Chapter 2
The Climate Impact of the Usage of Headphones and Headsets

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Abstract Based on disassembly studies, a life cycle assessment of the climate impact of the wireless over-ear headphone model Jabra Evolve2 85 (without charging station) is conducted regarding the life cycle phases of manufacturing, packaging, distribution, use and disposal. The total weight of all components is 280.7 g. The materials can be categorized into polymers (61.7%), metals (20.9%), circuit boards (4.8%), Li-ion battery (4.6%), foam (3.5%), cables (3.0%) and unidentifiable polymers (1.7%). The functional unit is defined as the wireless audio transmission through a stereo headphone over its lifetime. The lifecycle assessment results in a global warming potential of 12.17 kg CO_2-Eq with a contribution of the manufacturing phase of 81.2%, based on an assumed lifetime of 2,600 using hours. In the context of a sensitivity analysis, a repair scenario of a battery replacement of the over-ear headset is modelled. Assuming a doubled lifetime, the global warming potential per hour is reduced from 4.7 g CO_2-Eq/h to 2.4 g CO_2-Eq/h.

Keywords LCA · Headphones · Dismantling · Life cycle data inventory

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2.1 Introduction

Headphones are electronic devices worn on the head to transmit sound to human ears both in the business world and for private usage. They facilitate peoples' lives as they, for example, allow having calls or listening to music anywhere at any time without disturbing the environment. The usage of headphones is increasing: In 2020, around 15.5 million headphones were sold in Germany, an increase of 6.8% compared to 2019 (gfu Consumer & Home Electronics GmbH and Growth from Knowledge 2020).

GN Store Nord A/S is an international company based in Denmark which provides hearing, audio, and collaboration solutions under the brand name "Jabra". Their sustainability targets include goals referring to the sustainability of their products, packaging, manufacturing, and distribution (GN Audio A/S 2020a). In 2020, the trade-in-system "Jabra Green Initiative – Recycle and Benefit" started in collaboration with the German company TechProtect GmbH (GN Audio A/S n.d.a), a company that offers marketing integrated services and take back solutions. In this context, Pforzheim University students analyzed the environmental impact of one Jabra headphone model in cooperation with these two companies. The goal of this work was to identify the components and materials of this particular headphone model, the Jabra Evolve2 85 (28599-989-999), and to assess its climate impact measured as contribution to the global warming potential. To achieve this goal, dismantling trials were conducted, followed by a life cycle assessment including a sensitivity analysis with a repair scenario.

2.2 Background

2.2.1 Headphones' Components and Materials

The main elements of cordless headphones are the ear pads, ear cases, main circuit boards, speakers, the microphone arm, the headband, and the battery, displayed in Fig. 2.1.

The product data sheet of the Jabra Evolve2 85 (GN Audio A/S 2020b) and ten additional data sheets of selected current cordless on-ear and over-ear headphone models were identified in an online search. In order to provide some benchmark information and to verify the Jabra Evolve2 85 as a representative product, a comparison was conducted. For this purpose, all available information of the products' data sheets covering type of headphone, weight, components, materials, battery, microphones, and speakers were compiled. The products' data sheets of the following comparable headphone models were considered: Jabra Evolve 65 (GN Audio A/S 2020c), Jabra Elite 85 h (GN Audio A/S 2019), Poly Voyager 4200 Office & UC (Plantronics Inc. 2021), Logitech Zone Wireless (Logitech n.d.), JBL Live650BTNC (Harman International Industries Inc. 2019), Sony WH-1000XM3 (Sony Europe

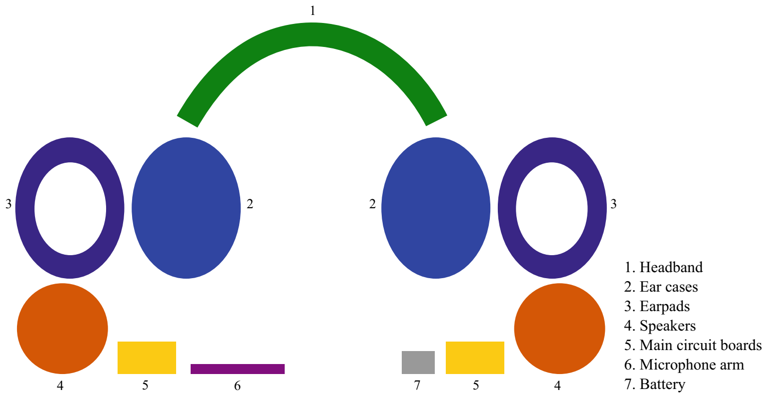

Fig. 2.1 Main components of a cordless headphone (schematic)

B.V. n.d.), ATH-M50xBT (audio-technica n.d.), Teufel Supreme on (Lautsprecher Teufel GmbH n.d.), B&O Beoplay H9 3rd gen (Bang & Olufsen n.d.), Panasonic RP-HD610N (Panasonic Deutschland n.d.).

The range of the stated weight is between 150 and 310 g. The stated weight of eight products is higher than 250 g, including the Jabra Evolve2 85 with 286 g. In the selected products, the loudspeaker housing consists of stainless steel, aluminum, and polymers. The headband is often covered in foam and wrapped with fabric or synthetic leather. The same materials can be found in the ear cushions. If specified, the battery is a lithium-ion-battery or a lithium-polymer-battery. This applies for the assessed product and seven additional products. Three different microphone types can be found: microelectromechanical systems (MEMS), electret condenser microphones (ECM), and condenser microphones. The assessed headphone contains 4 analogue MEMS (microelectromechanical systems) microphones and 6 digital MEMS microphones. In at least five of the eleven headphones, electrodynamic speakers are installed. In the other products' data sheets, the type of speakers is not specified, including the Jabra Evolve2 85. The speaker's diameter is stated in all product data sheets and ranges between 28 and 45 mm. The speakers' diameter of the assessed product is 40 mm.

2.2.2 *Expected Lifetime of Components and Headphone*

The lifetime of rechargeable lithium-ion-batteries can be measured and stated in two ways:

1. calendrical lifetime (time, for example in years, until the battery has a certain capacity left, e.g. 80% of the nominal capacity) and

2. cycle lifetime (number of charging cycles until the battery has a certain capacity left, e.g. 80% of the nominal capacity) (Job 2020).

An average battery provides approximately 500–1000 charging cycles until it loses 20% of its capacity (Korthauer 2013). In simulations by Maia et al., approximately 400 cycles with optimized charging are observed until a capacity of 80% is reached (Maia et al. 2019). Based on an assumption of a cycle lifetime of 500 cycles and recharging every third day, this would correspond to a calendrical lifetime of 4.1 years. This is in line with other literature (Broussely et al. 2001). According to Schulze and Buchert, a lifetime of 8 years with a standard deviation of 2 years can be assumed for acoustic transducers with neodymium-iron-boron magnets (Schulze and Buchert 2016). The lifetime of the ear pads is depending on material and usage, but the component is considered as rather susceptible to wear due to its position, purpose, and the large offer for spare parts, for example by Jabra (GN Audio A/S n.d.b). In a Swiss case study regarding the service lifetime, storage lifetime, and disposal pathways of electronic equipment, statistical data for several electronic devices, including headsets, were collected. The average service lifetime of already disposed or stored headsets is found to be at 3.3 years (Thiébaud-Müller et al. 2018). In agreement with the producer, a value of 2 years was applied in the life cycle assessment of the model Jabra Evolve2 85, based on the product's warranty time period. According to the manufacturer, a 2,600 using hour lifetime can then be assumed. This value can be justified by the assumption of a product use intensity of five hours per day, five days per week, and the product's warranty time period of two years.

2.3 Methods

Dismantling trials were carried out in the laboratory for sustainable product development at Pforzheim University as a part of a student project in the period from 31/03/2021 to 21/04/2021 by the authors. In total, three headphones Jabra Evolve2 85 (Product No. 28599-989-999) were dismantled which had been supplied by Jabra from product returns. With the first product, the construction, the components, and an appropriate way for dismantling were identified. One of the remaining products was used for the documentation of the single dismantling steps to homogenous material, including the needed time and tools. Conventional workshop tools only were used for this work, listed in Table 2.1.

The dismantling of the third headphone served for the documentation of the components and the development of the bill of materials. For this, the precision scale Kern 573–46 was used. Manufacturer's marks on the polymer parts, X-ray fluorescence analysis (XRF, Thermo Fisher Scientific, Niton XL2 air 980), and attenuated total reflection (ATR, Bruker, Alpha Platinum) analysis were used for material identification. For the ATR analysis, the BPAD.S01 (Brucker Optics ATR-Polymer Library) and Demolib.s01 (General Library IR) data bases were used. All measurements were carried out threefold.

Table 2.1 Tools used for dismantling

No	Tools
1	Screwdriver, crosstip, C.K. precision, N0.0
2	Screwdriver, C.K precision, T5
3	Screwdriver, C.K precision, T6
4	Utility knife, KS Tools
5	Cross-cut chisel, KS Tools, 5 mm
6	Flat chisel, KS Tools, 12 mm
7	Hammer, Projahn, DIN 1041 500
8	Wire cutter, diagonal, KS Tools Ergotorque, 115.1012
9	Pliers, Projahn, ISO 5746
10	Pliers, KS Tools, 115.1024
11	Plastic spatula, Kartell
12	Tweezers

The LCA was following the norm ISO14040, including the definition of the goal and scope, the inventory analysis, the impact assessment, and the interpretation. According to the request of Jabra, it was focused on the environmental impact category climate change. Therefore, the indicator "climate change w/o LT, GWP100" from the group "Midpoint (H) w/o LT" of the ReCiPe Method was applied. A hierarchical perspective (H) was selected which is based on scientific consensus regarding time frame and impact mechanisms (Huijbregts et al. 2017). GWP100 expresses the global warming potential over 100 years (Huijbregts et al. 2017) without long-term emissions taken into account (Ecoinvent 2021). The corresponding unit is kg CO_2-Equivalent.

A hotspot analysis was included to identify the life cycle stages and materials with the highest climate impact. The utilized data was based on the results of the product dismantling trials, especially on the bill of materials, and information provided by the manufacturer. Where necessary, additional assumptions were made, explained and justified in 4.2. Result activities (allocation: cut-off) from the database ecoinvent v3.7.1 were used for the evaluation of the environmental impacts of the background processes.

The wireless audio transmission by a headphone during its total lifetime was chosen as the functional unit. The following reference flow resulted from the functional unit:

- One headphone Jabra Evolve2 85 (28599-989-999)
- 2,600 using hours (2a $\times$ 52 weeks/a $\times$ 5 d/week $\times$ 5 h/d)

It is to be noted that the parameter "using hours" will sincerely influence the result which is why the effect of this parameter was to be re-viewed by a sensitivity analysis regarding a repair scenario.

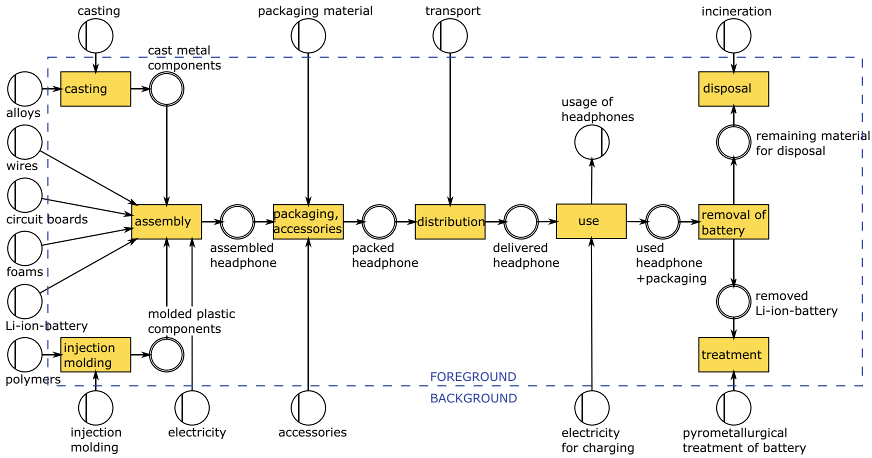

Fig. 2.2 System flow chart

The modeling of the product system and the impact assessment was conducted with the LCA software Umberto LCA + (ifu Hamburg). The system flow chart including foreground and background system identification is displayed in Fig. 2.2.

According to the resources availability in this student research project, the foreground system and its processes were reasonably simplified, but without compromising on the overall correctness of the results.

2.4 Results

2.4.1 Dismantling Trials

In total, 83 dismantling steps were documented. The dismantling hierarchy with all steps including the single required time and the needed tools for every step is displayed in the electronic supplementary material 2.1.

The initial weight of the product was 284.2 g excluding the packaging. Figure 2.3 shows the product before dismantling (left) and after dismantling (right). The mass recovery rate after dismantling was at 98.7% (280.7 g).

The respective masses of the single components and the identification of materials resulted in the bill of materials, displayed in Table 2.2. The product was found to be composed of 61.7% polymers, 20.9% metals, 4.8% circuit boards, 4.6% battery, 3.5% foams, 3.0% wires and 1.7% not identifiable polymers. Regarding the single materials, PC/ABS has the highest mass share with 30.9%, followed by polycarbonate with 16.8%.

Fig. 2.3 Headphone Jabra Evolve2 85 before (left) and after dismantling (right)

2.4.2 Life Cycle Assessment

Inventory analysis. Based on the bill of materials, information given by the manufacturer, and additional assumptions, all relevant input and output flows of the product system were quantified in the inventory analysis. The quantified flows, their corresponding types and the sources of the values are given in Table 2.3.

Simplifications and assumptions to fill data gaps were made as follows: For the processes injection molding and casting, the bill of materials was utilized with a cut-off criterion of <1% of the total product's mass. 50% of the weight of the PC/ABS blend was allocated to polycarbonate and 50% to acylonitrile-butadiene-styrene. It was assumed that all polymers are injection molded and all metals are cast. The electricity needed for assembly was calculated with the total energy consumption in the assembly factory and the model's share of batch size provided by the manufacturer. The masses of an exemplary package, shown in Fig. 2.4, were considered. The weight of the charging stand was not taken into account since it is not delivered with the headphone model 28599-989-999.

The assembly factory is located in Xiamen, China. The distribution in the European Union was to be presented by a combination of the distance from Xiamen to Rotterdam by ship and the average distance from Rotterdam to all EU capitals by lorry. With 2,600 using hours and a time between charges of 21 h with busy light and active noise cancellation on (GN Audio A/S 2020a, b, c), the number of charges was computed. The required electricity per charge is 2.7 Wh as labeled on the battery.

$$\text{Total charging electricity [kWh]} = 2,600\ \text{h}/21\ \text{h} \times 2,7\ \text{Wh} \times 10^{(-3)} = 0.334\ \text{kWh} \quad (2.1)$$

Table 2.2 Bill of materials

Material	Weight (g)	%
Circuit boards	13.4	4.8
Wires	8.3	3.0
Lithium-ion-battery	12.9	4.6
Foams	9.7	3.5
Not identifiable polymers	4.7	1.7
Metals	58.6	20.9
Copper alloy	0.2	0.1
Steel alloy	12.6	4.5
Iron-nickel–chromium alloy	20.4	7.3
Nickel alloy	0.2	0.1
Iron alloy	24.8	8.8
Gold alloy	0.4	0.1
Polymers	173.1	61.7
Polyamide	15.3	5.5
Butylformate	0.1	0.0
Polyethylene terephthalate	3.9	1.4
Polymethyl methacrylate	0.2	0.1
Polypropylene	3.9	1.4
Polydimethylsiloxane	0.1	0.0
Polyoxymethylene	0.1	0.0
Polycarbonate	47.1	16.8
PC/ABS	86.6	30.9
Polybutylene terephthalate	15.8	5.6
Sum	280.7	100.0

The end-of-life stage was simplified by assuming that all remaining material after the battery's removal are incinerated. It was assumed that the headphones have a size compatible with residual waste disposal collection bins, although disposal via this route is not compliant with EU rules for WEEE disposal (WEEE Directive 2012). Nonetheless when having reached their end of life, small WEEE may be disposed of via this route, resulting in the current (too low) collection rates e.g. in Germany (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2019).

Impact assessment. The total global warming potential results in 12.17 kg CO_2-Eq. Table 2.4 shows the contributions allocated to the life cycle stages manufacturing, packaging, distribution, use, and end-of-life.

The manufacturing phase provides 81.2% of the climate impact, which is by far the highest contribution to global warming potential of all headphone life cycle phases, followed by packaging with 10.9%, end-of-life with 3.6%, distribution with 2.8%, and use with 1.5%. The main contribution in the manufacturing phase stems

Table 2.3 Inventory analysis

Material	Unit	Value	Source	Boundary	Type	Input/ output
Injection molding						
Polyamide	g	15.3	Measurement	Extern	Primary product	Input
Polyethylene terephthalate	g	3.9	Measurement	Extern	Primary product	Input
Polypropylene	g	3.9	Measurement	Extern	Primary product	Input
Polybutylene terephthalate	g	15.8	Measurement	Extern	Primary product	Input
Polycarbonate	g	90.4	Calculation	Extern	Primary product	Input
Acrylonitrile–butadiene–styrene	g	43.3	Calculation	Extern	Primary product	Input
Injection molding	g	172.6	Calculation	Extern	Auxiliary and operating materials	Input
Molded plastic components	g	172.6	Calculation	Intern	Intermediate product	Output
Casting						
Steel alloy	g	12.6	Measurement	Extern	primary product	Input
Iron-nickel–chromium alloy	g	20.4	Measurement	Extern	Primary product	Input
Iron alloy	g	24.8	Measurement	Extern	Primary product	Input
Casting	g	57.8	Calculation	Extern	Auxiliary and operating materials	Input
Cast metal components	g	57.8	Calculation	Intern	Intermediate product	Output
Assembly						
Molded plastic components	g	172.6	Measurement	Intern	Intermediate product	Input
Cast metal components	g	57.8	Measurement	Intern	Intermediate product	Input
Li-ion battery	g	12.9	Measurement	Extern	Primary product	Input
Circuit boards	g	13.4	Measurement	Extern	Primary product	Input

(continued)

Table 2.3 (continued)

Material	Unit	Value	Source	Boundary	Type	Input/output
Wires	g	8.3	Measurement	Extern	Primary product	Input
Foams	g	9.7	Measurement	Extern	Primary product	Input
Electricity	kWh	2.13	Calculation	Extern	Energy	Input
Assembled headphone	Unit	1	Specification	Intern	Intermediate product	Output
Packaging + Adding Accessories						
Assembled headphone	Unit	1	Specification	Intern	Intermediate product	Input
Bag, polyester	g	166.6	Measurement	Extern	Primary product	Input
Carton	g	106.8	Measurement	Extern	Primary product	Input
Paper sleeve	g	55.5	Measurement	Extern	Primary product	Input
Accessories (wires and plugs)	g	41.5	Measurement	Extern	Primary product	Input
Packed headphone	unit	1	Specification	Intern	Intermediate product	Output
Distribution						
Packed headphone	Unit	1	Specification	Intern	Intermediate product	Input
Transport, ship	t*km	14.93	Calculation	Extern	Auxiliary and operating materials	Input
Transport, lorry	t*km	1.25	Calculation	Extern	Auxiliary and operating materials	Input
Delivered headphone	Unit	1	Specification	Intern	Product	Output
Use						
Delivered headphone	Unit	1	Specification	Intern	Product	Input
Electricity for charging	kWh	0.334	Calculation	Extern	Energy	Input
Used headphone + packaging	Unit	1	Specification	Intern	Waste	Output
Usage of headphone	Unit	1	Specification	Reference flow	Reference flow	Output
Removal of battery						
Used headphone + packaging	Unit	1	Specification	Intern	Waste	Input

(continued)

Table 2.3 (continued)

Material	Unit	Value	Source	Boundary	Type	Input/output
Removed Li-ion battery	g	12.9	Measurement	Intern	Waste	Output
Remaining material for disposal	g	804.8	Calculation	Intern	Waste	Output
Disposal						
Remaining material for disposal	g	804.8	Specification	Intern	Waste	Input
Incineration	g	804.8	Calculation	Extern	Auxiliary and operating materials	Input
Treatment						
Removed Li-ion battery	g	12.9	Specification	Intern	Waste	Input
Pyrometallurgical treatment	g	12.9	Calculation	Extern	Auxiliary and operating materials	Input

Fig. 2.4 Exemplary package

from circuit boards, molded plastic components, cast metal components, and the electricity needed for assembly. The polyester bag has the highest share of the GWP in the packaging phase with 66.2%. The transport by ship over the assumed distance of 18,258 km adds 0.14 kg CO_2-Eq and the transport by lorry over the assumed distance of 1,533 km contributes 0.2 kg CO_2-Eq. With the reference flow of 2,600 using hours, the contribution of the electricity for charging is comparatively low with 0.18 kg CO_2-Eq. The incineration of the remaining material after removing the battery has the main share of the GWP during the end-of-life phase with 95.5%.

Sensitivity analysis. The influence of prolonging the product's duration of use on the environmental impact assessment was analyzed by looking at an exemplary repair scenario, the replacement of the battery. It was assumed that the headphone can and will be used for an additional 2,600 h after the replacement of the battery, which results in a total of 0.668 kWh electricity required for charging (0.334 kWh × 2). The input of the new battery and the treatment of the old battery were considered as well. The scenario was simplified by assuming that the battery can be replaced

Table 2.4 Global warming potential allocated to life cycle stages (kg CO_2-Eq)

Manufacturing	GWP (kg CO_2-Eq)	Packaging	GWP (kg CO_2-Eq)	Distribution	GWP (kg CO_2-Eq)	Use	GWP (kg CO_2-Eq)	End-of-life	GWP (kg CO_2-Eq)
Electricity	1.43	Accessories	0.24	Transport, lorry	0.2	Electricity charging	0.18	Incineration	0.42
Foams	0.05	Bag, polyester	0.88	Transport, ship	0.14			Pyrometallurgic treatment	0.02
Wires	0.05	Carton	0.14						
Circuit boards	4.92	Paper sleeve	0.04						
Li-ion-battery	0.10								
Molded plastic components	1.32								
Cast metal components	2.02								
Total	9.88	Total	1.33	Total	0.34	Total	0.18	Total	0.44

Table 2.5 Repair scenario—total GWP

	GWP (kg CO_2-Eq)
Total GWP—scenario without battery replacement	12.17
+ new Li-ion-battery	0.1
+ additional electricity for charging	0.18
+ pyrometallurgical treatment of first battery	0.02
Total GWP—scenario with battery replacement	12.47

without destruction and without other efforts. The additional contribution to the total GWP for the scenario of the battery replacement is presented in Table 2.5.

To compare the environmental impact of the initial scenario and the repair scenario, the corresponding values for the total global warming potential were placed in relation to the two different assumptions for the using hours. Prolonging the assumed duration of use of the product by the exemplary repair scenario decreases the assessed global warming potential per hour from 4.7 g CO_2-Eq/h to 2.4 g CO_2-Eq/h. This effect is clearly caused by the extremely high climate relevance of the manufacturing phase of the product.

2.5 Discussion

The product Jabra Evolve2 85 was found to be composed of 61.7% polymers, 20.9% metals, 4.8% circuit boards, 4.6% battery, 3.5% foams, 3.0% wires and 1.7% not identifiable polymers. Many polymer components were not identifiable via FTIR-ATR due to their dark color, so the manufacturer's material marks had to be used for material identification. If material recycling in the end-of-life phase is intended in future, appropriate light colours could improve identification for mechanical recycling.

The GWP contribution of the Jabra Evolve2 85 of 12.17 kg CO_2-Eq can be compared to the result of an impact assessment of the materials of the Jabra Biz 1500 Mono QD, conducted by Master students at Pforzheim university. The product is a lightweight design, mono speaker headset for business use and can be taken as an extreme example of material saving. The assessed global warming potential of the 61 g mono-headset was 2.51 kg CO_2-Eq (Melter and Mai 2021), which equals around 21% of the GWP of the stereo headset Jabra Evolve2 85. The GWP per gram product is comparable with 41.1 g CO_2-Eq/g product for the lightweight mono speaker headset and 42.8 g CO_2-Eq/g for the stereo headset.

The result of the LCA entails some uncertainties due to simplifications and assumptions: In the inventory analysis, the manufacturing processes of the single materials could be considered in more detail, as in the current study all polymers were assumed to be injection molded and all alloys to be cast. Depending on the selected means of transport, the expected sales market and the markets distance to the incoming shipping port, the contribution of the distribution phase can vary. Other scenarios for the end-of-life phase could be developed, mainly the consideration of recycling as required by the WEEE regulation (WEEE Directive 2012; ElektroG 2015). As current collection rates are very low, the actual disposal way for not separately collected WEEE is unknown (Kummer et al. 2021), and headphones may geometrically fit into the residual waste collection bins, the disposal via residual waste was assumed as realistic for this study, although not legal.

The result of the impact assessment depends on the selected background data sets, e.g. the electricity mix for manufacturing. In some cases, no exactly matching data sets in ecoinvent were available which required adjustments and assumptions, for example the ecoinvent activity "market for textile, non-woven polyester" for the bag fabrics. For further improvement of data quality, additional data bases or other better-matching data sets could be utilized. The value of the lifetime of two years was based on manufacturer's specification. Additional market studies or surveys to provide data for further scenarios with different values could be conducted in future. The repair scenario used was highly simplified by assuming that the using hours of 2,600 h are doubling by repair. However, the basic finding that prolonging the lifetime by repair can be seen as environmentally beneficial can be regarded as valid for products with comparable low environmental impact in the use phase (Bovea et al. 2020; Hischier and Böni 2021; Pamminger et al. 2021).

2.6 Conclusion

By dismantling, ear cases, earpads, speakers, main circuit boards, the microphone arm, the battery, and the headband were assumed as main components. 98.3% of all materials' weight could be identified via manufacturer's marks, ATR and XRF. The identified materials could be categorized in polymers (61.7%), metals (20.9%), circuit boards (4.8%), Li-ion-battery (4.6%), foams (3.5%) and wires (3.0%). 97.9% of all materials' weight were used as input for the life cycle assessment. With a reference flow of one headphone and 2,600 using hours, the impact assessment of a Jabra Evolve2 85 headphone resulted in a total climate impact of 12.17 kg CO_2-Eq. This result of global warming potential covered all the relevant life cycle phases manufacturing, packaging, distribution, use, and end-of-life. Manufacturing shows by far the highest climate contribution with a total of 9.88 kg CO_2-Eq and a contribution of materials of 6.40 kg CO_2-Eq. Considering the repair scenario with a battery replacement, repairability and prolonging the lifetime can have a significant impact on the global warming potential per hour.

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