Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment

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Summary

The manufacturing of electronic and electrical equipment (EEE) is a major demand sector for precious and special metals with a strong growth potential. Both precious and special metals are contained in complex components with only small concentrations per unit. After the use-phase, waste electronic and electrical equipment (WEEE) is an important source of these "trace elements." Their recycling requires appropriate processes in order to cope with the hazardous substances contained in WEEE and to recover efficiently the valuable materials. Although state-of-the-art preprocessing facilities are optimized for recovering mass-relevant materials such as iron and copper, trace elements are often lost. The objective of this article is to show how a substance flow analysis (SFA) on a process level can be used for a holistic approach, covering technical improvement at process scale, optimization of product life cycles, and contributing to knowledge on economy-wide material cycles. An SFA in a full-scale preprocessing facility shows that only 11.5 wt.% of the silver and 25.6 wt.% of the gold and of the palladium reach output fractions from which they may potentially be recovered. For copper this percentage is 60. Considering the environmental rucksack of precious metals, an improvement of the recycling chain would significantly contribute to the optimization of the product life cycle impact of EEE and to ensuring the long-term supply of precious metals.

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Introduction

Due to the leverage of huge unit sales globally, the manufacturing of electrical and electronic equipment (EEE) is a major demand sector for precious and special metals with a strong further growth potential. Both precious metals (gold, silver, and platinum-group metals) and special metals such as selenium, tellurium, bismuth, antimony, and indium are contained in complex components with only small concentrations per unit. After the use phase, the waste electronic and electrical equipment (WEEE) is an important source of these "trace elements." Appropriate processes are required to cope with the hazardous substances contained in WEEE and to recover efficiently the resources.

To assess the recovery options for trace elements, the recycling chain for WEEE has to be analyzed. The recycling chain consists of several steps: collection, preprocessing, and end-processing. Each step is usually carried out by specialized operators. The achieved yield for individual substances depends on the recovery efficiency of each individual step and on the cooperation along the recycling chain. Preprocessing, that is, presorting, liberation through manual dismantling, and/or shredding and manual and/or mechanical separation plays a key role in the overall chain. Looking at the state-of-the-art process configurations the following argument can be formulated:

> Preprocessing determines which fractions and thus substances of WEEE are steered into appropriate end-processing streams. Any sorting of a specific target substance into the "wrong" output stream from preprocessing in most cases leads to the loss of this substance in the final recovery step (end-processing). Thus the effectiveness of preprocessing has a major impact on the recovery of a specific substance over the entire recycling chain.

The goal of this article is to substantiate his statement by using a substance flow analysis (SFA).

The specific objectives are as follows:

- to quantify and characterize the flows of precious metals (silver, gold, palladium) in and out of a preprocessing facility for WEEE;
- to determine the technical and economic implications for process optimization on a business and enterprise level based on the SFA results; and
- to illustrate the necessity of applying SFA on a process level to create a sufficient and reliable database for modeling regional and global material and substance flows for a holistic approach to systems optimization.

Background

Significance and Characteristics of WEEE

Waste electrical and electronic equipment (WEEE) is defined as "EEE which is waste [...], including all components, subassemblies and consumables which are part of the product at the time of discarding" (WEEE-Directive 2003, Article 3). Alternatively, the terminologies "e-scrap" and "e-waste" are widely used.

The use of EEE has increased exponentially in the last decades. The generation of obsolete products reached 8.3 million tonnes[1] in the European Union (EU-15) in 2005. From these only 2.2 million tonnes were collected and treated (Huisman et al. 2007). Although the per-capita production rate in populous developing countries such as China and India is still relatively low and estimated to be less than 1 kilogram (kg)[2] WEEE per capita per year, the absolute volume of end-of-life products generated in these countries is already huge (Widmer et al. 2005). The generation of WEEE is continuously increasing (COM 2005; Huisman et al. 2007; Rotter and Janz 2006; Widmer et al. 2005). This increase varies per product group. In Germany, the generation of waste information technology (IT) equipment is expected to increase by 72 wt.% between 2008 and 2013 while the generation of small waste consumer equipment may increase by 10% (Rotter and Janz 2006).

As a consequence of continuous modifications of function and design of EEE, WEEE is a highly heterogeneous mix of materials. Essential constituents of many electronic products, in particular IT and communication equipment (Behrendt et al. 2007; Hagelüken 2006), are precious metals (gold, silver, palladium) and special metals (indium, selenium, tellurium, tantalum, bismuth,

Table 1 Average concentration of precious metals in printed circuit boards from different equipment types (literature review)

Reference	Equipment type (origin of the printed circuit board)	Silver (g/t)	Gold (g/t)	Palladium (g/t)	Platinum (g/t)
Angerer et al. 1993	Audio and video equipment	674	31		
Huisman et al. 2007*	Radio set	520	68	8	
Huisman et al. 2007*	DVD player	700	100	21	
Angerer et al. 1993	Personal computer	905	81		
Hagelüken 2006	Personal computer	1000	250	110	
Huisman et al. 2007*	Personal computer	1000	230	90	
Keller 2006	Personal computer	775	156	99	
Kramer 1994	Personal computer	600	300		
Legarth et al. 1995	Personal computer	700	600	100	40
Art 2008	Computer keyboard and mouse	700	70	30	0
Huisman et al. 2007*	Computer CRT Monitor	150	9	3	
Huisman et al. 2007*	Computer LCD Monitor	1300	490	99	
Huisman et al. 2007*	Printer	350	47	9	
Ernst et al. 2003	Telephone	2244	50	241	
Ernst et al. 2003	Mobile telephone	3573	368	287	
Hagelüken and Buchert 2008	Mobile telephone	5540	980	285	7
Huisman et al. 2007*	Small IT and telecommunication equipment	5700	1300	470	
Hagelüken 2006	TV set—CRT-Monitor	280	17	10	
Huisman et al. 2007*	TV set—CRT-Monitor	1600	110	41	
Huisman et al. 2007*	TV set—LCD-Monitor	250	60	19	

*Combination of data from different sources.

antimony). The precious metals are mainly found in printed circuit boards (PCBs). Table 1 gives the average concentration of silver, gold, and palladium in PCBs from different types of equipment. The concentration of precious metals in PCBs is usually much higher than the concentration of precious metals in ores. In general, presently mined ores for the extraction of gold and palladium contain less than 10 g/t of precious metals (Hagelüken et al. 2005). Compared with the concentrations in PCBs of personal computers of 250 g/t of gold and of 110 g/t of palladium (table 1), the importance of recovering precious metals from electronics becomes obvious. Moreover, the extraction of precious metals through mining is associated with negative environmental impacts through significant emissions of greenhouse gases and energy, water, and land usage (Ayres 1997). The environmental impacts of the secondary production in state-of-the-art operations are much lower than primary production (Hagelüken and Buchert 2008).

Besides environmental protection and legislative pressure, recycling is also driven by economic interests. Precious metals contribute to more than 80% of the materials' market value of obsolete personal computers, despite their small quantity (Streicher-Porte et al. 2005). Moreover, the high economic value of precious metals on the world market as well as the limited available reserves of precious metals (Behrendt et al. 2007) provides additional incentives to improve the recovery of precious metals from WEEE.

Role of Preprocessing

EEE have a product life starting with product manufacture—as the design of the product

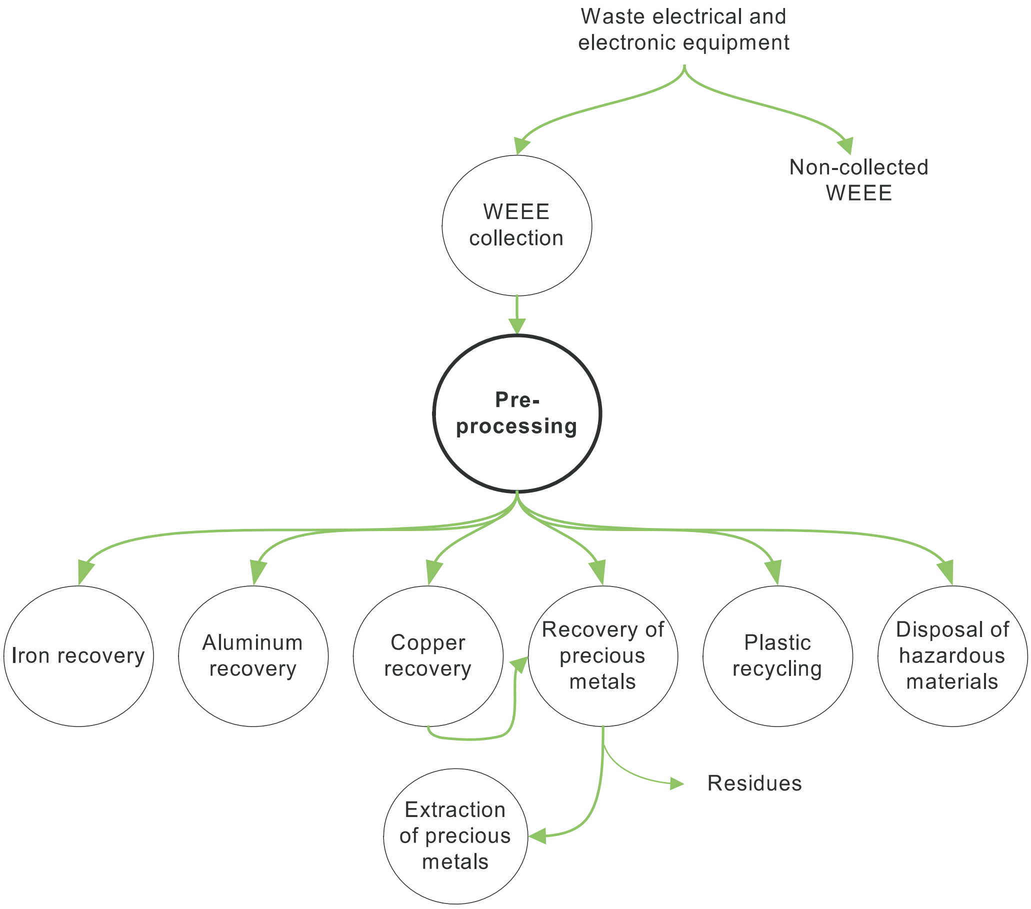

Figure 1 Simplified recycling chain for WEEE, focusing on recovery of precious metals in the “End-of-Life” and the “Raw materials production” phases.

determines the product characteristics and, therefore, the demand for raw materials—and ending with waste management (end of life).

The overall task of the end-of-life phase is to recover the raw materials as effectively as possible and to destroy or remove components with a high hazardous potential. Three steps can be distinguished (figure 1): collection of WEEE, preprocessing, and disposal. The material generated by preprocessing can be converted to useful materials by recovery facilities (for example, metal smelters), which belong to the phase “Raw materials production.”

After collection, WEEE is preprocessed to concentrate the substances and generate appropriate material streams that are sold to the end-processing stage. Preprocessing can be carried out manually, automatically (shredding and sorting of materials), or with a semiautomatic process combining manual and automatic techniques. Preprocessing is divided into the following major stages: (1) sorting, (2) selective disassembly, targeted on singling out hazardous or valuable components, and (3) upgrading, using mechanical/physical processing and/or metallurgical processing to prepare the materials for the final refining process (Cui and Forssberg 2003). Preprocessing must also ensure that hazardous materials are prepared for disposal in an environmentally sound way. The chain of preprocessing, recovery, and disposal processes used to recover the materials of WEEE is called “recycling process chain.”

As first step of the recycling process chain, preprocessing determines to which recovery processes the materials are fed (Chancerel and Rotter 2008). If a substance is sent to a recovery process that is not able to recover it, it is "lost" for the recycle-economy. During preprocessing of WEEE, the so-called "grade-recovery function" applies (Hagelüken 2006). The recovery of a specific material (for example metal) from an input stream decreases with increasing purity requirements of that material separated into an output fraction. The optimum operating conditions for preprocessing are, therefore, a compromise between grade (quality) and recovery (quantity).

To determine this optimum for each metal and for the overall preprocessing of WEEE and to minimize the losses of valuable metals, the distribution of precious metals over the outputs has to be known.

SFA Applied to Precious Metals and WEEE Recycling

MFA is a systematic assessment of the flows and stocks of materials within a system defined in time and space (Brunner and Rechberger 2004). As such, MFA is the first step of every life cycle assessment (LCA) (Brunner and Rechberger 2004; Tukker et al. 1997). The term material stands both for substances and goods. An SFA, which tracks elements or molecules within a system, is therefore a specific kind of MFA. The historic background and a detailed overview on the concepts of MFA and SFA are available in publications by Brunner and Rechberger (2004), Van der Voet (1996) and Udo de Haes and colleagues (2000). Based on MFA data, other tools such as exergy analysis can be used to further investigate and evaluate the recycling system while considering the quality of the material and energy flows (Reuter and Van Schaik 2008; Ignatenko et al. 2007; Meskers et al. 2008). The combination of different tools enables thorough quantitative evaluation of the system from different perspectives and the development of strategies to improve it.

In the past, SFA has been used to analyze flows of metals on a local, regional, or global scale. Table 2 presents an overview on SFA of precious metals with their scope of investigation. The previous studies had very large system boundaries, and the data at process level were estimated through rough assumptions. Johnson and colleagues (2005b), for example, quantified silver in WEEE based on an approximation of the amount of silver contained in the circuit boards of discarded electrical and electronic equipment as 0.2% of the circuit boards by weight. These assumptions are accompanied by high uncertainties as a consequence of the lack of data related to precious metals in WEEE and on the actual recycling processes.

Some publications report on MFA and SFA specifically for WEEE processing. Morf and Taverna (2004) carried out a SFA in a Swiss preprocessing facility for WEEE. Based on a sample of 230 tonnes of WEEE, some base and heavy metals, chlorine, bromine, potassium, polychlorinated biphenyl, and brominated flame retardants were tracked, but precious metals were not considered. Hischier and colleagues (2005) report on a MFA in Switzerland to gather data for an

Table 2 SFAs focusing on precious metals—Scope of published case studies

Metal	Scope of investigation	Reference
Silver	Flows in Europe	Lanzano et al. 2006
	Flows in 64 countries, 9 world regions, planet	Johnson et al. 2005b
	Flows in Asia	Johnson et al. 2005a
Gold	Process-oriented: processes for gold recovery from printed circuit boards in Bangalore, India	Keller 2006
Platinum- group metals (PGM)	Flows in Germany	Hagelüken et al. 2005
	Product-oriented: platinum in fuel cell vehicles	Elshkaki 2007
	Platinum in Russia	Babakina and Graedel 2005
	PGM in the environment	Ravindra et al. 2004

impact assessment. Streicher-Porte and colleagues (2005) carried out a material flow analysis of the recycling of personal computers in Delhi. The SFA of Tasaki and colleagues (2004) focused on brominated flame retardants in Japan. Bertram and colleagues (2002) investigated the flows of copper in the European waste management subsystem, considering explicitly WEEE. Huisman (2003, 2004) evaluated the environmental performance of different recycling scenarios for several equipment types. Reuter and Van Schaik carried out SFA as part of their investigations, focusing on WEEE and end-of-life vehicles (Reuter et al. 2005; Reuter and Van Schaik 2008; Van Schaik and Reuter 2007). None of these publications made quantitative data on the flows of precious metals during automated preprocessing of WEEE available.

Methodology

The investigation took place on March 31 and April 1, 2008, in a full-scale preprocessing facility for WEEE in Germany using state-of-the-art technology. Twenty-seven tonnes of WEEE classified in collection group 3 (IT, telecommunications, and consumer equipment) as defined in article 9 of the German ElektroG (2005) were processed. In practice, the treated scrap did not only contain IT, telecommunications, and consumer equipment, but also wrongly sorted waste products or nonelectronic waste (missorted waste equipment).

Figure 2 presents a general flow sheet of the preprocess. First, during manual dismantling the visible hazardous and problematic components such as batteries, large metal sheets, and motors are manually removed from the end-of-life products. Furthermore the easy-to-remove PCBs are manually taken out. After a coarse preshredding, a second manual sorting takes place to remove the remaining hazardous and disturbing components. Finally, the rest of the scrap is shredded and sorted automatically. Within approximately 24 hours, the 44 output material fractions were generated. The flows of gold, palladium, silver, copper, iron, and aluminum were investigated, of which the flows of the precious metals are discussed in more detail.

Before the test, the input material was weighed and qualitatively described. After processing, all output fractions were collected separately and weighed. The 24 most relevant fractions regarding precious metals were sampled according to the industry standard for WEEE. Figure 3 summarizes the applied methodology.

Characterization of the Input Material

The qualitative description of the input by exemplary counting of end-of-life products gave an

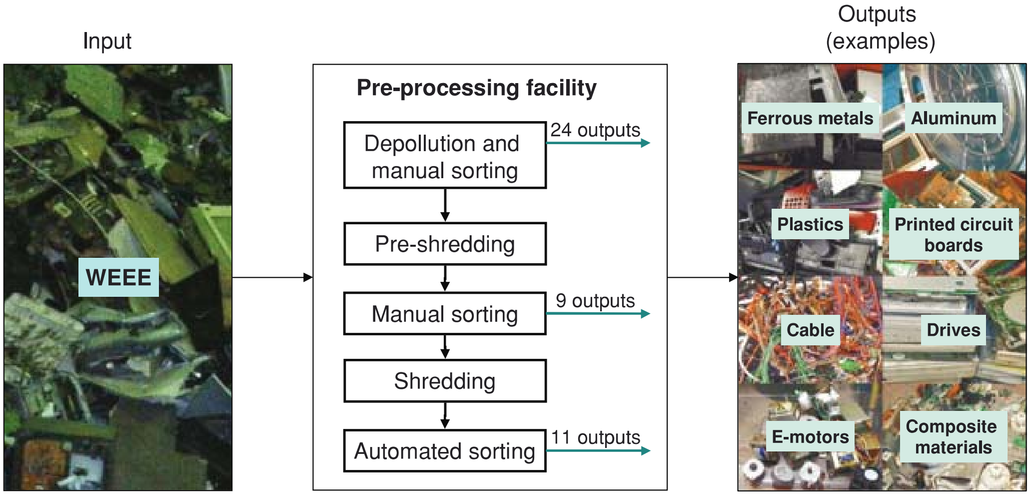

Figure 2 Overview of the unit processes applied in the preprocessing facility.

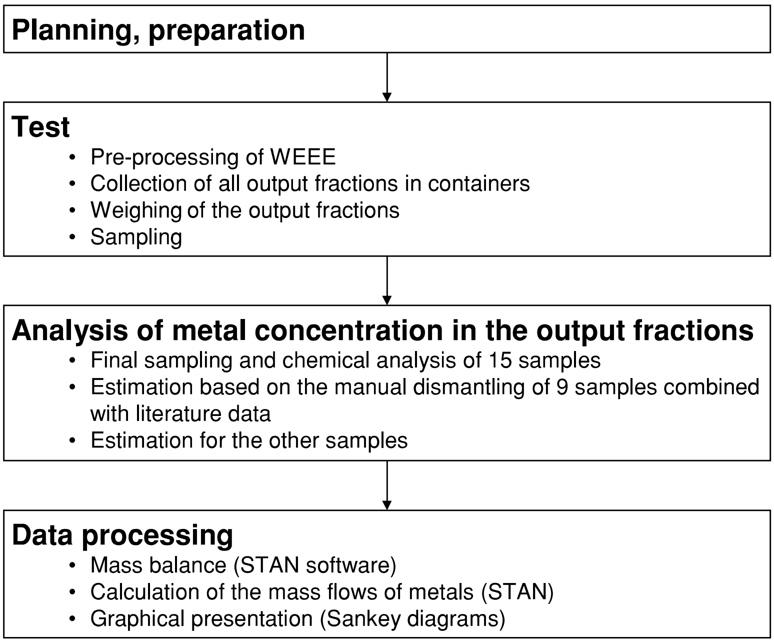

Figure 3 Methodology for the analysis of the substance flows through the preprocessing.

approximation of the distribution of equipment types in the input. The amount of precious metals contained in the input material was estimated by quantifying following parameters:

- the distribution of equipment types found in the input mix;
- the average content of PCBs in the equipment types taken from the WEEE characterization database (Chancerel and Rotter 2007); and
- the average content of precious metals in the PCBs (table 1). The precious metals concentrations in PCBs were assumed when results of measurements were not available in the literature.

Only the precious metals present in the PCBs (base material and components) were quantified, although precious metals are known to be contained in other parts such as connectors, contacts, cables, and solders (Gmünder 2007; Hagelüken 2006), but very few quantitative data are available regarding the precious metals contained in these components.

Determination of the Concentration of Precious Metals in the Outputs

The concentration of precious metals in 15 output fractions, including all outputs of the automated sorting process and the manually removed PCBs, was determined at Umicore Precious Metals Refining in Hoboken, Belgium. These outputs were selected because of their expected high content of precious metals, due either to a high concentration of precious metals or to a high mass flow. The applied sampling and analysis methods to analyze the output fractions were developed at Umicore considering the specific characteristics of WEEE (UPMR 2005). The challenge is to obtain representative samples from the still heterogeneous fractions, in which precious metals are often only present at parts per million (ppm) level. The concentration of precious metals was measured with inductively coupled plasma atomic emission spectrometry (ICP-AES).

Nine other output fractions such as motors, computer drives, and transformers were manually dismantled. The obtained material fractions (plastics, ferrous metals, nonferrous metals, cables, PCBs, and so on) were manually separated and weighed. Information about the concentration of precious metals in the material fractions was either taken from the literature or estimated. By multiplying the material composition with the concentrations of precious metals in the different materials, the content of precious metals in the output fractions was calculated.

For the remaining 20 output fractions, the content of precious metals was estimated based on visual observations. These output fractions such as wood and plastic foils had presumably low concentrations of precious metals. For most of the output fractions, it was assumed that the concentration of precious metals is zero. If the outputs contained small quantities of PCB pieces, low concentrations up to 20 g/t of silver and 5 g/t of gold were estimated on the basis of a visual quantification of the PCBs present in the output.

Determination of Uncertainties

The quantification of the uncertainties in the measurements is based on the following considerations:

- One of the scales used to weigh the input and output material fractions had an uncertainty of ± 1 kg; the other scale had an uncertainty of ± 10 kg. Because two weighings were necessary per container (one weighing of the full container, one weighing of the empty container to determine the tare), each weight had an uncertainty of ± 2 or ± 20 kg. For some larger fractions, several containers were used, which increased the uncertainty.
- To facilitate the SFA, the uncertainty for sampling is assumed to be 10% because of the heterogeneity of the material.
- The uncertainty for determining the concentration of precious metals is assumed to be 2% for the samples analyzed with ICP-AES, 20% for the samples that were manually dismantled, and 50% for the visual estimation.

The uncertainties were calculated by applying Gauss's Law of error propagation. Because the variables are independent, the variance (standard deviation squared) of the result is the sum of the variances of the input variables. In our case, the variance of the calculated mass flow of precious metals $Var(MF_{PM\ in\ Output})$ is calculated by adding the variance of the weight of the outputs Var(Weight), the variance of sampling Var(Sampling), and the variance of the analysis of the precious metal concentrations Var(Analysis):

$$Var(MF_{PM\ in\ Output}) = Var(Weight) + Var(Sampling) + Var(Analysis) \quad (1)$$

With:

Var: variance

$MF_{PM\ in\ Output}$: mass flow of precious metals

The uncertainty is quantified by calculating the standard deviation, which is the square root of the variance.

Data Processing

The substance flows were determined by multiplying the substance concentrations measured in the output materials with the mass flows:

$$M_{metal\ i\ in\ flow\ j} = M_{flow\ j} \times c_{metal\ i\ in\ flow\ j} \quad (2)$$

With:

$M_{metal\ i\ in\ flow\ j}$: mass flow of substance (metal) i contained in flow j

$M_{flow\ j}$: mass flow of flow j

$c_{metal\ i\ in\ flow\ j}$: concentration of substance (metal) i in flow j

The calculations were done using the STAN freeware (TU Vienna 2008). STAN (short for subSTance flow ANalysis) helps to perform MFA (Cencic and Rechberger 2008). To get clear and meaningful results, the material flows were aggregated according to the recovery processes they will be fed to. Sankey diagrams were drawn for visualization of the outcomes of the SFA using the software E!Sankey (E-Sankey 2008).

Results

Figure 4 presents the results of the mass balance for processing one tonne of WEEE (see also appendix 1 available as supplementary material

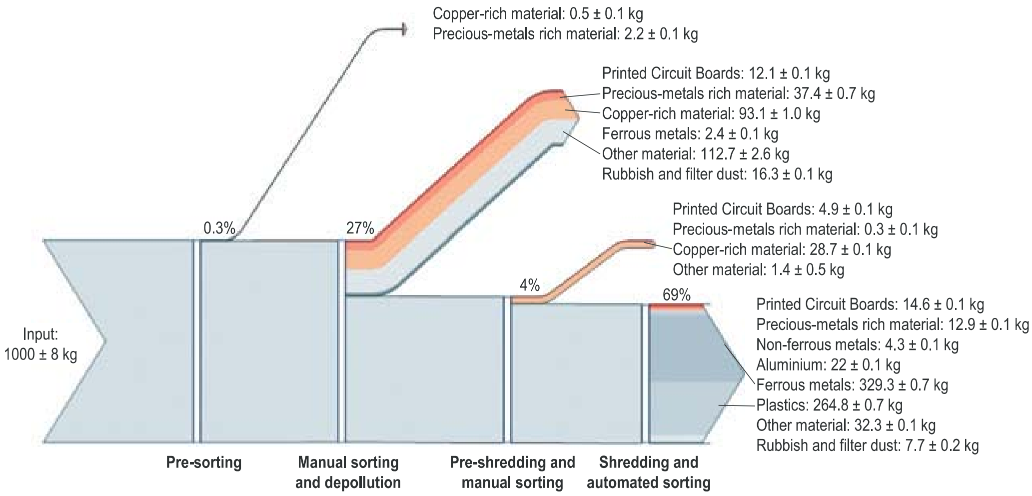

Figure 4 Mass balance of the preprocessing of 1,000 kg of input WEEE.

on the Journal's Web site). Twenty-seven wt.% of the input is sorted out manually before any shredding, 4 wt.% is sorted out manually after preshredding, and the majority of the mass (69 wt.%) is fed to the shredding and automated sorting process. The largest output fractions of the process are ferrous metals (almost 33 wt.%) and plastics (26 wt.%). Copper-rich materials such as motors, cables, and other composite materials containing a high fraction of copper represent 12 wt.% of the outputs. Precious metal-rich materials consist of the nonliberated PCBs in, for example, CD drives and power supplies of personal computers. Hazardous materials, wood, and other (precious) metal-poor materials are classified as "Other material."

Characterization of the Input Material

Table 3 presents the results of the estimated quantification of precious metals in one tonne of input material. The input mainly contains personal computers, printers, keyboards, and radio sets. It was estimated that around 67.6 grams (g)[3] of silver, 11.2 grams of gold, and 4.4 grams of palladium were in one tonne of input WEEE (table 3). These values, however, are only used as a cross-reference. For the calculation of yields, the input composition was obtained by summing the contents in the output streams.

Flows of Precious Metals

Based on the overall mass flows (figure 4), the mass flows of precious metals are calculated using formula 2. The results are presented in figure 5 for silver, gold, and palladium.

The fractions "Printed circuit boards," "Precious-metals rich material" and "Copper-rich material" are sent to facilities for recovery of the precious metals. Precious metals in the "Copper-rich material" are also assumed recovered because state-of-the-art metallurgical processes for copper recovery are designed to also recover precious metals. The recovery R of a metal in the investigated preprocessing facility is therefore calculated with the following formula:

$$R = \frac{M_{\text{in PCB}} + M_{\text{in PM-rich mat.}} + M_{\text{in Cu-rich mat.}}}{M_{\text{input}}} \quad (3)$$

With:

R: Recovery

$M_{\text{in PCB}}$: mass flow of metal contained in the output "PCB"

$M_{\text{in PM-rich mat.}}$: mass flow of metal contained in the output "Precious-metals rich material"

$M_{\text{in Cu-rich mat.}}$: mass flow of metal contained in the output "Copper-rich material"

M_{input}: mass flow of metal contained in the input

By adding the flows of silver of the outputs, it was calculated that 313.3 g of silver is present in

Table 3 Estimation of the content of silver (Ag), gold (Au), and palladium (Pd) in 1,000 kg of input (source: see table 1)

Equipment type	Amount in the input (kg/tonne)	PCBs* in equipment type (wt.%)	Metal concentration in the PCBs (g/t of PCB)			Mass of metals in the input (g/t of input)		
			Ag	Au	Pd	Ag	Au	Pd
Computer keyboard	100	2%	700	70	30	1.40	0.14	0.06
LCD monitor	10	4%	1,300	490	99	0.52	0.20	0.04
Computer mouse	5	8%	700	70	30	0.28	0.03	0.01
DVD player	40	10%	700	100	21	2.80	0.40	0.08
Hi-fi unit	50	8%	674	31	10	2.70	0.12	0.04
Laptop	5	15%	1,000	250	110	0.75	0.19	0.08
Loudspeaker	100	2%	674	31	10	1.35	0.06	0.02
Mobile telephone	1	22%	5,540	980	285	1.22	0.22	0.06
Personal computer	210	13%	1,000	250	110	27.30	6.83	3.00
Printer, fax	230	8%	350	47	9	6.44	0.86	0.17
Radio set	100	20%	520	68	8	10.40	1.36	0.16
Telephone	10	22%	2,244	50	241	4.94	0.11	0.53
Video recorder	50	10%	674	31	10	3.37	0.16	0.05
Others	89	9%	520	68	8	4.17	0.54	0.06
Sum:	1,000	9%				67.6	11.2	4.4

*PCB = printed circuit boards.

one tonne of input. With 35.9 g of silver analyzed in the output fractions for precious metals recovery, the recovery for silver is only 11.5%. Almost 35% of the silver ends up in the output "ferrous metals"; another 29% is found in plastics.

For gold, 40% of the 22.4 g/t of gold put in goes to the ferrous metals output. This is similar to the value found for silver. The recovery, conversely, is much higher compared with R_{Ag}: 25.6%, which means that 74.4 wt.% is still distributed to fractions from which gold is not likely to be recovered.

As with gold, only 25.6% of the 7.16 grams palladium is sent to a fraction where precious metals are recovered. The plastic output contains the biggest fraction of palladium (one third). Filter dust and rubbish (what was swept from the floor after the test) contain almost 5% of the palladium, which shows a tendency of palladium to be released into the air during shredding.

The SFA for copper and iron showed that 60% of the 43.5 kg of copper per tonne of input and 95.6% of the 402 kg of iron per tonne of input end up in fractions where the respective metals can be recovered in subsequent processes. This is significantly higher than the yield for the precious metals and underlines that the recovery of small and trace amounts of (precious) metals from complex materials requires special attention.

Comparison of Input Estimation and Output Analysis

The estimated precious metal content of the input is 67.6 g/t of silver, 11.2 g/t of gold and 4.4 g/t of palladium (table 3). However, the sum of precious metals in the outputs showed that the input contains 313.3 g/t of silver, 22.2 g/t of gold and 7.16 g/t of palladium. The estimated content of precious metals of the input material is, therefore, lower than the sum of the flows of precious metals in the outputs, especially regarding silver. The discrepancy can be explained by uncertainties due to the application of literature data but above all by the fact that precious metals are not only found in PCBs, but also in other parts of WEEE, such as silver in contacts, plugs, or solders.

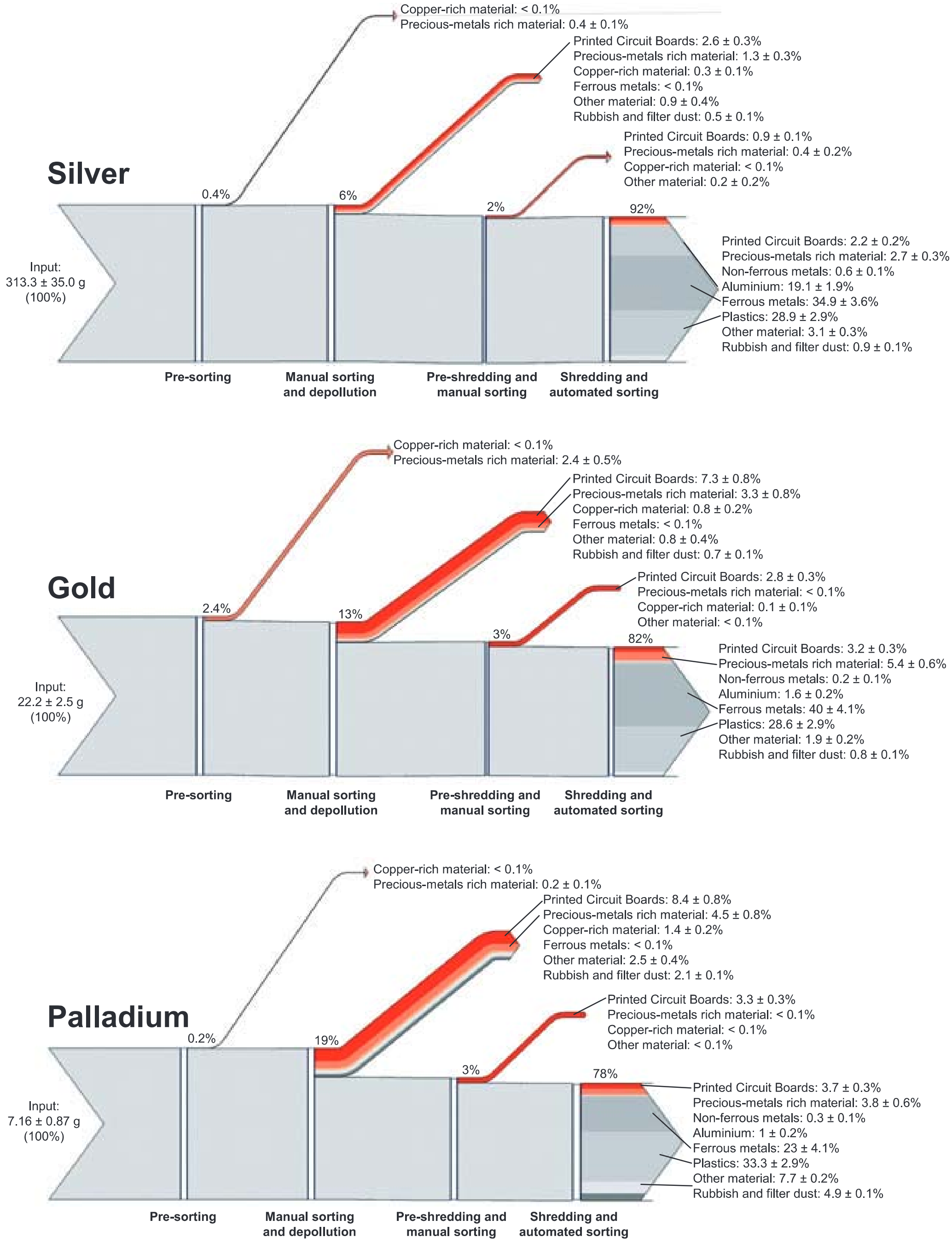

Figure 5 Flows of precious metals during preprocessing of one tonne of input WEEE (wt.%).

The estimation of the input, presented in preceding sections, leads to higher uncertainties than the calculation of the input flow by adding the output flows. Nevertheless, the results also show that the simplified approach of estimating the input quality and, specifically, the precious metal content based on counting the equipment types is as a

Table 4 Concentration of precious metals measured in the outputs 'unshredded PCB', "preshredded PCB" and "shredded PCB"

Concentration of metal	Silver (g/t)	Gold (g/t)	Palladium (g/t)
Unshredded printed circuit boards	669	135	50
Preshredded printed circuit boards (< 8 mm)	562	126	48
Shredded printed circuit boards (< 2.5 mm)	481	48	18

first approximation at least correct to an order of magnitude.

Losses of Precious Metals due to Shredding of Printed Circuit Boards

The test provided results on the concentration of precious metals in PCBs at the following points in the preprocessing chain (table 4): (1) unshredded PCBs from manually sorting, (2) pieces of PCB (8 millimeter [mm][4]) from preshredding, and (3) pieces of PCB (2.5 mm) from shredding.

The SFA indicates that more size reduction (shredding) of the material seems to lower the concentration of precious metals in the resulting PCB fraction (table 4). The difference in concentration between unshredded PCBs and preshredded PCBs (7% less precious metals in the preshredded PCBs compared with the unshredded PCBs) is not as large as the difference between preshredded PCBs and shredded PCBs (62% less precious metals in the shredded PCBs compared with the preshredded PCBs). At first glance it appears that the precious metals are spread over all the output fractions because of shredding, so that the concentration of precious metals in PCBs decreases.

The results may be influenced by the process characteristics, however, because the manually sorted PCBs (before or after preshredding) are mainly large and easily accessible with a high concentration of precious metals (e.g., main boards of personal computers). The PCBs that end up in the shredder are frequently encased in waste products such as printers, radio sets, or other small products and are not easily accessible for manual sorting. In these products, PCBs often have low concentrations of precious metals. During the test, no experiment could be carried out to verify the extent to which the lower concentration of precious metals in the shredded circuit boards is due to the shredding process and the extent to which it is due to the intrinsic characteristics of the PCBs. However, it is most likely that shredding indeed has a negative impact on the precious metal recovery.

Discussion

Process SFA as a Tool for Process Operators

Quantifying the Improvement Potentials

From the point of view of the process operators, the results of the test can be qualified as "disappointing" because only about a quarter of the gold and palladium and a tenth of the silver are sent to output fractions from which precious metals will be directly recovered. Compared with the recovery rates of major elements such as iron, aluminum, and copper, the recovery rates for precious metals are very low. Most of the precious metals go to the most mass-relevant fractions (plastics and ferrous metals). These fractions have relatively low concentrations of precious metals (24 g/t of gold and 8 g/t of palladium in the plastics, 24 g/t of gold and 5 g/t of palladium in the ferrous metals; see appendix 1 available as supplementary material on the Journal's Web site), but the considerable mass of the outputs makes the flows of precious metals very relevant.

These results imply that the operators of the process do not get any revenue for almost three quarters of the gold and the palladium (figure 5). Per tonne of input WEEE, the company operating the facility does not get any revenues for around 16.5 g of gold and 5.3 g of palladium. At a price of $900 per ounce of gold and $370 per ounce of palladium (average price for 2008 [USGS 2009]), this means that a metal value of $524 for gold and almost $70 for palladium per tonne of treated

WEEE is lost. By comparison, the gross intrinsic value[5] of the 43.5 kg of copper contained in one tonne of input scrap is $307 (at a price of $3.20 per pound of copper in 2008 [USGS 2009]).

Analysis of the Causes of Resource Losses

The outcomes of the SFA provide data for a better understanding of the process, as indicated by Morf and Taverna (2004). Two phenomena became obvious:

1. The low concentrations of precious metals in mass-relevant fractions (plastic and ferrous metals) generate high mass flows of precious metals in fractions that are not subsequently sold to processes for precious metals recovery.
2. More shredding results in a decrease of the concentration of precious metals in PCBs.

These two observations are supporting the hypothesis that an unselective fine shredding is causing unwanted losses of precious metals. The dilution of precious metals into other outputs happens mainly after shredding. This agrees with the results of Hagelüken (2006), Kreibe and colleagues (1996), and Veit and colleagues (2002).

Precious metals occur in PCBs as a component of complex material mixtures as they are mixed with or connected to other metals in contacts, connectors, solders, and hard disk drives; with ceramics in multilayer capacitors (MLCC), integrated circuits (ICs), and hybrid ceramics; or with plastics in PCBs tracks, interboard layers, and ICs (Hagelüken 2006). The liberation of layered materials and of (metallic) coatings is not possible in a shredder (Castro et al. 2005). The mechanical preprocessing disperses the precious metals depending on the materials with which they are mixed or connected. For example, palladium is often found in ceramics that are broken down to dust during shredding, which explains why almost 5% of the palladium ends up in the filter dust. Small pieces of boards may, after shredding, still contain a magnetic part and are pulled out because of the strong magnets in the magnetic separators.

Suggestions for Technical Improvement

To reduce the losses of precious metals in preprocessing, in particular during shredding and subsequent sorting, the first and most straightforward approach is to reduce the quantity of precious metals entering the shredder. In this manner the distribution of precious metals over a large number of fractions during the automatic sorting will be minimized. This implies adjusting the manual sorting step at the beginning of the process to remove most precious metal-rich materials. This requires knowledge about the location of precious metals in WEEE, which is currently partially missing. More experimental research, especially to quantify the amounts of precious metals contained in other parts of WEEE than PCBs, and a better communication with the manufacturers of EEE would provide the missing data.

A second approach would be adapting the mechanical liberation process and the used sorting technologies to recover more precious metals. This can be done through development and implementation of advanced preprocessing technologies addressing more specifically the recovery of precious and other trace metals.

However, the limits of technology will not allow achieving recoveries of 100% (Reuter et al. 2006). The grade-recovery curve implies that a compromise has to be found between concentration of precious metals in the outputs for precious metal recovery and losses of precious metal in other fractions. In case of high-grade and highly complex products such as mobile phones and digital cameras, this means that shredding should be completely avoided (Huisman 2004), and—unless manual dismantling is affordable—these devices are (after removal of the battery) directly fed into appropriate metallurgical recovery processes for precious and special metals.

Strengths and Weaknesses

Usually, the operational decisions are mainly driven by maximizing the recovery of mass-relevant material outputs such as copper, ferrous metals, and aluminum. For trace elements, decisions are mainly based on empirical knowledge. SFA is the basis for a more systematic approach to improve the recovery of trace metals because it is able to quantify resource losses on a mass and monetary basis at the process level and thus to determine the potential for optimization. The data have to be processed, aggregated, and presented in a user-friendly manner. As emphasized by Schmidt (2008) and illustrated in this article, Sankey diagrams are a potent means of visualizing inefficiencies in the system and also are useful for a nonspecialist audience.

The SFA presented in this article generated data on the characteristics of the input waste flow as an aggregation of the data on the output flows. SFA on a process level is, therefore, a possible method for generating data on waste characteristics because these data are difficult to gather directly due to difficulties of sampling and analyzing complex materials such as WEEE.

This investigation is an initial SFA giving a snapshot to describe the flows of precious metals within the system defined in time and space. Sampling issues in the broader sense such as the representativeness of the WEEE input mixture and of the applied process at the day of the test as well as the sampling of the outputs for analysis are key factors in properly evaluating the reliability of the results. The uncertainties of the sampling of the output materials could have been reduced by sampling and analyzing the input and the intermediary material flows in the facility in addition to sampling and analysis of the output fractions. Additional measurements allow for description of the system in a redundant way and then for determination of the best-fitting values by using a method for data reconciliation, for example, the method of least squares of Gauss (Brunner and Rechberger 2004). This could not be done in this research for cost reasons.

Though the effects of modifications of the applied preprocessing technology or in the characteristics of the input waste were not investigated, a periodic monitoring of metal flows (instead of a trial-and-error approach) will allow identifying further potential improvements and observing the effects of changes in the overall process. Both the company and society in general will benefit as economic viability is ensured and material resources are conserved.

Process SFA for Improving the Product Life Cycle

In addition to the application of the results to analyze and improve the preprocessing of WEEE described in the previous section, the results of process SFA can be aggregated and used as an input for optimizing a product life cycle and its subsystems. Figure 6 shows actors in the life cycle and how exchange of SFA-related data allows for improvement in the product life cycle.

Interface Preprocessing/Recovery

The importance of optimization of interfaces between "preprocessing" and "recovery" within the end-of-life phase was pointed out by Hagelüken (2006). Through suboptimal interfaces between preprocessing and recovery processes, precious metals are collected in streams from which they are not recovered, such as precious metals in plastic, steel, or aluminum. The operators of preprocessing act under the boundary conditions of the existing market situation and legislative framework. They can influence the substance flows in their process through

- technical decisions to determine the quantity and quality of the outputs and
- management decisions on the subsequent destination of the outputs.

In practice, the communication of data on substance flows out of preprocessing and in the recovery processes (see arrows 3 and 4 of figure 6) should develop iteratively driven by the expertise of preprocessing and recovery facility operators. This should go beyond the exchange of data to include technical discussions and tests to develop an optimal fit between output fractions in preprocessing (quantity, quality) and capabilities of the specific recovery plant. The communication between operators of preprocessing and recovery processes is suggested in article 7 of the WEEE-Directive (2003), which requires that the operators of recycling processes keep records on the material flows in and out of their facility to calculate recovery rates.

An approach to assessing and improving the interface between preprocessing and recovery is "process modeling." The data gathered by the process SFA can be used for designing and calibrating models of the preprocessing process for any type of waste consumer product (Chancerel and Rotter 2008; Reuter et al. 2005). By expressing in mathematical terms the SFA data on the behavior of precious metals in preprocessing facilities and combining it with scientific knowledge

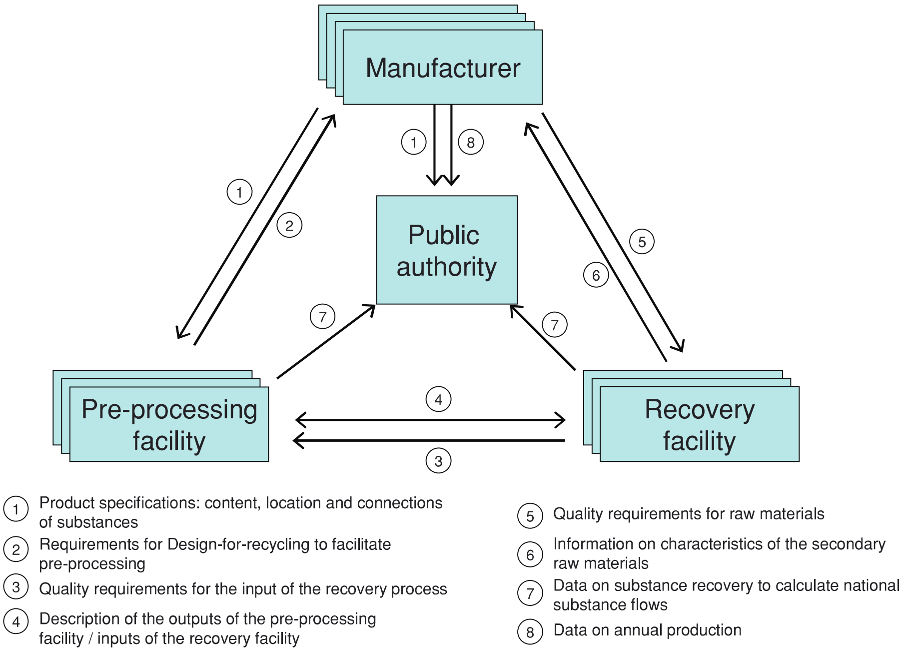

Figure 6 Communication between the system actors to optimize the substance flows.

in the fields of mechanics, chemistry, and process engineering, a process model can be built. The characteristics of the waste and of the recycling process are parameters. By formulating assumptions or by carrying experimentally further SFA out, the results of the SFA can be extrapolated to other process configurations (other input characteristics and/or other process parameters). The model can be expanded and used to simulate and improve the process. These considerations have been included in the models for recycling of end-of-life vehicles developed by Van Schaik and Reuter (2007). The improvement of the system must be multicriteria and take into account the different materials (precious metals, base metals, plastics, hazardous substances, and so on) and the process conflicts (e.g., iron is not recovered in a recovery process for copper).

Interface Recovery/Manufacturer

Arrows 5 and 6 of figure 6 show how information on substance flows can be exchanged to optimize the interface between material recovery and manufacturing of new products. According to the demand of the manufacturer for raw materials, the recovery process can be adapted. If the product does not require a very high purity of metals, the recovery facility can sell suitable materials. This implies that manufacturers share information on their needs for raw materials with the operators of the recovery facility.

Interface Manufacturer/Preprocessing

Here the idea of "producer's responsibility" comes in. The Organization for Economic Co-operation and Development (OECD) (2001) defines "extended producer responsibility" as "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle" (p. 18). Article 4 of the WEEE-Directive (2003) introduces the responsibility of the manufacturer in the European Union by stipulating that "Member States shall encourage the design and production of electrical and electronic equipment which takes into account and facilitates dismantling and recovery, in particular the reuse and recycling of WEEE, their components and materials" (Article 4).

The design of the product essentially determines the materials used in the product, the material combinations, and the type of connections (screws, glue, and so on). For this reason, the design of electrical and electronic equipment determines the maximum possible efficiency of the end-of-life process (preprocessing and recovery process). Design for recycling aims at increasing both the quality of the recyclates and the recovery rates (Reuter and Van Schaik 2008). A concrete example of this is the accessibility of printed circuit boards. The manual removal of printed circuit boards would partially prevent the losses of precious metals in sidestreams. The ease of the manual removal depends on product design. Design-for-recycling models, linking product design to the amount and composition of the output fractions of mechanical pretreatment and to the products of the subsequent material recovery processes, were developed by Van Schaik and Reuter (2004, 2007).

The communication between a manufacturer and an operator of preprocessing aims at exchanging data

- on the composition of the EEE, the location of the substances, and their connections (arrow 1 of figure 6) for the preprocessing to be adapted to the product characteristics, and
- on the requirements on product design for a more efficient preprocessing (arrow 2).

In case of considering new or uncommon combinations of substances in a product design, it is advisable that the manufacturer consults the operators of preprocessing and recovery facilities.

The literature review done for this investigation showed a lack of available information, for instance, regarding the exact location of precious metals in (W)EEE, which led in this investigation to an underestimation of the amount of precious metals in the input material, especially for silver. An adequate knowledge of the characteristics of input materials would allow anticipating their behavior during processing (ex-ante approach).

Strengths and Weaknesses

SFA and MFA provide very useful data for optimization of interfaces between the subsystems of the life cycle. The uncertainties and the representativeness of SFA data have to be known to be aware of the limitations in the data reliability and avoid uncontrolled error propagation.

For a systematic evaluation and optimization of the life cycle, tools such as LCA or exergy analysis can be used. To do this, the SFA data need to consider all relevant elements (not only precious metals) and have to be completed with data on process emissions, energy consumption, transport, and so on. These aspects are usually not considered in MFA and SFA and have been left out in this investigation. The combination of different tools enables thorough quantitative evaluation of the system and developing strategies to improve it, as shown by Unger and colleagues (2008), whose research aimed at comparing ecodesign and environmental assessment tools for EEE taking the life cycle perspective.

Process SFA for Economy-wide Applications in Industrial Ecology

The life cycle of EEE includes many material and metal cycles such as copper, aluminum, nickel, cadmium, lead, gold, palladium, silver, indium, and plastics. Although the amount of a particular metal in a single unit of EEE can be small, the number of EEE manufactured and entering the end-of-life phase is very large. Therefore, the amount of metal used in EEE and which can be potentially recovered becomes considerable. Knowledge about flows of WEEE and WEEE-related substances within a country or region can be valuable but is often not available, as emphasized by various authors (Bertram et al. 2002; Reck et al. 2008).

The results of SFA from industrial trials at the process level provide data required for SFA and MFA at the macroscopic level (regions, countries, world). In the European Union, the WEEE-directive (2003) requires the calculation of recovery rates on a country level based on the data provided by the recycling industry (arrow 7 of figure 6). These data could be completed and compared with data from EEE manufacturers (arrows 1 and 8).

The next research project aims at incorporating the results of the SFA presented in this article in a larger investigation on the cycles of precious metals by quantifying the flows of precious metals related to recycling of WEEE at local, regional, or global level. Clearly, the questions relating to representativeness and uncertainties of the SFA results have to be considered for the extrapolation of the results at the process level to the macro level. Besides precious metals, quantitative research on the flows of other trace metals present in WEEE should be encouraged. Recently, more discussions and reports on the limits of metal reserves, especially of the "critical metals," have appeared, for example through the Raw Materials Initiative of the European Union. In these discussions, the contribution of recycling plays an important role. To properly determine "scarcity" and the contribution of recycling, good data are key. In this light, strategic considerations are a driving force for improving the recovery of these metals.

Conclusions and Recommendations

As a starting point for the conclusion, it has to be noted that the investigation was carried out at a state-of-the-art facility fulfilling all European legal requirements of the WEEE-directive (2003) and the German ElektroG (2005) and in particular achieving the required mass-based rates of recovery. The recovery of precious metals is not driven by those legal requirements but by economic interest of stakeholders. Therefore, SFA is a useful tool for optimizing material and product life cycles beyond the regulatory framework in the interest of single companies and the society:

- At the process level, the SFA in general allows monitoring and assessing the process to identify improvement potentials. This investigation showed that after preprocessing, despite the high recovery rates for mass-relevant elements such as ferrous and copper, only a quarter of gold and palladium ends up in outputs from which precious metals may be recovered. This and a detailed insight in the process are relevant information for technical adaptations. A possible solution to reduce the losses of precious metals is to manually remove the relevant materials, for instance PCBs, to avoid shredding them and dispersing part of the metal content.
- The results of the process SFA also provide a database for larger investigations, for example, aiming at assessing the performance of end-of-life process chains regarding recovery of precious metals. A scheme for exchange of information on substance flows between actors was proposed.

Limitations of using SFA are related to its representativeness. Static SFAs deal with a defined input material within a defined time frame. The extrapolation of the data for further investigations must take into account uncertainties linked with the system boundaries. This emphasizes the fact that the correct application of the method is crucial to get reliable results.

Especially regarding trace elements such as precious metals, SFA allows a better understanding of resource flows, identifying weaknesses, and developing strategies to improve the system. As far as possible, the method applied to carry out the SFA should be standardized to make the results comparable.

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Notes

1. All tons in this article are metric tons (as denoted by "tonnes"). One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.
2. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
3. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz).
4. One millimeter (mm) = 10^{-3} meters (m, SI) ≈ 0.039 inches.
5. Gross intrinsic value is the economic value of the metal without considering the costs of recovering it.

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Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Supplement S1. This supplement contains an appendix with a table displaying the mass of the output fractions and concentration of silver, gold, palladium, copper, aluminum, and iron in WEEE.

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