RESMAC: REpurposing of SMArtphone Capabilities

WP2: Mapping of the current state

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Executive summary

The challenge:

The aim of the RESMAC (REpurposing of SMArtphone Capabilities) project is developing the foundation of a business-viable system of repurposing and upcycling smartphones and their functioning capabilities into new innovative products-and-service applications.
In fact, although the real-life expectancy of a mobile phone (aka, when the device's performance starts remarkably degrading) ranges from 3.5 years to 4.7 years, mobile phone users worldwide change their device at an average frequency of 18 months.
This suggests that a copious amount of mobile phones that are currently being taken care of by the collection schemes drawn from the WEEE (Waste Electrical and Electronic Equipment) Directive, or stored in households and not yet collected (15 million units in 2008 in Sweden), contain advanced and still-working functionalities: powerful CPUs, accelerometer and GPS, data connectivity, to name a few.
The aim of RESMAC is therefore capturing value from used smartphone components - otherwise lost – and repurpose it in a novel product concept.

Aim of the work package and links with following work packages:

Work Package (WP) 2 results in a summary of the current state of material and information flows that are relevant for the end-of-life phase of used smartphones. The current state analysis is given by the definition of the following elements:

- material flows in the end-of-life phase of used smartphones, according to electronics' reverse-logistics and collection schemes (material perspective)
- lost value due to inaccessible product information from key actors of the electronics' supply chain (information perspective)
- smartphone models suitable for feeding the product concept, which will be the outcome of *WP3: Idea and concept generation.*
- a baseline of values of environmental impact indicators for a smartphone relevant for the analyses in *WP4: Feasibility and sustainability study of volume-production scenario*s.

Research methods:

A mixed-method research design has been adopted, combining secondary data from scientific articles and reports with primary data from interviews. Data pertaining materials and information flows has been visualized through illustrations and flowcharts.

Key findings:

The few available data pertaining smartphones' use and end of life does not offer opportunities for aggregation in a comprehensive material flow analysis for the Swedish market. However, this obstacle did not hinder the representation of a qualitative modelling of stocks and flows that represent the current state of the smartphones' use phase and end of life phase. This visualization is available at page 10.

Environmental impacts of material stocks and flows are likely to be reduced by the introduction of the novel product concept designed in ReSmaC. In fact, the project partners aim at using almost a 100% between materials and components of a smartphone which is not suitable for reuse wholly.

Key quantitative and qualitative pieces of finding laid the foundation for a baseline against which comparing the performance of the novel product concept developed in WP3.

Resources' use and human toxicity are the most relevant environmental impact categories against which to measure mobile phones' end of life strategies. However, results from life cycle assessment (LCA) analyses emphasize above all impacts on climate change and energy use, to which the end of life phase brings a negligible contribution. This partially causes an undervaluation of less burdensome end of life strategies for smartphones. Furthermore, results from LCA analyses of smartphones showed great variability because of sensitivity of assumptions and methodological issues.

Values of life cycle impact category indicators have been retrieved from a study applied to a Sony Xperia™ T. Indicators refer to the whole smartphone, and, when available, to a subset of candidate components for repurpose: Integrated circuits, printed circuit boards, camera, battery and shell.

An excerpt from the LCA results has been provided, alongside an example to picture their extent: avoiding the global warming potential of 28 kg of CO2e (27 kg of CO2e avoided in raw material extraction & production+ 1 kg of CO2e avoided in end of life for key components of the smartphone) is the same as avoiding a trip by car from central Göteborg to Landskrona. The value of human toxicity potential of the key components of the smartphone is around one third of the human toxicity potential caused by working in a rough mill producing raw material for furniture in Indonesia.

This is a preliminary, partial consideration about environmental savings that are possible to achieve through repurposing. Additional figures about savings and burdens in terms of GWP will be provided in WP4 deliverable, against the novel product concept designed in ReSmaC.

1. Background

In order to promote a full understanding of ReSmaC's goal and scope, this document starts by clarifying the meaning of key words that are part of the project title. For starters, a definition of the umbrella key word of the project – circular economy - is given. Then, a definition of repurposing and smartphone capabilities is specified. To conclude, key figures of the challenge pertaining smartphones' end of life are provided.

Circular Economy

The term 'Circular Economy' has been conceptualized with at least 114 definitions, given the review by (Kirchherr, Reike, and Hekkert 2017). The authors of this document selected the one which encompasses the goal of ReSmaC in simple terms. According to the Ellen MacArthur Foundation, circular economy decouples economic activity from the consumption of finite resources, and designs waste out of the system. For this to happen, a circular economy looks beyond the take-make-dispose extractive industrial models and redefines growth, focusing on positive society-wide benefits (Ellen MacArthur Foundation).

The authors of the studies done in ReSmaC aimed indeed at realizing a viable business model which captures value from products and services that would be otherwise lost in linear business models and that would guarantee long-term environmental savings.

The goal of the project is in fact delivering a novel product concept whose key components come from still-functioning smartphones' components.

Repurpose

The three Rs of *Reduce, Reuse, and Recycle* have been central to the concept of the Circular Economy (Murray, Skene, and Haynes 2017). A further "R" that has been added to the triad is *Repurpose*. Repurposing means using something for a different purpose to the one for which it was originally intended (Cambridge Dictionary). In ReSmaC, the protagonist of the repurposing strategy is a smartphone, or, better yet, key components of it. Unlike industrial symbiosis, repurposing products happens at a later date after their consumption (Gregson et al. 2015). This determines the technical system boundaries of the smartphone's life cycle that concern ReSmaC: use phase and the end-of-life (EoL) phase.

Smartphone capabilities

The term "capabilities" relates to the capacity of still-functioning components of used smartphones to deliver a service or a specific functionality. These functionalities are: powerful

Figure 1: A disassembled Sony Xperia Z5. Source: IFixIt webpage

CPUs, data storage, a vast array of sensors such as: microphones, cameras, lighting and proximity sensors, gyro, compass, accelerometer and GPS, connectivity in the form of mobile data, Wi-Fi and Bluetooth, integration with platforms for distribution and monetization of software and content through Google Play and Apple App Store.

The goal of ReSmaC is to install these capabilities in a novel product concept within a viable business model.

The challenge

High turnover rates of smartphones

Although the real-life expectancy of a mobile phone (aka, when the device's performance starts remarkably degrading) ranges from 3.5 years to 4.7 years (Puustinen and Zadok 2010), mobile phone users worldwide change their device at an average frequency of 18 months (Bossuet 2014). Such a high turnover rate stems partially from the frequency with which offers telecommunication service providers place to the smartphone's industry consumer population. In fact, when a contract that binds the customer to the carrier for a defined time period (e.g., two years) is about to expire, the customer is given the option to upgrade his/her phone for free or for a discounted price. As a result, such offering induces customers to upgrade their phone at least once every two years. (Venkitachalam et al. 2015).

Increased demand for devices and mobile data connectivity triggers environmental and social hazards

Furthermore, on a global scale, Statista's data forecasts an increase of number of shipments of smartphones from 1.45 billion by the end of 2018 to 1.71 in 2021 (Statista 2018a).
This high turnover rate, fuelled by an intrinsic increased demand for mobile phones worldwide, causes not only increased overexploitation of environmental, non-renewable resources, but also

hazardous human health conditions in the developing countries that host informal recycling activities. E-waste has in fact become the fastest growing waste stream (Orlins and Guan 2016).
In the Swedish market, counting a population of 9.98 million people today, there were 12.6 million mobile phone subscriptions and 8.2 million smartphone users in 2017 (Statista 2018b).

Non-appraised material and functional value loss in current smartphones' end of life strategies

Hibernation refers to the dead storage period when a mobile phone is still retained by the user at its end-of-life (Wilson et al. 2017). As reported by UNEP (2009), a smartphone contains more than 40 different elements many of which are classified as having a high risk of supply disruption. Given the figures previously provided and the high material and functional value contained in functioning used phones, it appears clear that a user who either hibernates or disposes the device before the performance decay contributes to enhanced value losses both in material and in functionalities. Figure 2 shows which "R" strategies decrease the sustainability performance of a mobile phone's supply chain as they are closer to the bottom of the illustration.

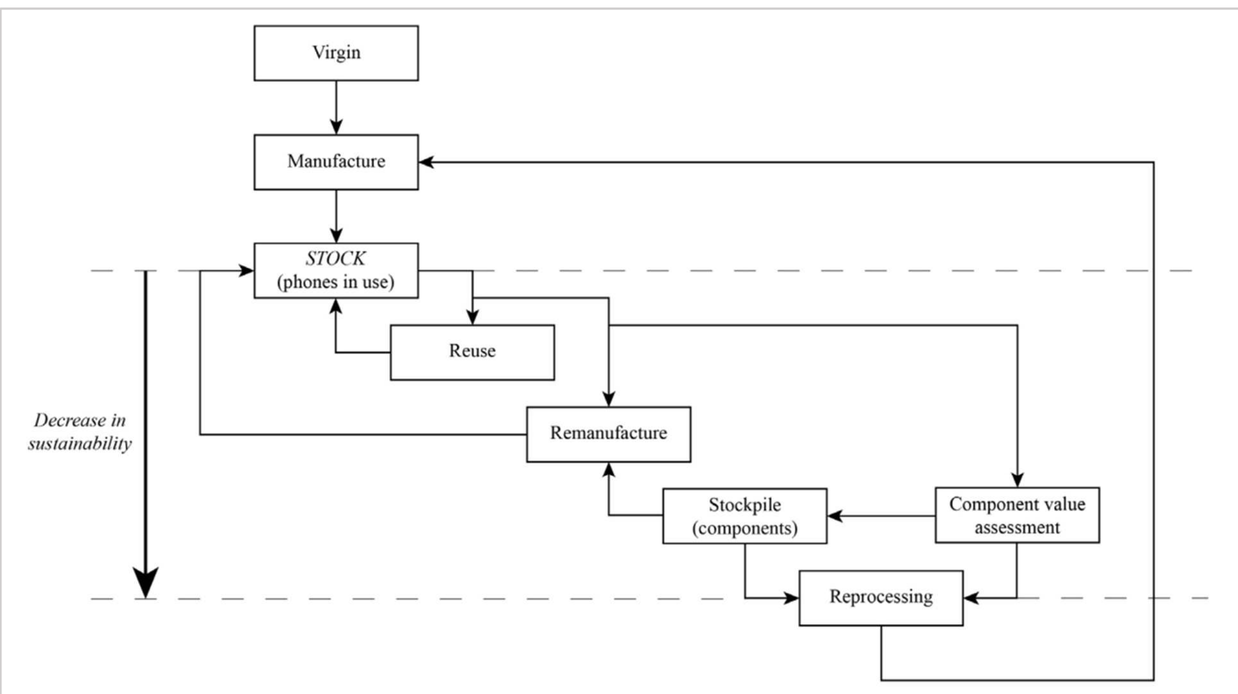

Figure 2: Stocks and flows system of a mobile phone. From Wilson et al. (2017) and adapted from Lee et al. (2017)

To conclude, a copious amount of mobile phones that are currently being taken care of by the collection schemes drawn from the WEEE (Waste Electrical and Electronic Equipment) Directive, or stored in households and not yet collected contain advanced and still-working functionalities whose value is still poorly tapped.

2. Current state of material stock and flows in the smartphones' end of life

Material Flow Analysis (MFA) is a common technique adopted to visualize products' EoL management strategies. It is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger 2016), based on the principle of mass conservation.
A task that the authors of this study aimed at carrying out was in fact a MFA of smartphones' EoL in Sweden. As the investigation progressed, it occurred that the size each stock and the rate of each flow within the Swedish market could neither be retrieved from published scientific studies nor from first-hand interviews. Important reasons that explain data unavailability are the following:

- The figures provided by El-Kretsen[1] do not count smartphones and mobile phones separately. In fact, they belong to the e-waste stream item "ICT[2]-products". There are also no estimations available, neither in Sweden or on an EU base, about the percentage of used mobile phones to the total amount of ICT product waste.
- Private companies that operate in the electronics' second-hand market treat their data confidentially.

The few available data pertaining smartphones' use and EoL does not offer opportunities for aggregation in a comprehensive MFA. In fact, much of this data does not refer to the same year, and high variations between one year and the following one that exist in the electronics' consumer market would jeopardize the reliability of the whole analysis. Furthermore, data of each stock and flow does not come from the same source (often not being a scientific study), which means that the reliability of the whole analysis would be jeopardized by different accounting methods and different assumptions used by the different studies.

However, it is still possible to understand the current use phase and EoL phase of a smartphone through a flowchart (Figure 3 at page 10) and link this visual representation to the small set of key figures available.

[1] El-Kretsen is a non-profit organization and nationally-approved collector of e-waste in Sweden.
[2] ICT stands for information and telecommunication technology.

Figure 3 illustrates several different status where a smartphone can exist in the Swedish market and therefore illustrates the main players in the smartphone's reverse logistics. The main skeleton of the illustration is an adaptation from Tojo and Manomaivibool (2011).

Use phase:

A brand-new smartphone is shipped to Sweden by the electronics' manufacturer, is sold in the telecommunication service provider's retail store and used.

In 2017, the number of mobile subscriptions in Sweden accounted for 14.4 million (Fransén and Wigren 2018)

After the use phase, the customers disposes the phone or, as happening in the vast majority of the cases, hibernates it before disposing it.

End of life:

Hibernation:

Figures from 2008 estimated 15 million units of mobile phones "hibernating" in households (Computer Sweden 2008), whereas a survey made by the operator Tele2 and published in 2015 showed figures of 11.8 million units (Feber 2015).

Disposal and EoL management (reverse logistics):

The user could choose to dispose the smartphone through one of these options:

1. Dump the phone together with non-separated waste streams. This results in the phone ending up in a landfill.
2. Dispose the phone in recycling stations (in households, stores, etc). The phone is then handled by El-Kretsen within the ICT-products stream. Its handling is regulated by the WEEE Directive (Naturvårdsverket 2009).
3. Sell the phone in the second-hand market for reuse or for components' recycling. The sell may happen either to a private citizen or to a private organization[3].

If the phone is still functioning, it appears evident that option 1 entails the major environmental loss whereas option 3 entails a fewer loss in comparison to the scenario of keeping on using the phone instead of replacing it.

[3] A global survey carried out by Deloitte predicted that "in 2016 consumers will sell outright or trade in approximately 120 million used smartphones generating an average value of $140 per device. This is a 50% increase from the 80 million smartphones traded in 2015 (Deloitte 2016).

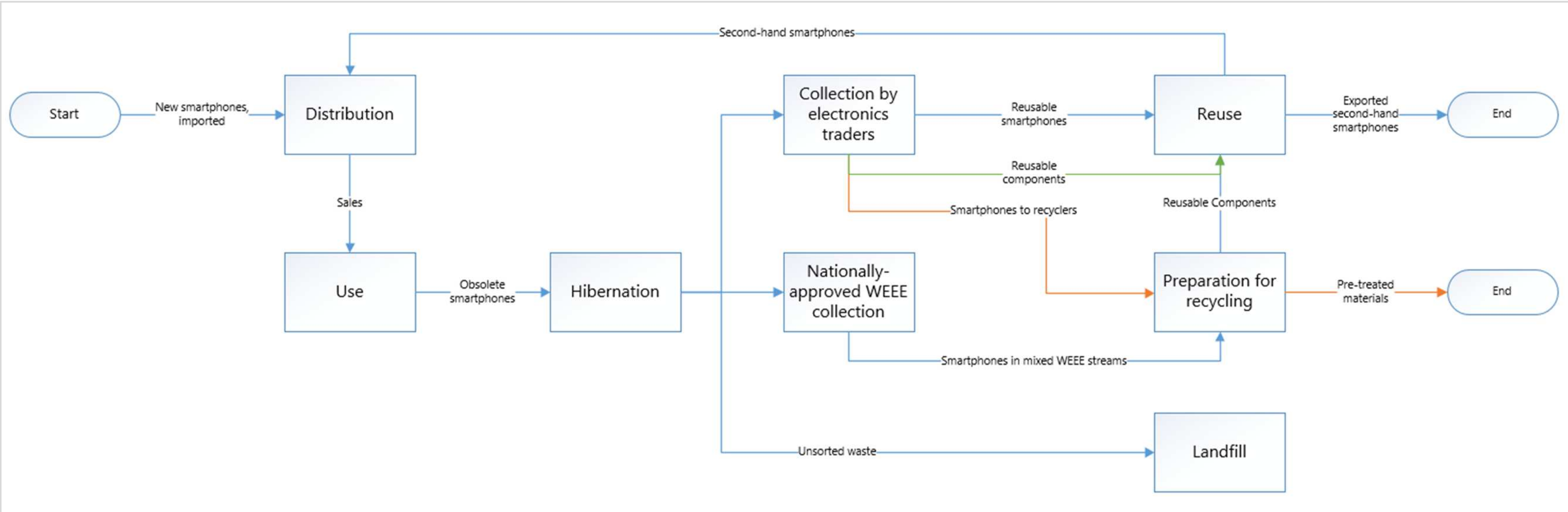

Figure 3: Modelling of stocks and flows of current smartphones' use and end of life - Swedish market. Orange arrows represent the flows that ReSmaC aims at reducing the rate of, whereas green arrows represent the flows that ReSmaC aims at increasing the rate of. Adapted from Tojo and Manomaivibool (2011).

In order to simplify the illustration in figure 3, the box "Reuse" refers not only to the reuse of the entire smartphones when still functioning, but also reuse of working components in other smartphones.

In ReSmaC, option 3 in the aforementioned list lays the starting point for achieving greater environmental gains from the smartphones' second hand market, where the "R" of "repurpose" is added to the option of Recycle and Reuse. This is corroborated by Zink et al. (2014) whose study compared the reuse[4] of a smartphone with two possible reuse alternatives in semi-novel products carrying the smartphone's core structure. The findings show robust results of the environmental gains achieved by repurposing, which "allows freedom to target reuse opportunities with high displacement potential."

Suitable smartphone models: preliminary consideration

In the desired future state of the rudimental MFA in Figure 3, repurposed components of a smartphones contribute to the creation of a new electronic device that it is not a smartphone. The intention of ReSmaC is creating a product concept owning a positive social or environmental connotation.

It is licit to state that the set of smartphones' models suitable for the ReSmaC product concept can be narrowed once the product concept itself is defined. This in turn allows for volume scenarios of the producibility of the product concept to be drawn. Further details on the matter are available in WP3 and WP4 deliverable.

Smartphones produced by electronic devices' manufacturers that do not allow any manipulation of the phone and its components have been excluded.

All in all, the project partners of ReSmaC aim at using almost a 100% between materials and components of a smartphone which is not suitable for reuse wholly.

[4] Called "refurbishment" in the study.

3. Environmental product data – Baseline

A reliable account of the value of the environmental impact of a given smartphone in each of its key components is challenging to get. In an extensive review of the most recent and highly-cited literature related to life cycle assessment (LCA) (ISO14044 2006) applied to ICT products, André (2018) showed how "the representation of use patterns [of the product] and methodological choices, such as functional unit, inventory approaches and system boundaries cause LCA results to diverge significantly". This means that the values of life cycle assessment indicators of a smartphone that will be chosen in ReSmaC are the ones whose information is deemed methodologically transparent and easily related to the project case.

A more comforting finding is that the same literature review by (André 2018) showed overwhelming evidence that manufacturing and use phase are the most environmentally burdensome life cycle phases for ICT. Furthermore, within manufacturing, printed circuit boards (PCB) and especially integrated circuits (ICs) are the most burdensome components (Andrae and Andersen 2010; Arushanyan 2013; Arushanyan, Ekener-Petersen, and Finnveden 2014), due to process energy-intensity and the production of high-purity silicon.

Because of this, the environmental impact of ICT products' EoL phase has had low coverage in scientific studies. In fact, the current most pressing environmental issues trigger a higher focus on climate change and energy use, whose impact results are negligible in the EoL phase in comparison with the manufacturing and use phase (Arushanyan, Ekener-Petersen, and Finnveden 2014). This focus unintentionally obscures impact categories which the EoL phase affects significantly, such as resource use and human toxicity (André 2018).
The unavailability of data pertaining mobile phones' EoL - discussed in the previous section - is also deemed a contributing factor to the low coverage of solutions to reduce the environmental impact of smartphones' EoL strategies.

A list of values of life cycle assessment impact categories (LCIA) of a smartphone concludes this deliverable. This specific data has been surveyed across a set of published LCA studies in scientific journals and scientific reports: Ercan (2013), Andrae and Vaija (2014), Zink et al. (2014) Suckling and Lee (2015), Andrae (2016) and (Ercan et al. 2016). The studies that have been selected for values of global warming potentials are Ercan (2013) and (Ercan et al. 2016), as the functional unit of the study was a Sony Xperia™ T (likely to feed components to the product designed in ReSmaC). Both the study used Gabi software as modelling tool for LCA and data sets from Ecoinvent and

Gabi's data itself. The study that has been selected for values about human toxicity[5] is Ercan et al. (2016).

Table 1, Table 2, Table 4 show the data that will constitute the baseline for the environmental evaluation of the product concept realized in ReSmaC. The green values marked in the tables relate to the avoidance of the environmental burden occurred in the phases of raw material extraction and production for the key components of the product concept. Similarly, the burden avoidance applies also to the end of life processing of these key components. The red values marked in the tables relate to the increased environmental burden given by the product concept's use via the repurposed components.

Table 1: Global Warming Potential (GWP) of a Sony Xperia™ T in the Swedish market. Source: Ercan (2013) and (Ercan et al. 2016).

GWP [kg CO_2e]	Raw material extraction + Production	Use[6]	End of Life
Entire smartphone	35.4	3.8	1

Table 2: Global Warming Potential (GWP) of a subset of components of a smartphone that would be suitable for repurposing in ReSmaC. Sources Ercan (2013) and Ercan et al. (2016).

GWP [kg CO_2e]	Raw material extraction + Production
Most environmentally burdensome components (Total) of which:	27
Integrated Circuits	19
Shell	4
Printed Circuit Board	2.1
Battery	1.4
Camera	0.5[7]

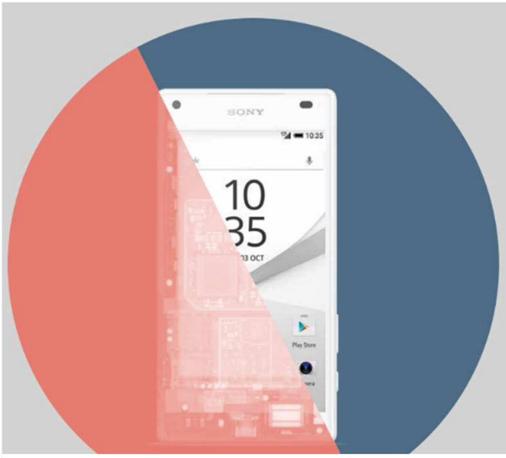

Figure 4: A figurative representation of a Sony smartphone to be repurposed in ReSmaC. Illustration by Boid.

[5] The Human Toxicity Potential (HTP) is a quantitative toxic equivalency potential (TEP) that has been introduced previously to express the potential harm of a unit of chemical released into the environment (McKone and Hertwich 2001).

[6] 3-year life span, network coverage excluded

[7] Variability of ± 0.1 Qualitative estimation from extent of the bar chart provided in Ercan (2013).

The scientific literature offered no figures per component about use phase and end of life phase. Estimations about the precise environmental burden given by the use of the components highlighted in Table 2 will depend on the precise design of the product concept and the functionalities it provides. Further details can be found in the WP4 deliverable. For now, it is possible to consider a value slightly < 3.8 kg of CO_2e. (value in Table 2) as the maximum extent of GWP added by the product concept, in case it is going to use the functionalities of a smartphone fully. Therefore, considering a value slightly < 3.8 kg of CO_2e for a 3-year life span of the product concept would entail a conservative position in evaluating the environmental cost and benefit of the product concept created in ReSmaC.
When it comes to the end of life phase, the saved environmental burden can be considered close to the one of the entire smartphone, therefore ≈ 1 kg of CO_2e. The reason behind this assumption is that the components represented in Table 2 are also the bulkiest ones and therefore would be responsible for the highest effort spent in recycling activities.

Avoiding a GWP of 28 kg of CO_2e (27 kg of CO_2e avoided in raw material extraction + production+ 1 kg of CO_2e avoided in end of life) is the same as avoiding a trip by car from central Göteborg to Landskrona[8].
This is a preliminary, partial consideration about environmental savings that are possible to achieve through repurposing. Additional figures about savings and burdens in terms of GWP will be provided in WP4 deliverable.

Figures related to human toxicity indicator for the same smartphone model analysed in Ercan (2013)[9] were found in (Ercan et al. 2016) and reported in Table 3. In it, cancer potential is indicated with "HumToxCan" and Human Toxicity non-Cancer potential is indicated with "HumTox".

Table 3: Human Toxicity Potential of a Sony Xperia™ T. Source: Ercan et al. (2016).

Human Toxicity [CTUh[10]]	Raw material Extraction + Production	Use	End of Life
Entire smartphone			
HumToxCan	$1*10^{-7}$	N/A	N/A
HumTox	$\approx 5*10^{-6}$	Negligible	N/A

[8] Central Göteborg – Landskrona is 237 km. Average CO_2 emissions from cars in EU measured through the NEDC test in 2016 are 0.1181 kg CO_2e (European Environment Agency 2017).
[9] Ercan (2013) analysed GWP only.
[10] In practice: disease cases per kg emitted = CTUh (comparative toxic units) per kg of chemical emitted.

Also for the case of human toxicity indicators data is available with less granularity than desired. In fact, data provided by Ercan et al. (2016) relates to the whole smartphone and does not come drilled down per each key component. A rough estimation of saved environmental burden from the spared production of the set of components of interest (ICs, PCBs, Camera, Battery, Shell) would argue for a reduction of the human toxicity potential of 10 percentage points from the human-toxicity value calculated for the whole smartphone. To exemplify the figures in Table 4, $0.9*10^{-7}$ is around one third of the human toxicity potential caused by working in a rough mill producing raw material for furniture in Indonesia (Rinawati, Sari, and Prayodha 2018)[11].

Table 4: Estimation of Human Toxicity Potential of a Sony Xperia™ T for the following set of components: ICs, PCBs, Camera, Battery, Shell. Values are 90% of values in Table 3.

Human Toxicity [CTUh]	Raw material Extraction + Production	Use	End of Life
Subset of key components suitable for repurpose			
HumToxCan	$0.9*10^{-7}$	N/A	N/A
HumTox	$\approx 4.5*10^{-6}$	Negligible	N/A

The values displayed in Table 4 also contribute to the accounting of environmental savings delivered in WP4.

[11] CTUh in rough mill: 0.000000263.

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