The IMRE Journal Volume 9 (3) 2015
2015. TU Bergakademie Freiberg
http://tu-freiberg.de/fakult6/imre/imre-journal

Cost-Benefit Analysis of WEEE Recycling in Germany

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Revised: 21.10.2015
Online Publication Date: 14.12.2015

Abstract

The paper analyzes the monetary value of precious and critical metals stocks in selected electronic equipment sold during 2004-2014 in Germany and at global level, as well as the value of the metals stock which is not being put to use. Initially a literature review on the definition of critical metals is being provided, followed by an analysis of the precious and critical metal stock content and monetary value for Electrical and Electronic Equipment (EEE). The stocks of precious and critical metals inside mobile phones and smartphones are assessed on the basis of sales volumes. Moreover, a cost benefit analysis of the end-of-life management of mobile phones and smartphones is being realized reaching the conclusion that the potential revenues from recycling these products can be quite significant. Furthermore, the issues and challenges in the German Waste Electrical and Electronic Equipment (WEEE) Management System are also being analyzed with a closer look at mobile phone and smartphone waste streams with the goal of identifying the potential of closing the resources loop.

Keywords: Waste Electrical and Electronic Equipment, Recycling, Cost-Benefit Analysis

Introduction

Scarcity of natural resources and supply chain risks represent one of today's most vital topics. As Tiess wrote, "raw materials are the foundation of development and growth in every national economy" (Tiess, 2010).

The domestic raw minerals' production of the European Union is only about 3% of the global production, which makes the EU very much import and recycling dependent (European Commission, DG Enterprise and Industry, 2010). As such, ensuring opportunities for a secure supply of minerals is a very important task for the European Union, and in consequence, in 2008, the EU Raw Materials Initiative was set up as an integrated strategy to increase resource efficiency, reduce raw materials consumption, promote recycling and provide a framework for sustainable supply of minerals (European Commission, DG Enterprise, 2008b).

This issue very much applies to the electrical and electronic equipment (EEE) sector, as its production requires a mixture of various different kinds of raw materials, metals and precious metals, partly classified as critical by the European Commission. Since the beginning of the 1990's, the global market of EEE continuously grew at a high rate, and it is expected to continue to grow, while the lifetime of these products reduces as a result of rapid technological innovations and changes in consumers' interaction with the products they buy. According to Khurrum, M., Bhutta, S., et al., (2011), the United Nations University estimates that 20 to 50 tons of Waste from EEE (WEEE) are being generated each year globally (Khurrum, M., Bhutta, S., et al., 2011). In Europe, WEEE is the fastest growing solid waste stream and it is continue to grow (Computer Aid International, 2010).

The paper analyses the monetary value of precious and critical metals in selected EEE sold from 2004 to 2014 in Germany and at global level as well as the value of the metals stock which is not being put to use. Initially, a literature review of the definition of critical metals by the US National Research Council and the European Commission is provided, followed by an analysis of the precious and critical metal stock content and monetary value for selected EEE such as mobile phones and smartphones. Overall, for the selected EEE, a total stock of 5.6 thousand tonnes of precious and critical metals can be estimated, with a total monetary value of more than € 558 million. However, the short life-cycle of these products combined with their inappropriate disposal when becoming waste leads to a major loss of these metals. Moreover, a cost benefit analysis of the end-of-life management of mobile phones and smartphones is being performed reaching the conclusion that the potential revenues from recycling these products can be quite significant. Furthermore, the issues and challenges in the German WEEE Management System are also being analyzed with a closer look at mobile phone and smartphone waste streams with the goal of identifying the potential of closing the resources loop.

1 Criticality

In general, metals are classified as „critical" based on their geological scarcity and supply risks. For example, in the USA, the term "critical metal" was first used in the Strategic and Critical Materials Stock Piling Act of 1939, and it defined "critical" materials as "materials that are needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency that are not found or produced in the United States in enough quantities to meet such needs" (DeYoung et al., 2006). The National Research Council of the US defines critical metals as materials which perform an essential function in key applications for which substitutes are not easy to find, and which possess a high possibility of supply risks (National Research Council, 2008). Robinson describes critical metals as those on which the economy and security of a nation depend on (Robinson, 1986).

According to the European Union, metals can be classified as critical "when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials". The supply risk depends on the economic and political stability of the manufacturing countries, the production level, the possibility or substitution as well as recycling rates (European Commission, 2010). Table 1.1 contains the twenty critical materials identified by the European Commission.

Table 1.1: List of critical raw materials at EU level:

Antimony	Cobalt
Gallium	Magnesium
PGMs	Silicon Metal
Beryllium	Coking Coal
Germanium	Natural Graphite
Phosphate Rock	Tungsten
REEs (heavy)	Niobium
REEs (light)	Fluorspar
Chromium	Magnesite
Borates	Indium

Source: European Commission, 2014

According to the literature the term strategic is used for national security and military needs or requirements during national emergencies, while a critical material has a larger meaning. "*In accordance with these definitions, a critical material may or may not be strategic, while a strategic mineral will always be critical*" (National Research Council, 2008).

Whereas the definition of critical metals in the European Union is very new, the term "precious metal" has been in use for a longer time period and it is not based upon a precise definition. It seems that this term is used in a generic way to distinguish a particular metal with a so-called high value (as expressed by a particular market price) from another metal which does not have this high-value characteristic. For example, gold is seen as a precious metal and lead is not a precious metal. With the entrance of the definition of critical metals by the European Commission, confusion occurred since PGM are considered to be both critical and precious. Silver and gold, however, are considered to be precious but they are not critical. Since they are contained in the electronic products studies in this paper, a pragmatic approach towards the definition of precious metals had to be chosen. Hence, in this paper, precious metals include silver and gold whereas PGM are included in the category of critical metals. The wordings “critical and precious metals”, therefore, include all critical metals of the European Commission definition and silver and gold.

2. Methodology

Qualitative and quantitative data were employed to conduct the study. The qualitative data was fundamental to understand the subject matters; raw materials, electrical and electronic waste management and materials recycling. As a result, a comprehensive understanding of mobile phones and smartphones recycling can be obtained.

For the quantitative section, data such as the numerical values for the sales of mobile phones and smartphones in Germany, collection rates, reuse rates, recycling rates[1], and content of precious and critical metals in mobile phones and smartphones, as well as costs involved at each step of the recycling chain were obtained through an extensive literature research.

Subsequently, formulas have been developed to conduct the study based on the data found. The research method was descriptive quantitative.

To forecast the potential total value of precious and critical metals content in mobile phones and smartphones in Germany and to perform a cost-benefit analysis, several fundamental aspects are needed in order to establish the end results, including:

- Sales of mobile phones and smartphones. Sales values for 2004-2014 have been retrieved to estimate available stocks of mobile phones and smartphones (Bundesverband Technik des Einzelhandels e.V. (BVT), 2015).
- Reserves of mobile phones and smartphones have been calculated by assuming a 2 years life time of mobile phones and smartphones. The 'reserves' also include 'stocks', which are the non-collected mobile phones from previous years. The 'reserves' are available for recycling in a particular year.
- Identification of collection rates of mobile phones and smartphones (Öko-Institut e.V., 2012). The amount of collected mobile phones and smartphones is calculated by multiplying the collection rate with the amount of reserves.
- Identification of content of precious and critical metals in mobile phones and smartphones (Geyer & Blass, 2009; World-UN, 2009).
- Calculation of stocks of precious and critical metals in mobile phones and smartphones sold in Germany. To obtain the total stock of precious and critical metals contained in mobile phones and smartphones, the content of precious and critical metals (e.g. gold) contained in a mobile phone or a smartphone was multiplied with the amounts of mobile phones and smartphones sold. Similar calculations have been performed to identify the stocks of precious and critical metals contained in amounts of mobile phones and smartphones collected and amounts recycled.
- Calculation of potential monetary value of the precious and critical metals content in mobile phones and smartphones as well as monetary value not put to any use due to inefficiencies in the recycling process.
- Identification of recycling rates of precious and critical metals based on UNEP estimations (UNEP, 2013).
- Calculation of the potential monetary value of recycled materials (the prices for the precious and

[1] Informal collection and treatment rates have not been considered in this study.

critical metals have been retrieved from: Die Recyclinghütte, 2014; Institut für Seltene Erden und Metalle, 2014; Infomine, 2014; Finanzen.net, 2014).

- Cost benefit analysis for mobile phones and smartphones recycling in Germany

3. Critical and precious metals stocks in mobile phones and smartphones sold in Germany

Based on the raw material composition of mobile phones (Geyer & Blass, 2009; World-UN, 2009) and smartphones (Öko-Institut, 2012), and according to the list of critical metals issued by the European Union (2014), the following twelve precious and critical metals have been selected for further analysis in this paper: *Gold, Silver, Palladium, Cobalt, Gallium, Indium, Chromium, Magnesium, Antimony, Beryllium, Praseodymium and Neodymium*. Copper is also taken into account due to its high content in the composition of both mobile phones and smartphones.

From 2004 to 2014, more than 159 million mobile phones have been sold in Germany (Bundesverband Technik des Einzelhandels e.V. (BVT), 2015), accounting in total for more than 5 thousand tonnes of precious and critical metals contained in them. Taking the average amounts of the selected critical and precious metals contained in a typical mobile phone and multiplying with the volume of sales, the following total stocks of these metals can be calculated (Table 3.1 – see at the end).

Highest metal potential content is represented by copper (2.394 t), followed by magnesium (1.860 t) and cobalt (607 t). Making use of average base metal prices, the monetary value of the metals in a typical mobile phone is estimated to be around € 2.7. Hence, the total monetary value of these metals in the entire stock of mobile phones sold in the same time period can be estimated at € 439 million. Since only around 5% of all mobile phones are recycled (Öko-Institut e.V., 2012), equivalent to 7,987,550 mobile phones, an estimated monetary value of approx. € 303 million is not put to use. It can be considered as a "hidden treasure".

A similar analysis can be performed for smartphones which entered the market at a later date. From 2009 to 2014 around more than 90 million smartphones were sold. The critical and precious metals contained in this stock comprises more than 600 tonnes, with the highest amount represented by cobalt (approx. 567 tonnes), followed by silver (approx. 27 tonnes) and gold (approx. 2.7 tonnes). Similar to the case of mobile phones, the monetary value of critical and precious metals in a typical smartphone is estimated at € 1.32 and the total monetary value of these metals in all smartphones sold during the same time period can be set at around € 119 million. This value is three times less than that for mobile phones and it is due to the differences in the time periods and, eventually, also to advances in design resulting from technological developments. Assuming the same 5% collection and recycling rate (representing about 4,503,900 smartphones), an estimated monetary value of € 104 million is not put to any use. Since it is expected that the market for smartphones will continue to grow, and, if present low collection rates are kept, it can be assumed that the value of the total materials stock not put to use will continue to grow in the future.

At global level similar results can be calculated and they are shown in Table 3.2. More than 7.5 thousand tonnes of silver, 1.3 thousand tonnes of palladium and 438 tonnes of gold are contained in more than 14 billion mobile phones (14,871,825,200) sold from 2004 to 2014. The estimated monetary value of these metals is calculated at almost € 41 billion (40,842,009,392).

Table 3.2 Monetary value of metals in global sales of mobile phones (2004-2014)

Mobile phones				
Worldwide sold units between 2004-2014				14.871.825.200
Monetary value of sales between 2004-2014 (€)				40.842.009.392
Collection rate				5%
Unused material value				38.799.908.922
Metal		Metal price (€/g)	Mobile phone precious and critical metals composition (g)	Metals potential of mobile phones (t)
Gold	Au	29,5100	0,0295	438,72
Silver	Ag	0,4033	0,5050	7.510,27
Palladium	Pd	16,5000	0,0900	1.338,46
Cobalt	Co	0,0195	3,8000	56.512,94
Gallium	Ga	0,1995	0,0009	13,38
Indium	In	0,3251	0,0062	92,21
Copper	Cu	0,0051	14,9900	222.928,66
Chromium	Cr	0,0017	0,4600	6.841,04
Magnesium	Mg	0,0017	11,6450	173.182,40
Antimony	Sb	0,0081	0,0030	44,62
Beryllium	Be	6,5290	0,0020	29,74
Total				468.932,44

Source: Self-prepared

Overall, for the selected products, a total stock of 5.6 thousand tonnes of critical and precious metals can be estimated, with a total monetary value of more than € 558 million. Given the considered collection rate, as shown above, it can be estimated that most of this monetary value is not put to any use (€ 408 million). The monetary value of the precious metals gold, silver and palladium account for 93 % to 89% of the total monetary value of the selected products.

In addition to this apparent neglect of a "hidden treasure", it should also be noted that the concentration rates of gold and silver in the analyzed products are much higher than in deposits which are currently mined. Taking the example of gold, it is reported that the average concentration of gold in deposits which can mined is around 5 grams per tonne of ore (Gunn, 2014). In mobile phones and in smartphones, the gold concentrations are substantially higher (Table 3.3):

Table 3.3 – Gold content of selected electronic equipment (g/unit)

Electronic equipment	Gold content (g/unit)	Gold content (g/t)
Mobile phones	0,0295	261,06
Smartphones	0,03	177,51

Source: Self-prepared

Assuming an average weight of a mobile phone of 113 g (Nokia, 2005), resulting in 8.849,55 units per tonne of mobile phones, a total amount of 261.06 g gold/tonne of mobile phones can be calculated. This is 52 times more than in a tonne of primary ore. Based on a similar computation, and assuming 169g (SpecTRAX, 2012) as the average weight of a smartphone (resulting in a number of 5.917,159 units), the current stock of smartphones contains about 177.51 g gold per tonne. If this gold is not being used, a substantial source of supply is neglected.

Recycling critical and precious metals

According to Chancerel (2010) 5% of amounts collected in Germany are reused. By discounting the amounts of mobile phones and smartphones being reused, the potential precious and critical metals available for final treatment can be calculated. Overall, for the selected products, a total stock of 2.1 thousand tonnes of critical and precious metals can be estimated, with a total monetary value of more than € 142 million. This would mean that only 37% of the precious and critical metals content makes it to final treatment.

Next, UNEP recycling rates have been considered in order to calculate the amounts of precious and critical metals which could potentially be recycled. Based on the calculations, only 931 tonnes of precious and critical metals, 0.02% of total amount of precious and critical metals contained in mobile phones and smartphones can potentially be recycled in final treatment, with an estimated monetary value of € 70 million, representing 12% of the total monetary value of precious and critical metals contained in the mobile phones and smartphones sold during 2004 - 2014 in Germany (Figure 3.1).

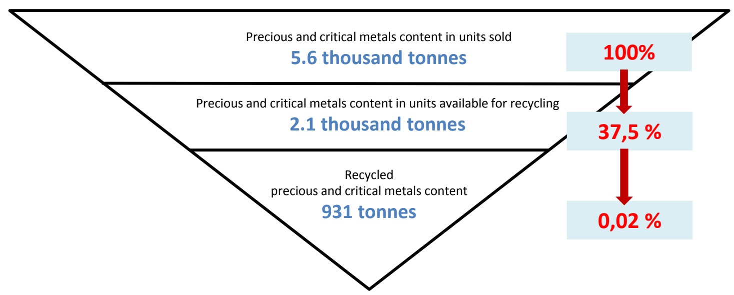

Figure 3.1: Precious and critical metals stocks along the recycling chain
Source: Self-prepared

The major reason for the large "hidden treasury" monetary values which are not put to use clearly relates to the currently level of collection and recycling, in particular the very low collection rates at the end-of-life stage of mobile phones and smartphones. It seems that consumers do not have any substantial incentives to return these products at the end-of-life stage. Consumers are, however, vital for the creation of circular material supply chains since they are physically holders of these products. The creation of materials cycles also requires a receiving and processing industry, which currently is developed at a very small level.

4. Cost benefit analysis

A cost-benefit analysis allows for an evaluation of the actual situation of WEEE recycling in terms of costs and revenues. The economics of WEEE end-of-life treatment are shaped by several activities including collection, transportation, pre-processing and final treatment. First, data has been collected through literature research regarding the costs of each step in the end-of-life management of mobile phones and smartphones (Table 4.1 – see at the end).

Next, the costs of each activity of the end-of-life treatment for each year from 2006 to 2013 were collected and cumulatively added (Table 4.2 – see at the end). For the analyzed time frame a total cost of almost € 3.1 million can be estimated for all activities in the end-of-life management of the considered products. Compared with the potential revenues from secondary materials recovered after final treatment which account around € 70 million, it can be concluded that mobile phones and smartphones recycling represent an important source of precious and critical metals.

From Table 4.2 it can be observed that 46% of the costs (€ 1.4 million) arise from a financial guarantee which all producers and importers in Germany must provide for the end-of-life treatment of their products. The formula for calculating the financial guarantee has been developed by the Clearing House (EAR)[2], as follows:

Financial Guarantee (in EUR) = Registration amount (in tons) x Expected return rate (as a percentage, as specified by EAR) x Estimated disposal costs (in EUR / tonne, as specified by EAR)

For the present study, for "Registration amount (in tons)", the amounts sold per year have been considered. The "Expected return rate" assumed by EAR for mobile phones is 32% (the same has been assumed by the author for smartphones). If the collection rate of 5% considered in the present study would have been used, the total costs for guarantee would have been much smaller. It can be concluded that probably the expected return rate calculated by EAR is much higher than actual present reality, leading to increased costs for the producers for the end-of-life management of their products.

Final treatment accounts for more than 30% of the costs (€ 954.5 thousand). Considerable costs occur during pre-processing (€ 632.5 thousand), while lowest costs arise at the collection level (€ 527) (Figure 4.1).

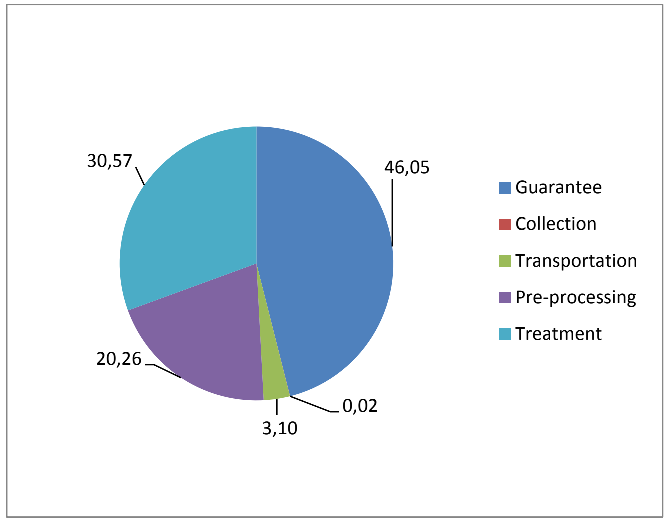

Figure 4.1: Share of recycling costs per activity (%)
Source: Self-prepared

Existing state-of-the-art metallurgical plants have the appropriate technology to achieve high recovery rates for valuable materials, as long as these materials reach the right material fraction. According to (Hagelüken & Corti, 2010), due to inefficiencies in collection, dismantling and pre-processing "less than 20% of the gold recycling potential from European WEEE is realized". According to the present study, just 0.02% of the precious and critical metals contained in mobile phones and smartphones can be recycled. As such, better and separate collection rates and specific focus that the precious and critical metals reach the right material fraction for an optimal recovering process can have a positive impact on recycling of WEEE.

Also, looking at the European WEEE II Directive[3], it still contains mass-based instead of value-based recovery rates. Hence, WEEE recyclers have an incentive to achieve such mass-based recovery rates and they tend to collect materials which dominate in terms of weight. In this process, they neglect valuable materials which are lost along the recycling chain[4] by ending up in materials fractions from which they cannot

[2] Clearing House (Stiftung Elektro-Altgeraete Register [EAR]) which is the designated authority carrying all functions and duties to ensure the proper implementation of the ElektroG (https://www.stiftung-ear.de/)

[3] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE)

[4] A recycling chain is defined as "the sequence of operation leading to the recovery of materials from waste. These operations include (1) collection which is the beginning of any waste management process, (2) preparation for material recovery which covers manual and/or mechanical operations & sorting and (3) material recovery which consists in chemical, physical or metallurgical operations, but does not include incineration for energy recovery and the reprocessing into materials that are to be used as fuels" (European Association of Metals, 2013)

be recovered. A value-based recovery objective would, instead, set incentives to increase the collection of small WEEE and extract valuable materials in low concentrations, such as found in mobile phones and smartphones. Hence, the current mass-based recovery rates of the European WEEE II Directive have a prohibitive effect on the recovery and recycling of mobile phones and smartphones.

5. Conclusion

The outcomes of the study can be summarized as follows: (a) the precious and critical metals stocks in selected electronic equipment have been identified; (b) the monetary value of the precious and critical metals in the selected products has been calculated; (c) the value of metals not put to any use due to the low collection rates and inefficient pre-processing has been estimated; (4) a cost benefit analysis of mobile phones and smartphones recycling has been realized; (5) major issues and challenges in the management of WEEE have been identified. Based on the case study of Germany on a limited number of types of electronic equipment it can be assumed that the urban mine potential of the planet is huge.

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Table 3.1: Stock of precious and critical metals contained in mobile phones and smartphones sold in Germany (2004-2014)

			Mobile phones			**Smartphones**		
Units sold (2004-2014)			**159.751.000**			**90.078.000**		
Monetary value of units sold (€)			**438.718.971**			**119.044.042**		
Collection rate			**5%**			**5%**		
Unused material value			**303.974.937**			**104.201.911**		
Metal		**Metallpreis (€/g)**	**Mobile phone precious and critical metals composition (g)**	**Metal potential of mobile phones (t)**	**Monetary value of one mobile phone (€)**	**Smartphons precious and critical metals composition (g)**	**Metal potential of Smartphons (t)**	**Monetary value of one Smartphone (€)**
Gold	Au	29,5100	0,0295	4,71	0,8705	0,0300	2,7023	0,8853
Silver	Ag	0,4033	0,5050	80,67	0,2036	0,3050	27,4738	0,1230
Palladium	Pd	16,5000	0,0900	14,38	1,4850	0,0110	0,9909	0,1815
Cobalt	Co	0,0195	3,8000	607,05	0,0743	6,3000	567,4914	0,1232
Gallium	Ga	0,1995	0,0009	0,14	0,0002	0,0090	0,8107	0,0018
Indium	In	0,3251	0,0062	0,99	0,0020			
Copper	Cu	0,0051	14,9900	2394,67	0,0770			
Chromium	Cr	0,0017	0,4600	73,49	0,0008			
Magnesium	Mg	0,0017	11,6450	1860,30	0,0197			
Antimony	Sb	0,0081	0,0030	0,48	0,0000			
Beryllium	Be	6,5290	0,0020	0,32	0,0131			
Praseodymium	Pr	0,1650				0,010	0,9008	0,0017
Neodymium €/g	Nd	0,1034				0,05	0,0000	0,0000
Total				**5.037**	**2,7463**		**600,370**	**1,3164**

Source: Self-prepared

Table 4.1 Costs of mobile phones and smartphones recycling

Activity	**Guarantee**	**Collection**	**Transportation**	**Pre-processing**	**Treatment**
Costs	*Financial Guarantee (in EUR) = Registration amount (in tons) x Expected return rate (as a percentage, as specified by EAR) x Estimated disposal costs (in EUR / tonne, as specified by EAR)*	0,01 €/unit	13 €/t	85 €/t	135 €/t

Source: Self-prepared based on Das Elektrogesetz (2015), HP (2006), Walther et al. (2010), Walther & Spengler (2005).

Table 4.2: Costs of recycling per year and activity

	Sales (units)	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
COSTS	Mobile phones	18.000.000	20.000.000	20.740.000	24.000.000	20.809.000	16.550.000	14.629.000	10.821.000	6.891.000	4.306.000	3.005.000			
	Smartphones						2.947.000	7.702.000	14.547.000	18.380.000	22.374.000	24.128.000			
Guarantee (€/t)	Mobile phones			87.869	97.632	101.244	117.158	101.581	80.790	71.413	52.824	33.639	21.020	14.669	
	Smartphones								21.515	56.231	106.205	134.189	163.348	176.154	
				87.868,80	**97.632,00**	**101.244,38**	**117.158,40**	**101.581,21**	**102.305,94**	**127.643,69**	**159.028,53**	**167.827,81**	**184.368,27**	**190.822,91**	**1.437.481,94**
Collection (€/t)	Mobile phones			7,21	14,87	22,43	30,93	37,72	42,47	46,21	48,23	48,58	47,88	46,69	
	Smartphones								1,77	6,29	14,70	24,98	37,14	49,74	
				7,21	**14,87**	**22,43**	**30,93**	**37,72**	**44,23**	**52,50**	**62,93**	**73,56**	**85,01**	**96,43**	**527,82**
Transportation (€/t)	Mobile phones			1.322,10	2.725,00	4.112,10	5.669,29	6.914,25	7.784,13	8.469,43	8.840,76	8.904,87	8.775,90	8.557,82	
	Smartphones								323,73	1.153,61	2.693,91	4.578,26	6.807,13	9.117,24	
				1.322,10	**2.725,00**	**4.112,10**	**5.669,29**	**6.914,25**	**8.107,86**	**9.623,03**	**11.534,67**	**13.483,13**	**15.583,03**	**17.675,06**	**96.749,52**
Pre-processing (€/t)	Mobile phones			8.644,50	17.817,28	26.886,80	37.068,46	45.208,56	50.896,27	55.377,03	57.804,96	58.224,12	57.380,87	55.954,98	
	Smartphones								2.116,68	7.542,81	17.614,05	29.934,78	44.508,17	59.612,70	
				8.644,50	**17.817,28**	**26.886,80**	**37.068,46**	**45.208,56**	**53.012,95**	**62.919,84**	**75.419,02**	**88.158,90**	**101.889,04**	**115.567,67**	**632.593,00**
Treatment (€/t)	Mobile phones			13.043,03	26.883,12	40.567,43	55.929,76	68.211,73	76.793,48	83.554,17	87.217,49	87.849,92	86.577,60	84.426,18	
	Smartphones								3.193,70	11.380,77	26.576,50	45.166,31	67.154,98	89.945,04	
				13.043,03	**26.883,12**	**40.567,43**	**55.929,76**	**68.211,73**	**79.987,18**	**94.934,93**	**113.793,99**	**133.016,23**	**153.732,58**	**174.371,23**	**954.471,21**
Total															**3.121.823,50**

Source: Self-prepared