Life cycle assessment of an Internet of Things product: Environmental impact of an intelligent smoke detector

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ABSTRACT

Digitization and sustainability are the two big topics of our current time. As the usage of digital products like IoT devices continues to grow, it affects the energy consumption caused by the Internet. At the same time, more and more companies feel the need to become carbon neutral and sustainable. Determining the environmental impact of an IoT device is challenging, as the production of the hardware components should be considered and the electricity consumption of the Internet since this is the primary communication medium of an IoT device. Estimating the electricity consumption of the Internet itself is a complex task. We performed a life cycle assessment (LCA) to determine the environmental impact of an intelligent smoke detector sold in Germany, taking its whole life-cycle from cradle-to-grave into account. We applied the impact assessment method ReCiPe 2016 Midpoint and compared its results with ILCD 2011 Midpoint+ to check the robustness of our results. The LCA results showed that electricity consumption during the use phase is the main contributor to environmental impacts. The mining of coal causes this contribution, which is a part of the German electricity mix. Consequently, the smoke detector mainly contributes to the impact categories of freshwater and marine ecotoxicity, but only marginally to global warming.

CCS CONCEPTS

• **Hardware → Impact on the environment**.

KEYWORDS

Internet of Things, IoT, Smart Home, smoke detector, sustainability, Life Cycle Assessment, LCA

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1 INTRODUCTION

In digitization, diverse innovations emerge [4], while a sustainable way of living demands us to consume Earths' resources carefully [29]. However, can digitization pave the way to a sustainable future? There are two approaches focusing on that topic: Decreasing the energy consumption *of* and *through* digital products (mainly energy consumption during the use phase, but also during the production phase) [27].

This paper presents a case study to determine the sustainability of a specific Internet of Things (IoT) product. The examined product is the Twinguard smoke detector from Bosch Smart Home. In 2019, the Bosch Group announced its target to become carbon neutral in 2020 [32]. We performed an LCA to determine the environmental impact of the smoke detector. This life cycle assessment (LCA) considers its life-cycle from cradle-to-grave: Resource extraction and production of its hardware components and their final assembly, electricity consumption during its use phase (also considering the electricity consumption caused by the Internet), and its final disposal in the end-of-life-phase. We also conducted a hotspot analysis to determine the main contributors to environmental impacts during the life cycle of the smoke detector, as well as a sensitivity analysis to assess the effects of some of the assumptions and estimations we had to make due to insufficient data. This paper presents the results of our work. Possible solutions are discussed, as well as some of the limits of this study and points to improve.

2 RELATED WORK

As mentioned in section 1, there are two approaches to decreasing energy consumption of or through digital products [27]. Regarding the former approach, [41] presents a literature review on the various possibilities to save energy consumption of the IoT's different components. Applications for the latter approach are also diverse. For example, [24] describes a cloud-based smart home solution where users can monitor their power consumption and change their behavior accordingly. The IoT can also impact aspects other than energy consumption, like the minimization of waste [3]. IoT is not without its problems, several of them mentioned in [7] like private user data collection.

[42] observes that the CO_2 emissions during the production phase of ICT devices positively correlate with their mass. However, the production phase's share in energy consumption over the whole life-cycle is higher in smaller devices [23]. According to a study made by Belkhir and Elmeligi in 2017, the share of ICT in global

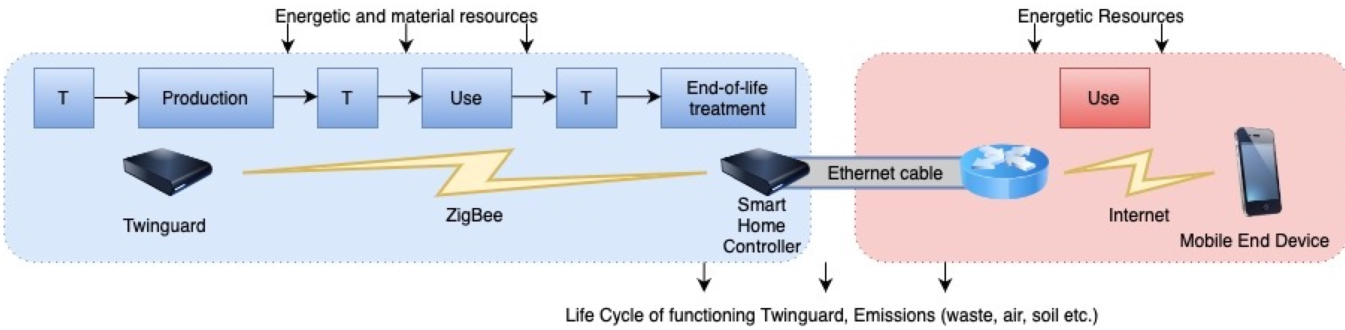

Figure 1: Basic structure of a Smart Home Network including Twinguard.

greenhouse gas emissions is 3.06 to 3.6 % in 2020, a value estimated to increase to 14 % by 2040 by their estimations [2].

[6] and [38] developed a formula to calculate the energy consumption of the Internet. [6] calculates the energy consumption of customer premises equipment (CPE) – modems and home routers – and the access network using the formula

$$i_{CPE\&AN} = (1 + \frac{t_{Idle}}{t_{Use}})P_{CPE} + \frac{P_{AN}}{N_{AN}} pue_{AN} \quad (1)$$

with t_{Idle} and t_{Use} being the idle and usage time of the CPE, P_{CPE} being the power of the CPE, P_{AN} the power of the access network, N_{AN} the number of subscribers and pue_{AN} the PUE of the access network. [38] provides an average value of 0.052 kWh per Gigabyte for the energy intensity of the edge and core network.

The work of [6] and [38] forms the basis for the calculation model of an online footprint tracker, which students developed at HTWG Konstanz [1]. It also considers the energy consumption of end devices and data centers, which used data from the Shift Project presented in [35] and [36].

3 GOAL AND SCOPE DEFINITION

The authors chose Twinguard as the research object of this LCA because Bosch were interested in knowing the environmental impact of their IoT product. To the authors' knowledge, no LCA studies on IoT products made by Bosch exist at the moment. The LCA presented in this paper intends to examine the Twinguard for its environmental impact and show potential for improvement.

3.1 Research object

The research object is the Twinguard smoke detector from Bosch Smart Home. It contains a smoke sensor and an air quality sensor and can be connected to another Bosch product; the Smart Home Controller can send alarms to the Bosch Smart Home App on a mobile device [17]. Furthermore, the air quality data are also visible in the Bosch Smart Home App [19]. The Smart Home Controller must be connected to a Wi-Fi router via a network cable [18]. Figure 1 shows the basic structure of this Smart Home network.

3.2 Functional unit

We define the functional unit for this LCA as a complete life cycle of a functioning Twinguard with a use phase of ten years (based on statements by Bosch Smart Home).

3.3 System boundaries

The authors considered the life cycle of the product from cradle to grave.

3.3.1 *Geographical.*

This LCA focuses on Twinguards sold in Germany. The validity of this LCA is therefore limited to the Federal Republic of Germany.

The system boundary also includes China since the Twinguard is produced there [19]. Where possible, we used region-specific ecoinvent data sets on country-level to model the Twinguard (e.g., German electricity mix for the usage of the Twinguard, Chinese electricity mix for its production, etc.). Otherwise, if there were no data sets on country-level available, we used continent-level data sets or even global-level data sets.

3.3.2 *Temporal.*

The Twinguard was launched in 2017 [15]. The ecoinvent dataset for the german electricity mix represents the situation in the year 2016 [44].

3.3.3 *Technological.*

The focus of this life cycle assessment is the devices produced by Bosch Smart Home: the Twinguard smoke detector and the Smart Home Controller, as the latter enables the smart home functionality of the former [17]. The entire life cycle is considered for these two devices (including required alkaline batteries): production, use, and disposal. Smartphones, routers, and the Internet backbone, including data centers, are only considered by including the electricity consumption during their use phase. The hotspot analysis mainly focuses on the Bosch devices. The development of the Bosch Smart Home app is also not taken into account, only its electricity consumption on the smartphone. Figure 1 shows the technological system boundaries. The calculation of the total energy consumption closely follows the prototypical calculation model of the online footprint tracker from [1] (see section 2). Figure 1 shows the system boundaries of this study.

3.4 Acquisition and quality of data

For modeling the product life cycle, the authors used data sets from the LCA database ecoinvent version 3.6 [47] and did the modeling with the LCA software SimaPro, version 9.1.1.1 [5]. We requested relevant data for this LCA, such as transport routes and technical details directly from the selling company. If it could not share information on some points, we requested comparable data by desktop research. Weights and sizes of the components of the Twinguard were either measured, estimated, or determined using technical datasheets from the manufacturer or specialist dealers. We chose suitable or similar data records from ecoinvent for the hardware components of the devices that we could identify. If there were no matching data sets in ecoinvent for specific parts, those were not considered. Details that we could not identify were also not considered. Alkaline batteries required to operate the Twinguard had to be modeled, but the disposal of those is only based on the modeling of the recycling of alkaline batteries at Fernwärme Wien found in [48]. The electricity consumption during the development of the Bosch Smart Home App and the firmware of these devices was also not considered due to unavailable data. Also, we used data from the Shift Project [35] for our calculation model, which is not peer-reviewed, being one of the weak points of this work.

Regarding the modeling, we were using the cut-off method. The end-of-life phase follows the avoided burden approach.

4 LIFE CYCLE INVENTORY

In this section, we identify the processes and materials relevant for modeling the life cycle of the Twinguard and the Smart Home Controller. A life cycle consists of the four phases resource extraction, production, use, and disposal [16]. As the ecoinvent processes chosen to represent the hardware components of both devices already consist of material extraction processes, it was not necessary to model the resource extraction phase ourselves. In the following subsections, we modeled the production phase (final assembly of the hardware components and the transport of the finished devices), the use phase (both devices are installed in homes), and the end-of-life phase (collection and disposal of used hardware).

4.1 Production phase

Both devices, the Twinguard and the Smart Home Controller consist of a plastic housing with a printed circuit board (PCB) in each of them. Electronic components such as LEDs, microchips, capacitors, and SMD components are mounted on both PCBs. We used suitable or similar data sets from ecoinvent to model the circuit boards and these components. Furthermore, the authors asked the manufacturing company about the material composition of the sensor that is responsible for measuring the air quality. Several elements, such as the acoustic alarm siren, a LAN port, the ZigBee modules, and some microchips, were not considered in this LCA, either because there were no existing data sets in ecoinvent or because of unclear background data. Both devices' plastic housings include multiple parts; some consist of polycarbonate (PC), some ABS, and others of a PC+ABS mixture. Analysis with an infrared spectrometer showed that polycarbonate makes up the more significant part of this plastic mixture, although the exact mixing ratio could not be determined. Therefore, we assume a mixing ratio of 60 % PC and 40 % ABS for the PC+ABS parts. The uncertainty that comes with this assumption was later analyzed with a sensitivity analysis. A perforated grid made of magnetic metal is also embedded in the smoke detector. We assumed that the metal in question was steel and chose a data set for unalloyed steel for the life cycle assessment. No data were available concerning the energy consumption during the production phase of the Twinguard and the Smart Home Controller. An ecoinvent data set on desktop PCs shows an electricity consumption of 2.7124 kWh in the medium-voltage range during their production [30]. Based on this value, we estimated the power consumption for both devices as 1 kWh. However, it should be noted that this is a very rough estimate and probably involves a relatively high level of uncertainty also examined in the sensitivity analysis.

Based on information about the transport routes of the smoke detector, which is manufactured in China [19] and transported to Germany, their distances were calculated with online tools (the exact stations of these transport routes are confidential). We used Google Maps [20] for calculating the distances of the lorry transport within China and Germany, while searates.com [40] and seadistances.org [39] were used for calculating the transport from China to Germany on a container ship. The authors used data from the German Federal Motor Transport Authority [28] to estimate an average transport distance for the shipping of both devices to consumers in Germany.

The alkaline batteries required to operate the smoke detector also had to be taken into account. No data sets for alkaline batteries exist in the ecoinvent version used for this LCA (version 3.6). Therefore, we modeled a life cycle of alkaline batteries based on some existing life cycle assessment studies on alkaline batteries ([21], [34], [48]). For the transport of alkaline batteries during their production phase, we took the transport services (in tonkilometre) from existing ecoinvent datasets of NaCl- [10], NiMh- [11], and Li-ion batteries [9] and used them as an assumption. Likewise, we used the transport services given in other ecoinvent data sets ([22], [8]) for the transport of alkaline batteries during their end-of-life phase as an assumption.

The air emissions, which beside other processes are modelled for the end-of-life-phase, and that are created during the recycling process based on data of Fernwärme Wien are given in units of mg per m^3 in [48], but in SimaPro it is only possible to enter weight units such as mg for air emissions. We took the air emissions provided in [48]. Nevertheless, since SimaPro may expect total air emissions and not air emissions per m^3, the input data may have to be adjusted accordingly in the future.

We created assemblies in SimaPro for the air quality sensor, the Twinguard, and the Smart Home Controller. We added the chosen data sets for materials, components, energy consumption, and transport to the respective assemblies. Finally, the packs are available in the supplementary material under section 1.

4.2 Use phase

Concerning the calculation of the Internets' electricity consumption, our work closely followed the calculation model of the online footprint tracker by students at HTWG Konstanz [1] (see section 2). However, instead of the value of 8 W assumed in [6] for the power of the CPE, the power of the router was measured with a power meter. Likewise, the electricity consumption of the mobile end device was also calculated based on a self-measured value.

4.2.1 Twinguard. Six AA size alkaline batteries are required to operate the smoke detector, which must be replaced about every two years [17]. With an assumed product life of ten years, the smoke detector therefore needs a total of 30 batteries during its use phase.

4.2.2 *Smart Home Controller.*
The power of the Smart Home Controller was measured with a power meter. The measured value was 1.9 watts, which corresponds to an electricity consumption of $1.9 * 10^{-3}$ kWh per hour. Extrapolated over ten years, this sums up to 166.44 kWh.

4.2.3 *Router.*
The power measured on the router[1] was 1.5 watts. This value is inserted into the formula of the energy intensity of the CPE from [6], and like them we also assumed an active time of 4 hours and an idle time of 20 hours:

$$i_{CPE} = (1 + \frac{t_{Idle}}{t_{Use}})P_{CPE} = (1 + \frac{20\,h}{4\,h})1.5\,W = \;9W \tag{2}$$

The total energy intensity is therefore 9 watts. In ten years, the router will therefore consume 788.4 kWh of electricity. In addition, the data traffic that went through the router was measured with the online footprint calculator from [1]. The measurement period was 24 hours. During this time, 218.12 megabyte of data were transmitted via the router, of which 1.16 megabyte were from the smoke detector. This corresponds to 0.5306%. Only the portion of electricity consumption caused by data packages from the smoke detector were taken into account. This amounts to:

$$788.4\,kWh * \frac{1.16\,MByte}{218.12\,MByte} = 4.18\,kWh \tag{3}$$

For this study, the calculated value of 4.18 kWh of electricity consumption was used.

4.2.4 *Internet.*
For the access network, we used the value of 4W from [6]. Over a period of ten years, the electricity consumption is 350.4 kWh. For the edge+core network, the electricity consumption is 0.052 kWh per GByte, according to [38]. With a measured amount of data of 1.16 megabyte, the following electricity consumption was calculated for the edge+core network during the measurement period:

$$0.052\frac{kWh}{GByte} * \frac{1.16\,MByte}{1024} = 5.88 * 10^{-5}\,kWh \tag{4}$$

Extrapolated over 10 years, this is 0.215 kWh. In order to take also data centres into account, we used the value of an electricity consumption of $7.2 * 10^{-11}$ kWh per byte from [35]:

$$\begin{aligned} 7.2 * 10^{-11}\frac{kWh}{Byte} &* 1.16\,MByte * 1024^2 \\ &= 8,74 * 10^{-5}\,kWh \end{aligned} \tag{5}$$

Extrapolated over 10 years, this is 0.319 kWh.

4.2.5 *Mobile end device.*
A Motorola moto e6s with a battery capacity of 3000 mAh (see [31]) was used for the measurement. The associated charger has a power of 5 watts and an output current of 1 A. Only the power consumption caused by the Bosch Smart Home app was taken into account. After 24 hours, the app had used 5% of the battery capacity, which corresponds to 150 mAh. The charging time to recharge this capacity can be calculated using the following formula [43]:

$$\begin{aligned} Charging\ time = \frac{Capacity}{Output\ Current} * 1.3 &= \frac{150\,mAh}{1000\,mA} * 1.3 \\ &= 0.195\,h \end{aligned} \tag{6}$$

[1]We used the GLinet 300M Mini Smart Router for this study

In this case, it would take 0.195 hours to recharge. With a charger output of 5 watts, $9.75 * 10^{-4}$ kWh of electricity are used to recharge the battery capacity lost in 24 hours. Extrapolated over ten years, this corresponds to 3.56 kWh.

4.2.6 *Modeling in SimaPro.*
In SimaPro, we added the value of an electricity consumption of 166.44 kWh to the life cycle of the Smart Home Controller. The sum of all other calculated values (which is 358.64 kWh) was added to the life cycle of the Twinguard. In both cases, we used an ecoinvent data set for the german electricity mix [44]. The life cycles are available in the supplementary material under section 1.

4.3 End-of-life phase

Used Twinguards are sent back to Bosch. Devices that are no longer functional are scrapped, while the remaining devices are returned to the sale or used internally for test purposes. No data was available on the share of smoke detectors that are no longer functional, nor was there any information about the scrapping process. In order to calculate an average transport route for the return transport, data from the German Federal Motor Transport Authority [28] were used again. Furthermore, ecoinvent provides data records for the waste treatment of plastic, mounted printed circuit boards and steel. A waste scenario for the Twinguard was created in SimaPro and these three data sets were added as waste streams to it. Similarly, a waste scenario for the Smart Home Controller was also created using these data sets. The waste scenarios are available in the supplementary material under section 1.

5 LIFE CYCLE IMPACT ASSESSMENT

In this section, we present the environmental impacts of the Twinguard, calculated with the impact assessment method ReCiPe 2016 Midpoint using the SimaPro software. We focus on just six of its impact categories: Global warming because there is a big public interest in this impact category, ecotoxicity (terrestrial, freshwater and marine) because toxic substances during the production and disposal process may harm the environment, mineral resource scarcity because metals have to be mined for electronic components, and fossil resource scarcity because fossil resources are a part of the german electricity mix. Note that the quantities of environmentally harmful emissions are given in standardized equivalence values: CO_2 equivalents for Global Warming, 1.4-DCB for all three types of ecotoxicities, copper equivalents for mineral resource scarcity and oil equivalents for fossil resource scarcity [26]. For example, one kilogram of fossil methane constitutes to 36 kilogram CO_2 equivalents in the hierarchist version of ReCiPe 2016 Midpoint [25].

Diagrams for the impact assessment are available in the supplementary material under section 2.

5.1 Inventory analysis

5.1.1 *Global Warming.*
The analysis showed that a total of 321 kg of CO_2 equivalents are emitted during the life cycle of the smoke detector. The main contributors from fossil sources are CO_2 itself with 293 kg CO_{2eq} and fossil methane with 15.3 kg CO_{2eq} (which are, given the conversion factor from [25] of 1 kg fossil methane = 36 kg CO_{2eq}, actually 0.425 kg of fossil methane).

Table 1: Results of the inventory analysis of the Twinguard life cycle, calculated with SimaPro version 9.1.1.1 from ecoinvent version 3.6 datasets

Scenario	Global Warming (kg CO_2 eq)	Ecotoxicity (kg 1.4-DCB eq)			Resource Scarcity	
		Terrestrial	Freshwater	Marine	Mineral (kg Cu eq)	Fossil (kg oil eq)
Carbon dioxide, fossil	293					
Methane, fossil	15.3					
Copper		648	23.5	28.1	0.19	
Silver		98.3				
Nickel		63.8	1.66	2.06	0.0672	
Zinc		31.5	9.79	14		
Iron					0.0877	
Uranium					0.0481	
Gold					-1.2	
Coal, brown						35.4
Coal, hard						25.1
Gas, natural						13.5
Remaining substances	12.7	86.6	1.54	2.46	0.0696	3.27
Total	**321**	**928**	**36.5**	**46.6**	**-0.741**	**77.3**

5.1.2 Terrestrial ecotoxicity. 928 kg of 1.4-DCB equivalents are emitted, of which 648 kg are from copper and 98.3 kg are from silver.

5.1.3 Freshwater ecotoxity. 36.5 kg of 1.4-DCB equivalents are emitted, of which 23.5 kg are from copper and 9.79 kg are from zinc.

5.1.4 Marine ecotoxicity. 46.6 kg of 1.4-DCB equivalents are emitted, of which 28.1 kg are from copper and 14 kg are from zinc.

5.1.5 Mineral resource scarcity. The resource depletion in this impact category is -0.741 kg Cu equivalents. This negative value is caused by gold, which has a value of -1.2 kg Cu equivalents. Copper has the highest positive value with 0.19 kg Cu equivalents.

5.1.6 Fossil resource scarcity. The value in this impact category is a resource depletion of 77.3 kg oil equivalents. Lignite and hard coal do have the biggest share here with 35.4 kg and 25.1 kg oil equivalents respectively.

5.2 Characterization

The analysis on level characterization showed that the electricity consumption during the use phase of the smoke detector is the main contributor to environmental impacts in all of the selected six impact categories. It ranges from 47.3 % in terrestrial ecotoxicity to 65.3 % in global warming. In mineral resource scarcity, it has the highest positive share (25.5 %). The second-highest contributor is the life cycle of the Smart Home Controller, ranging from 31.8 % in both global warming and fossil resource scarcity up to 35.2 % in terrestrial ecotoxicity (and having the second-highest positive share in mineral resource scarcity with 16.7 %). The production phase of the smoke detector does not have a high contribution to these impact categories, out of all six of them, its highest share is in the impact category of terrestrial ecotoxicity with 16.2 % and its lowest in global warming with 2.16 %. The end-of-life phase of the smoke detector does have a share of less than 1 % in all six impact categories. The life cycle of Alkaline batteries also has a rather small contribution: Only 1.27 % in terrestrial ecotoxicity, which is also where they have their highest positive share. In mineral resource scarcity, they have a negative contribution of -100 %.

5.3 Normalization

Calculating the normalization of ReCiPe 2016 Midpoint with SimaPro, the results showed that the smoke detector has a rather small contribution to the impact categories of global warming as well as mineral and fossil resource scarcity (the reference value for the normalization in ReCiPe 2016 is a person in the year 2010 [37]). It produces over its entire product life cycle only 0.0402 as many CO_2 equivalents as a person in 2010. Looking at mineral and fossil resource scarcity, the impacts in these two categories are $-6.17*10^{-6}$ and 0.0788 times as much as a person in 2010. The smoke detector has only a little bit higher impact on terrestrial ecotoxicity as it produces 0.896 times the 1.4-DCB equivalent than a person in 2010. However, in the categories of freshwater and marine ecotoxicity, these factors are 29.8 and 45.2, respectively. These results show that the smoke detector has a high impact on these two categories, but rather small impacts on global warming and resource scarcity. To check robustness of the results, a normalization with the impact assessment method ILCD 2011 Midpoint+ was done, using the impact categories global warming, freshwater ecotoxicity and resource scarcity. It showed that freshwater ecotoxicity also had rather high impacts compared to global warming and resource scarcity.

6 INTERPRETATION

In the following section, we interpret the results of our LCA by determining the main causes for environmental impacts in a hotspot analysis and checking our assumptions and estimations with different values in a sensitivity analysis. Diagrams are available in the supplementary material under section 3.

Table 2: Results of the sensitivity analysis of the Twinguard life cycle, calculated with SimaPro version 9.1.1.1 from ecoinvent version 3.6 datasets

Scenario	Global Warming ($kg\ CO_2$ eq)	Ecotoxicity (kg 1.4-DCB eq)			Resource Scarcity	
		Terrestrial	Freshwater	Marine	Mineral (kg Cu eq)	Fossil (kg oil eq)
Default	321	928	36.5	46.6	-0.741	77.3
PC-ABS 90:10	321	928	36.5	46.6	-0.741	77.3
Embodied energy 0.2 kWh	320	927	36.5	46.6	-0.742	77
Embodied energy 0.5 kWh	320	928	36.5	46.6	-0.741	77.1
Embodied energy 2 kWh	323	929	36.6	46.7	-0.74	77.7
Embodied energy 5 kWh	328	933	36.7	46.9	-0.737	78.7
Lorry EURO III emission class	321	928	36.5	46.6	-0.741	77.3
Mounted PCB	354	1120	61.9	80	0.727	85.6

6.1 Hotspot analysis

The hotspot analysis showed that the electricity consumption by the Twinguard and Smart Home Controller is the main cause of harmful environmental impacts in all six impact categories (see also the diagrams in section 3.1 of the supplementary material). In the categories of global warming, freshwater ecotoxicity, marine ecotoxicity and fossil resource scarcity, this is mainly due to the mining of coal (lignite and hard coal). Another relevant hotspot behind electricity consumption in the categories of terrestrial, freshwater and marine ecotoxicity can be traced back to the construction of electricity distribution networks. Here, a main contributor is the production of copper, where sulfidic tailings are entering water and soil while mining them. Another, though smaller, hotspot in the impact category of terrestrial ecotoxicity is the production of the PCB, with the extraction of copper again being the main contributor.

In the category of mineral resource scarcity, the impact of both devices is rather small. A credit is given for the recycling of material from alkaline batteries, for which zinc is fed back into the material cycle. This has a very positive impact and is the reason for the high negative value of the alkaline battery life cycle in the characterization of mineral resource scarcity. As gold is a co-product of zinc mining [46], a credit is given for it in the inventory analysis, which appears as negative values.

As of 2019, lignite is the main source of non-renewable electricity in the German electricity mix (the gross electricity consumption was 114.0 TWh), while hard coal ranks on 4th place among non-renewable electricity sources with a gross electricity consumption of 57.5 TWh (on second and third place are natural gas and nuclear energy with 90.5 TWh and 75.1 TWh respectively) [13]. The mining of coal (hard coal and lignite, of which the latter is a significant part of the German electricity mix) comes with considerable environmental pollution: CO_2 is emitted and water is polluted by substances such as mercury, sulfate and chloride [45].

The cause for the impact of printed circuit boards is mainly due to the mining of copper which is used in their production (see the diagrams in section 3.1 of the supplementary material). As metals are mostly mined in developing countries, this comes with a lot of negative impacts on the environment, e.g. the pollution of soil and water with cynanide (which is used for the mining) and damages to farmland [14], as well as the aforementioned sulfidic tailings entering water and soil during the extraction of copper (see also the diagrams in section 3.1 of the supplementary material).

6.2 Sensitivity analysis

For some of the process steps in the life cycle of the smoke detector, assumptions and estimates had to be made. In the following sensitivity analysis, the impacts of these uncertainties on the results of the inventory analysis (see subsection 5.1) are evaluated.

Seven different scenarios were considered for the sensitivity analysis:

1) The mixing ratio of PC+ABS was assumed to be 60:40 in the default model based on the IR spectrometer analysis that PC makes up the greater part of the plastic mixture. In the sensitivity analysis this was changed to 90:10.

2-5) The energy consumption during the production phase of both the Twinguard and the Smart Home Controller was assumed to be 1 kWh (see subsection 5.1). For the sensitivity analysis, four different scenarios were considered with an energy consumption of 0.2 kWh, 0.5 kWh, 2 kWh and 5 kWh, respectively.

6) For the lorry transport, it was assumed that the lorrys were from the EURO VI emission class, for which we used the corresponding ecoinvent data sets. This was changed to the datasets for a EURO III emission class lorry transport.

7) The datasets for the unmounted PCBs and for the various electronic components were removed from the Twinguard and Smart Home Controller assemblies in SimaPro and replaced with a dataset for mounted PCBs.

Table 2 shows the results of these scenarios compared to the default scenario described in the previous sections of this paper.

A different mixing ratio of PC and ABS had no real effect on the inventory analysis results. A reduction of the energy consumption showed no significant impact on the inventory analysis. In the 0.2 kWh and 0.5 kWh scenarios, the results either changed very little or not at all. The 2 kWh and 5 kWh scenarios do show a slight, but not dramatic increase in all impact categories. The scenario in which the lorry emission class is assumed to be EURO III shows no changes from the default scenario with the EURO VI emission class.

The first six alternative scenarios so far showed only small (or even none) impacts on the results of the inventory analysis. However, the seventh scenario resulted in more significant impacts in all categories: Compared to the default scenario, it shows an increase of 10.3 % in Global Warming, 20.7 % in terrestrial ecotoxicity, 69.6 % in freshwater ecotoxicity, 71.7 % in marine ecotoxicity and 10.7 % in fossil resource scarcity. In mineral resource scarcity, there is a change in algebraic sign (+/-), and therefore the relative change is not calculable. The absolute change here is an increase of 1.468 kg Cu equivalents. Although the data set for mounted printed circuit boards [12] does not represent the actual assembly of the PCBs in the Twinguard and the Smart Home Controller, this scenario shows that the actual assembly of the PCBs and its components may be significant. Since some components could not be considered in the modeling of the Twinguard and the Smart Home Controller in SimaPro, the uncertainties are rather high in this respect.

7 OUTLOOK AND FUTURE WORK

In this work, we presented a first comprehensive LCA of an IoT device with some weaknesses. We could not consider all hardware components for the production phase of both devices. Moreover, our sensitivity analysis points out that especially the assembly of the PCBs has a considerable effect on the results of the overall LCA. We modeled a life cycle of alkaline batteries, but the disposal is so far based on only one recycling process [48]. Another point not considered yet is the environmental impacts of the development of the Smart Home App and the firmware of both devices. Besides this, the data traffic should be measured under different circumstances (e.g., different rooms, ranges for air quality, or seasons) than just the one we mentioned in Section 4.2.3 to better understand the data traffic of this particular device. The system boundaries of this study do not include the production and disposal of devices (such as the mobile phone or the remaining Internet infrastructure) and exclusively cover the two Bosch devices and the batteries. The ecoinvent dataset of the German electricity mix represents the situation in 2016 [44] and is slightly outdated. Last, we used non-peer-reviewed data from The Shift Project [35] for an initial approximation to calculate the electricity consumption of data centers. These are the reasons why this LCA may not represent reality accurately. It offers an initial overview of the environmental impact of the smoke detector and a general guideline on how to create a cradle-to-grave LCA of an IoT product.

We plan to minimize these weaknesses in our future work. In a potential successor project, we shall analyze the electronic components of IoT devices regarding their environmental impacts. Intensive measurements of IoT data traffic are also one of the points we want to tackle. Thereby, our calculation model can include the entire life cycle of the Internet infrastructure and end devices, not just their usage phase. Once more reliable data is available due to our future work, we plan to update this LCA and perform LCA studies on different IoT products.

There are possible solutions regarding the hotspots of environmental impacts during the life cycle of this product: We like to positively mention that the share of renewable energies in the German electricity mix has increased in recent years: from 16.8 % in 2010 to 44.9 % in 2019 [13]. The German federal government plans to increase this share to 65 % by 2030 and phase out coal energy entirely in 2038 [33], which means that the hotspot of coal mining will disappear. Regarding the devices themselves, possible approaches to reduce negative environmental impacts would be eco-design or the use of non-toxic materials during the production. However, their sustainability potential would have to be analyzed and assessed also.

SUPPLEMENTARY MATERIAL

The supplementary material to this paper contains tables depicting the life cycle inventory in SimaPro version 9.1.1.1 using data sets from ecoinvent, version 3.6, and diagrams depicting the results of the life cycle impact assessment. It can be found under the repository: https://github.com/omanz90/Supplementary_Material_LCA_IoT_Device under the file "Supplementary_Material.md".

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