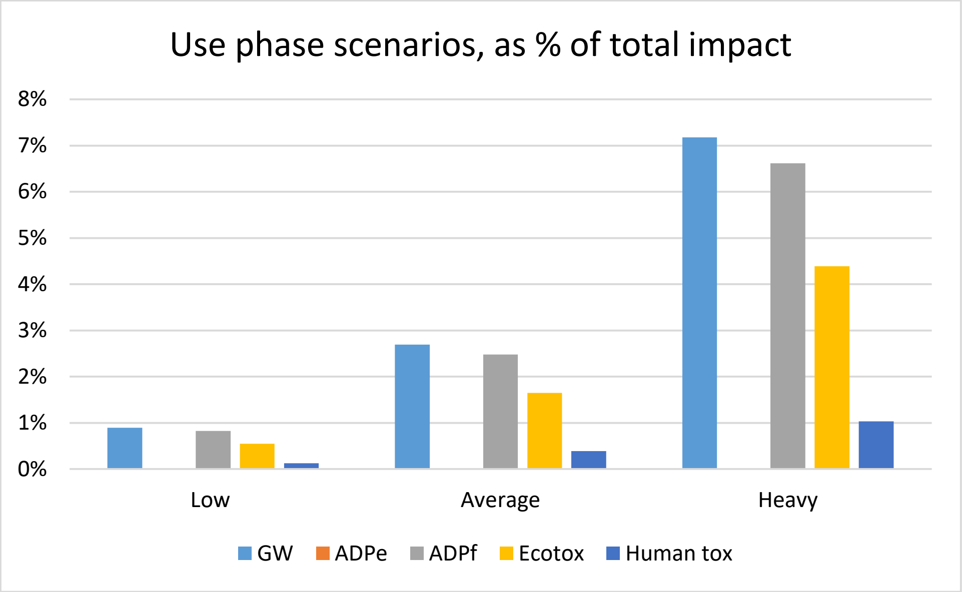

Figure 4-10: Comparison of different user profiles, based on the number of hours of daily use (profiles explained in more detail in the LCI section). Graphic presents different environmental impacts and the columns represent the percentage of the use phase in the total life cycle value for each impact category.

Table 4-9: Environmental impacts for the different user profiles

Impact category name	Low user profile	Average user profile	Heavy user profile
Total emissions [kg CO_2-eq.]	2,03E-02	6,10E-02	1,63E-01
Air craft emissions [kg CO_2-eq.]	3,22E-08	9,67E-08	2,58E-07
Biogenic GHG emissions [kg CO_2-eq.]	7,37E-03	2,21E-02	5,90E-02
Biogenic GHG removal [kg CO_2-eq.]	-7,13E-03	-2,14E-02	-5,70E-02
Emissions from land use change [kg CO_2-eq.]	2,91E-06	8,72E-06	2,32E-05
Fossil GHG emissions [kg CO_2-eq.]	2,01E-02	6,03E-02	1,61E-01
Abiotic depletion elements [Kg Sb eq.]	5,33E-09	1,60E-08	4,27E-08
Abiotic depletion fossil [MJ]	2,25E-01	6,76E-01	1,80E+00
Freshwater ecotoxicity [CTUe]	1,05E-01	3,15E-01	8,39E-01
Human toxicity potential [kg DCB eq.]	9,64E-04	2,89E-03	7,71E-03

4.3.4
End-of-Life

As described in Section 3.6, the end-of-life modelling in the baseline scenario includes only transport to waste treatment and disposal activities. Figure *4-11* shows the impact distribution for this life cycle phase. For all impact categories, the main contributor is the transport to the treatment facility. For global warming, the incineration of the plastic fraction that is not recycled makes up almost half of the EoL emissions. For human toxicity the hotspot can be found in the pre-treatment step of the EoL, most importantly shredding. According to the Ecoinvent documentation of the dataset used for modelling this step (Ecoinvent, 2007), a set of metal particles to urban air results from this activity and is likely directly linked to the human toxicity values[9].

Further insight in the impacts associated with the recycling steps that follow, but are not in scope of the baseline case, can be seen in Section 4.5.1 under the sensitivity analysis.

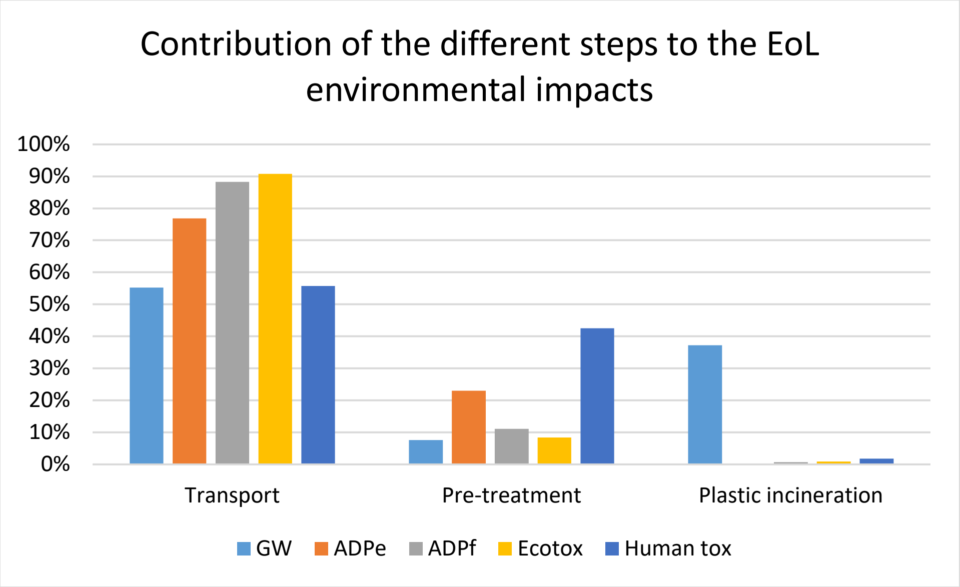

Figure 4-11: Environmental impact share for EoL, for the baseline scenario (and thus not including in scope the recycling impacts). Bars represent the contribution of each EoL step to the total of each impact category.

Table 4-10: Environmental impacts of end of life phase

Impact category name	Total	Transport	Pre-treatment	Plastic incineration
Total emissions [kg CO_2-eq.]	9,45E-02	5,22E-02	7,14E-03	3,52E-02
Air craft emissions [kg CO_2-eq.]	1,82E-09	1,61E-09	0,00E+00	2,18E-10
Biogenic GHG emissions [kg CO_2-eq.]	7,30E-04	5,27E-04	1,55E-04	4,85E-05

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[9] Although the dataset is old and might be outdated in this regard, there is also reason to think that particulate matter emissions during shredding may still be an issue (e.g. piece of news on this topic from 2021 as in https://ehsdailyadvisor.blr.com/2021/09/limiting-air-emissions-from-scrap-metal-recycling/)

Biogenic GHG removal [kg CO_2-eq.]	-8,07E-04	-5,33E-04	-2,28E-04	-4,65E-05
Emissions from land use change [kg CO_2-eq.]	1,34E-05	6,71E-07	1,26E-05	9,17E-08
Fossil GHG emissions [kg CO_2-eq.]	9,45E-02	5,22E-02	7,20E-03	3,52E-02
Abiotic depletion elements [Kg Sb eq.]	1,60E-07	1,23E-07	3,66E-08	2,74E-10
Abiotic depletion fossil [MJ]	8,96E-01	7,91E-01	9,92E-02	5,71E-03
Freshwater ecotoxicity [CTUe]	2,88E-01	2,62E-01	2,42E-02	2,47E-03
Human toxicity potential [kg DCB eq.]	1,78E-02	9,91E-03	7,57E-03	3,15E-04

4.3.5

Modularity overhead

In section 3.1.14 above, the modelling approach for the modularity overhead is explained. In Figure 4-12 below the share of the final impact that can be allocated to the modularity overhead is shown. It can be seen that the additional connectors contribute very significantly to the ADP elements. While smaller board-to-board connectors have a more modest ADP impact, the necessary additional USB connectors in this case drive this impact category, because they use more metals due to their bigger size.

The rest of impact categories related to the modular design show to be less relevant: GW represents 4% of the total, Human toxicity 6% and Ecotoxicity 15%, this last one mostly related to the metals required for the fittings and magnets added to the headband cover.

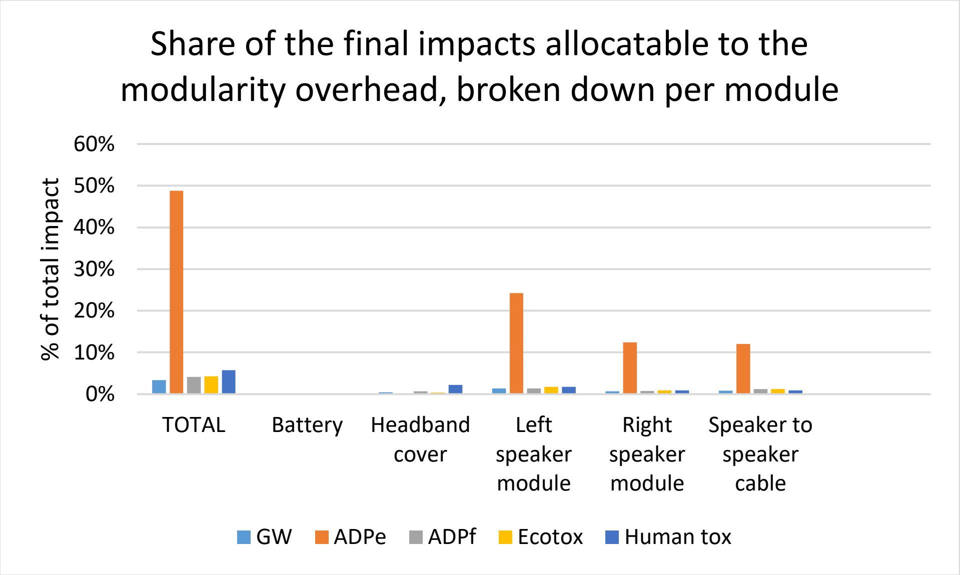

Figure 4-12: Modularity overhead. The bars represent the share of the total life cycle value for each impact category.

Table 4-11: Environmental impacts of modularity

Impact category name	Total modularity overhead	Battery	Headband cover	Left speaker module	Right speaker module	Speaker to speaker cable
Total emissions [kg CO_2-eq.]	2,30E-01	3,34E-03	2,97E-02	9,30E-02	4,76E-02	5,68E-02
Air craft emissions [kg CO_2-eq.]	4,59E-08	0,00E+00	1,87E-09	2,08E-08	1,07E-08	1,25E-08
Biogenic GHG emissions [kg CO_2-eq.]	2,66E-02	1,44E-05	1,34E-03	1,23E-02	6,30E-03	6,66E-03
Biogenic GHG removal [kg CO_2-eq.]	-2,57E-02	-1,99E-05	-1,19E-03	-1,19E-02	-6,11E-03	-6,42E-03
Emissions from land use change [kg CO_2-eq.]	4,54E-04	4,31E-07	2,50E-05	2,13E-04	1,08E-04	1,08E-04
Fossil GHG emissions [kg CO_2-eq.]	2,29E-01	3,35E-03	2,95E-02	9,24E-02	4,73E-02	5,64E-02
Abiotic depletion elements [Kg Sb eq.]	3,63E-04	9,04E-09	3,46E-07	1,80E-04	9,24E-05	8,97E-05
Abiotic depletion fossil [MJ]	3,37E+00	1,37E-01	5,40E-01	1,14E+00	5,85E-01	9,62E-01
Freshwater ecotoxicity [CTUe]	2,45E+00	3,61E-02	1,95E-01	1,01E+00	5,15E-01	6,95E-01
Human toxicity potential [kg DCB eq.]	1,29E-01	1,56E-03	4,93E-02	3,87E-02	1,97E-02	1,98E-02

4.3.6 Accessories

The accessories of the FairBuds XL are the travel pouch (made of recycled polyester) and the audio adapter. None of these are sold with the product and thus are not considered in the results shown above and are instead presented in this separate section. Table 4-12 below shows a summary of the results.

Table 4-12: Summary of environmental impacts of accessories, including the % of the total production impacts of the FairBuds XL (baseline scenario)

Impact category name	Audio adapter cable	Travel pouch	% of total impacts
Total emissions [kg CO_2-eq.]	3,01E-04	8,37E-09	41%
Air craft emissions [kg CO_2-eq.]	1,96E+00	1,55E+00	5%
Biogenic GHG emissions [kg CO_2-eq.]	1,46E-01	1,39E-02	9%

Biogenic GHG removal [kg CO_2-eq.]	3,51E-08	4,35E-08	0%
Emissions from land use change [kg CO_2-eq.]	2,04E-02	5,24E-03	8%
Fossil GHG emissions [kg CO_2-eq.]	-1,98E-02	-5,31E-03	8%
Abiotic depletion elements [Kg Sb eq.]	3,42E-04	9,75E-05	9%
Abiotic depletion fossil [MJ]	1,57E-01	1,55E-01	6%
Freshwater ecotoxicity [CTUe]	1,58E-01	1,55E-01	6%
Human toxicity potential [kg DCB eq.]	1,73E+00	2,29E-01	4%

In all impact categories the cable shows higher impacts, since it consists of more environmentally relevant materials (connectors, cable). It can also be seen that for ADP elements, the impacts are considerably high as when compared with the FairBuds XL production impacts, mostly because connectors drive this impact category very clearly and this piece consists of basically a cable and two connectors. For the rest of impact categories, the values are rather low, always below 10% of the production of the FairBuds XL.

4.4
Repair and environmental payback time

The modular design of the headphones allows for reparability. As outlined in Section 3.5, no primary data on failure statistics exists and therefore the analysis here will be limited to the analysis of the repair strategies at a module level and the visualization through the theoretical environmental payback time of the potential benefits of repair. For simplicity, the analysis in the report focuses on global warming.

4.4.1
Replacement vs repair

For this analysis, two strategies are compared: replacement (replacing the entire faulty module) and repair (replacing only the faulty component, keeping the rest of the module intact). In some modules, for example, the right speaker; many components could potentially benefit from board level repair. For the calculations, the component with the highest emissions has been chosen, for the modules with several potentially replaceable components. Figure *4-13* shows an overview of the comparison.

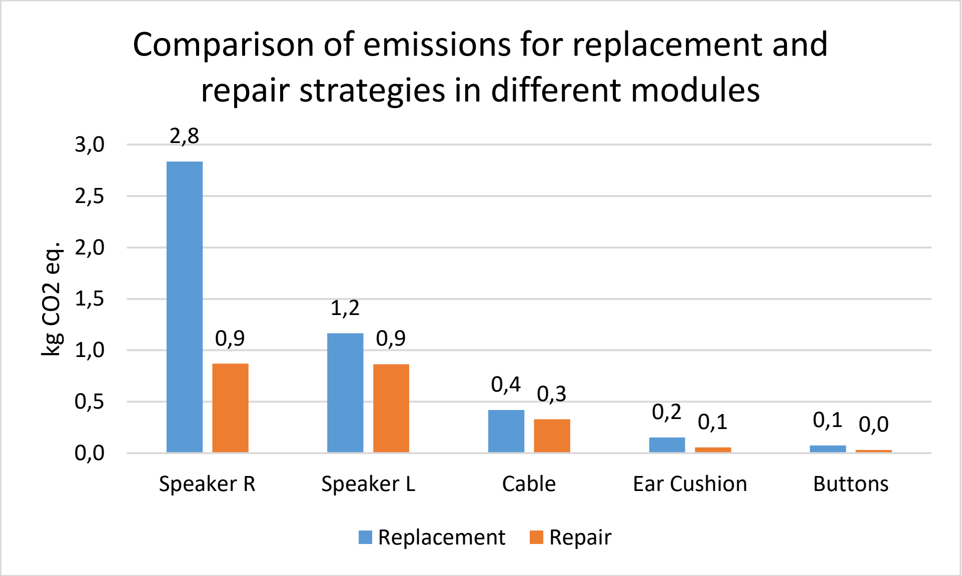

Figure 4-13: GW100 values per module repair strategy, replacement vs repair. Bars represent the total emissions for the repair scenario of each module, which includes additional packaging, necessary transport and the production of the spare part or spare component.

As can be seen, the speaker right module shows the greatest potential benefits for repair over replacement, which becomes less relevant for other modules. This is related with the observation made earlier in the general results that production impacts are mostly driven by the electronics production, which are most prominently housed in the right speaker. Therefore, being able to keep these in use (more importantly the mainboard) is greatly beneficial compared to discarding all the electronics. For other modules with lower share of electronics (or none at all), the difference of both strategies from an emissions point of view is limited or negligible.

4.4.2
Environmental payback time

In order to assess the general benefits of repair (both module replacement and module repair), the environmental payback time is estimated (for more on how it is done, see Section 3.5 or (Sánchez, Proske, & Baur, 2022)). Figure *4-14*, *Figure 4-15* and Figure *4-16* show the yearly impact evolution curves for the baseline and the different repair strategies.

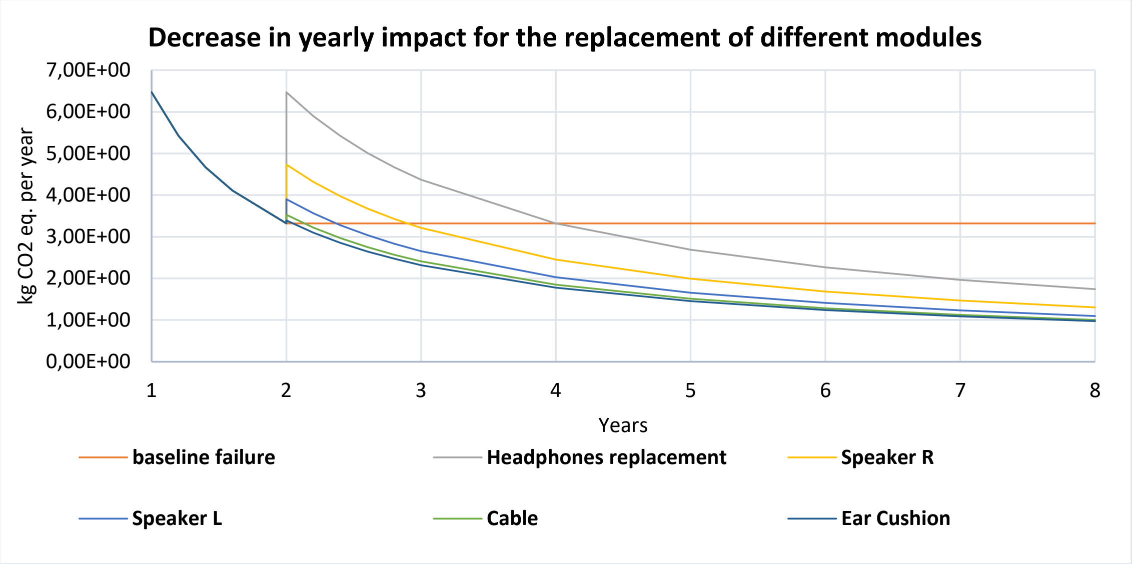

Figure 4-14: Curves representing the decreasing yearly impacts estimated for the FairBuds XL for different repair scenarios and a baseline scenario with no repair. The failure is assumed to happen at the second year in all repair scenarios, in which the faulty module is replaced (reflected in the jump in emissions). At the point in time where the repair line intersects the yearly impacts at the moment of failure (horizontal line), it is assumed that the repair paid off.

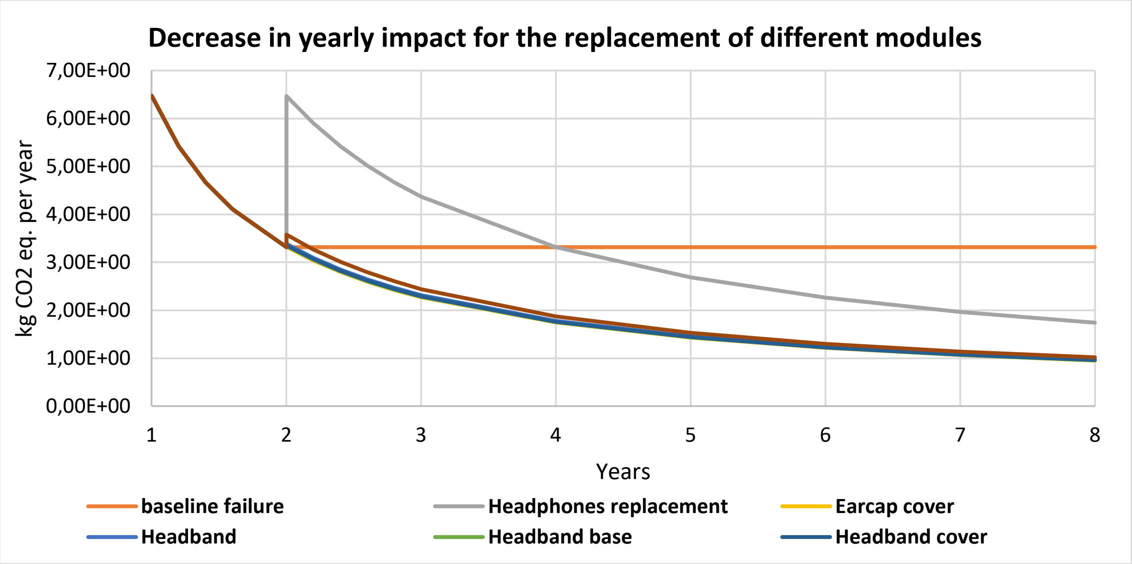

Figure 4-15: Figure includes the modules not seen in the figure above.

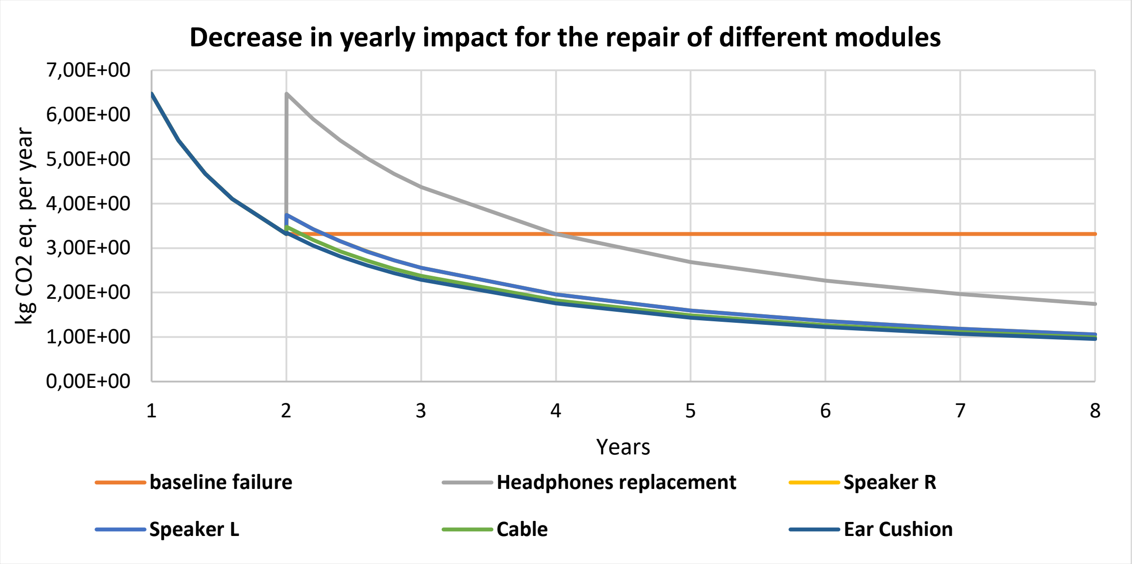

Figure 4-16: Curves representing the decreasing yearly impacts estimated for the FairBuds XL for different repair scenarios and a baseline scenario with no repair. The failure is assumed to happen at the second year in all repair scenarios, in which the faulty module is repaired at a board level (reflected in the jump in emissions). At the point in time where the repair line intersects the yearly impacts at the moment of failure (horizontal line), it is assumed that the repair *paid off*.

In all graphics the grey line represents the worst case i.e. the replacement of the whole device after failure (assumed to happen in the 2nd year of use). The best case then would be represented by baseline per year of use or, in other words, uninterrupted use with no replacement. Whenever the failure happens and a repair is made, there is a jump in the environmental impact which represents the additional efforts made to produce and ship the new parts (or entire device). The intersection with the baseline failure then represents the moment in time when the theoretical yearly impacts fall back to the level at the moment of failure, thus representing the extended use time needed to virtually pay off the repair effort. Table 4-13 shows the calculated values[10].

Table 4-13: Environmental payback times

	Replacement	*Repair*
Full device	2 years	-
Speaker right	~1 year	3 months
Speaker left	4 months	3 months
Speaker to speaker cable	1 month	1 month
Ear cushion	1 month	4 days
Earcap cover	~1 day	-
Headband	13 days	-
Headband base	3 days	-

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[10] Please keep in mind that this payback time is a theoretical value based on the assumption that the yearly impacts decrease with longer use, since the longer a product is used, the less impact in total is to be attributed to each year. In reality however, the impacts of this product do not map homogeneously in time e.g. the production impacts all happen in the beginning of its life and the EoL impacts at the end.

Headband cover	15 days	-
Battery	2 months	-

From the table it can be seen, firstly, that repair always shows benefits from the environmental point of view when compared with direct replacement of the entire device. The smaller parts show the greatest benefits but even the most electronics-intensive modules show significant benefits. As for repair and replacement, as seen in the previous sub-section, the right speaker module shows the most potential for the board level repair, while in the rest of cases the benefit of this approach is limited.

4.5
Sensitivity Analysis and Interpretation

4.5.1
Allocation approaches

As explained in Section 3.6, the baseline scenario uses a simple cut-off allocation approach where the impacts of extraction of the recycled content in the product are considered, whereas the impacts of recycling material from the headphones in their EoL is understood to belong to the product where those materials will be used. However, the simple cut-off approach can also be understood inversely. Furthermore, unlike the procedure followed in the Fairphone 4 LCA (Sánchez, Proske, & Baur, 2022), in this case no credits are given since the reuse of plastics can’t be argued to be closed loop.

In this section, a comparison between the baseline approach to allocation and possible alternatives is performed, in order to better understand what effect this has in the results presented above. The scenarios analysed in this section are the following:

- Baseline allocation, no credits. In the baseline allocation, the impacts associated with the extraction of the recycled materials from their previous life cycle are allocated to the headphones, while the effort needed to recycle materials at their end of life is out of scope. This allocation procedure, also known as cut-off allocation, is allowed by both ISO 14044 and ISO 14067 (under the case of open-loop systems) and recommended by other guidelines such as the International EPD system, PAS 2050 or the Greenhouse Gas Protocol according to (Ekvall, et al., 2020).
- Alternative allocation, no credits. As an inverse interpretation of the baseline, the recycled content of the headphones is considered *free of burden* (i.e. the impacts associated with their extraction from the previous product are considered to be allocated to that product) and the efforts needed to recycle materials on the end of life of the headphones are allocated this time to the headphones.
- Baseline allocation, credits. Same as the baseline allocation, but in this scenario, credits are given to this product for the avoided disposal (incineration) of the materials that the headphones are effectively reusing.
- Alternative allocation, credits. Same as the alternative scenario but in this case, credits are given for the avoided production of primary materials thanks to the recovery (recycling) performed at the end of life of this product.

The Figure 4-17 shows how the different allocation scenarios compare for the different impact categories. For global warming there is only minor differences between scenarios, with the alternative scenario being the highest (1% higher than the baseline) and the alternative scenario with credits for avoided production being the lowest (3% lower). ADP elements shows a similar situation with only a slightly higher difference for the alternative scenario with credits (6% lower than baseline). ADP fossil shows even higher uniformity. For ecotoxicity, the alternative scenarios, both with and without credits are shown to be lower (4% and 19% respectively) mainly due to the plastics: in the alternative scenario recycled content including plastics comes in *burden free* (meaning that the recovery impacts are allocated to the previous product and not the headphones). Furthermore, in the alternative scenario with credits, the avoided production of the plastic recovered at the EoL is credited. The opposite is true for human toxicity, where the addition of further metal recycling steps into the scope increases the toxicity connected to metal particles emissions to air (Ecoinvent, 2009). The impact distribution for EoL is shown in Figure 4-18.

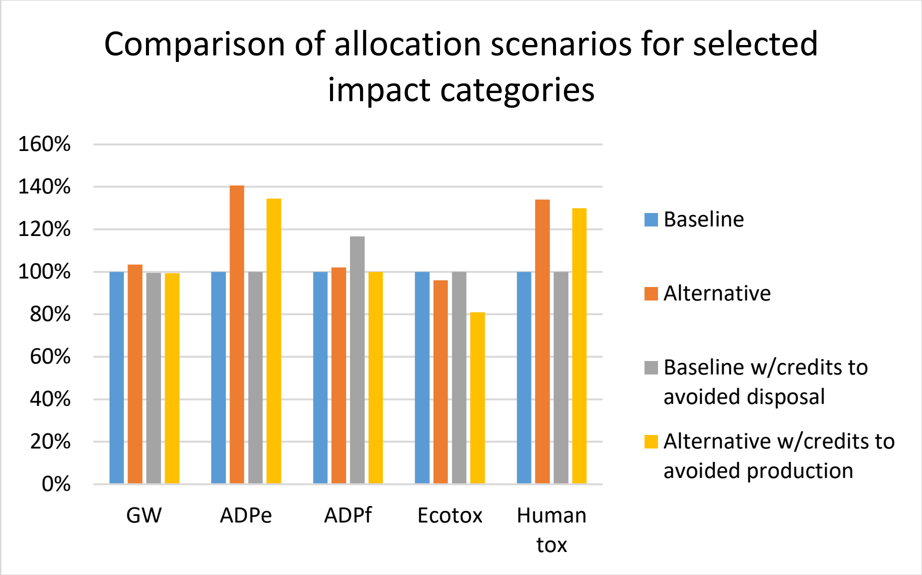

Figure 4-17: Comparison of environmental impacts for different allocation approaches. Baseline scenario used as reference (always 100%) and the rest shown in relation to it (100% meaning same or very similar value).

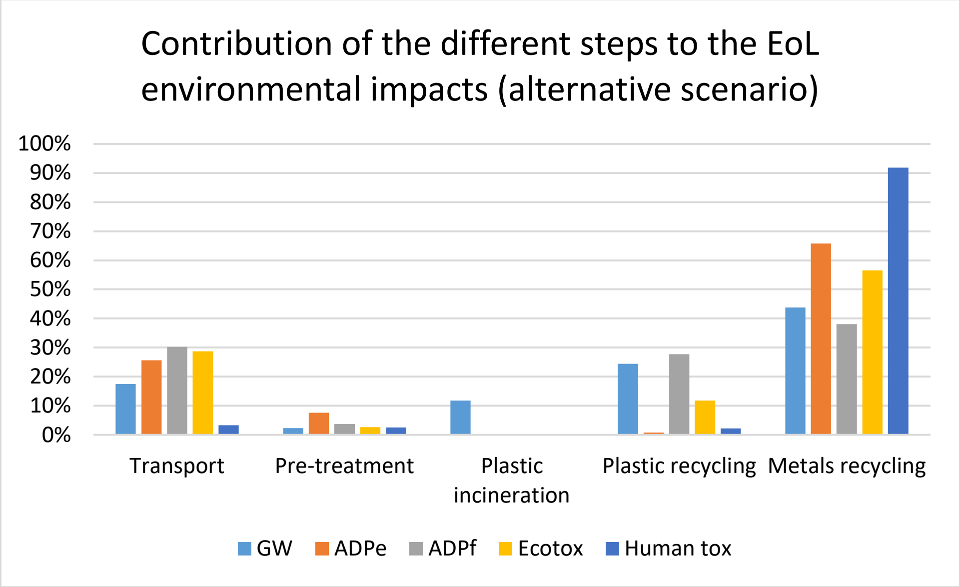

Figure 4-18: EoL impacts distribution, alternative allocation scenario. In this scenario, the scope includes the recycling impacts, for both plastic and metal fraction.

Figure *4-19* shows the distribution of impacts per life cycle phase for the alternative allocation scenario (also without credits for avoided production or disposal). In this scenario the main environmental hotspots do not change from the baseline (see *Figure* 4-1) and remains in production, although for some categories human toxicity and in a minor scale global warming, a slight increase in the share for EoL can be seen.

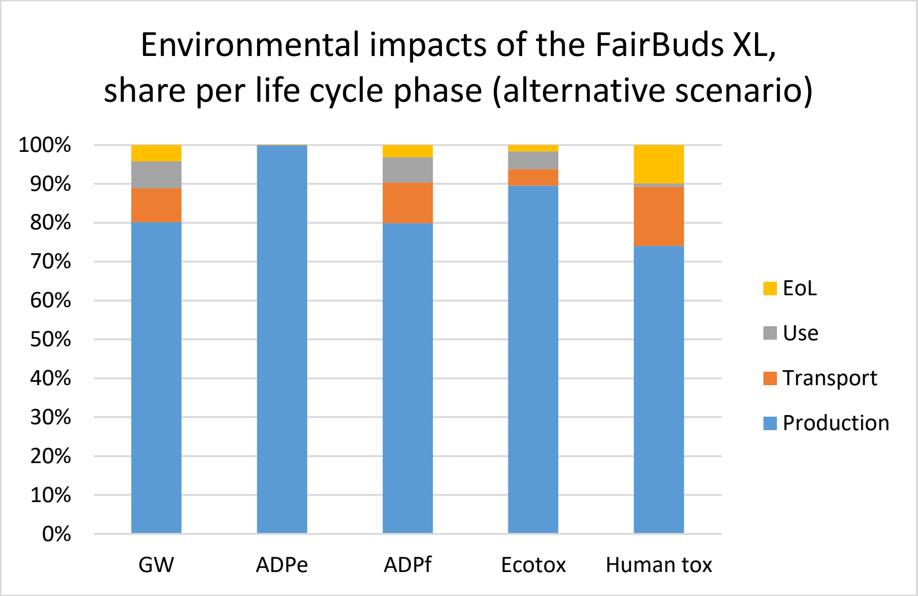

Figure 4-19: Environmental impacts distribution, alternative allocation scenario i.e. including recycling impacts but not the recovery impacts for the secondary material in the product

Table 4-14: Environmental impacts per life cycle phase, alternative allocation scenario

Impact category name	Total	Production	Distribution	Use	EoL
Total emissions [kg CO_2-eq.]	7,03E+00	5,63E+00	6,12E-01	4,88E-01	2,97E-01
Air craft emissions [kg CO_2-eq.]	6,91E-01	5,07E-01	1,03E-03	1,77E-01	5,37E-03
Biogenic GHG emissions [kg CO_2-eq.]	-6,69E-01	-4,93E-01	-8,77E-04	-1,71E-01	-4,15E-03
Biogenic GHG removal [kg CO_2-eq.]	6,00E-03	5,72E-03	7,29E-05	6,97E-05	1,39E-04
Emissions from land use change [kg CO_2-eq.]	7,00E+00	5,61E+00	6,12E-01	4,82E-01	2,96E-01
Fossil GHG emissions [kg CO_2-eq.]	6,91E-01	5,07E-01	1,03E-03	1,77E-01	5,37E-03
Abiotic depletion elements [Kg Sb eq.]	1,05E-03	1,04E-03	1,77E-07	1,28E-07	4,77E-07
Abiotic depletion fossil [MJ]	8,34E+01	6,67E+01	8,75E+00	5,41E+00	2,61E+00
Freshwater ecotoxicity [CTUe]	5,50E+01	4,93E+01	2,32E+00	2,52E+00	9,11E-01
Human toxicity potential [kg DCB eq.]	3,00E+00	2,22E+00	4,59E-01	2,31E-02	2,97E-01

For categories like global warming, not much change is observed for different allocation procedures overall. While the EoL part of the emissions does indeed increase (doubling up from the baseline case to the alternative case), the production related emissions decrease in a similar amount, due to the fact that the recycled content is considered burden free in the alternative allocation approach. This can easily be seen in Figure *4-20*.

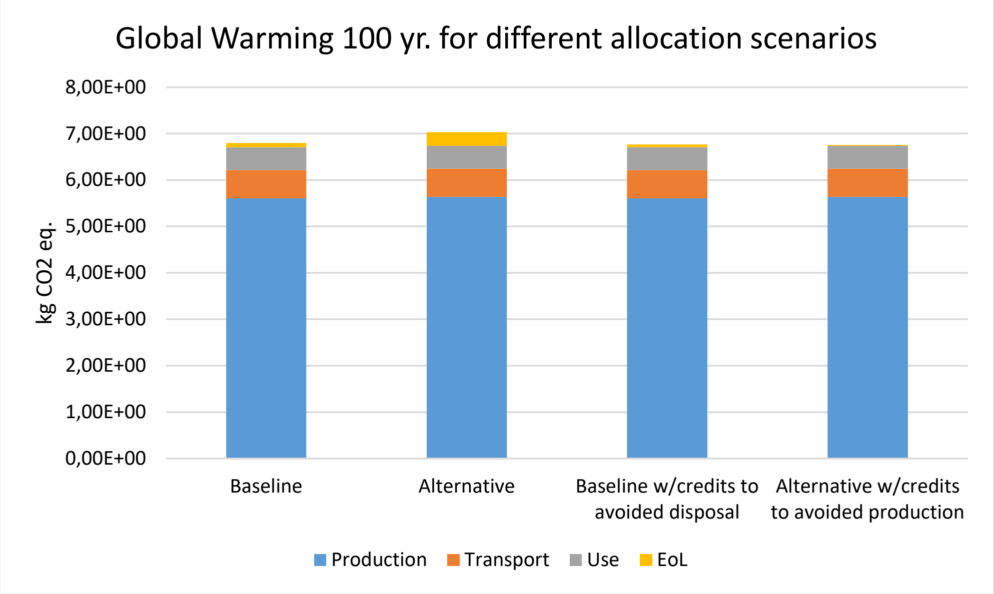

Figure 4-20: GW100 across allocation approaches: baseline scenario (no credits), alternative scenario (no credits), baseline scenario with credits to avoided disposal and alternative scenario with credits to avoided production.

In this product, different materials are reused and can be recovered. Mostly PC is included as recycled material in the device and at its end-of-life mostly metals (precious metals most relevantly) are recovered. This is why the effects of the chosen system boundaries and allocation rules have differing effects across the different impact categories. From the figures above it may seem that the recycling (considered in the alternative allocation scenario) only adds impact and has little benefit. However, when comparing the scenario with a simplified *worst case EoL* scenario (see Figure *4-21*) where the plastics, the electronics, and metals of the device are altogether incinerated, the benefits of recycling become visible. Furthermore, the credits for avoided disposal and production can also be seen. Thus, although recycling does add extra efforts and associated impacts, it still has environmental benefits.

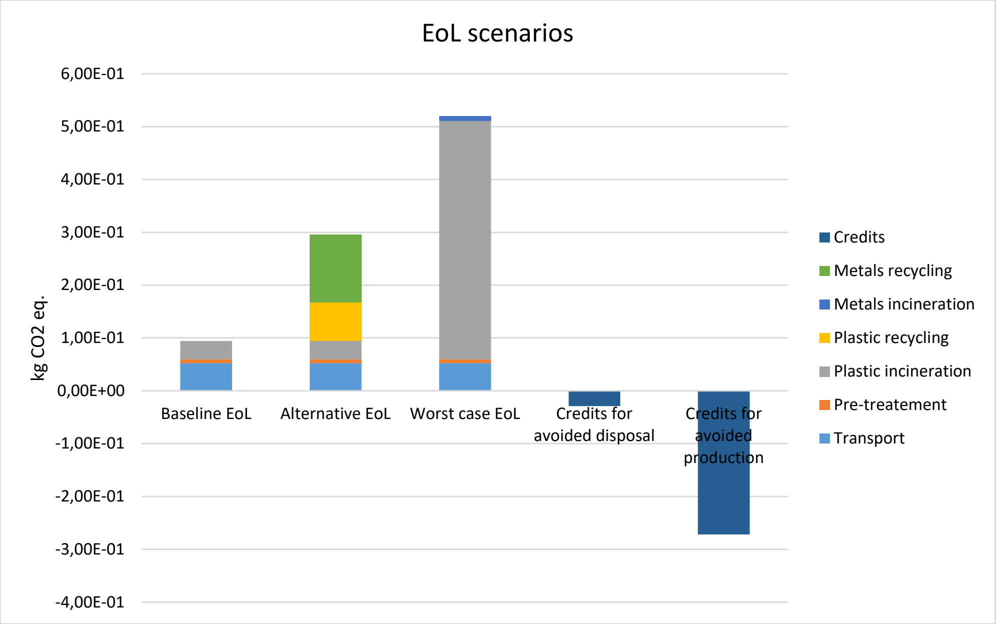

Figure 4-21: EoL comparison across allocation approaches*. A worst case scenario is included as a reference, in order to visualize the potential benefits of recycling. Both credits to avoided disposal and avoided production are shown separately, being negative as they represent environmental benefits i.e. they represent avoided damage.*

4.5.2 Use of primary material

In this section of the sensitivity analysis, an alternate scenario is built where all the recycled content of the device is replaced by primary material. The comparison for the total results can be seen in the Figure *4-22*. As it can be seen, the potential benefits of using secondary materials vary depending on the impact category.

For ADP elements for example, the difference is negligible (the primary materials scenario is not even 1% higher). As for the latest update of the ADPe model used in this LCA (van Oers, Guinée, & Heijungs, 2020), the key contributor is gold, with almost a 73% share of the total for the category, followed by copper (7,9%) and silver (3,8%). These elements are not amongst the recycled materials in the FairBuds XL and thus this impact category does not show significant change.

For global warming and ADP fossil, the difference is more visible, 10% and 17% respectively (% of increase in the primary materials scenario).

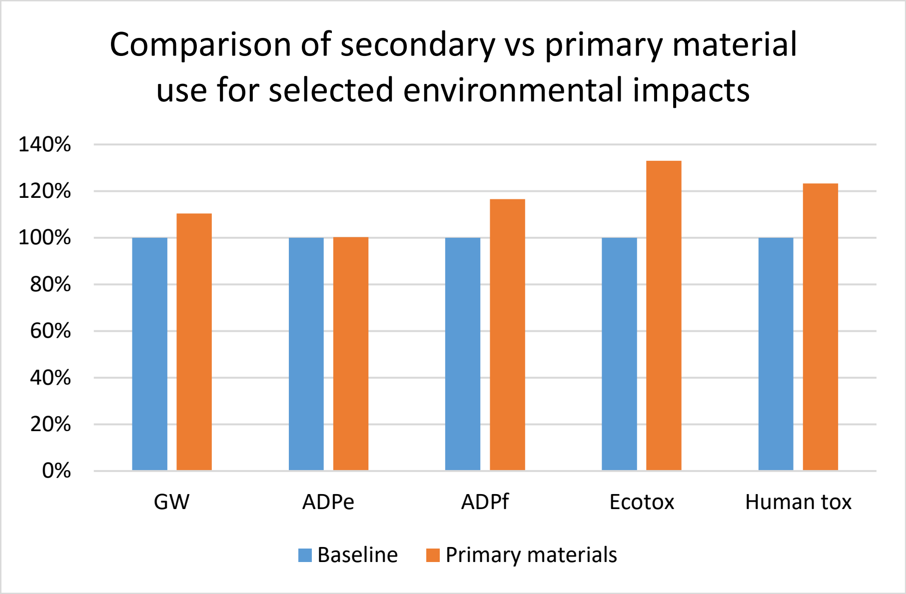

Figure 4-22: Recycled content vs primary content for the entire life cycle, various impact categories. Baseline scenario incl. secondary material is used as a reference and the primary materials scenario is then shown in relation to it.

The sources of the increase of emissions can be seen in *Figure* 4-23 below, which shows that they are evenly distributed across all modules using secondary materials.

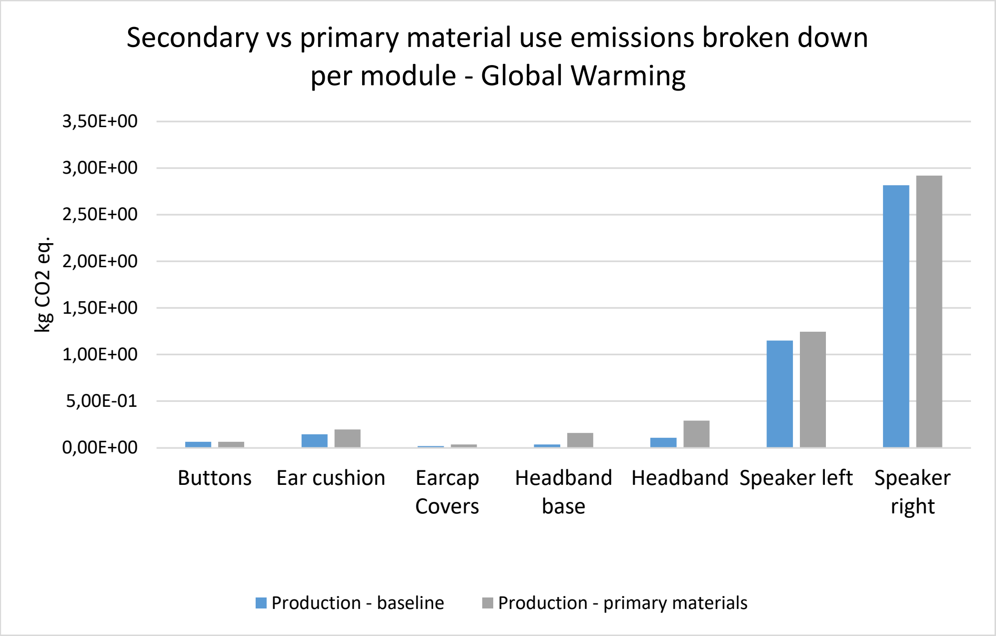

Figure 4-23: Emissions comparison for production, recycled content vs primary content

The impact categories that show the biggest increase when employing fully primary materials are both ecotoxicity (33% higher) and human toxicity (23% higher). Ecotoxicity is mostly related to the reduced toxicity of secondary polycarbonate while human toxicity is mainly driven by the use of secondary aluminium. This can be better seen in Figure 4-24 and Figure 4-25 below, where it can be seen that the ecotoxicity impacts are reduced more in modules where secondary plastic is more prominently used. In the case of human toxicity however, most of the reduction comes from modules where secondary metal parts are used.

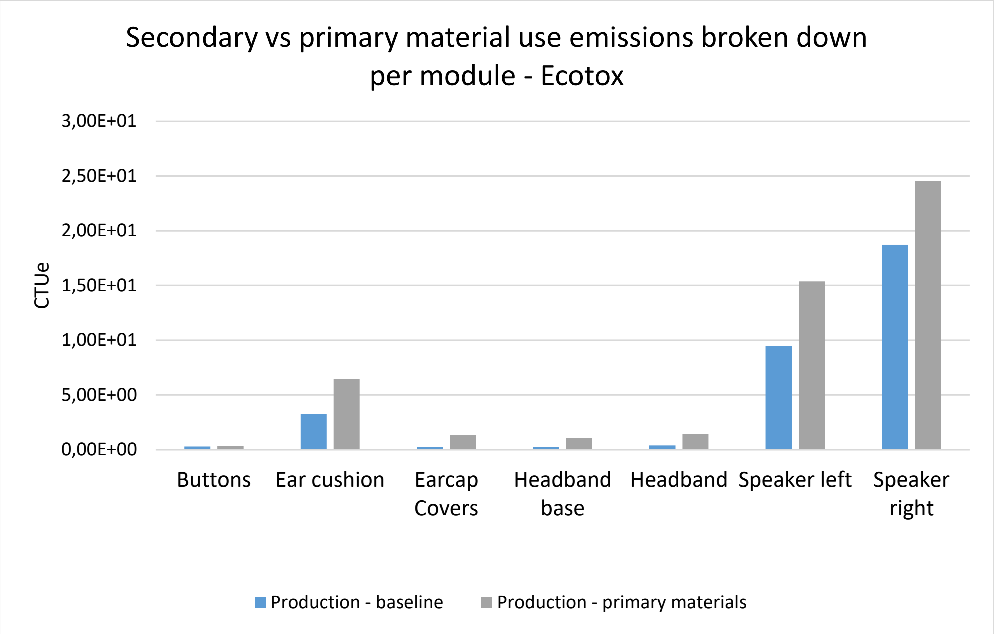

Figure 4-24: Ecotoxicity comparison between secondary material use and primary material use, for modules where recycled content is present

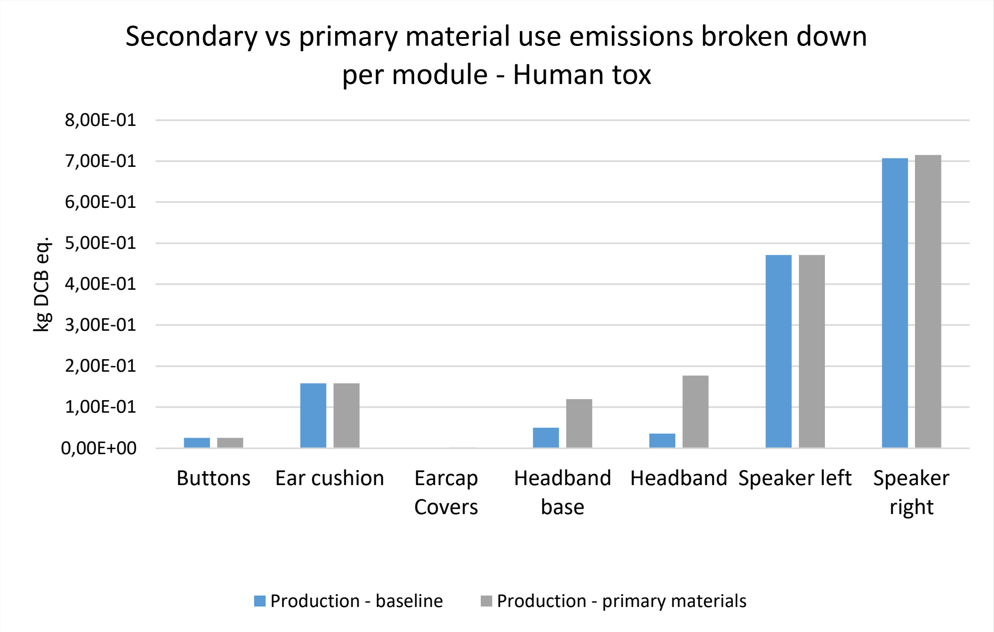

Figure 4-25: Human toxicity comparison between secondary material use and primary material use, for modules where recycled content is present

Table 4-15: Environmental impacts per life cycle phase, primary materials use scenario

Impact category name	**Total**	**Production**	**Distribution**	**Use**	**EoL**
Total emissions [kg CO_2-eq.]	7,51E+00	6,32E+00	6,12E-01	4,88E-01	9,45E-02

Air craft emissions [kg CO_2-eq.]	1,50E-03	1,50E-03	0,00E+00	7,74E-07	1,82E-09
Biogenic GHG emissions [kg CO_2-eq.]	7,26E-01	5,48E-01	1,03E-03	1,77E-01	7,30E-04
Biogenic GHG removal [kg CO_2-eq.]	-7,02E-01	-5,30E-01	-8,77E-04	-1,71E-01	-8,07E-04
Emissions from land use change [kg CO_2-eq.]	5,69E-03	5,54E-03	7,29E-05	6,97E-05	1,34E-05
Fossil GHG emissions [kg CO_2-eq.]	7,48E+00	6,29E+00	6,12E-01	4,82E-01	9,45E-02
Abiotic depletion elements [Kg Sb eq.]	7,46E-04	7,45E-04	1,77E-07	1,28E-07	1,60E-07
Abiotic depletion fossil [MJ]	9,53E+01	8,03E+01	8,75E+00	5,41E+00	8,96E-01
Freshwater ecotoxicity [CTUe]	7,63E+01	7,05E+01	2,32E+00	2,52E+00	9,11E-01
Human toxicity potential [kg DCB eq.]	2,76E+00	2,26E+00	4,59E-01	2,31E-02	1,78E-02

5

Conclusions and Recommendations

Similarly to the previously for Fairphone B.V. conducted smartphone LCAs, electronics drive most impact categories for the FairBuds XL. More specifically, PCBs and the main ICs are the most relevant components from an environmental standpoint. For a device like this, however, which in comparison with the Fairphone uses less electronics and bigger housing, toxicity related aspects of the battery, plastics and metals gain some significance.

In any case all impact categories are clearly production driven which proves the environmental benefits of repair, more so in this product which is less energy intensive than the smartphones of Fairphone. Compared to the Fairphone smartphones however, board level repair seems only partially more beneficial than module replacement in this case due to its lower environmental impact.

When comparing the current use of secondary materials with the use of exclusively primary materials, the benefits can be seen. While the reduction in GHG emissions is clear although limited (10% lower with the use of secondary materials), the reduction of toxicity related indicators is much more significant (20%-30%), relating to both recycling of plastics (mostly ecotoxicity) and metals (mostly human toxicity). On the other hand, recycling of metals at the EoL proves significant benefits also for ADP elements which can better be seen with a different allocation method (applied in the sensitivity analysis), the credits for avoided production, although it also shows a certain increase in environmental impacts of the EoL, more importantly regarding human toxicity.

Distribution plays a less central role in the final impacts but is still dominated mostly by air transport, despite this not being the main way in which Fairphone B.V. ships its products. This reinforces once again the relevance of air shipping in the logistics related impacts. The headphones are not an intensively energy using product and thus the use phase also plays a minor role. The scenario analysis however has revealed that use intensity does have an impact on this, with a lower intensity use having the potential of reducing the use associated emissions to less than half, which suggests that improvements in energy efficiency may have a limited impact but still make sense.

The modularity overhead of the headphones is very significant for ADP elements due to the fact that it needs several USB-C connectors that would otherwise not be necessary and since the FairBuds do not use as much electronics as e.g. the Fairphone 4, these stand out more in the impact distribution. These impacts are however paid off if the device is in fact repaired and its lifetime effectively extended, as the scenario analyses have shown.

Furthermore, the use of alternative scenarios has proven a good tool of getting a measure of the benefits of secondary material recovery. Firstly, the baseline allocation method disregards impacts related to recycling, reducing the relevance of EoL in the analysis. Secondly, the alternative method doesn’t give much information on which materials are more environmentally interesting to reuse, since all get into scope equally burden free. Thirdly, in their open loop versions i.e. with no credits from past or upcoming life cycles, both allocation methods show the risk of not sufficiently or clearly showing the benefits of both use of recycled materials and recycling of materials. Since ISO requirements also set some guidelines for allocation choices, when moving forward adding a 50/50 approach to the sensitivity analysis may be a good way to capture better the overall picture.

In terms of data availability and provision, Fairphone B.V. continues with the good work developed until now by providing extensive BoM and material data from their suppliers. The same can be said for distribution. As for use data, in this case its contribution is limited and therefore the employed assumptions are deemed representative enough. A key aspect where more and better data would be of assistance is the EoL modelling. Currently it is not possible to track what actually happens with discarded products and existing literature data is scarce and oftentimes it is not fully clear to what extent the estimations and best practices described in literature are met. Thus, building a truly representative EoL model that doesn’t unfairly punish the results but that is also not too optimistic is complicated. The results of this LCA show that the EoL can have significant impacts and is a relevant part of the life cycle, thus meriting for more clarity and research.

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