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Substance flow analysis of the recycling of small waste electrical and electronic equipment

An assessment of the recovery of gold and palladium

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vorgelegt von

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Para Lola.

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Abstract

The demand for precious metals by manufacturers of electrical and electronic equipment has increased significantly over the past few years. Although precious metal concentrations in appliances are very low, these metals have a high economic and environmental relevance compared to other substances present at much higher levels (for example iron, copper, plastics).

This thesis aims at describing and quantifying the flows of small waste electrical and electronic equipment (sWEEE) in Germany and in the USA for the year 2007, as well as the flows of gold and palladium associated with the sWEEE. Although collection systems have been set up, in many cases sWEEE is not collected separately for recycling but instead is disposed of. Regarding treatment of sWEEE, the model differentiates between reuse and treatments carried out by the formal and informal sector (including illegal export of sWEEE).

The material flows were quantified based on a combination of expansive experimental investigations and a review of the relevant literature. The results revealed that, in 2007, 370 000 to 430 000 tonnes of sWEEE were generated in Germany, containing 1.9 to 2.4 tonnes of gold and 580 to 720 kg of palladium. In the USA, 26 to 36 tonnes of gold and 9 to 12 tonnes of palladium were contained in the 3.1 to 4.3 million tonnes of sWEEE generated in 2007. In Germany, the collection rates are much higher (77% of the generated sWEEE is collected) than in the USA (30%). In the USA, 6% of the generated sWEEE is reused, whereas in Germany the reuse rate amounts to 3%. 72% of the gold contained in the sWEEE was discarded in Germany and therefore lost for the recycling economy. The discarding rate is around 75% for the USA. The economic value of the discarded gold and palladium in 2007 amounted to 34 to 44 million US-dollars in Germany and 466 to 714 million US-dollars in the USA.

In conclusion, the recycling infrastructures in Germany and in the USA do not allow an efficient recovery of the precious metals. The losses are caused by the non-separated collection of sWEEE and by inappropriate treatment, for instance during pre-processing. The characteristics of the different types of sWEEE considerably influence the recovery of precious metals. This has to be considered by developing strategies to improve it. Besides the recommendations how to improve the system, some suggestions to improve the data collection for the conduction of further substance flow analyses were formulated. The applied methodology can be used to assess waste management systems and develop improvement strategies. The method is not only useful for assessing the recovery of valuable substances as presented in this thesis, but in a more general way allows a quantitative analysis of the destination of substances fed into a waste management system.

Kurzfassung

Die Nachfrage nach Edelmetallen von Herstellern elektrischer und elektronischer Geräte ist in den letzten Jahren bedeutsam gestiegen. Obwohl die Edelmetallkonzentrationen in den Geräten sehr niedrig sind, sind diese Metalle wirtschaftlich und ökologisch relevant, verglichen mit anderen in höheren Konzentrationen enthaltenen Stoffen (z.B. Eisen, Kupfer, Kunststoffe).

Das Ziel dieser Dissertation ist es, die Stoffflüsse von kleinen elektrischen und elektronischen Altgeräten (Kleingeräten) in Deutschland und in den USA bezogen auf das Jahr 2007 zu beschreiben, sowie die mit den Kleingeräten verbundenen Flüsse von Gold und Palladium zu quantifizieren. Obwohl Sammelsysteme für Kleingeräte existieren, werden Kleingeräte häufig nicht erfasst sondern im Restabfall entsorgt. Bezüglich der Verwertung von Kleingeräten unterscheidet das Modell Wiederverwendung und Behandlung durch den formellen und den informellen Sektor (inklusive illegalen Export von Kleingeräten).

Die Stoffströme wurden, basierend auf einer Kombination von aufwendigen experimentellen Untersuchungen und Literaturauswertung, quantifiziert. Die Ergebnisse zeigen, dass 370 000 bis 430 000 Tonnen von Kleingeräten 2007 in Deutschland angefallen sind. Sie beinhalteten 1,9 bis 2,4 Tonnen Gold und 580 bis 720 kg Palladium. In den USA befanden sich in den 2007 angefallenen 3,1 bis 4,3 Million Tonnen Altgeräten 26 bis 36 Tonnen Gold und 9 bis 12 Tonnen Palladium. In Deutschland sind die Sammelquoten deutlich höher (77%) als in den USA (30%). In den USA wurden 6% der angefallenen Kleingeräte wieder verwendet, während die Wiederverwendungsquote in Deutschland 3% beträgt. 72% des in den Kleingeräten beinhalteten Goldes ging deshalb für die Kreislaufwirtschaft verloren. Die Verlustquote beträgt in den USA ca. 75%. Der wirtschaftliche Wert des verlorenen Goldes und Palladium betrug 2007 34 bis 44 Million US-Dollar in Deutschland und 466 bis 714 Million US-Dollar in den USA.

Die Recyclinginfrastrukturen in Deutschland und in den USA ermöglichen keine effiziente Rückgewinnung der Edelmetalle. Die Verluste werden durch die nicht-getrennte Erfassung der Kleingeräte und durch die ungeeignete Behandlung, insbesondere bei der Aufbereitung, verursacht. Die Charakteristika der Kleingeräte beeinflussen stark die Rückgewinnung der Edelmetalle. Das soll bei der Entwicklung von Verbesserungsstrategien betrachtet werden. Neben Empfehlungen zur Systemverbesserung wurden Vorschläge zur Verbesserung der Datenerfassung zur Durchführung weiterer Stoffflussanalysen formuliert. Die angewandte Methode kann benutzt werden, um Abfallwirtschaftsysteme zu bewerten und Verbesserungsstrategien zu entwickeln. Die Methode ist nicht nur für die Bewertung der Verwertung von Wertstoffen nützlich, sondern ermöglicht im Allgemeinen eine quantitative Analyse des Verbleibs der in einem Abfallmanagementsystem behandelten Stoffe.

Résumé

La demande en métaux précieux des producteurs d'équipements électriques et électroniques a augmenté de façon significative durant les dernières années. Bien que leurs concentrations dans les appareils soient très faibles, les métaux précieux sont très pertinents d'un point de vue économique et environnemental comparés à d'autres substances présentes en plus grande quantité (par exemple fer, cuivre ou plastiques).

Le but de cette thèse est de décrire et de quantifier les flux de déchets de petits équipements électriques et électroniques (DEEE) en Allemagne et aux Etats-Unis pour l'année 2007, ainsi que les flux d'or et de palladium associés avec ces DEEE. Même si des systèmes de collecte ont été mis en place, les DEEE y échappent et sont éliminés avec d'autres déchets. En ce qui concerne le traitement des DEEE, le modèle distingue réutilisation et traitement par le secteur formel ou informel (qui inclut l'export illégal de DEEE).

Les flux de matériaux ont été quantifiés à partir d'une compilation de travaux expérimentaux et d'analyse de la littérature. Les résultats montrent qu'en 2007, 370 000 à 430 000 tonnes de DEEE ont été générées en Allemagne, contenant 1,9 à 2,4 tonnes d'or et 580 à 720 kg de palladium. Aux Etats-Unis, 26 à 36 tonnes d'or et 9 à 12 tonnes de palladium se trouvaient dans les 3,1 à 4,3 millions de tonnes de DEEE générées en 2007. Les taux de collecte sont beaucoup plus élevés en Allemagne qu'aux Etats-Unis (77% des DEEE collectés contre 30%). Aux Etats-Unis, 6% des DEEE sont réutilisés, alors qu'en Allemagne le taux de réutilisation est de 3%. En Allemagne, 72% de l'or contenu dans les DEEE a été perdu pour l'économie circulaire, ce taux étant d'environ 75% aux Etats-Unis. La valeur économique de l'or et du palladium perdus en 2007 est de 34 à 44 million US-dollars en Allemagne et de 466 à 714 million US-dollars aux Etats-Unis.

Pour conclure, les infrastructures de recyclage ne permettent une récupération efficace des métaux précieux ni en Allemagne ni aux Etats-Unis. Les pertes résultent du manque de collecte séparée des DEEE et de procédés de traitement inadéquats, en particulier lors du prétraitement. Les caractéristiques des différents types de DEEE influencent considérablement la récupération des métaux précieux et il faut en tenir compte pour développer des stratégies d'amélioration du système. En complément de recommandations pour améliorer le système, des suggestions pour une meilleure collecte de données pour la réalisation d'autres analyses de flux de matières ont pu être formulées. La méthode appliquée peut servir à évaluer d'autres systèmes de gestion de déchets et à développer des stratégies d'amélioration. Elle ne s'applique pas uniquement à la récupération de matériaux de valeur comme présenté dans cette thèse, mais permet d'une façon générale d'analyser quantitativement la destination des substances introduites dans un système de gestion de déchets.

Composition of the doctoral thesis

The doctoral thesis consists of three parts:

1. This **monograph** entitled “Substance flow analysis of the recycling of small waste electrical and electronic equipment – An assessment of the recovery of gold and palladium”

2. Chancerel, P.; Rotter, V.S. Recycling-oriented characterization of small waste electric and electronic equipment. Waste Management 29 (8), 2009: 2336–2352. DOI: 10.1016/j.wasman.2009.04.003 (**Paper 1**)

3. Chancerel, P.; Meskers, C.E.M.; Hagelüken, C.; Rotter, V.S. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. Journal of Industrial Ecology 13 (5), 2009: 791–810. DOI: 10.1111/j.1530-9290.2009.00171.x (**Paper 2**)

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List of abbreviations

Ag	Silver (chemical element)
Au	Gold (chemical element)
BAT	Best available technique
CE	Consumer equipment
CRT	Cathode-ray tube
EAR	Foundation Elektro-Altgeräte Register
EEE	Electrical and Electronic Equipment
Eq.	Equipment
EU	European Union
HH	Household
kt	Kilotonne (million kilograms)
IC	Integrated Circuit
IT	Information Technology
MFA	Material flow analysis
NGO	Non-governmental organization
OECD	Organisation for Economic Co-operation and Development
PC	Personal computer
PCB	Printed circuit board
Pd	Palladium (chemical element)
PGM	Platinum-group metal
PM	Precious metal
Pt	Platinum (chemical element)
SFA	Substance flow analysis
sWEEE	Small Waste Electrical and Electronic Equipment
WEEE	Waste Electrical and Electronic Equipment
WSR	Waste Shipment Regulation

1. Introduction and objectives of the work

Due to the leverage of huge unit sales, the manufacturing of electrical and electronic equipment (EEE) is a major global demand sector for precious and special metals, with a strong further growth potential. Both precious and special metals are contained in complex components with only small concentrations per unit. After the use-phase, the waste electrical and electronic equipment (WEEE) is an important source of these “trace metals”. The recovery requires appropriate processes in order to cope with the hazardous substances contained in WEEE and to recover the resources efficiently.

In the European Union, the operational decisions regarding management of WEEE are mainly driven by maximizing the recovery of mass relevant material outputs like copper, ferrous metals, plastics and aluminium in order to achieve the recovery rates specified in the legislation. Improving the recovery of trace metals is currently a challenge both for policy-makers and for the operators of collection and treatment facilities, who need to design and implement adequate infrastructures.

The goal of this thesis is to describe and quantify the flows of small waste electrical and electronic equipment (sWEEE) and in particular the flows of gold and palladium contained in this sWEEE. The term ‘sWEEE’ covers small household appliances, IT and telecommunication equipment, consumer electronics, tools and toys generated by households or similar to sWEEE generated by households. The material and substance flows are considered in the whole recycling chain (from the generation of sWEEE by the last user up to the exit of the end-of-life phase). As an example, the flows in Germany and in the USA in 2007 are investigated, so that the losses of precious metals are quantified and recommendations for more efficient recovery can be formulated.

To achieve this goal, the following objectives were defined:

1. Qualitative description of the system ‘management of sWEEE’,
2. Quantification of the material flows in the system based on a review of the relevant literature, as well as identification of data gaps,
3. Quantification of the concentration of precious metals in sWEEE based on a combination of experimental investigations conducted at Technische Universität Berlin and data in the literature,
4. Quantification of the transfer coefficients of the treatment processes applied in 2007 regarding the recovery of precious metals,
5. Determination of the flows of gold and palladium in the investigated system (from generation up to refining of precious metals), by conducting a substance flow analysis,

6. Identification of relevant indicators to describe the performance of the management system and quantification of the losses of precious metals,
7. Based on the results of the substance flow analysis, formulation of recommendations to improve the recovery of precious metals from sWEEE.

In chapter 2, background information on the life-cycle of EEE, on management of WEEE and on precious metals in WEEE is presented. The objectives of WEEE management and the legislation relative to this waste are described, as well as the relevance of precious metals from an economic and environmental point of view. The method ‘Substance Flow Analysis’ (SFA) used to track the flows of precious metals in the sWEEE management systems of Germany and the USA is described.

The boundaries of the investigation in terms of processes, time, location and tracked materials are presented in chapter 3. Chapter 3 also addresses the methods used to gather the data necessary to conduct the SFA and to deal with uncertainties.

Chapter 4 and 5 present the results of the SFA. First, the flows of generated, collected, reused and treated sWEEE, and the concentration of precious metals in sWEEE are quantified (chapter 4). The results are then aggregated in chapter 5 to depict the flows of precious metals associated with six groups of waste equipment, as well as the total flows of precious metals contained in sWEEE.

The results of chapter 5 are assessed in chapter 6. The origin of the losses of precious metals are identified and discussed. The results of the SFA are compared with other research results from other countries. The changes of the material flows expected in the future are presented.

Chapter 7 suggests measures for a more efficient recovery of precious metals. For the long-term implementation of SFA as a monitoring tool, some recommendations concerning the collection of data related to the material flows are formulated. The strengths and the weaknesses of the methodology to assess waste management systems are addressed.

2. Background and definitions

Electrical and electronic equipment (EEE) has invaded our all-day life. On average, between 24 devices (GfK 2007) and 60 devices (EERA 2008) are in use in a European household. CEA (2008) estimated that about 2.9 billion devices can be found in the homes and cars in the USA. Some of these products are used daily (for example primary TV, PC, cell phone), others are used periodically (for example camcorder or printer) and others are used infrequently or not at all (CEA 2008). After being used, the devices from households, businesses, industries, institutions etc. are discarded and form a large flow of materials called 'Waste electrical and electronic equipment' (WEEE).

2.1. About EEE and WEEE

2.1.1. Lifecycle of EEE

According to the WEEE Directive of the European Union, 'Electrical and electronic equipment' or 'EEE' is equipment which is dependent on electric currents or electromagnetic fields in order to work properly or serves the generation, transfer and measurement of such currents and fields falling under the categories set out in Annex IA of the Directive and designed for use with a voltage rating not exceeding 1000 volts for alternating current and 1500 Volt for direct current.

EEE has a product life starting with product manufacture, as the design of the product determines the product characteristics and, therefore, the demand for raw materials, and ending with end-of-life management (Figure 1).

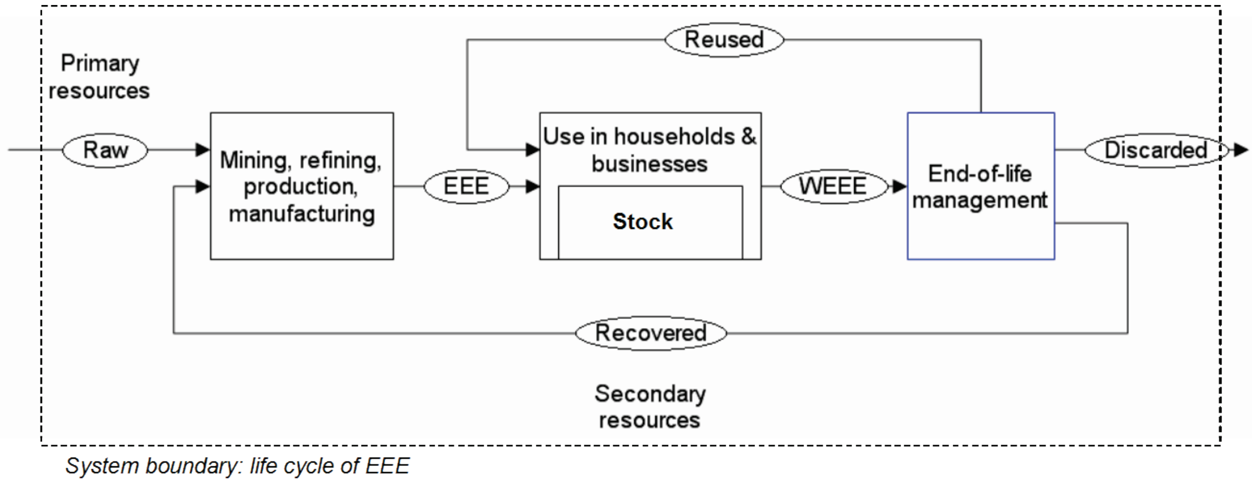

Figure 1 Simplified illustration of the product life cycle consisting of mining and refining of the raw materials, production and manufacturing of the product, product use, and end-of-life management

During product use, EEE is stocked by the users, who can be households, businesses, industries, or institutions. When the user discards the EEE, it becomes WEEE and enters the end-of-life phase. The overall task of the end-of-life phase is to recover valuable substances and to destroy or remove substances with a high hazardous potential in an environmentally-friendly way. The arrow 'discarded' refers both to the disposed hazardous substances and to the resources that could not be 'recovered'. Another option for end-of-life management is to 'reuse' the equipment by bringing the WEEE back to the use phase.

2.1.2. Definitions of WEEE

'Waste electrical and electronic equipment' or 'WEEE' means EEE which is waste, including all components, subassemblies and consumables which are part of the product at the time of discarding. According to section 3(a) of the Waste Framework Directive 2008 of the European Union (Directive 2008/98/EC), 'waste' means "any substance or object which the holder discards or intends or is required to discard".

Other definitions of WEEE, also called e-waste or e-scrap, can be found in the literature (Widmer et al. 2005). According to BAN (2002), "e-waste encompasses a broad and growing range of electronic devices ranging from large household devices such as refrigerators, air conditioners, cell phones, personal stereos, and consumer electronics to computers which have been discarded by their users". OECD (2001) defines e-waste as "any appliance using an electric power supply that has reached its end-of-life". StEP (2009) wrote that "e-waste is a term used to cover almost all types of electrical and electronic equipment that has or could enter the waste stream. Although e-waste is a general term, it can be often considered to cover TVs, computers, mobile phones, white goods (fridges, washing machines, cookers, etc.), home entertainment and stereo systems, toys, toasters, kettles – almost any household or business item with circuitry or electrical components with power or battery supply." According to Kahhat et al. (2008), "electronic waste, commonly known as e-waste, waste electrical and electronic equipment (WEEE), or end-of-life (EOL) electronics, denotes electronic and electrical equipment, including all components, sub-assemblies, and consumables, deemed obsolete or unwanted by a user".

Huisman et al. (2007) pointed out that WEEE is a particularly complex waste flow in terms of:

- The variety of products,
- The association of different materials and components,
- The hazardous substance concentration, and
- The growth patterns of this waste stream which can be influenced not only by need but also by changes in technology, design and marketing.

Small WEEE (sWEEE) is defined in this thesis as the WEEE belonging to categories ‘small household appliances’, ‘IT and telecommunications equipment’, ‘consumer equipment’, ‘electrical and electronic tools’ and ‘toys, leisure and sports equipment’ of the WEEE Directive (categories 2, 3, 4, 6 and 7).

2.1.3. Objectives of WEEE management

End-of-life management of WEEE serves the following goals (Huisman et al. 2004):

- Reduction of materials going to landfill, and minimization of landfill-volumes.
- Recycling of materials in order to keep the maximum economic and environmental value and to avoid new material extraction.
- Reduction of emissions of environmentally relevant substances, for example through leaching from landfill sites, incineration slags and off-gases from combustion processes.

These objectives are partly interlinked (Huisman et al. 2004). From a broader point of view, WEEE management aims at reducing environmental impacts by “developing a society that learns to balance rapid technological evolution with responsible product/material management” (Kahhat et al. 2008). Meadows et al. (2004) refer to separating and recycling materials after the use phase as a “step toward sustainability”, where materials are moved “through the human economy the way they move through nature – in closed cycles”.

2.2. Legislation

Both in Germany and in the USA, legislation came into effect to define and achieve objectives related to the management of WEEE.

2.2.1. European legislation

The member states of the European Union had to comply by 13 August 2004 with the Directive 2002/96/EC of the European parliament and of the council on waste electrical and electronic equipment, also called the WEEE Directive.

The objectives of the WEEE Directive are to reduce the consumption of natural resources through recycling and to prevent the pollution caused by inappropriate treatment of WEEE. In this context, the WEEE Directive requires the implementation of the principle of producer responsibility, making the manufacturers of EEE responsible for financing operations concerning WEEE management. In addition, the WEEE Directive stipulates that the design and production of electrical and electronic equipment which take into account and facilitate dismantling and recovery should be encouraged (section 4). The general concept of producer responsibility for WEEE was discussed by Davis (1998), Lindhqvist & Lifset (2003), and OECD (2001). Clift & France (2006), Sander et al. (2007), and Schill (2007) analysed the implementation of the principle of producer responsibility in the European Union. The analyses showed that the producer responsibility permits financing WEEE management but does not create incentives for design-for-recycling because of the large number of EEE producers and of different products.

The WEEE Directive sets up targets for collection (section 5) and treatment (sections 6 and 7). The “member states shall adopt appropriate measures in order to minimise the disposal of WEEE as unsorted municipal waste” and shall “ensure that a rate of separate collection of at least four kilograms on average per capita per year of WEEE from private households is achieved”. During the review process of the WEEE Directive in 2008, it was proposed to modify the collection target and make it depend on the weight of the EEE sold on the national market. In the coming years, producers or third parties could have to achieve a minimum collection rate of 65% of the weight of the EEE placed on the market in the two preceding years (COM 2008), instead of having to collect 4 kg of WEEE per capita and year.

According to the WEEE Directive, the member states have to set up systems to provide for the treatment of WEEE using best available treatment, recovery and recycling techniques. Any establishment or undertaking carrying out treatment operations has to obtain a permit. Annex II defines requirements for selective treatment of some substances, preparations and components (for example cathode ray tubes, components containing mercury, batteries, printed circuit boards with a surface area greater than 10 square centimetres). The targets for recovery for the ten categories of WEEE are listed in section 7 of the WEEE Directive (Table 1).

Table 1 Targets for recovery according to section 7 of the WEEE Directive

Categories (WEEE Directive)	**Rate of recovery (by average weight)**	
	Component, material and substance reuse and recycling	**Recovery (incl. energy recovery)**
1. Large household appliances 10. Automatic dispensers	75 %	80 %
3. IT and telecommunications equipment 4. Consumer equipment	65 %	80 %
5. Lighting equipment	80 %	

Categories (WEEE Directive)	Rate of recovery (by average weight)	
	Component, material and substance reuse and recycling	Recovery (incl. energy recovery)
2. Small household appliances 5. Lighting equipment 6. Electrical and electronic tools 7. Toys, leisure and sports equipment 9. Monitoring and control instruments	50 %	70 %

The recovery targets are defined as a percentage of the weight of the input WEEE. To calculate the recovery rates, the producers must report the quantities and categories of electrical and electronic equipment put on their national market, collected through all routes, reused, recycled and recovered, and exported. In the proposal for the revision of WEEE Directive, it is planned to increase all the recovery targets by 5% (COM 2008).

In the review process, the research groups of Bogaert et al. (2008), Huisman et al. (2007), IPTS (2006), Sander et al. (2007) published recommendations to improve the WEEE Directive. The European Commission received during the open consultation 168 responses from stakeholders, among others member states, non-governmental organisations, producers of EEE, consumers, retail and distribution sector, municipalities, treatment operators, recyclers and recovery operators, producer responsibility organisations and national producer registers (COM 2008). A summary of the opinions is publicly available on the internet (CIRCA 2008).

Regarding export of WEEE, the European Union is a signatory of the Basel Convention (1989) of the United Nations. Among other things, the Basel Convention prohibits exports that violate national import prohibitions, and exports or imports of hazardous waste without prior consent. Moreover, the Waste Shipment Regulation (WSR, Regulation EC 1013/2006) prohibits any export of hazardous waste to or through a non-OECD, non-EU country. An orange list requires notification and consent. The WSR is completed by the Revised Correspondents' Guidelines N°1 on Shipments of Waste Electrical and Electronic Equipment. These guidelines are not legally binding and “represent the common understanding of all Member States on how Regulation (EC) No 1013/2006 should be interpreted”. The guidelines provide a list of characteristics of EEE that are likely to indicate whether the exported material is WEEE or EEE, and a categorization of the different types of materials relating to WEEE subject to the WSR regulations.

2.2.2. German legislation

The Act Governing the Sale, Return and Environmentally Sound Disposal of Electrical and Electronic Equipment of 16 March 2005 (ElektroG) transposed the European WEEE Directive into German legislation.

The producer responsibility defined by the ElektroG is a shared responsibility (Rotter et al. 2008), since the producers are responsible for taking back and treating WEEE, whereas public waste management authorities (municipalities) provide free of charge the collected equipment for pick-up by the producers. According to Section 9 (6) of ElektroG, public waste management authorities can also choose not to make the WEEE available for pick-up. At municipal collection facilities in Germany, WEEE has to be collected in the following five collection groups:

1. Large household appliances and automatic dispensers
2. Refrigerators and freezers
3. IT and telecommunications equipment and consumer equipment
4. Gas-discharge lamps
5. Small household appliances, lighting equipment, electric and electronic tools, toys, sports and leisure equipment, medical products, monitoring and control instruments.

SWEEE as defined in this thesis belongs to the collection groups 3 and 5.

In addition to the municipal collection scheme, producers may choose to set up and operate individual or collective take-back systems for WEEE from private households. In this case, the producer has to cover all additional costs of collection. Retailers may voluntarily accept returned WEEE and transport it to the producer or the municipal collection facilities.

In accordance with section 6 of ElektroG, the producers set up a clearing house, the foundation Elektro-Altgeräte Register (EAR). The clearing house serves as a national register for producers, a coordinating body for container pick-up (allocation of responsibilities) and collects the data reported by producers on quantities of WEEE collected and treated to submit them to the Federal Environmental Agency (‘Umweltbundesamt’). Figure 2 illustrates the flows of WEEE and of information between municipalities, clearing house, producers and recyclers. Bilitewski et al. (2008), Gallenkemper et al. (2008), Prelle (2008), Rhein et al. (2008), Rhein et al. (2008b) and Rotter et al. (2008) discussed various aspects related to the practical implementation of the regulations of the ElektroG. The studies report practical difficulties related to a fair distribution of the financial responsibility over the producers.

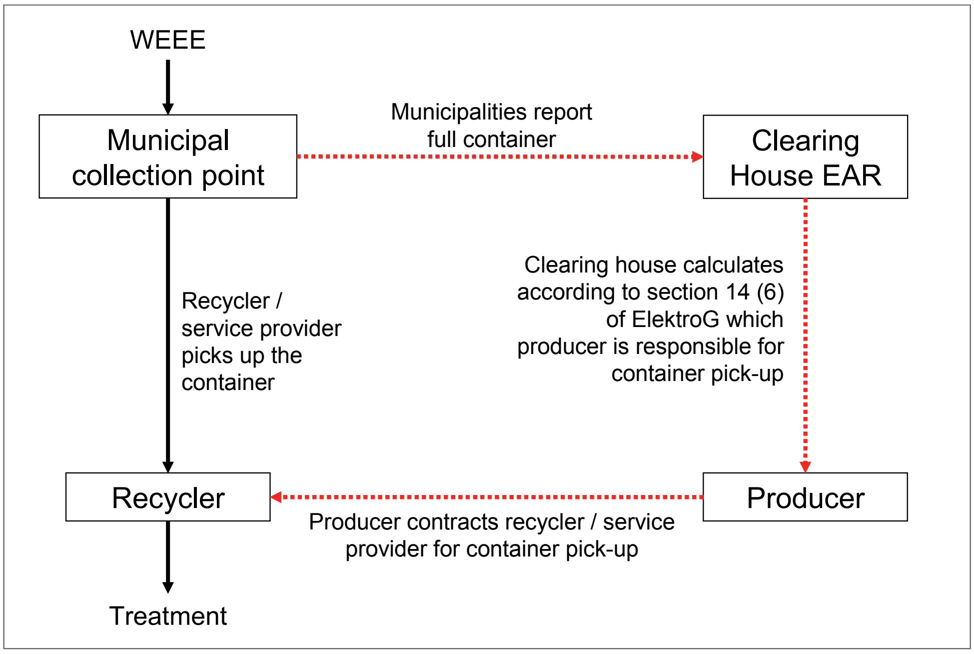

Figure 2 Flows of WEEE and information between municipalities, clearing house, producers and recyclers

Germany, as a member state of the European Union, has to comply with the export regulations of the Basel Convention and of the Waste Shipment Regulation.

2.2.3. Legislation in the United States

To date, there is no federal legislation in the USA directly addressing collection and recycling of WEEE. The USA implemented various legal requirements on waste management that apply on WEEE. The principle one is the Resource Conservation and Recovery Act (RCRA contained in United States Code Title 42 §§6901-6992) governing the disposal of solid and hazardous waste. Other waste management regulations are administered by the United States Environmental Protection Agency and codified in Title 40 of the Code of Federal Regulations parts 239-282. Colour cathode-ray tubes (CRT) computer monitors, colour CRT TV sets are specifically addressed by the CRT rule. CRTs and smaller items such as cell phones are rated as “hazardous” under federal law under some conditions. For example, they are not “hazardous waste” if they are generated by households, or by businesses and other organizations that send less than 100 kilograms of hazardous waste per month for disposal (US EPA 2009). The need for federal legislation has been discussed for many years in the US (BAN 2002; Computer TakeBack 2009; GAO 2008; Kahhat et al. 2008). The USA did not sign the Basel Convention or implement legislations on export of WEEE.

In 2008, nineteen states and New York City had passed a law or bill related to WEEE (Computer TakeBack 2009). Eighteen states and New York City implemented producer responsibility laws covering between 3 and 16 types of equipment (monitors, computers, laptops, and TV sets are covered by the majority of the state legislations). In 2005, California implemented a consumer fee law, where the consumers pay an ‘Advanced Recycling Fee’ at purchase that goes to the state and is used to finance recycling and collecting operators. Five states implemented targets for collection (based on market shares in New York and in Minnesota) and nine states ban some types of WEEE (mainly cathode-ray tubes) from landfills. Another eleven states are expected to introduce bills in 2009 (Computer TakeBack 2009).

2.3. WEEE and precious metals

As a consequence of continuous modifications of function and design of appliances, WEEE contains a highly heterogeneous mix of materials. Essential constituents of much EEE include precious metals (gold, silver, palladium) and special metals (indium, selenium, tellurium, tantalum, bismuth, antimony) (Behrendt et al. 2007; Hagelüken 2006a).

2.3.1. Precious metals

Precious metals (PM) include gold, silver and the platinum-group metals (PGM): platinum, palladium, rhodium, ruthenium, iridium and osmium. All precious metals belong to the transition elements. Precious metals are characterised by high economic value, beauty and particular chemical and physical properties, i.e. low electron affinity, high resistance to corrosion and high density (Hagelüken et al. 2005). Precious metals are all electrochemically noble metals (Renner et al. 2001), which means that their standard reduction-oxidation potential has a positive value. Silver has the highest electrical conductivity, the highest thermal conductivity, and the lowest electrical contact resistance of all metals (Brumby et al. 2008). Table 2 summarizes the properties of some precious metals.

Table 2 Properties of the precious metals gold, silver, palladium and platinum

	Gold Au	**Silver Ag**	**Palladium Pd**	**Platinum Pt**
Atomic number	79	47	46	78
Atomic mass	196.96654	107.8682	106.42	195.08
Melting point	1064.43 °C	961.9 °C	1554 °C	1772 °C
Boiling point	2808 °C	2212 °C	2970 °C	3827 °C
Density at 20 ◦C	19.32 g.cm^{-3}	10.49 g.cm^{-3}	12.02 g.cm^{-3}	21.45 g.cm^{-3}
Electrical resistivity at 0 ◦C	2.06 µΩ.cm	1.465 µΩ.cm	9.725 µΩ.cm	9.825 µΩ.cm
Thermal conductivity at 0 ◦C	314 W.m^{-1}K^{-1}	418 W.m^{-1}K^{-1}	75 W.m^{-1}K^{-1}	73 W.m^{-1}K^{-1}
Average price in 2007[1]	21 701 US-$ per kg	431 US-$ per kg	11 574 US-$ per kg	40 509 US-$ per kg
World mine production in 2007[1]	2500 t	20 500 t	232 t	230 t
Reserve base[1]	90 000 t	570 000 t	80 000 t (including all PGM)	

[1] USGS 2008

The extraction of precious metals through mining is associated with significant environmental impacts like emissions of greenhouse gases, and consumption of energy, water and land (Ayres 1997). According to the Wuppertal Institute (2003), gold has a material intensity (MIT) of 540 000, which means that 540 tonnes of material have to be used to produce one gram of gold (Ritthoff et al. 2002). The MIT of silver is 7 500 (Wuppertal Institute 2003). Palladium has a MIT of 99 891 (primary production) or 2 394 (secondary production) (Saurat & Bringezu 2008). For comparison, primary copper has a MIT of 348.47 and secondary copper of 2.38 (Wuppertal Institute 2003). The environmental impacts of the secondary production of precious metals in state-of-the-art operations are much lower than primary production (Hagelüken & Meskers 2008). According to Saurat & Bringezu (2008), carbon dioxide equivalent emissions associated with secondary production of platinum-group metals in Europe are lower by a factor 13 than primary production outside of Europe, and sulphur dioxide equivalent emissions are lower by a factor 107.

2.3.2. Use of precious metals for manufacturing EEE

Around 12% of the primary production of gold, 30% of the primary production of silver and 15% of the the primary production of palladium were used in 2006 for manufacturing EEE (Hagelüken & Meskers 2008). Precious metals are used in printed circuit boards (PCB) as a component of complex material mixtures, as they are mixed with or connected to other metals in contacts, connectors, cables, solders, hard disk drives, etc., with ceramics in multi layer capacitors, integrated circuits, hybrid ceramics, etc. or with plastics in PCB-tracks, interboard layers, integrated circuits, etc. (Hagelüken 2006a).

The great advantage of gold is its high resistance to oxidation and corrosion and its high conductivity (Renner et al. 2000). Gold and gold alloys are used for conductor material and low-voltage contacts for communication and information transfer equipment, where even very thin oxide layers would cause interruptions or failures in signal transfer (Renner et al. 2000). Silver, due to its high electrical and thermal conductivity, is used as conductor and electrode material (Brumby et al. 2008). Palladium, pure or in combination with silver, is the most important component in pastes used for the production of inner electrodes of multilayer capacitors. Palladium is also used as a component in silver-based conductor pastes and for resistor elements in thick-film circuitry. Platinum finds application for data storage in harddisk drives, as barrier layers and as contact pads on semiconductor chips (Hagelüken & Meskers 2008, Renner et al. 2001). Table 3 gives a survey of the main application fields of gold, silver, palladium, platinum and their alloys.

Table 3 Application of gold, gold alloys, silver and silver alloys, palladium and platinum in electronics (Schlamp 1996, Hagelüken & Meskers 2008)

	Bulk	Bimetal	Surface Coat			
			electroplated	sputtered or evaporated	pastes, lacquers	solder connection
Gold	bonding wires for integrated circuits, transistors, diodes	plug-in contacts	PCBs, plug-in contacts, solderable and bond surfaces, switches, corrosion protection of semiconductor device packages	thin film hybrid circuits, conductor contact, bond surfaces	thick film hybrid circuits, solderable areas for contacts, die-attach, IC technology	special solders for die-attach, package soldering, and connections in semiconductor power devices
Silver	pressure-contact plates for power semiconductor devices	plug-in contacts, pressure-contact and soldered base plates	PCB for high frequencies, system carrier, Mo and W base-plates, lead frames	contact surfaces on Si diodes lead frames	Conductor pastes for thick film circuits, potentio-meter capacitors, contact foils, screening, glass solders	tubes, package joining components, soft solders in semiconductor devices, die-attach
Palladium	bonding wires for transistors, diodes	plug-in contacts	plug-in contacts	multilayer capacitors	Conductor and electrode paste for thick-film circuits, multilayer capacitors	Ag–Cu–Pd solders for electron tubes package joining
Platinum	test resistors			test resistors, diffusion barriers, magnetic data storage in harddisk drives		

2.3.3. Relevance of precious metals in WEEE

Although the concentrations of precious metals in the appliances are very low, in some equipment types these metals have a high economic and environmental relevance compared to other substances present in much higher quantity (e.g. iron, copper, plastics) (Herrmann 2004; Huisman 2004). The economic relevance of precious metals in WEEE was emphasized by Hagelüken (2006a), Koehnlechner (2008), Malhotra (1985) and Streicher-Porte et al. (2005). Precious metals make up more than 80% of the economic value of printed circuit boards in personal computers, mobile phones and calculators. For printed circuit boards in TV sets and for DVD-players, they still contribute more than 40% (Hagelüken 2006a). Huisman (2004) revealed that in mobile phones, three–quarters of the environmental impacts result from the gold and palladium content. Gold accounts for 16% of the total environmental weight of the materials contained in waste IT and telecommunication equipment (excluding monitors), and palladium represents over 12% (Huisman et al. 2007). However, precious metals are not very relevant from an environmental point of view in all equipment types. For example, gold and palladium contribute about 2% to the environmental weight of the materials contained in cathode-ray-tube TV sets, the majority of the environmental weight coming from plastics and from the lead-containing glass cone and glass screen (Huisman et al. 2007). Table 4 presents the contribution of the precious metals gold, silver and palladium to the environmental weight of various types of sWEEE.

Table 4 Contribution of precious metals to the environmental weight of some categories of sWEEE (Huisman et al. 2007)

Category	Gold Au	Silver Ag	Palladium Pd
Small household appliances	0.02%	0.00%	0.09%
IT and telecommunication excluding monitors	16.20%	0.32%	12.46%
CRT computer monitors	1.12%	0.06%	0.83%
LCD computer monitors	26.22%	0.22%	10.50%
Consumer electronics excluding TV sets	3.78%	0.09%	1.33%
CRT TV sets	7.62%	0.38%	5.84%
LCD TV sets	4.16%	0.06%	2.61%
Electrical and electronic tools	0.04%	0.00%	0.15%
Toys, leisure and sports equipment	0.69%	0.02%	0.10%

The concentration of precious metals in printed circuit boards is usually much higher than the concentration of precious metals in mined ores. Presently mined ores for the extraction of gold and palladium usually contain less than 10 g/t of precious metals (Hagelüken et al. 2005). Compared to the concentrations for PCB of personal computers of 250 g/t of gold and of 110 g/t of palladium (Hagelüken 2006a), the importance of recovering precious metals from electronics becomes obvious. Moreover, the environmental impacts of the secondary production in state-of-the-art operations are much lower than primary production (see 2.3.1).

2.4. Management of sWEEE

According to Figure 1, the subsystem ‘management of sWEEE’ has one input, coming from the use phase, and three outputs (recovered, reused and discarded materials). WEEE management can be divided into following steps (Figure 3): (1) collection of sWEEE, (2) pre-processing, (3) recovery, reuse and/or disposal.

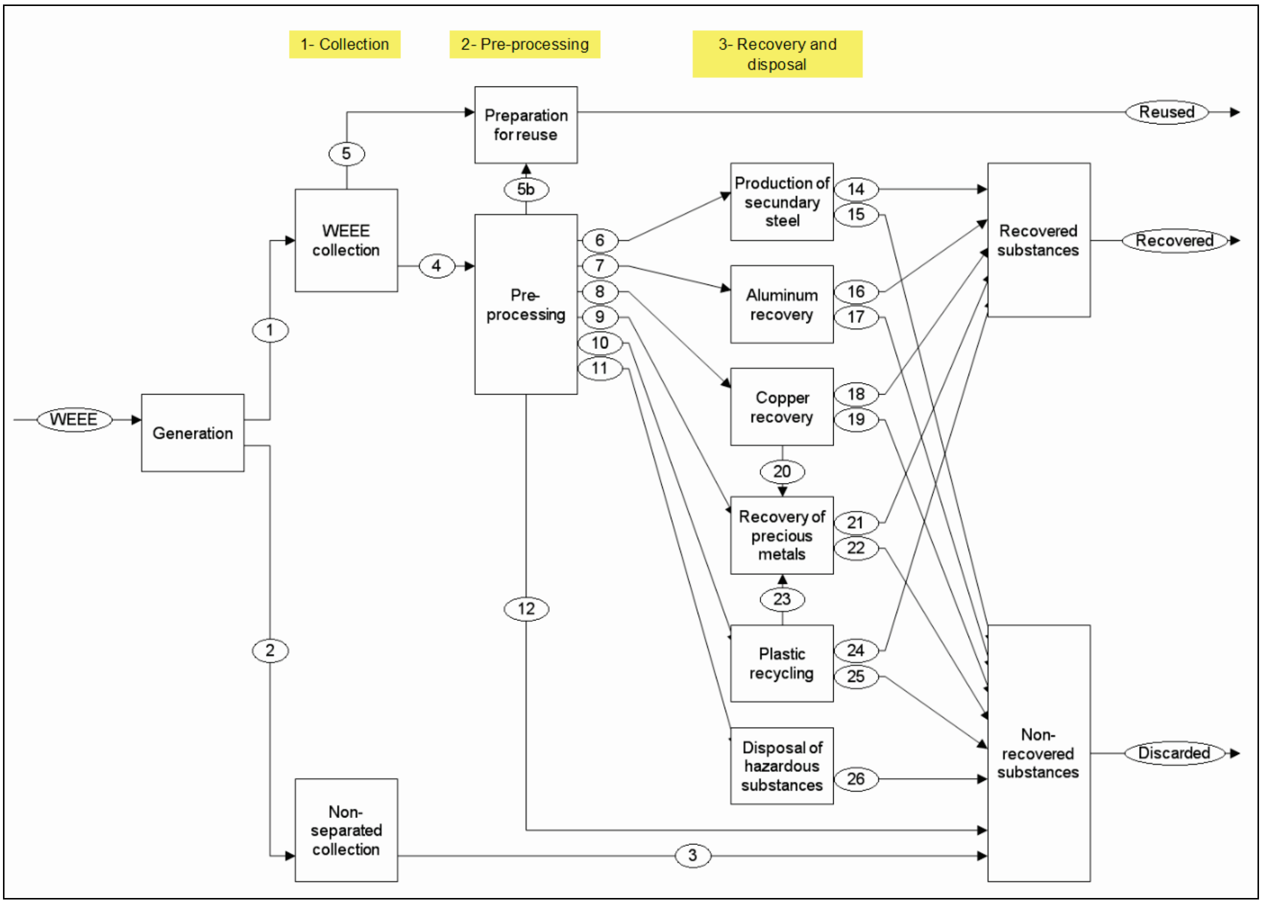

Figure 3 Simplified chain of collection, pre-processing, reuse, recovery and disposal processes for sWEEE, focusing on recovery of precious metals

After collection, sWEEE is in most cases pre-processed in order to generate appropriate material streams that are sent to the subsequent end-processing stages (recovery, reuse or disposal). Some sWEEE is not collected separately and, therefore, does not enter the recycling process chain.

2.4.1. Generation

The WEEE discarded by the users is called 'generated WEEE'. In this thesis, EEE going as second-hand good from a user to the next user is not considered as WEEE. Unused EEE stored for some years in households, businesses or institutions before being discarded is not considered either.

2.4.1.1. Previous estimations of WEEE generation

UNEP (2005) reported that 20 to 50 million tonnes of WEEE are generated worldwide every year. Various researchers have estimated the sWEEE generated yearly in Germany and in the USA (Table 5). The total quantity of sWEEE produced in Germany per year was evaluated between 3.5 and 12.3 kg per capita per year. The studies refer to various periods (years 1992 to 2005). The discrepancies in the methods and basic assumptions used for the estimates explain the diverging results (Widmer et al. 2005). It is difficult to measure or estimate actual WEEE generation, since the routes for disposal are manifold (Huisman et al. 2007).

Table 5 Estimations of the quantity of sWEEE generated annually in Germany and in the USA

Country	Source	Year	sWEEE generated		Considered sWEEE (categories according to WEEE Directive)
			kt/year	kg/cap*a	
Germany	Hafkesbrink et al. 1998	1992	611	7.6	2, 3, 4
	Wissing 1995	1994	483	5.9	2, 3, 4, 6
	BVSE 1998	1997	890	10.9	2, 3, 4
	Hafkesbrink et al. 1998	1998	923	11.2	2, 3, 4
	Hanke et al. 2001	1998	650	7.9	2, 3, 4
	IZT 2004	2000	971	11.8	2, 3, 4
	BVSE 2003	2000	1007	12.3	2, 3, 4
	IFEU 2005	2003	429	5.2	2, 3, 4, 6, 7
	ZVEI 2005	2005	286	3.5	2, 3, 4
	Huisman et al. 2007[1]	2007	715	8.7	2, 3, 4, 6, 7
USA	US EPA 2008	2007	2043	6.8	3, 4 [2]

[1] Forecast WEEE arising in Germany combined with average category composition of WEEE

[2] Six EEE related to computers, TV sets and mobile phones were considered - expressed in US short tons in the report of the US EPA (2008)

Although the results of studies aimed at quantifying the generation of WEEE differ considerably, many researchers agree that worldwide, the generation of WEEE is continuously increasing (Kahhat et al. 2008; IAER 2006; Widmer et al. 2005). Huisman et al. 2007 reports that the generation of household WEEE in Europe could grow annually at between 2.5% and 2.7%. Hischier et al. (2005) mentioned an increase between 3% and 5%. This increase is different according to the product groups. In the USA, the proportion of computer-related products reaching the end-of-life stage has increased over time relative to TVs (US EPA 2008). In Germany, the generation of waste IT equipment is expected to increase by 72% between 2008 and 2013, while the generation of small waste consumer equipment will increase by “only” 10% (calculated from the data of Rotter & Janz 2006).

2.4.1.2. Lifetime of EEE

The lifetime of EEE is an important parameter that influences the generation of WEEE. As reported by Babbitt et al. (2009), three kinds of time periods possibly called "lifetimes" in the literature can be distinguished:

1. First use time: Time from sale to the end of the use by the first user
2. Total use time: Time from sale to the end of the use by the last user, including reuse(s)
3. Total lifetime: Use, reuse(s) and storage of unused devices (time from sale to collection as waste)

Matthews et al. (1997) described these three periods and quantified the fractions of personal computers that are reused and stored after first use (Figure 4).

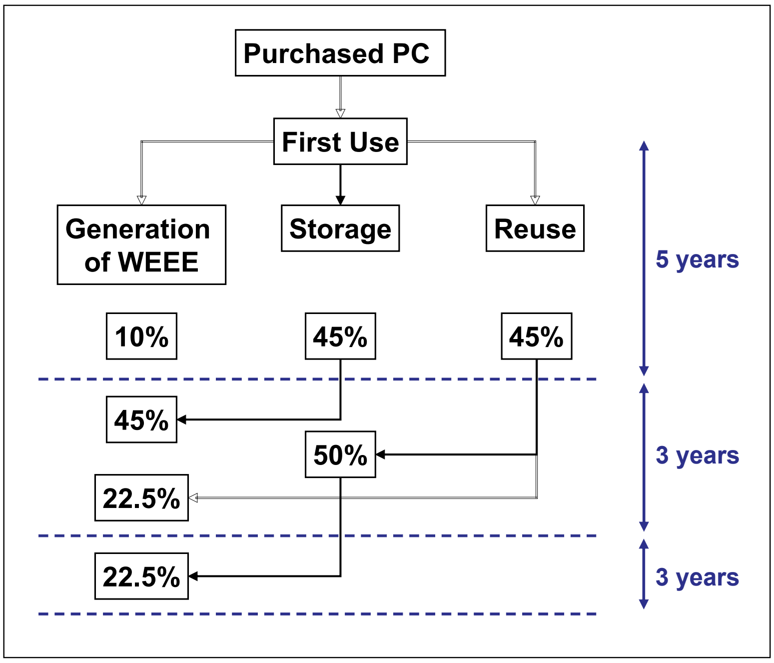

Figure 4 Lifetime of PC from purchase of EEE to generation of WEEE, including first use, reuse and storage (Matthews et al. 1997, designed by EEA 2002)

According to Scheidt (2007), ICT products are often stored by the householder for 3 to 5 years before they are discarded. Nokia (2008) and Murakami et al. (2009) also reported the tendency of the users to temporarily store unused WEEE before recycling. US EPA (2007a) estimated that in 2005, approximately 460 million devices were put into storage and/or reuse in the USA. Three-quarters of all of the computers sold in the USA remain in a garage, closet or storage space (NSC 1999). Murakami et al. (2009) calls these stocks of unused EEE 'hibernating stocks'. To approximate the WEEE generation, which begins when the user discards an EEE, the 'total lifetime' including reuse and storage is needed. The average total lifetime is, therefore, the average time between purchase of EEE and generation of WEEE when the EEE is discarded by its last user.

2.4.1.3. Overview of possible methods to estimate the WEEE generation

Different methods can be used to estimate the generation of sWEEE, using data on volumes of sold EEE, stocks of EEE by the users, average lifetime of EEE and other data on the behaviour of the users regarding discard of WEEE. Table 6 shows an overview of these methods. Table 6 also presents the formula and the data required to apply them, the suitability of the methods for saturated and dynamic markets, and a rough assessment of their accuracy.

Table 6 Methods to estimate the WEEE generation – modified from EEA (2002) and Terazono (2007)

Method	Calculation	Required data			Applicable to		Accuracy
		Sales	Stock*	Lifetime	Saturated markets	Dynamic markets	
Sales	Sales at t	X			X		Low
Simple delay	Sales at (t – lifetime)	X		X	X		Medium
Distribution delay	Sales in previous years and distribution of lifetime	X		X	X	X	High
Time step	Stock at (t-1) – Stock at t + (Sales - WEEE)until t	X	X		X	X	High
Camegie Mellon	Includes data on behaviour of end user (hibernation / reuse / disposal)	X		X	X	(X)	High
Batch leaching (Stock& lifetime)	Stock at t / lifetime (or other parameter α)		X	X	X		Low
Econometric analysis	Depending on GDP or other parameters						Low

* Stock = penetration rate in households x number of households + penetration rate in businesses x number of businesses

The ‘simple delay’ method consists of assuming that after a fixed lifetime, the devices are discarded, i.e. the amount of WEEE generated at a time t is equal to the amount of EEE sold at the time ‘t minus lifetime’.
By the ‘distribution delay’ method, also called ‘survival analysis’ by Wen et al. (2009), a lifetime distribution is assumed. The lifetime distribution is defined as the probability density function that EEE that entered the use phase at time t_0 exits use as WEEE at time t_1. Several authors mentioned that the lifetime distribution of EEE is best approached with Weibull functions (Davis et al. 2007; Mueller et al. 2007; Terazono et al. 2006). However, plotting Weibull distributions requires knowing a shape and a scale parameter (Davis et al. 2007; Mazhar et al. 2007), which would depend on the equipment types. No data on these parameters are available in the literature. According to Mueller et al. (2007), normal distribution functions can also fit well to model the lifetime distribution of EEE. This distribution was used in this research, taking as mean the average lifetime and as standard deviation 30% of the average lifetime (variation coefficient of 30% as modelled by Bilitewski et al. (2008)). The estimated WEEE generation for 2007 is the sum of the amounts of WEEE generated by the discarding of the EEE sold in the years before 2007.
The ‘batch leaching’ method consists of dividing the stocks of EEE in households and businesses by the average lifetime. The stocks are determined by multiplying the penetration rates in the households (businesses) by the number of households (businesses). Penetration rates are defined as the average number of appliances per capita or per household. This method was applied by EEA (2002), Kumar & Shrihari (2007), Rotter & Janz (2006) and Fraunhofer IZM (2007).
More information on the other methods listed in Table 6 can be found in the publications of EEA (2002) and Terazono (2007).

2.4.2. Collection

The separate collection of WEEE conditions the recycling and reuse of WEEE. WEEE can be collected on a voluntary basis or in order to fulfil legislative regulations, driven by economic and/or idealist motivations (for environmental protection). Collecting large amounts of WEEE to divert it from being disposed of is one of the main objectives of the majority of the current legislations.

In practice, the channels used to collect WEEE differ both in terms of the applied models and the persons or organisations responsible for organising and/or financing the operations. The following models are available for collection:

1. Bring systems, with permanent collection centres with fixed opening times, containers on the streets, or temporary collection events;

2. Pick-up systems, where the WEEE is collected at the homes or offices of the last users, optionally together with other kinds of waste like packaging waste, as in the project ‘Gelbe Tonne Plus’ described by SenGUV (2007);
3. Distance collection, where the user sends the WEEE by post to the collector.

The responsibility to finance and/or to organise the collection can be in the hands of the following stakeholders:

1. Public authorities like municipalities and governments;
2. Private commercial organisations like EEE manufacturers, EEE retailers or WEEE recyclers. Besides registered companies, the collection of WEEE by individuals or non-registered commercial organisations belonging to the ‘informal sector’ was observed in Germany (Janz et al. 2009a) and in many other countries (Terazono et al. 2006);
3. Private non-commercial organisations like non-governmental organisations or citizen initiatives.

Benefits and barriers to various collection channels were presented by CIWMB (2004a). Seddigh et al. (1996) compared different collection options regarding the willingness of the citizens to use them. Nagel et al. (1998) analysed the collection systems used in Germany, the Netherlands and Sweden. The strengths of temporary collection events, especially the careful handling of the EEE and, therefore, the preservation of the reuse value, were presented by Legler (2009).

Various authors reported that only a small fraction of the generated WEEE is collected (Huisman et al. 2007; US EPA 2008) and that the majority of WEEE still finds its way to landfill (Barba-Gutiérrez et al. 2008). Also in Germany, WEEE is often disposed of together with residual waste, even though the ElektroG requires the separate collection of WEEE (Janz & Bilitewski 2007; 2009). Rotter (2002) estimated that 47% of the lead, over 50% of the cadmium and 31% of the mercury in residual household waste is from WEEE. Musson et al. (2006) investigated the leaching of heavy metals, especially lead, due to WEEE disposal on landfills and found lead concentrations in the leachates above the legal limit. Townsend et al. (1999; 2003; 2008) provided data on the environmental impacts of WEEE disposal on landfills and waste-to-energy facilities in Florida, regarding especially the concentrations of heavy metals and brominated flame retardants in the leachates. Especially cathode ray tubes can cause environmental problems when disposed to landfill, in particular due to the leaching of lead and other heavy metals into ground water (Greenpeace 2005; ICER 2003). Janz & Bilitewski (2009) investigated the transmission of heavy metals contained in WEEE and in batteries to other material fractions and to the leachates during mechanical-biological treatment and landfilling. They concluded that 65% of the WEEE and the batteries contained in the waste treated with mechanical-biological processes should be removed before treatment for the produced residue-derived fuel to fulfil the quality requirements. Moreover, the valuable materials and substances contained in WEEE cannot be recycled if WEEE is disposed of.

2.4.3. Reuse of WEEE

The term reuse has several definitions in international legislations, standards, academia and re-use practice, all embracing different contexts (Scheidt et al. 2008). According to the WEEE Directive , ‘Reuse’ means any operation by which WEEE or components thereof are used for the same purpose for which they were conceived, including the continued use of the equipment or components thereof which are returned to collection facilities, distributors, recyclers or manufacturers.

Reuse brings economic and environmental advantages, because a large fraction of the economic value of the EEE is preserved, the waste generation is reduced and virgin materials and energy are conserved (Prelle 2008; Rifer et al. 2009; Scheidt et al. 2008). Truttmann & Rechberger (2006) and Tasaki et al. (2008) compared the waste reduction and the resource conservation created by re-use to the additional energy consumption during the use phase due to the use of older reused devices in a life-cycle perspective. According to Lynch (2004), reselling or upgrading computers saves 5 to 20 times more energy over the life cycle than recycling. Broehl-Kerner (2008) and Williams et al. (2008) describe the advantages of reuse from a social point of view. However, reuse can also have environmental disadvantages. Thus, the re-use of devices from countries with a large recycling infrastructure in countries with a weak recycling infrastructure raises questions about resource conservation, since the shifting of the devices for re-use probably prevents the resources from being recycled after the use phase (Chancerel & Rotter 2009). Re-use is sometimes used as pretence for illegal waste export (Brohl-Kerner 2008). Moreover, new EEE usually consumes less energy in the use phase than reused WEEE (Prelle 2008).

In this thesis, reuse refers to reuse of WEEE, which implies that EEE has first become waste. Prelle (2008) discussed the difficulty to draw a distinct line between reuse of EEE and reuse of WEEE. According to the European legislation, EEE becomes WEEE if its holder discards it, or intends or is required to discard it. The characteristics listed in Revised Correspondents' Guidelines N°1 on Shipments of Waste Electrical and Electronic Equipment can be used to distinguish EEE from WEEE. Anyway, it is necessary to examine the history of an item on a case-by-case basis to determine if it is EEE or WEEE.

Scheidt et al. (2008) distinguished the following methods of reuse: (1) sell the product to another user, (2) donate the product to another user, (3) if the product is damaged, restore the product prior to moving it to another user and (4) harvest components from it. Regarding re-use of WEEE in practice, three kinds of re-use activities can be differentiated:

- Re-use of working equipment,
- Re-use of equipment after repair and/or refurbishment, and
- Re-use of parts or components.

Re-use processes fall under the scope of some guidelines on WEEE management (Appendix 4 summarizes the scope and other information on these guidelines). Li et al. (2008) wrote that before entering the waste stream, there is “huge” potential for re-use of EEE, but only 1.27% of products in the WEEE collection system in Germany are economically reusable. According to Rose & Stevels (2001), discarded consumer EEE in Europe is regarded as economically or technically so old that higher levels of reuse options are usually not attractive. In the USA, managers of end-of-life facilities indicated that only about 10 to 15% of residential WEEE, which is typically much older and more heterogeneous than commercial WEEE, has resale value. About 90% of the commercially generated IT waste equipment had resale value, but less than 50% is refurbished and resold due to customer requirements that equipment should be destroyed (Rifer et al. 2009).

2.4.4. Treatment

The chain of pre-processing, recovery and disposal processes used to recover the materials and substances contained in sWEEE (Figure 3) is called in this thesis the ‘treatment process chain’. According to the WEEE Directive, ‘treatment’ means any activity after the WEEE has been handed over to a facility for depollution, disassembly, shredding, recovery or preparation for disposal and any other operation carried out for the recovery and/or the disposal of the WEEE.

Recommendations for treating WEEE in the form of standards, manuals and guidelines have been issued by different groups (Appendix 4). The actual amount of precious metals recovered, and hence the amount of precious metals leaving the cycle, depends on the overall efficiency of the chain of material recovery processes during the end-of-life phase. In turn, this efficiency is affected by both the design of the product and the combination of pre-processing and recovery processes in the end-of-life phase (Castro et al. 2005).

2.4.4.1. Pre-processing

As first step of the treatment process chain, pre-processing determines to which recovery or disposal processes the materials are fed (Paper 2). Pre-processing is divided into three major stages: (1) sorting, (2) selective disassembly, targeting on singling out (liberating) 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 & Forssberg 2003). In the European Union, the pre-processing must fulfil the requirements on selective treatment of certain assemblies of materials defined in the WEEE Directive. Pre-processing must also ensure that hazardous materials are prepared for disposal in an environmentally-sound way. Ferrous metals, non-ferrous metals, cables, printed circuit boards, plastics, capacitors, batteries and others (for example glass, wood and hazardous materials containing mercury) are typical output fractions of sWEEE pre-processing (Hischier et al. 2005).

Pre-processing can be carried out:

- manually,
- mechanically (automatic size reduction and sorting of materials through successive sorting process units) or
- with a semi-automatic process combining manual and mechanical techniques.

A high variety of technologies for automatic size reduction are available on the market (for example hammer mills, chain shredders or rotary shears). Cui & Forssberg (2003) present automatic sorting technologies that can be found in pre-processing facilities. Gmünder (2007), Willems et al. (2006) and Zhang & Forssberg (1998) discuss the advantages and limitations of applying and combining the different technologies.

By pre-processing WEEE, like by processing mineral ores, the so-called 'concentration dilemma' or ‘grade-recovery function’ applies (Hagelüken 2006a, Hodouin et al. 2001). Figure 5 illustrates the concentration dilemma. The recovery of a specific material (for example metal) from an input stream decreases with increasing purity requirements on that material separated into an output fraction. The optimum operating conditions for pre-processing are, therefore, a compromise between grade (quality) and recovery (quantity), in order to minimize the losses and at the same time to produce output materials with an acceptable quality.

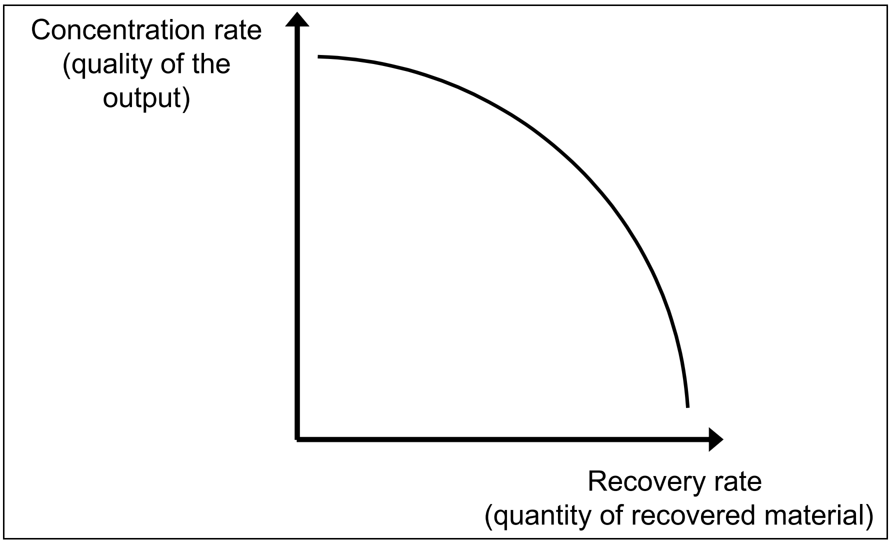

Figure 5 The grade-recovery function in mechanical processing (Hagelüken 2006a)

Most of precious metal in WEEE is found at trace level concentrations in the printed circuit boards. Pre-processing usually aims at grouping the printed circuit boards in one or several precious metal-rich output fractions to send them to a facility able to recover precious metals. If pre-processing sends a substance, for example gold, to a recovery process that is not able to recover it, it is “lost” for the recycle-economy. This cannot be completely avoided, so that some printed circuit boards end up in side-streams like plastics or ferrous metals that are not set up for precious metal recovery (Hagelüken 2006a). Because of the concentration dilemma shown by Figure 5, all processes used to recover precious metals involve losses (Kreibe et al. 1996). A reduction of the losses of precious metals possibly means reducing the concentration of precious metals in the fraction sent for precious metal recovery and increasing the losses of other materials like ferrous metals that cannot be recovered in processes for precious metals.

The printed circuit boards coming from pre-processing can either be intact (for example if the WEEE was manually dismantled) or shredded. Sometimes, the precious-metal rich outputs coming out of pre-processing are not sent directly to facilities for precious metals refining, but are first concentrated in another upstream process using mechanical or melting processes like pyrolisis (Goosey & Kellner 2003; Hall & Williams 2007; Kreibe et al. 1996; Veit et al. 2002; Yoo et al. 2009).

2.4.4.2. Recovery of precious metals

According to the WEEE Directive, ‘recovery’ means any of the applicable operations provided for in Annex IIB to Directive 75/442/EEC of the European Commission. Recovery of precious metals is listed in Annex IIB as ‘Recycling/reclamation of metals and metal compounds'. Like all metals, precious metals are characterised by metallic bonding that is not affected by melting, so that they can be recycled over and over again (Heinrich 2007).

Reviews on metallurgical processes to recover and refine (precious) metals from printed circuit boards were issued by Cui & Zhang (2008), Goosey & Kellner (2003) and Huang et al. (2009). The European Commission (2001) provided an overview of the "Best Available Techniques" to recover precious and other non-ferrous metals. Currently, mainly pyrometallurgical and hydrometallurgical processes are used to recover the precious metals. Modern facilities using a complex succession of processes including pyrometallurgical techniques, hydrometallurgical process, and electrochemical technology are able recover base metals, precious metals and special metals (Cui & Zhang 2008; Hagelüken 2006b).

Pyrometallurgical processing involves heating the crushed WEEE in a furnace or in a molten bath to remove plastics, so that the refractory oxides form a slag phase together with some metal oxides (Cui & Zhang 2008). Incineration, smelting in a plasma arc furnace or blast furnace, drossing, sintering, melting and reactions in a gas phase at high temperatures are techniques presently applied (Cui & Zhang 2008; Hagelüken 2006b; Lee et al. 2007; Lehner 1998; Veldhuizen & Sippel 1994).

The main steps in hydrometallurgical processing consist of a series of acidic or caustic leaches of solid material. The most common leaching agents used in recovery of precious metals include cyanide, halide, thiourea, and thiosulfate (Cui & Zhang 2008). The solutions are then subjected to separation and purification procedures such as precipitation of impurities, solvent extraction, adsorption and ion-exchange to isolate and concentrate the metals of interest. Subsequently, the solutions are treated by electrorefining, chemical reduction, or crystallization for metal recovery (Cui & Zhang 2008). Chmielewski et al. (1997), Mishra (2002), Park & Fray (2009), Quinet et al. (2005) and Sheng & Etsell (2007) have published experimental results on the application of hydrometallurgical processes to recover precious metals from printed circuit boards. The efficiency of hydrometallurgical recovery highly depends on the technology used for size reduction and liberation before the recovery process itself.

In addition to the precious metal-rich materials coming from pre-processing facilities, precious metals can be recovered out of other material flows related to WEEE. Several plastic recycling companies in Europe and in the USA reported during interviews that some of the precious metals contained in the plastic fractions are recovered in the course of the separation out of the disturbing substances, to which metals belong (Biddle et al. 1998; Novak 2001). More precise data on these processes are not available. In addition, research is conducted to develop processes to recover the precious metals contained in bottom ashes of incinerators for municipal solid waste (Bakker et al. 2007). The implementation of these processes would allow the recovery of some precious metals contained in the sWEEE incinerated in waste-to-energy facilities.

2.4.4.3. Informal treatment of WEEE

The research conducted by EERA (2008), Friege et al. (2008), Janz et al. (2009a), Rhein & Meyer (2009) and Sander & Schilling (2009) aimed at identifying the sinks from which WEEE can leave the formal management system to enter the informal sector. These sinks can be classified into the following categories:

1. Diversion of generated WEEE before collection
2. Diversion of generated WEEE during or after collection and before treatment
3. Diversion of generated WEEE during or after treatment

Figure 6 illustrates the possible channels, which include informal waste collection and the illegal trading of WEEE and of valuable or hazardous parts of WEEE. So far, very few quantitative data are available on these material flows.

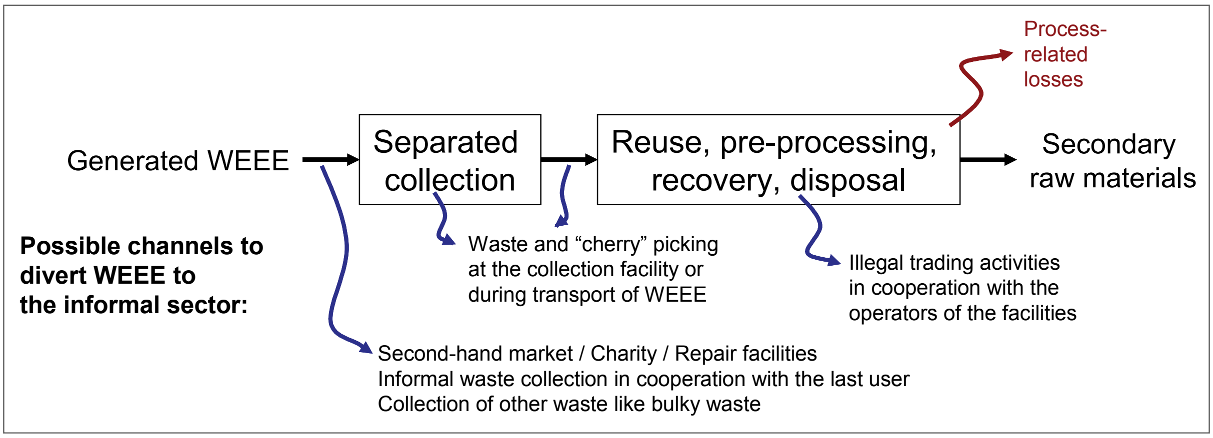

Figure 6 Possible channels for the WEEE to leave the formal management system and enter the informal sector

Many different geographical destinations are possible for the WEEE that entered the informal sector. BAN (2002; 2005), GAO (2008), Greenpeace (2005), Manomaivibool (2009), Osibanjo & Nnorom (2007), Sepúlveda et al. (2010), Sinha-Khetriwal et al. (2005), Terazono et al. (2006), Toxics Link (2003), Williams et al. (2008) and Yoshida (2005) reported that developed countries export WEEE to developing countries, where it is processed in a way causing harm to the human health and to the environment. According to BAN (2005), about 45% of the WEEE imported in Nigeria comes from Europe, 45% from the USA, while the remaining 10% were from other locations such as Japan and Israel. In the USA, 74% of the output materials of the electronics recycling industry are exported (IAER 2006). According to the US EPA (2008), approximately 97 500 metric tonnes of CRT monitors and TVs collected for recycling were exported out of the USA in 2005. Despite the legislation, also WEEE generated in Germany is exported to developing countries, as reported by Buchert et al. (2007), DUH (2006), Faulstich & Baron (2008) and Janz et al. (2009a). Broehl-Kerner (2008), ICER (2004), UNEP (2005) and DUH (2006) reported that the WEEE is often supposedly exported as 'articles of trade' or as 'charity' for re-use. Anyway, up to 75% of these materials are non-functional or irreparable (BAN 2005).

UNEP (2005) depicted the flows of WEEE from Europe and North America shipped to Asia for recycling (Figure 7). According to Terazono (2008), the destination of the WEEE imported in Asia changed in 2007. In 2007, China received less WEEE than in 2006 and Vietnam and Philippines became the principal end destinations of the exported WEEE.

Figure 7 Major exporters and receivers of WEEE in 2005 (UNEP 2005; designer: Philippe Rekacewicz)

2.5. Mapping metal flows related to WEEE

2.5.1. Substance flow analyses in previous studies

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in time and space (Brunner & Rechberger 2004). The term material stands both for chemical substances and goods, where ‘goods’ are mixtures of substances that have economic values assigned by markets (Brunner & Rechberger 2004). A substance flow analysis (SFA), which aims at tracking substances within a system, is a specific kind of MFA. The historic background and a detailed overview of the concepts of MFA and SFA are available in Brunner & Rechberger (2004), Van der Voet (1996) and Udo de Haes et al. (2000). EEA (2002) provided a four-step method based on SFA to calculate emissions of dangerous substances and materials (mercury, lead, cadmium and persistent organic pollutants) from WEEE treatment.

Loeschau (2006) differentiates the regional approach and the life-cycle approach to define system boundaries of analyses of waste management systems (Figure 8). The regional approach focuses on the flows of waste that are generated, collected and treated in a region, which means that the waste treated in another region is not considered. The life-cycle approach follows the waste from generation to the last steps of the waste management, even though some waste management processes do not take place in the region. In this case, the waste treated in the region but generated outside the region is not considered. For sustainable waste management, the life-cycle approach (called ‘end-of-life recycling approach’ by Heinrich (2007)) makes sense, because negative impacts of the waste should be minimized regardless of the place where these impacts occur (Loeschau 2006). Life-cycle thinking is required for waste policy (COM 2005) and, therefore, for research aiming at providing data for policy-making.

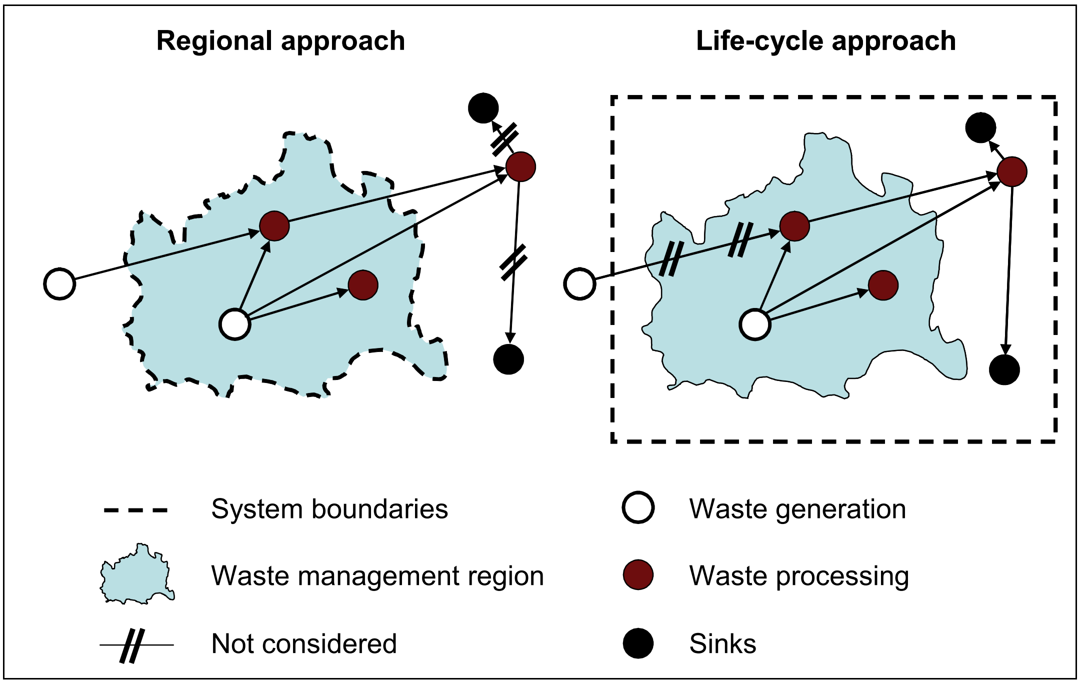

Figure 8 Definition of system boundaries according to the regional and the life-cycle approaches for material flow analysis of waste management systems (Loeschau 2006)

2.5.2. Literature review

Extensive general studies on the flows of materials related to WEEE management in different regions of the world have been published by Hischier et al. (2005), Huisman et al. (2007), Kahhat et al. (2008), ICER (2005), Oguchi et al. (2008), Tesar & Öhlinger (2009), Terazono & Yoshida (2008), Terazono et al. (2006), Widmer et al. (2005), Witteveen+Bos (2008) and Yoshida et al. (2009) among others.

The substance flows related to WEEE have been investigated by various authors. Morf & Taverna (2004) analysed the substance flows in a Swiss pre-processing 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 from the entrance to the exit of the facility. Streicher-Porte et al. (2005) carried out a material flow analysis of the recycling of personal computers in Delhi. Bertram et al. (2002) investigated the flows of copper in the European waste management subsystem, considering explicitly WEEE. Huisman (2003, 2004) evaluated the environmental performance of various recycling scenarios for several equipment types considering the final destination of hazardous and valuable substances. Some authors focussed especially on the quantification of flows of precious metals related to WEEE (Table 7).

Table 7 Studies reporting quantitative data on the flows of precious metals related to the management of WEEE

Metal	Reference	Geographical boundaries	Considered systems related to WEEE
Silver	Lanzano et al. 2006	Europe	Rough assumption of the quantity of silver in WEEE and of the recycling rates at large scale
	Johnson et al. 2005b	64 countries, 9 world regions, world	
	Johnson et al. 2005a	Asia	
Gold	Keller 2006	Bangalore, India	'Backyard recycling' processes for gold recovery from printed circuit boards
	Van Schaik & Reuter 2009	Pre-processing facilities in the Netherlands	Mechanical pre-processing of WEEE
Platinum-group metals	Hagelüken et al. 2005	Germany	From collection to final refining
	Saurat & Bringezu 2008	Europe	Output of the use phase, exports, collection, processing and recycling of WEEE
	Babakina & Graedel 2005	Russia	Platinum in WEEE, which "does not contribute a considerable amount"
Several precious metals	Deubzer 2007	World	From collection to final refining
	Meskers et al. 2009	Pre-processing facilities in Europe	Comparison of manual dismantling and mechanical pre-processing
	Shirahase et al. 2007	Japan	Flows of gold and palladium associated with waste personal computers

According to estimations of Hagelüken et al. (2005), 37.6% of the platinum-group metals contained in WEEE are recovered in Germany. 50% is lost through insufficient collection, 10% through pre-processing, 2% through copper-smelter and 0.4% through final refining. Saurat & Bringezu (2008) reported that 13 945 of the 22 563 kg (around 62%) of the platinum-group metals contained in electronics in Europe were recycled in 2004. Deubzer (2007) assumed that the worldwide recycling rates for gold, palladium and silver are 7% for low and medium grade WEEE, and 9% for high-grade WEEE. Van Schaik & Reuter (2009) described a model developed to predict the quality of the output materials of recycling processes, which was calibrated through extensive experimental work. They found that only around 15% of the gold is recovered in pre-processing facilities using size reduction. The detailed results of the experiments are not publicly available. Other experimental investigations to assess the recovery of precious metals in pre-processing facilities were conducted by Meskers et al. (2009).

Some of the studies listed in Table 7 had very large system boundaries and used very rough assumptions to estimate the flows of WEEE. Johnson et al. (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 gap of data on flows of WEEE, as emphasized by various authors (Bertram et al. 2002; Reck et al. 2008). The data gaps and the different assumptions that had to be made also explain the diverging results. More research is, therefore, needed to bring quantitative findings on cycles of precious metals and to support the development of strategies for reducing the losses of precious metals related to WEEE management.

3. Methods

The method “Substance flow analysis” was applied in this study, focussing on flows of precious metals.

3.1. System boundaries

The boundaries of the study are restricted to the management of sWEEE as defined in chapter 2.1.2, i.e. the equipment belonging to the categories ‘small household appliances’, ‘IT and telecommunications equipment’, ‘consumer equipment’, ‘electrical and electronic tools’, and ‘toys, leisure and sports equipment’ according to the WEEE Directive. Moreover, only ‘WEEE from private households’ as defined in the WEEE Directive, i.e. WEEE which comes from private households and WEEE from commercial, industrial, institutional and other sources which, because of its nature and quantity, is similar to that from private households, is considered in this thesis. For example, a personal computer discarded by a business is within the system boundaries, because personal computers can also be used by households, whereas mainframe computers that are usually not used by households are not considered. The remaining categories of the WEEE Directive (‘large household equipment’, ‘lighting equipment’, ‘medical products’, ‘monitoring and control instruments’, and ‘automatic dispensers’) were excluded from the framework of the investigation because the routes followed by this equipment and the applied recycling processes differ from the ones used for sWEEE. The waste equipment generated only by commercial, industrial, institutional and other sources than households were excluded for the same reason.

For simplification, the equipment types considered in this study were grouped (Table 8). The assumption behind this is that a similar recycling process chain is applied to the equipment types of one group. For example, it is assumed that the probability that a DVD player is disposed of together with residual waste is as high as the probability for a video game console, because DVD players and video game consoles both belong to the group ‘Large high-grade equipment’. Mobile phones and personal computers are very common appliances and were the object of a large part of the investigations. Because more data are available on mobile phones and personal computers than on other equipment types, the material flows related to these both equipment types were not grouped with other equipment types but investigated separately.

Table 8 Groups of equipment types considered in this investigation (see Appendix 1)

Group	Number of eq. types	Examples of equipment types
Mobile telephone	1	
Desktop personal computer	1	Includes the drives, excludes the monitors
CRT monitor	2	Cathode-Ray-Tube computer monitors, TV sets
Large high-grade equipment	12	DVD player, Video game console, Computer LCD Monitor, Notebook
Small high-grade equipment	13	GPS, digital camera, MP3 player
Low-grade equipment	26	Vacuum cleaner, wall clock, radio control vehicle, electrical drill, remote control
Total	55	

High-grade equipment is defined as equipment containing printed circuit boards with a gold concentration of at least 100 g/t. even though there are no sharp and universally accepted criteria to differentiate between the different grades of printed circuit boards (Deubzer 2007), the boundary of 100 g/t is often used by the precious metals industry to differentiate between low and high-grade printed circuit boards. Regarding the differentiation between large and small equipment, it was presumed that small equipment weighs less than one kilogram and large equipment more than one kilogram. This rough criterion should not be considered too strictly since due to the variety of models and manufacturers, some devices belonging to the group ‘large high-grade equipment’ weigh less than 1 kg and some devices belonging to the group ‘small high-grade equipment’ weigh more than 1 kg. The classification of the equipment types into the equipment groups is presented in Appendix 1.

Gold and palladium contained in sWEEE are the focus of this substance flow analysis. As introduced in chapter 2.3, precious metals are widely used for the manufacturing of EEE and the recovery of precious metals from WEEE is very relevant from an economic and an environmental point of view, but only few and uncertain data are available on cycles of precious metals (see chapter 2.5). The life-cycle approach as defined in chapter 2.5.1 was selected to set up the system boundaries of this investigation. The flows of gold and palladium are tracked from the waste generation in Germany and in the USA in 2007 up to the exit of the sWEEE management system as defined in chapter 2.4, regardless of when this takes place.

3.2. Qualitative system modelling

As presented in chapter 2.4, end-of-life management consists of various phases: generation, collection, and reuse/treatment/disposal.

In the model illustrated in Figure 9, five collection channels were differentiated according to the organisation responsible for the collection operations. Besides collective municipal collection and individual producer and retailer collection, sWEEE can be collected by the informal sector (waste pickers). Other initiatives like charity and small-scale pilot projects aiming at collecting sWEEE are classified as “Others”. The non-separated collection of WEEE, e.g. the disposal together with residual waste, is a reality both in the USA and in Germany, even though it is explicitly forbidden by the German legislation.

Regarding treatment of sWEEE, it was differentiated between treatment carried out by the formal and by the informal sector, which includes the illegal export (Figure 9). The flows of sWEEE directed to reuse are considered in the model. The arrows RF, FR, IR and RI depict the flows of materials going from reuse to formal or informal treatment and vice versa. Materials going from reuse to treatment are for example damaged displays replaced by new ones during refurbishing, so that the damaged displays have to be treated. WEEE sorted for reuse out of the input of a treatment facility belongs to the materials going from treatment to reuse (arrows RF and RI). Flows between the formal and the informal treatment are neglected. The applied collection, reuse and treatment processes result in the precious metals contained in WEEE being recovered, reused or discarded.

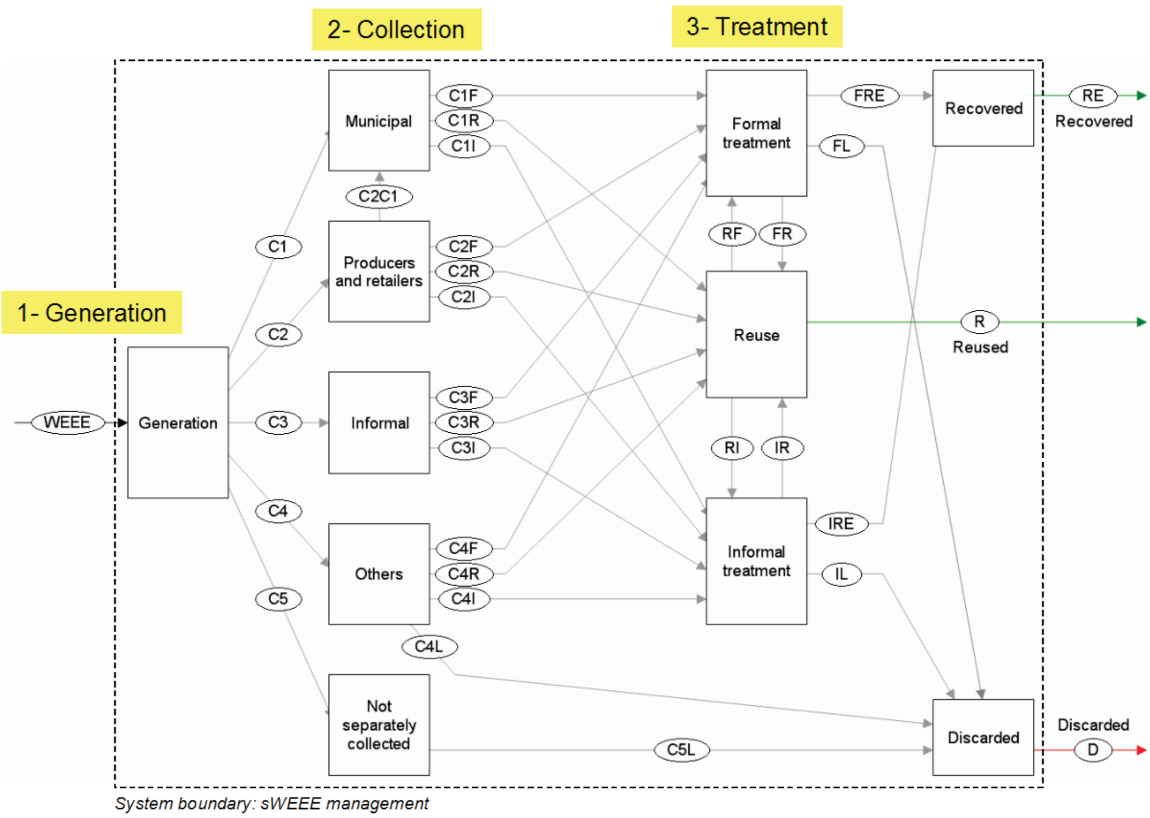

Figure 9 Model of the processes and material flows in the management system for sWEEE

Because many data on collection flows are not differentiated according to the collection channels, especially in the USA, the results are presented in a simplified form, where the flows of collected sWEEE are aggregated into one single flow (arrow C in Figure 10). The flows of sWEEE to reuse were assumed to come directly from collection, so that the flows from treatment to reuse (arrows IR and FR) are neglected.

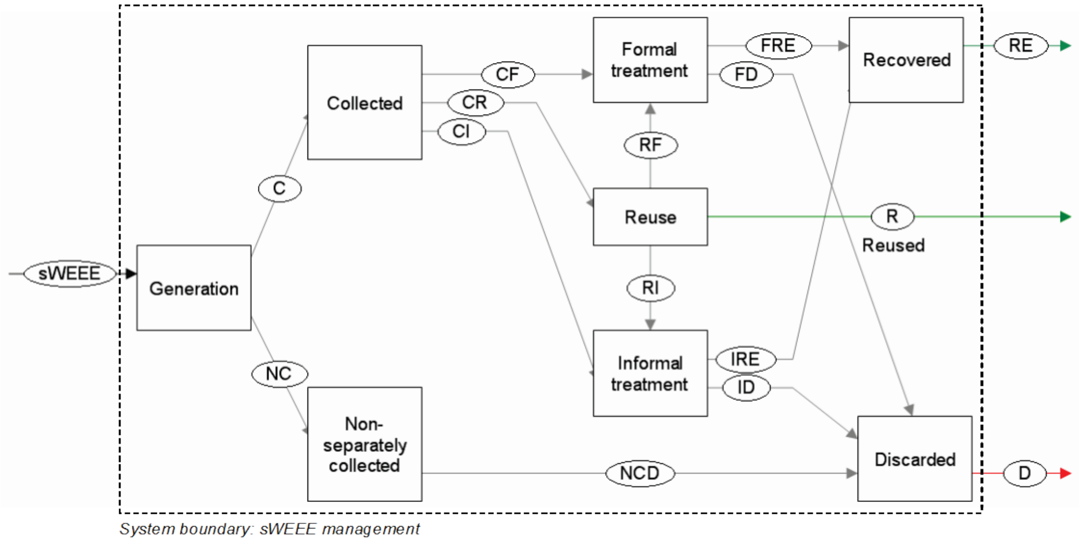

Figure 10 Simplified model of the material flows in the management system for sWEEE

3.3. Data gathering

The quantification of the material and substance flows related to the management of sWEEE requires a large amount of data. Table 9 presents an overview of the data needed to conduct the substance flow analysis.

Table 9 Data required for mapping the flows of materials and precious metals related to the management of sWEEE

Subsystem	Required data	Possible methods for data gathering
EOL equipment characterisation	Content of precious metals	Experimental determination of the composition of sWEEE at material and substance level
Generation	Average lifetime	Study on the age of discarded WEEE Surveys on user behaviour
	Stock in household and businesses	Surveys on quantities of EEE in use in the households and businesses
	Sales	Market analysis, compilation of sales data of the different manufacturers
Collection	Quantity and destination of collected sWEEE	Compilation of data from the operators of collection systems
	Non-separately collected sWEEE	Sorting analysis of residual waste Surveys on user behaviour
Reuse	Quantity of sWEEE sent to reuse processes	Compilation of data from the recycling/reuse industry
	Reuse rates for precious metals (mass of PM in the reused devices divided by mass of PM in input)	Compilation of data from the reuse industry, experimental monitoring of reuse process
Formal treatment	Quantity of sWEEE sent to formal treatment processes	Compilation of data from the recycling industry
	Recovery rates for precious metals (mass of recovered PM divided by mass of PM in input)	Experimental monitoring of treatment processes
Informal treatment	Quantity of sWEEE sent to informal treatment processes	Compilation of data on informal treatment of WEEE gathered through observations of the informal sector
	Recovery rates for precious metals (mass of recovered PM divided by mass of PM in input)	Experimental monitoring of treatment processes

3.3.1. Data on characteristics of sWEEE

The characteristics of WEEE vary according to numerous parameters (type and function of the appliances, producer, model, production year etc.). The appliances are classified in equipment types according to their function. In general, an appliance is made of various assemblies. Some of the assemblies are made of homogeneous materials (plastic, metal parts), while others are made of composites containing various materials. The model presented in Figure 11 illustrates this hierarchy.

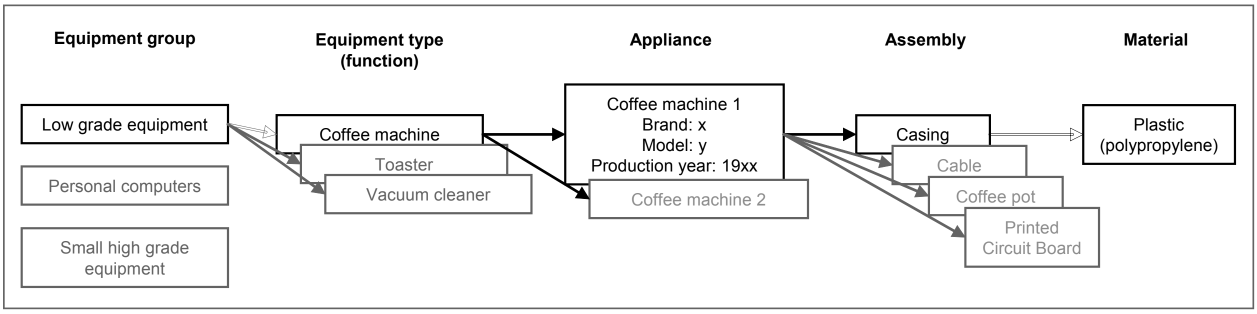

Figure 11 Classification of materials contained in WEEE

To collect and organize data on characteristics of WEEE, a database initially developed by Srocka (2006) was continuously expanded (Chancerel & Rotter 2007). The database consists of datasets on composition of WEEE at material and substance level. The data were gathered from disassembling investigations and chemical analyses at the Technische Universität Berlin and through a literature review. The data contained in the database can be classified as follows:

1. Data on single appliances: the investigation unit is the single appliance. The investigations are conducted on single devices by dismantling and analysing each assembly (for example: dismantling of one mobile phone, weighing of the assemblies, identification of the casing plastic, elementary analysis on the printed circuit board). A dataset is created for every investigated appliance (no data aggregation).
2. Data on “Group investigations”: a group investigation refers to the characterisation of groups of similar appliances or similar assemblies (for example: elementary analysis of 10 printed circuit boards from mobile phones). The investigation unit is the group of appliances or assemblies and one dataset is created per group of appliances or assemblies. In practise, two ways are possible to carry out group investigations:
    - either the investigations are directly conducted on groups of appliances or assemblies (example: size reduction of a mix of 10 printed circuit boards and determination of the chemical composition)
    - or the investigations are carried out on single appliances or assemblies and the analysis results are aggregated for interpretation and publications.

In total, data on the material composition and other characteristics of 797 appliances and the results of 234 group investigations were integrated in the database. 8550 results of analyses like measurements of metal concentrations and determination of the polymer(s) contained in plastic parts are available in the database. The data of the database was used in Paper 1 to determine the mechanical properties, the material composition, the polymer composition and the chemical composition of selected types of WEEE. These characteristics vary not only between equipment types with different functions, but also between single appliances within one equipment type.

If no data on the average concentration of precious metals in the equipment groups was directly available, quantifying the concentration of precious metals in the different equipment groups in 2007 requires data at the following information levels (see hierarchy illustrated in Figure 11):

(1) The types of equipment contained in the equipment groups (mass-based breakdown),
(2) The average material composition of the equipment types and
(3) The average precious metals concentration in the different equipment types.

The average concentration of precious metals in the devices was calculated by assuming that the precious metals in sWEEE can only be found in printed circuit boards. Precious metals may be contained in other parts like connectors, contacts, cables and solders (Gmünder 2007; Hagelüken 2006a), but no quantitative data are available regarding the precious metals contained in these components.
The following formula was used:

$$c_{PM,G} = \frac{\sum_{T=1}^{n} c_{PM,PCB,T} \times M_T}{M_G}$$

With:
$c_{PM,G}$: mean concentration of precious metal in the equipment group G
$c_{PM,PCB,T}$: mean concentration of precious metal in the printed circuit boards of equipment type T
M_T: mass of devices of equipment type T (belonging to equipment group G) generated in 2007
M_G: total mass of devices of equipment group G generated in 2007

The estimation of the mean concentrations of precious metals does not take into consideration the temporal and spatial variations of the characteristics of sWEEE. These variations are originated by technological changes (for example implementation of new nanotechnologies in EEE), market changes or legislative requirements, like experienced since 2006 in the European Union through the implementation of the Restriction of Hazardous Substances Directive, which restricts the use of six hazardous materials in the manufacture of various types of EEE. Since not enough data is available on the characteristics of WEEE in 2007 and in the investigated regions (Germany and USA), the results of characterisation studies conducted in other periods and at other locations had to be considered.

3.3.2. Data on material and substance flows

Reuter et al. (2005) observed that the data to conduct SFA are sometimes hardly available, and must be obtained from very heterogeneous sources. Two approaches are possible to quantify the flows entering and leaving a system: either all the input and output flows are quantified independently from each others, or transfer coefficients are determined to quantify how the input of the subsystem is distributed over the outputs. On a case-by-case basis depending on the processes and on the available data, both approaches were combined or an approach was preferred to the other one.
Five subsystems, in which flows of sWEEE and of precious metals occur, can be distinguished (Table 8):

- Generation
- Collection
- Reuse
- Formal treatment
- Informal treatment

If previous research works already gathered and published data on the material flows or on the transfer coefficients in one or various subsystems, these results were taken into consideration. Some experimental investigations were carried out to quantify material flows for which no data is available in the literature. The information that was still missing was then gathered through observations, interviews and estimates. The quality of all these data was assessed by quantifying uncertainties (see 3.3.3).

3.3.2.1. Literature review

An extensive review of the available data on the flows of sWEEE in Germany and in the USA was carried out. The data made available by other studies were integrated in this research as far as possible, considering the following challenges related to the data consistency:

- The definition of equipment groups and of sWEEE: if the material flows are defined in another way than in this investigation, the data had to be “adapted” to provide data on flows of sWEEE as defined in this thesis;
- The considered processes, which are not always defined as in Table 9;
- The geographical system boundaries, because some investigations focussed on other regions (for example only one state in Germany or in the USA);
- The temporal system boundaries, because previous studies usually mapped the flows of sWEEE in years previous to 2007.

Some pragmatic assumptions or adaptations were needed to apply the data to conduct the SFA. Chapter 4 explains on a case-by-case basis the assumptions that were made to integrate the data from the literature into this investigation.

3.3.2.2. Experimental substance flow analyses in pre-processing facilities

Experimental substance flow analyses were conducted to provide data on the ability of two pre-processing processes to recover precious metals. The investigations took place in two full-scale German facilities. The method and the results are presented in detail in Chancerel & Rotter (2008b) and in Paper 2.

Figure 12 summarizes the methodology applied for both experimental SFA. Before the test, the input material was weighed and qualitatively described. After processing, all output fractions were collected separately and weighed. The metal concentration was determined in all the outputs by analysing the samples with inductively coupled plasma atomic emission spectroscopy or in case of less precious metals relevant fractions, by estimates using data from the literature and visual observations. By multiplying the metal concentration with the weight of each output, the metal content was determined, which allowed describing the distribution of the metals over the outputs of the pre-processing. Sankey diagrams, in which the width of a flow is proportional to its value, were drawn to visualize the outcomes of the SFA. Sankey diagrams are a potent means of visualizing inefficiencies in the system, also for a non-specialist audience (Schmidt 2008).

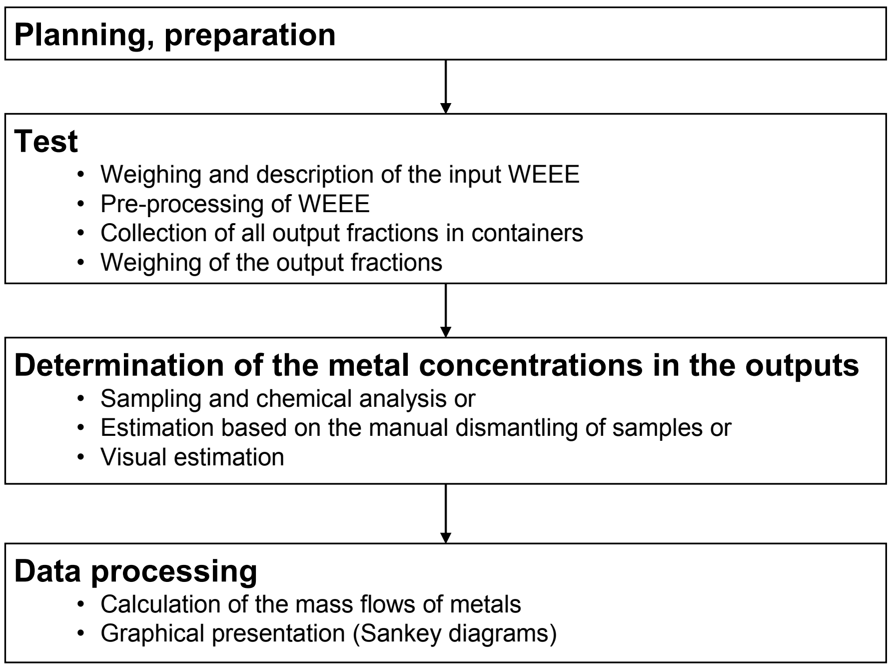

Figure 12 Methodology for the experimental substance flow analysis (Paper 2)

The first investigation was conducted in a facility operating a manual process, in which the waste appliances are manually disassembled (Chancerel & Rotter 2008b). The second experimental SFA investigated a facility using a three-step process:

1. The visible hazardous and disturbing components like batteries, large metal sheets and motors and the “easy-to-remove” printed circuit boards are first manually removed from the end-of-life appliances.
2. After a coarse pre-shredding, a second manual sorting takes place to remove the remaining hazardous and disturbing components.
3. The remaining scrap is shredded and sorted automatically.

44 output material fractions were generated by the processing of waste IT, telecommunications and consumer equipment (German collection group 3) in the second facility (Paper 2).

3.3.2.3. Visits and interviews

The data gathered from the literature and from experimental tests were completed by the visit of 20 industrial facilities and by numerous interviews of stakeholders of WEEE recycling, i.e. non-governmental organisations, retail and distribution sector, municipalities and other public authorities, pre-processing and recovery operators, associations of the recycling industry and research groups. The exchange of information took place either directly through meetings or at distance by mail, e-mail, fax or telephone. Some of the information is confidential in the sense that it can be used for the research but the provider of the information does not wish to be named.

Since every stakeholder has a point of view to defend, questions can legitimately be raised as to how far this method allows to collect representative and reliable data. As far as possible, the data quality was increased by crossing the information, i.e. by asking different persons for the same information. Visits and interviews made it possible to collect information that could not be collected experimentally or by the literature review.

3.3.2.4. Estimates

If necessary data were not available in the literature, could not be gathered experimentally or were not provided by the stakeholders, they had to be estimated. Even though efforts were made to produce plausible estimations, they are associated with very high uncertainties.

3.3.3. Uncertainties

The uncertainty is the doubt about a result, i.e. an evaluation of its quality and accuracy (DIN V ENV 13005). As concerns the scientific disciplines, the numerical evaluation of the uncertainty is usually considered as the best one, because it simplifies synthesis and facilitates the communication of results (Caria 2000).

The ‘Guide to the Expression of Uncertainty in Measurement’ (German pre-standard DIN V ENV 13005) aimed at developing a universal, self-consistent and transferable method to determine and express the uncertainty of any kind of measurements. Without the specification of the uncertainty, measurement results cannot be compared with each other or with reference values (DIN V ENV 13005). According to this guide, the uncertainty of a measurement results consists of several components, which can be classified into two types according to the method used to quantify them:

A. Components calculated with statistical methods
B. Components determined in another way.

The standard deviation (square root of the variance) is calculated to quantify the components of type A. For components of type B, a variable is determined to approximate the standard deviation, the existence of which is assumed.

In this thesis, the standard deviation of every component used to calculate a mass flow (mass, metal concentration, transfer coefficient) was either calculated or estimated. If the standard deviation could not be calculated, the radius (half the width) of the 95% confidence interval of the variable was estimated. Based on the assumption that the distribution of the uncertainty was normal, the standard deviation of components was assumed to be half of the radius of the 95% confidence interval. The variation coefficient, which is the standard deviation divided by the value of the variable, can also express the uncertainty. The uncertainties of the components were combined according to Gauss's law of error propagation by summing the square of the standard deviations of the components (DIN V ENV 13005). The resulting uncertainty is also expressed as a standard deviation.

3.4. Data compilation

The compilation of the data gathered through the methods presented in 3.3 requires the following steps:

1. A qualitative description of the system, defining the collection, treatment and reuse processes and modelling the material and substance flows from one process to the next one;
2. The integration of the quantitative data on the flows of sWEEE into the system model;
3. Data reconciliation to calculate observable unknown quantities and to eliminate discrepancy of redundant information (Reuter et al. 2005);
4. Calculation of the flows of precious metals based on the concentration of precious metals in the material flows.

These four steps were realised by the STAN freeware (TU Vienna 2008), which helps to perform material flow analysis (Cencic & Rechberger 2008). After drawing the processes and material flows in the graphical interface of STAN, the data on the flows with their uncertainties were entered into the model. Data reconciliation was necessary to calculate the unknown flows from the available data and to eliminate discrepancy of redundant information (Reuter et al. 2005), i.e. to observe the law of conservation of mass (sum of the inputs equal to the sum of the outputs if the stocks remain constant). According to Reuter et al. (2005), data reconciliation aims at minimizing a sum of errors (difference between each measurement and its reconciled value) weighted by the measurement error, subject to a number of constraints (the mass balance equations). STAN uses Gauss's method of least squares for data reconciliation (Brunner & Rechberger 2004). Based on the reconciled flows of sWEEE and on a concentration of gold and palladium in sWEEE that was assumed to be constant, STAN calculated the flows of precious metals associated with sWEEE. The resulting flows of gold and palladium are displayed as Sankey diagrams.

3.5. Selection and calculation of indicators

"Indicators perform many functions. They can lead to better decisions and more effective actions by simplifying, clarifying and making aggregated information available to policy makers. They can help incorporate physical and social science knowledge into decision-making, and they can help measure and calibrate progress toward sustainable development goals. They can provide an early warning to prevent economic, social and environmental setbacks. They are also useful tools to communicate ideas, thoughts and values."

(United Nations 2007)

The selection of indicators must fulfil scientific, practical and user-related requirements, such as adequacy to the social, economic and environmental context, reproducibility, traceability, transparency, comprehensibility and availability of the data needed to calculate the indicator (Abdul Rida 2008). In this thesis, the goal of the indicators is to synthesize the quantitative data on materials and substances that are collected, recovered, reused or discarded by the WEEE management system. Different ways to calculate collection rates were compared by Wen et al. (2009). The indicators selected to assess the results of the SFA are presented in Table 10.

Table 10 Indicators selected to assess the flows of sWEEE and of precious metals quantified by the SFA and formula to calculate them

Subsystem	Indicator	Formula
Collection	Collection rate	$\frac{M_C}{M_G}$
Reuse	Reuse rate	$\frac{M_{RU}}{M_G}$

Subsystem	Indicator	Formula
Treatment	Formal treatment rate	$\frac{M_{FT}}{M_G}$
	Informal treatment rate	$\frac{M_{IT}}{M_G}$
Precious metal recovery	Recovery rate for precious metals	$\frac{M_{PM.R}}{M_{PM,G}}$
	Discarding rate for precious metals	$\frac{M_{PM.D}}{M_{PM,G}}$

With: M_G: Mass of generated sWEEE

M_C: Mass of collected sWEEE

M_{RU}: Mass of reused sWEEE

M_{FT}: Mass of sWEEE fed into formal treatment processes

M_{IT}: Mass of sWEEE fed into informal treatment processes

$M_{PM,G}$: Mass of precious metal (gold or palladium) in the generated sWEEE

$M_{PM,G}$: Mass of recovered precious metal

$M_{PM,G}$: Mass of discarded precious metal

4. Data inventory

In this chapter, the origin of the data and the assumptions used to quantify the flows of sWEEE in the different subsystems and the concentration of gold and palladium in sWEEE are described.

4.1. Quantification of the flows related to sWEEE

4.1.1. Generation

Three methods were selected to carry out estimates of the WEEE generation: ‘simple delay’, ‘distribution delay’ and ‘batch leaching’ (see chapter 2.4.1). Data on historic sales volumes, penetration rates in households and businesses, average lifetimes and average weights of the different equipment types were needed to estimate the WEEE generation with these methods. Some previous studies, like EEA (2002), US EPA (2007a; 2008) and Huisman et al. (2007) published estimates of the generation of WEEE. Because the underlying assumptions and the geographical boundaries of their estimates differ from the ones used in this thesis, the results from these studies could not be used.

4.1.1.1. Sources of data

To estimate the WEEE generation, data reporting the sales volumes over at least the past 20 years are required, due to the long lifetimes of some equipment types. Some public institutions like the German Federal Statistical Office Destatis, the US Census Bureau and the statistical office of the European Union Eurostat make some sales data publicly available. However, sales data are primarily provided by private market research institutes like Gartner, IDC, the Consumer Electronics Association, Inform or the European Information Technology Observatory (EITO). The data is usually a part of market studies designed for the manufacturing industry. Financial units (for example revenues from sales in million dollars) are often used, so that some conversions are needed for a material flow analysis, where mass units are required. If the data is available in financial units, additional information or assumptions on the average sales price of a device are necessary to convert the financial flows into flows in units of devices. These flows can then be converted into mass flows by multiplying by the average weight of the devices. Since both the average price and the average weight differ depending on the equipment type, each equipment type has to be considered separately.

The high price of the private market studies did not allow a direct access to the full studies, but the historic sales data are partially published in other studies. For example, US EPA (2008) makes data available on sales of televisions, mobile phones and computer-related products to households from 1980 to 2007 in the USA. IVF (2007) provides data on sales of desktops, laptops and monitors in Germany and other countries of the European Union from 2000 to 2007. BITKOM (2007), CEA (2007) and GFU (2006a; 2006b) provide data on sales of consumer equipment.

Data on penetration rates expressed for 100 inhabitants or 100 households in Germany are available in BITKOM (2007) and Destatis (2008). BITKOM (2007) also provided penetration rates in the USA. The US Census bureau publishes no penetration rates, but data on the percentage of households having some kind of equipment (which means that this percentage cannot exceed 100%), which cannot be used to estimate the WEEE generation.

Table 11 summarizes the data on average lifetimes available in the literature. Whereas US EPA (2007a) investigated the time between the production year of the EEE and the waste generation year, which corresponds to the total lifetime according to chapter 2.4.1, BMF (2000) and IVF (2007) provide data on average first use times. IVF (2007) and GfK (2007) published data on total use time. The times provided by BMF (2000) are the fiscal amortization times defined by the Federal Ministry of Finance in Germany and are, therefore, assumed to address first use times. They were used by Rotter & Janz (2006) to estimate the WEEE generation.

Table 11 Estimations of the average lifetime of different products available in the literature (years)

Reference	BMF 2000	IVF 2007	IVF 2007	GfK 2007	US EPA 2007a
Addressed time period	**First use time**	**First use time**	**Total use time**	**Total use time**	**Total lifetime***
Desktop personal computer	3	5.9	6.6	7.7	12.2
Laptop	3	4.7	5.6	7.7	6.5
Computer monitor	5	6	6.6	7.7	9.3
Printer	3			7.7	8.8
Fax	5			7.7	9.8
TV set	7			10.9	13.5 – 15.1
Vacuum cleaner	7			11.4	
Coffee machine	4			11.4	
Mobile phone	5			3	
Telephone	5			7.7	
Radio set	7			10.9	
DVD-player	7			10.9	
Electrical tool				12	
Hand-held video console				5	

* only EEE in households is considered

Table 11 shows how the estimations differ according to the data source. Only US EPA (2007a) refers to the total lifetime of EEE, but considered exclusively EEE in households. EEE in businesses or institutions, for instance personal computers, usually has a shorter lifetime than EEE in households. A rough analysis of the data demonstrates that the total lifetime is about twice the first use time, which is confirmed by the research of Matthews et al. (1997) (Figure 4). The available data was completed by own estimates. The assumed lifetimes are presented in Appendix 5. Because of the limited availability of data, variations of EEE lifetimes due to geographical, temporal, social and economic factors could not be considered.

4.1.1.2. Quantity of sWEEE generated in 2007

The methods ‘simple delay’, ‘distribution delay’ and ‘batch leaching’ (see chapter 2.4.1.3) were applied to estimate the sWEEE generation for the groups ‘mobile telephones’ and ‘desktop personal computers’.

For both equipment types in the USA, the extensive data on sales volumes between 1980 and 2007 published by US EPA (2008) were used to apply the methods ‘simple delay’ and ‘distribution delay’. Concerning Germany, GFU (2006a, 2006b) supplies data on sales volumes of mobile phones for the years 2001 to 2006 (Table 12). Some assumptions were needed to convert the data from revenue volumes (euros or US-dollars) to sales volumes in units and finally into mass-based sales volumes in tonnes.

Table 12 Sales volumes of mobile phones in Germany for the years 2001 to 2007 (from GFU 2006a, 2006b)

Year	Sold mobile phones (Mio. units)	Sales volumes (tonnes)
2001	6.1	2169
2002	5.3	1759
2003	13.7	4145
2004	19.1	5233
2005	20.0	4990
2006	20.8	4580

The sales data for the previous years (not available in the literature) in Germany were assumed to be proportional to the sales in the USA. The ratio between mass of mobile phones sold in the USA in 2001 and mass of mobile phones sold in Germany in 2001 was chosen as proportionality factor. The average weight of a mobile phone depends on the production year. US EPA (2008) published data on the decrease of the average weight of a mobile phone from over 1.5 kg in 1984 to around 100 g in 2007. Regarding Germany, the

EITO published data on sales of desktop computers between 2003 and 2007 that were reproduced by IVF (2007). Like for mobile phones, the sales data for the previous years were assumed to be proportional to the sales of personal computers in the USA.

Data on penetration rates of mobile phones and personal computers in the USA and in Germany are supplied by BITKOM (2007). In 2006, the penetration rates for personal computers amounted to 45% in Germany and 89% in the USA (related to the number of inhabitants, not to the number of households), whereas the penetration rates for mobile phones amount to 104% in Germany and to 76% in the USA. These numbers were multiplied by the population in both countries and divided by the total lifetime to estimate the theoretical waste generation (Table 13).

Table 13 Generation of end-of-life mobile phones, desktop personal computers and CRT monitors in the USA and in Germany estimated with three different methods (in tonnes)

Country	Equipment group	Total lifetime	Simple delay	Distribution delay	Batch leaching
Germany	Mobile telephone	6 years	2 169	2 273	2 817
	Desktop personal computer	9 years	43 827	39 957	50 097
USA	Mobile telephone	6 years	16 197	14 916	7 532
	Desktop personal computer	9 years	335 051	305 995	362 511

Table 13 shows that the ‘batch leaching’ method mostly leads to a higher estimate of the waste generation than the other two methods (except for mobile phones in the USA, maybe because of insufficient accuracy of the data used for the calculation). This is due to the market dynamics (Wen et al. 2009). If the stocks of EEE in households and businesses are increasing, i.e. if less WEEE is discarded than new EEE is bought, the current stock is not a reliable indicator of the waste generation. Other researchers mention that the ‘batch leaching’ method is not appropriate for dynamic markets (Table 6). The methods ‘simple delay’ and ‘distribution delay’ delivered comparable results (difference smaller than 10%).

Insufficient sales data were available to apply the methods ‘simple delay’ and ‘distribution delay’ for the other equipment groups. The method ‘batch leaching’, in spite of its disadvantages (above all overestimation of the generation when the stock is increasing and underestimation when the stock is decreasing) and the high uncertainties, was used to estimate the generation for the other equipment groups. In total, the calculations using the ‘batch leaching’ method show that around 330 000 tonnes of sWEEE were generated in Germany in 2007, and around 2 700 000 tonnes in the USA. The detailed results and the assumptions are presented in Appendix 5.

The following adjustments of the estimates were made due to pragmatic considerations. For mobile phones and personal computers, the theoretical generation estimated with the method ‘distribution delay’ was assumed to be more accurate than the results of the ‘batch leaching’ method, and was considered for the SFA. Concerning CRT monitors, a technological change can currently be observed. Both businesses and households are replacing their old CRT computer monitors and TV sets by flat displays, so that the generation of end-of-life CRT monitors is very probably underestimated by the ‘batch leaching’ method. US EPA (2008) estimated with the method ‘distribution delay’ that in 2007, 1 125 000 metric tonnes of end-of-life CRT monitors were generated in the USA in 2007 (641 000 tonnes of CRT-TV sets and 484 000 tonnes of computer monitors). This quantity was assumed to be more realistic that the 484 721 tonnes estimated by the ‘batch leaching’ method, and was taken into account for the quantification of the flows. In Germany, CRT monitors are also currently replaced by flat displays, so that it was assumed that around twice as many CRT monitors are generated in the reality than estimated by the ‘batch leaching’ method, which leads to a theoretical generation of around 200 000 tonnes. The estimates of the generation are summarised in Table 14.

Table 14 Estimated sWEEE generation for the different equipment groups in 2007 in tonnes – data considered for the SFA

Group	Estimation of sWEEE generation in tonnes	
	In Germany	**In the USA**
Mobile telephone	2 273	14 916
Desktop personal computer	39 957	305 995
CRT monitor	200 000	1 125 000
Large high-grade equipment	87 071	409 309
Small high-grade equipment	2 550	21 186
Low-grade equipment	93 513	1 454 882
Total	**425 364**	**3 331 288**

The uncertainties of the estimations of the sWEEE generation depend on the quality of the data on lifetime distribution, average equipment weight, sales volumes and penetration rates. Quantifying the generation is difficult (Huisman et al. 2007; Widmer et al. 2005), so that the uncertainties of the results are assumed to be very high. The variation coefficient for the theoretical sWEEE generation was assumed to amount to 30%.

4.1.2. Collection

The data on collected sWEEE is supplied by the operators of collecting facilities. Beside separately collected sWEEE, sWEEE is often disposed of together with residual waste. This material flow was quantified using the results of sorting analyses of residual waste in Germany and in the USA.

4.1.2.1. Collection in Germany

Every year in Germany, the producers have to report the quantity of WEEE collected from public waste management and from individual or collective take-back systems (according to Section 13 (1) of ElektroG). The data supplied by the producers are compiled by the clearing house EAR and made available by the German Federal Environment Ministry (BMU 2008).
BMU (2008) reported that 287 000 tonnes of sWEEE were collected in Germany in 2007 (Table 15). Some assumptions were made on the distribution of the collected waste over the equipment groups defined in this thesis. The assumptions are based on unpublished sorting analyses of containers of WEEE, on observations at pre-processing facilities and on data from the literature. Rauch (2008) showed that 25.1% by mass of toys (category 7) collected by the municipality in Berlin belong to IT electronics (for example children laptops), and 26.1% are large and small video game consoles. Table 15 summarizes the distribution of the collected sWEEE over the equipment groups.

Table 15 Quantity of sWEEE collected under the responsibility of the equipment manufacturers in Germany in 2007 and assumed distribution over the equipment groups (in tonnes)

Category according to WEEE Directive	2- Small HH	3- IT and telecom.	4- CE	6- Tools	7- Toys, leisure, sports	Total
Total collected (BMU 2008)	**47 932**	**109 680**	**114 219**	**11 662**	**3 542**	**287 035**
Mobile telephone	0	110	0	0	0	**110**
Desktop personal computer	0	8 774	0	0	0	**8 774**
CRT monitor	0	82 260	45 688	0	0	**127 948**
Large high-grade equipment	0	16 452	22 844	0	1 417	**40 713**
Small high-grade equipment	0	110	228	0	354	**692**
Low-grade equipment	47 932	1 974	45 459	11 662	1 771	**108 798**

The company Greener Solutions (2008) reported that they collected 450 000 mobile phones in 2007 on behalf of manufacturers of mobile phones. Assuming that additional 100 000 mobile phones were collected by other manufacturers and retailers and assuming an average weight of 197 grams[1] per end-of-life mobile phone (Paper 1), in total around 108 tonnes of end-of-life mobile phones were collected by the manufacturers and retailers. These 108 tonnes are assumed to be collected in addition to the 110 tonnes of mobile phones presented in Table 15.

German public waste management authorities may choose not to make all WEEE of a specific collection group available to the producers, according to section 9 (6) of ElektroG. This collected WEEE is not taken into account in the official reporting on collection of WEEE of BMU (2008). Theusner (2008), representing the clearing house EAR, published data on the number of containers for which the public waste management authorities used the option offered by Section 9 (6) of ElektroG. Based on this data and on the average weight of a container of WEEE, which depends on the collection group considered, the mass of WEEE treated under the responsibility of the municipalities in 2007 was estimated (Table 16). The municipalities use section 9 (6) of ElektroG above all for large household equipment (containers of collection group 1). Janz et al. (2009b) mentioned that the municipalities sometimes treat WEEE without reporting it to the EAR. For this reason, the quantities presented in Table 16 could be too low.

Table 16 Quantity of WEEE treated under the responsibility of the municipal waste management authorities in Germany in 2007

Collection group	Number of containers treated by the municipalities	Average container mass in tonnes (Bilitewski et al. 2008)	Mass of WEEE in tonnes treated by the municipalities
1	4 320	4.5	19 440
2	36	2.4	86
3	449	4.2	1 886
4	44	1	44
5	1 336	6.5	8 684
		Total	**30 140**

The composition of the collection groups 3 (grouping the categories 3 and 4 according to the WEEE Directive) and 5 (categories 2, 6 and 7, the categories 8 and 9 are neglected) in terms of equipment groups was calculated based on the same assumptions as the assumptions that led to the results presented in Table 15. Table 17 shows that public waste

[1] Modern mobile phones have a weight lower that 197 grams; however, the market for smartphones, which can be considered as mobile phones and are usually heavier, is expanding. The assumption on average weight of a mobile phone influences largely the results of the substance flow analysis.

management authorities chose the option described by section 9 (6) of ElektroG for relevant quantities of CRT monitors and low-grade equipment.

Table 17 Quantity of sWEEE treated under the responsibility of the municipal waste management authorities in Germany in 2007 and distribution over the equipment groups (in tonnes)

Collection group	3	5	Total
Mobile telephone	1	0	**1**
Desktop personal computer	74	0	**74**
CRT monitor	1078	0	**1078**
Large high grade equipment	331	195	**526**
Small high grade equipment	3	49	**52**
Low grade equipment	400	8440	**8840**

Besides the collection channel described in the legislation, collection activities were also conducted by the informal sector and by other companies, institutions or NGOs.

Janz et al. (2009a) reported that 120 000 tonnes of WEEE are exported yearly to Eastern Europe after collection through informal channels. In practice, the actors of informal collection usually offer to pick up WEEE at the homes of the citizens or ask for end-of-life equipment at the entrance gate of municipal collection facilities. According to the authors of this article, large household appliances account for at least 80% of the WEEE exported to Eastern Europe. No data on informal collection of WEEE for informal treatment in Germany was found.

Through the project ‘Gelbe Tonne Plus’ in Berlin, 9 700 tonnes of waste containing 3% of sWEEE were collected between January 2005 and September 2006 (SenGUV 2007). The project ‘Gelbe Tonne Plus’ was also implemented in Leipzig. In total, approximately 300 tonnes of sWEEE were assumed to have been collected by ‘Gelbe Tonne Plus’ in 2007, belonging mainly to the equipment group ‘low-grade equipment’. Figures on the quantity of sWEEE collected by NGOs in charity actions are not available, but it is assumed to be low (less than 1000 tonnes in total). Table 18 summarizes the quantities of sWEEE collected in Germany in 2007 through the different collection channels.

Table 18 Quantity of sWEEE collected in Germany in 2007 (in tonnes)

Collection channel	Clearing house EAR	Public waste management authorities (section 9 (6) of ElektroG)	Informal sector	Others	Total
Mobile telephone	218	1	10	10	239
Desktop personal computer	8 774	74	1 000	100	9 948

Collection channel	Clearing house EAR	Public waste management authorities (section 9 (6) of ElektroG)	Informal sector	Others	Total
CRT monitor	127 948	1 078	5 000	100	134 126
Large high-grade equipment	40 713	526	3 000	100	44 339
Small high-grade equipment	692	52	10	10	764
Low-grade equipment	108 798	8 840	10 000	300	127 938
Total	287 143	10 571	19 020	620	317 354

No data are available on the uncertainties of the quantity of WEEE collected. The variation coefficient was assumed to be 10%.

4.1.2.2. Collection in the USA

In the USA, WEEE is mainly collected through numerous small and temporary initiatives. Many computer manufacturers, TV manufacturers, and electronics retailers offer some kind of take back programme or sponsor recycling events (Kang & Schoenung 2005; US EPA 2007a). Since no federal institution organizes and coordinates WEEE collection, data on collected WEEE in the USA are scarce. The research report of the US EPA (2008) provided some data on collected WEEE in the USA. According to this report, 375 500 metric tonnes (414 000 short tons) of WEEE were collected from households for recycling in 2007, including 152 500 tonnes of TV sets, 221 300 tonnes of computer products and 1 720 tonnes of mobile phones. The International Association of Electronics Recyclers (IAER 2006) considered both WEEE from households and WEEE from businesses, and published that 1.27 million metric tonnes (1.4 million short tons) of WEEE were collected and treated by the recycling industry in 2005. This quantity is supposed to at least double by 2010. Computer equipment accounted for around 62% of the collected WEEE, telecom equipment 10%, consumer electronics 13%, industrial equipment 7%, and others 8% (IAER 2006). Only around 20% of this WEEE comes from consumers and the residential area, which means that a large amount of the collected WEEE is usually used exclusively by businesses and institutions (for example servers, main frames or copiers) and is, therefore, not a part of this investigation. In the USA, the collection activities focus on a few equipment types like PCs and CRT monitors (see chapter 2.2.3). While some equipment types with high-grade printed circuit boards like DVD-players are collected, the infrastructure for low-grade equipment types, which are usually not considered as 'electronic waste', is very limited. The US EPA (2007b) classifies 'small appliances' as 'durable goods' found in municipal solid waste.

Some private organisations also published data on collected WEEE. The company ReCellular reported that in 2007, they collected four million mobile phones, which corresponds to around half the mobile phones collected in the country (ReCellular 2008). This estimate matches the results of the US Environmental Protection Agency, which reports that 1 720 tonnes of mobile phones were collected in the USA in 2007 (US EPA 2008). According to ReCellular, the events aiming at collecting larger appliances like computers and monitors do not collect significant numbers of end-of-life mobile phones.

Table 19 summarises the quantities of WEEE collected in the USA in 2007. Assumptions augmented the available data. The uncertainties were assumed to be higher than the uncertainties for the quantities of WEEE collected in Germany, i.e. the variation coefficient was assumed to amount to 20%.

Table 19 Quantity of sWEEE collected in the USA in 2007 and distribution over the equipment groups (tonnes)

	Collected sWEEE in tonnes
Mobile telephone	1 700
Desktop personal computer	220 000
CRT monitor	600 000[1]
Large high-grade equipment	300 000
Small high-grade equipment	5 000
Low-grade equipment	10 000
Total	1 136 700

[1] mainly computer CRT monitors from businesses and institutions

4.1.2.3. Non-separately collected sWEEE

In Germany, Rotter & Janz (2006) found during five waste sorting analyses in Saxony in 2004/2005 that 0.8% of residual waste is sWEEE. The sorting analyses of residual waste were repeated periodically and their results show that the implementation of the ElektroG did not significantly affect the quantity and the characteristics of the WEEE found in residual waste (Janz & Bilitewski 2007). According to Janz & Bilitewski (2007), the fraction of around 1% of sWEEE in residual waste is realistic for the majority of the German municipalities. This is also confirmed by the sorting analyses of Seddigh et al. (1996), conducted in 1994/1995 in several German cities. In 2007, 13 912 000 tonnes of residual waste were collected (Destatis 2007), so that under this assumption around 111 300 tonnes of sWEEE ended up in the residual waste in 2007.

Janz (2006) classified the devices found in residual waste by type. Table 20 shows the results of the sorting analysis aggregated according to the equipment groups defined in this thesis and the estimate of the mass of sWEEE disposed of together with residual waste in 2007. The variation coefficient is assumed to depend on the equipment groups.

Table 20 Repartition of the sWEEE contained in residual waste in Germany according to the equipment groups defined in Table 8

Group	Mass fraction in residual waste (Janz 2006)	Mass of sWEEE in residual waste in 2007 (tonnes)	Variation coefficient
Mobile telephone	0.9%	979	20%
Desktop personal computer *	2.7%	3 013	20%
CRT monitor	1.3%	1 487	20%
Large high-grade equipment	3.5%	3 918	20%
Small high-grade equipment	0.6%	631	20%
Low-grade equipment	81.5%	90 690	10%
Others	9.5%	10 578	
Total	**100%**	**111 296**	

* including separate drives, power supplies and hard disk drives

Concerning the disposal of sWEEE together with municipal solid waste in the USA, the following data were published:

- In 2007, approximately 230 million tonnes (254 million short tons) of municipal solid waste were generated in the USA (US EPA 2007b). If, like in Germany, around 1% of the municipal solid waste is sWEEE, that means that around 2.3 million tonnes of sWEEE were disposed of.
- Consumer electronics disposed of in the municipal waste stream in the USA were estimated by the IAER (2006) to approach 2.7 million metric tonnes (3 million short tons) annually.
- USGS (2001) estimated that more than 122 400 metric tonnes of personal computers, workstations, and mainframes were being added to landfills in 2001.
- The US EPA (2008) analysed the data from six sorting analyses of residual waste (Table 21) and estimated that around 1.67 million tonnes of computer-related electronics and CRT monitors were disposed of in 2007. The sWEEE was not defined and classified in a homogeneous way in the six studies, which complicates the extrapolation of the quantity of WEEE in residual waste to the national level. The US EPA (2008) solved this problem by calculating the average sWEEE in residual waste per capita multiplied by the number of inhabitants in the USA.

Table 21 Mass of sWEEE in discards according to various studies in the USA (in kg/capita/year)

Data source	CIWMB 2004b	GDCA 2005	MSWMCB 2000	Cascadia 2003	ODEQ 2002	SPU 2002 SPU 2004
Reference year	**2003**	**2003/2004**	**1999**	**2001**	**2005**	**2004/2006**
Geographical area	**California**	**Georgia**	**Minnesota**	**Wisconsin**	**Oregon**	**Seattle**
Inhabitants 2007	36 553 215	9 544 750	5 197 621	5 601 640	3 747 455	2 536 182
Computer-related electronics	3.3	0.9	1.2	0.5	2.5	0.4
CRTs (PC-monitors and TV sets)	6.2	0.4	0.6	6.1	4.4	0.1
Other (consumer) electronics	3.7	12.3	9.2	11.5	4.8	0.8
Small appliances non electronic					4.4	0.3

According to the report on municipal solid waste in the USA of the US EPA (2007b), 1.26 million tonnes (1.39 million short tons) of small appliances like toasters, hair dryers, electric coffee pots, which corresponds to the group ‘low-grade equipment’, were generated in 2007 and collected in the municipal residual waste stream.

Assumptions based on these data in the literature were necessary to estimate the repartition of the sWEEE contained in residual waste according to the equipment groups (Table 22). The uncertainties presented in Table 22 depend on the equipment group. The data quality was better for PCs, CRT monitors and low-grade equipment than for the other three equipment groups.

Table 22 sWEEE in residual waste in the USA according to the equipment groups defined in Table 8

Group	Mass of WEEE in residual waste in 2007 (tonnes)	Variation coefficient
Mobile telephone	16 000	30%
Desktop personal computer	200 000	20%
CRT monitor	1 000 000	20%
Large high-grade equipment	1 600 000	30%
Small high-grade equipment	20 000	30%
Low-grade equipment	1 260 000	20%

The report of the US EPA (2007b) on treatment of US municipal solid waste mentions that almost 30% of the ferrous metals contained in the end-of-life durable goods disposed of by the households were recovered, but makes no mention of recovery of precious metals. Both for Germany and for the USA, it was assumed that no sorting technology of residual waste was applied to sort the WEEE out of the residual waste and feed this to a treatment facility for WEEE, so that the gold and palladium contained in sWEEE disposed of together with residual waste are assumed to be discarded.

4.1.3. Reuse

Because reuse of EEE is covered by this investigation, “only” data on reuse of WEEE are needed. Defining a clear boundary between reuse of WEEE and reuse of EEE in practice is a challenge, as emphasized by Prelle (2008).
Data on reuse of WEEE in Germany in 2007 under the responsibility of the manufacturers were published by BMU (2008), and this is summarized by Table 23.

Table 23 Quantity of WEEE reused under the responsibility of the manufacturers in Germany in 2007 (tonnes)

Category according to WEEE Directive	Reused
2- Small household appliances	662
3- IT and telecommunications equipment	2705
4- Consumer equipment	343
6- Electrical and electronic tools	181
7- Toys, leisure and sports equipment	25

Little information is available about the reuse of sWEEE in Germany besides the data from BMU (2008). Greener Solutions (2008) reported that mobile phones they collected in 2007 were reused in Asia or Africa.
The reuse rates depend not only on the collection channel, but also on the equipment types. It was assumed that the reuse rates are higher for sWEEE collected by the informal sector than for sWEEE collected through the ElektroG. For Germany, the following assumptions were used to quantify the flows to reuse:

- 50% of the sWEEE collected by the informal sector and by ‘others’ is sent for reuse;
- 50% of the end-of-life mobile phones collected by the producers is sent for reuse;
- 5% of the end-of-life personal computers and 2% of the large high-grade equipment collected by the municipalities is sent for reuse;
- 1% of the sWEEE belonging to the other three equipment groups collected by the municipalities is sent for reuse.

Table 24 summarizes the results. They include the parts of sWEEE sorted out for reuse before or during treatment (this flow of reused parts of sWEEE is assumed to be very small). The orders of magnitude of the data of Table 24 match the data reported by BMU (2008).

Table 24 Quantity of sWEEE reused in Germany in 2007 (in tonnes)

Collection channel	Clearing house EAR	Public waste management authorities	Informal sector	Others	Total
Mobile telephone	56	0	5	5	**66**
Desktop personal computer	439	4	500	50	**992**
CRT monitor	1 279	11	2 500	50	**3 840**
Large high-grade equipment	407	5	1 500	50	**1 962**
Small high-grade equipment	7	1	5	5	**17**
Low-grade equipment	1 088	88	5 000	150	**6 326**

In the USA, no distinction is made between reuse of EEE and reuse of WEEE neither in the legislation nor in the industrial practice, so that the data have to be selected and used cautiously.

Concerning mobile phones, ReCellular (2008) reported that around half of the mobile phones they collected were reused, either within the USA or abroad. The Northeast Recycling Council (NERC 2003) published data on computer-related products reused in 34 for-profit and non-profit organisations in the Northeast of the USA (Table 25), without distinguishing reuse of EEE and of WEEE. The IAER (2006) reports that 31% of the output from the recycling industry is equipment for reuse and 16% are parts for reuse (around 508 000 and 263 000 tonnes in 2007 respectively).

Table 25 Outgoing products sold or donated in the Northeast in tonnes (NERC 2003)

	CPU	Key-board	Monitor /CRT	Laptop	TV	Hard Drive	CD Drive	Disk Drive	Mother -board	Other	Total
Non-profit	311	40	1324	4	113	0.40	0.41	0.48	0.48		1794
For-profit	734	35	1463	36	225	0.05	0.05	0	125	240	2857
Total	1045	75	2787	40	338	0.45	0.46	0.48	125.48	240	4651

These data were combined with assumptions to obtain the results presented in Table 26, which include both reused devices and reused parts. The uncertainties of these results and on the results presented in Table 24 are very high, so that the variation coefficient was assumed to amount to 30%.

Table 26 Quantity of sWEEE (including whole equipment and parts) reused in 2007 in the USA (tonnes)

Group	Reused sWEEE
Mobile telephone	800
Desktop personal computer	70 000
CRT monitor	100 000
Large high-grade equipment	100 000
Small high-grade equipment	1 000
Low-grade equipment	5 000

It is assumed that 90% of the mass of sWEEE entering a reuse process is actually reused. The remaining 10% are non-reusable parts that are sent to treatment (5% to formal and 5% to informal treatment). The concentration of precious metals is assumed to be identical in the reused and in the non-reused parts.

4.1.4. Treatment

4.1.4.1. Material flows to formal and informal treatment

The first analysis of the material flows in the treatment subsystem involves distinguishing the flows to the formal and informal treatment. Very few data are available on the material flows in input of the recycling facilities of the formal sector in Germany (Bolland 2009).
The informal sector can be located outside or inside Germany:

- Quantitative data on illegal export of WEEE out of Germany for treatment through the informal sector located outside of Germany were published by Buchert et al. (2007). According to these authors, a client of a shipping company reported that he exports 100 000 PC-monitors per month from Hamburg harbour to Asia, which corresponds to a material flow of around 12 000 tonnes a year (Janz et al. 2009a). Very likely, sWEEE generated in Germany is also exported from other harbours in Germany and in the neighbouring countries. Sander & Schilling (2009) analysed statistical data on export of WEEE and of second-hand EEE from the harbour of Hamburg in Germany, but various weaknesses in the methods used to collect these data prevented the research groups from quantifying the flows.
- The existence of informal treatment not only in developing countries, but also inside Germany was reported by Faulstich & Baron (2008), Friege et al. (2008) and Schönekerl (2009). These authors mentioned that in some cities, over 50% of the most valuable parts of sWEEE (for instance printed circuit boards and copper-rich parts) are frequently stolen by non-identified persons before the sWEEE reaches the treatment facilities of the formal sector.

For economic reasons, which partially depend on the legislation, some equipment types like CRT monitors are more likely to be treated by the informal sector that other equipment types like high-grade equipment. Also the used collection channel influences whether the sWEEE will be treated by the formal or by the informal treatment. Thus, sWEEE collected by informal collectors is assumed to be more likely to end up in an informal treatment than sWEEE collected by the formal sector.

For Germany, the following assumptions were used to quantify the flows to formal and informal treatment:

- 80% of the sWEEE collected by the informal sector and not sent for reuse is fed to a treatment process of the informal sector;
- 20% of the CRT monitors that are collected by the formal sector and not reused are treated by the informal sector in Germany or in another country.

5% of the sWEEE belonging to other equipment groups, collected by the formal sector and not reused are treated by the informal sector.

Concerning the USA, the IAER (2005) reported that around 907 000 tonnes (one million short tons) of materials out of the recycling industry were exported in 2005, including working equipment (25.1% of total output), non-working equipment (12.9%), parts (9.1%) and materials (26.9%). BAN (2002) estimated that 50% to 80% of the monitors collected for recycling are exported. For the USA, the following assumptions were made:

- 60% of the CRT monitors that are collected by the formal sector and not reused are treated by the informal sector;
- 20% of the collected sWEEE belonging to other equipment groups are treated by the informal sector.

Table 27 shows the results of the quantification of the flows to formal and informal treatment.

Table 27 Destination of the sWEEE sent for treatment in 2007 in Germany and in the USA (tonnes)

Group	Germany		USA	
	To formal treatment	To informal treatment	To formal treatment	To informal treatment
Mobile telephone	157	16	880	220
Desktop personal computer	8 095	860	120 000	30 000
CRT monitor	102 699	27 587	200 000	300 000
Large high-grade equipment	39 095	3 281	160 000	40 000
Small high-grade equipment	702	45	4 000	1 000
Low-grade equipment	111 669	9943	4 000	1 000

The variation coefficient was assumed to amount to 10% for the flows to formal treatment and 20% for the flows to informal treatment.

No data on intermediate flows of material in the process chain are made available by the companies operating the facilities. For example, no suitable data on the quantity of parts of sWEEE entering the processes for recovery of precious metals are available. To be useful for this research, these data would have to be differentiated according to the geographical origin of the waste material (to be in line with the geographical boundaries of the investigation) and according to the type of waste material (for example: printed circuit boards from personal computers), because the facilities do not only treat end-of-life electronics but many kinds of materials containing precious metals. For commercial and legislative reasons, these details are treated as confidential by the operators of the facilities or are not available in this level of detail.

4.1.4.2. Recovery rates for precious metals during treatment

The step following the determination of the quantities of sWEEE fed to formal and informal treatment in Germany and in the USA is the evaluation of the performance of the applied treatment processes regarding recovery of precious metals. Recovery rates, which may also be called 'yields' in the literature, were selected as indicators to quantify the recovery of precious metals. The recovery rate of the whole treatment process chain is the product of the recovery rates of the pre-processing and recovery processes used along the treatment chain.

Regarding formal treatment of sWEEE, Bolland (2009) classified the pre-processing facilities in Germany into the following categories:

- Manual: exclusively manual pre-processing (dismantling). However, in practice some precious-metal rich parts like power supplies or computer drives and some low-grade equipment are not manually dismantled but sent to other facilities for mechanical treatment, or sold to traders and then largely exported;
- Mechanical 1: selective treatment according to ElektroG and automated mechanical pre-processing;
- Mechanical 2: selective treatment according to ElektroG and combination of manual and mechanical pre-processing. In some facilities of type 'Mechanical 2', selected equipment types like personal computers or CRT monitors are dismantled manually.

Another option, used for small high-grade equipment like mobile phones, is to remove the battery manually and feed the whole devices into a recovery process for precious metals (so there are no losses of precious metals due to pre-processing). Bolland (2009) revealed that in 2007 on average 76% of the sWEEE of collection group 3 treated by the formal sector is processed in a facility of type ‘mechanical 2’, whereas the remaining 24% is pre-processed manually. 26% of collection group 5 is pre-processed manually, 25% in facilities of type ‘mechanical 1’ and 49% in facilities of type ‘mechanical 2’. Table 28 presents the assumed distribution of the sWEEE over the four kinds of pre-processing facilities in 2007, as well as assumptions on the recovery rates for precious metals achieved by the three types of pre-processing facilities. The assumptions are based on the results of experimental substance flow analyses conducted in pre-processing facilities for sWEEE.

Chancerel & Rotter (2008b) investigated a manual dismantling process and estimated that around 82% of the gold contained in sWEEE of collection group 3 is sent directly to a precious-metals recovery process. The remaining gold is either sent to further mechanical pre-processing or sent to plastic recycling and lost. It is assumed that in total, pre-processing through manual dismantling allows the recovery of 90% of the gold and palladium. The results have the same order of magnitude as the results of Meskers et al. (2009), who investigated only personal computers. Van Schaik & Reuter (2009) mentioned recovery rates of 15% for gold in a shredding facility that can be assumed to be of type ‘mechanical 1’. The results presented in Paper 2 showed that around 24% of gold and palladium are recovered in a German facility of type ‘mechanical 2’. Meskers et al. (2009) conducted similar experimental investigations in another facility using another type of technology, and considering only personal computers. Much higher recovery rates (70%) were determined by Meskers et al. (2009) compared to the results of Paper 2, probably due to the use of another liberation technology and the homogeneity of the input material (only PCs) compared to the input mix considered in Paper 2.

All these investigations are restricted to a certain facility at a certain time for a certain input material. The limitations regarding representativeness of the studies cause high uncertainties by the extrapolation of the data to the whole subsystem ‘pre-processing of sWEEE’ in Germany. However, these experimental results are the only available data.

Because personal computers are sometimes dismantled manually in ‘mechanical 2’ facilities, an average recovery rate of 50% was assumed. Regarding CRT monitors, observations showed that in Germany the printed circuit boards are usually removed manually (Bolland 2009). Afterwards, they are usually treated mechanically to separate the iron and the aluminium from the precious metals and the copper-rich materials. This mechanical treatment leads to losses of precious metals that have, so far, not been quantified by experimental investigations. An overall recovery rate for gold from CRT monitors of 60% was assumed.

Due to the limited available data, the recovery rates for gold were assumed to be equal to the recovery rates for palladium. This was the case in the results of Paper 2.

Table 28 Recovery rates for gold and palladium achieved in 2007 by the pre-processing technologies used for formal treatment in Germany (PP= pre-processing; Mech.= Mechanical)

Treatment type	Distribution of the sWEEE over the process types (modified from Bolland 2009)				Recovery rate of types of pre-processing			Total recovery rate of pre-processing
	No PP	Manual	Mech. 1	Mech. 2	Manual	Mech. 1	Mech. 2	
Mobile telephone	40%	10%		50%	90%		24%	**61%**
Desktop personal computer		24%		76%	90%		50%	**60%**
CRT monitor		24%		76%	60%[1]		60%[1]	**60%**
Large high-grade equipment		24%		76%	90%		24%	**40%**
Small high-grade equipment		24%		76%	90%		24%	**40%**
Low-grade equipment		26%	25%	49%	50%	15%	24%	**29%**

[1] including mechanical treatment of the separated printed circuit boards, which is widely used after after all kinds of pre-processing including manual pre-processing

Quantitative data are not available on the types of pre-processing technologies used in the USA. Some visits to facilities and publications like the article of Koehnlechner (2008) showed that on average, the operators of recycling facilities were more aware of the economic relevance of precious metals in sWEEE, at least in 2007, than the operators of facilities in Germany. Moreover, the pre-processing facilities in the USA receive a more homogeneous waste material for treatment than in Germany, because the sWEEE does not have to be classified in collection groups like required in Germany by the ElektroG. For these reasons, the recovery rates for gold and palladium in the USA were estimated to be higher than in Germany. The estimates are presented in Table 29.

Table 29 Recovery rates for gold and palladium achieved in 2007 by the pre-processing technologies used for formal treatment in the USA

Treatment type	Total recovery rate of pre-processing
Mobile telephone	**75%**
Desktop personal computer	**75%**
CRT monitor	**60%**
Large high-grade equipment	**50%**
Small high-grade equipment	**50%**
Low-grade equipment	**30%**

The recovery rates for precious metals achieved by the processes for recovery of precious metals of the formal sector was estimated by several authors to exceed 90% (Table 30). A differentiation between recovery of precious metals from the sWEEE generated in Germany and in the USA was not necessary, because the materials are commodities traded on a global scale. It is very common that precious metals from printed circuit boards from a pre-processing facility in the USA are recovered in Europe.

Table 30 Recovery rates for gold and palladium achieved by the recovery processes of the formal sector

Reference	Recovery rate for gold	Recovery rate for palladium
Huisman (2004)	> 99%	> 99%
Deubzer (2007)	98%	99%
Hagelüken & Meskers (2008)	>95%	

[1] 5% are lost in the copper smelter, and 1% during palladium refining

The recovery rates in the recovery processes were assumed to be 98% for gold and palladium. The overall recovery rates achieved by the whole process chain of the formal treatment are presented in Table 31. In both regions, the highest recovery rates are achieved for mobile telephones and personal computers, and the lowest for low-grade equipment. For Germany, the quantification of the uncertainties of the recovery rates is based on the statistical analysis of the experimental results presented in Paper 2. The variation coefficient was assumed to amount to 10%. For the USA, where no quantitative data are available, the variation coefficient was assumed to amount to 20%.

Table 31 Recovery rates for gold and palladium achieved by formal treatment of sWEEE in Germany and in the USA in 2007

Country	Germany	USA
Mobile telephone	60%	74%
Desktop personal computer	58%	74%
CRT monitor	59%	59%
Large high-grade equipment	39%	49%
Small high-grade equipment	39%	49%
Low-grade equipment	28%	29%

Keller (2006) investigated the processes applied in the informal sector to recover gold from printed circuit boards in Bangalore in India. Two different processes were compared, both beginning with the dismantling of printed circuit boards to remove the parts containing apparent gold. Afterwards, the gold was recovered by cyanide leaching (process 1) or gold stripping (process 2). Figure 13 presents the results of the substance flow analysis. Between 40% and 84% of the gold contained in the printed circuit boards (basic raw material) was lost during pre-processing, mainly because of the visual checking for apparent gold. The recovery of gold through chemical processes causes further losses, so that in total, only 8% to 18% of the gold is recovered (Figure 13).

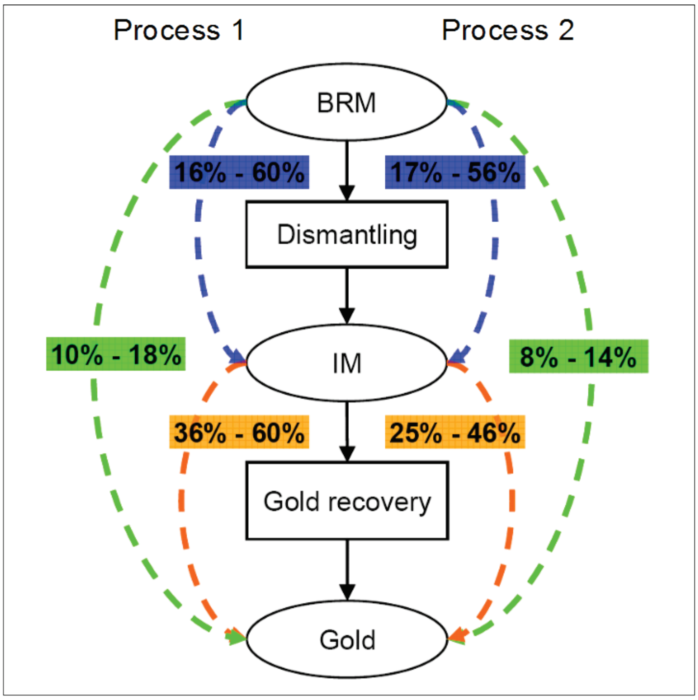

Figure 13 Gold yields of two recycling processes for printed circuit boards in Bangalore; BRM= Basic raw material (printed circuit boards), IM= Input material (apparent gold parts) (Keller 2006)

In this thesis, it was assumed that the chain of treatment processes applied by the informal sector allows the recovery of 13% of the gold. The variation coefficient was assumed to amount to 10%, which means that 10% to 16% of the gold is assumed to be recovered during treatment in the informal sector. Palladium is usually not recovered by the informal sector (assumed recovery rate of 0%).

4.2. Concentration of precious metals in sWEEE

The quantification of the metal flows requires knowledge of the average concentration of gold and palladium in the equipment groups. As presented in chapter 3.3.1, the concentration of precious metals in the different equipment groups was assumed to be constant in the entire system.

Data on the concentration of precious metals in some equipment types are directly available in the literature (see Appendix 2). Hagelüken & Buchert (2008) measured in 105 tonnes of end-of-life mobile phones (without battery) an average gold concentration of 347 grams per tonne and an average palladium concentration of 151 grams per tonne. For personal computers, Gmünder (2007) reports a gold concentration of 26.7 grams per tonne of PCs, and a palladium concentration of 12.3 g/t. Shirahase et al. (2007) reported that one tonne of PCs contains 13 grams of gold and 17 grams of palladium. The Microelectronics and Computer Technology Corporation (MCC 1996) mentioned an average gold concentration of 16 g/t and a palladium concentration of 3 g/t in computers including central units and CRT monitors. Because of the conflicting values in the literature, calculations were conducted (Table 32), showing that PCs contain around 31 g/t of gold and 13 g/t of palladium.

Table 32 Precious metals concentration in personal computers

Component	Reference	Mass fraction of part in PC	PM concentration (g/t in part)		PM concentration (g/t in PC)	
			Gold	Palladium	Gold	Palladium
PCB from central unit	Hagelüken 2007	8.9%	250	110	22.3	9.8
Processor	Analysis at Umicore	0.2%	2737	27	5.2	0.1
PCB from CD drive	Gmünder, 2007	0.6%	87.5	52	0.6	0.3
PCB from floppy drive	Gmünder, 2007	0.4%	112	203	0.4	0.8
PCB from hard drive	Gmünder, 2007	0.5%	415	286	2.2	1.5
PCB from power supply	Gmünder, 2007	2.1%	10	17	0.2	0.4
				Total	**30.8**	**12.8**

The concentration of precious metals in the other equipment groups was determined by using the formula presented in chapter 3.3.1, assuming that only printed circuit boards contain precious metals. Appendix 3 compiles literature data on the concentrations of silver, gold, palladium and platinum in printed circuit boards from different equipment types published by several authors. Sampling issues, time and place of the investigation and applied analysis method may explain the discrepancies of the results. Table 33 presents the estimated average concentrations of gold and palladium in the different equipment groups in Germany and in the USA. Details on the calculations, which results for Germany differ slightly from the results for the USA, can be found in Appendix 6. The variation coefficient is assumed to vary according to the equipment groups and to amount to:

- 5% for mobile phones,
- 10% for desktop personal computers,
- 20% for the remaining four equipment groups.

Table 33 Average concentration of precious metals of different equipment groups (grams)

Equipment group	Average mass of PM per tonne of sWEEE in the USA		Average mass of PM per tonne of sWEEE in Germany		Average mass of PM per device in Germany		Average mass of PM per tonne of PCB from the eq. group in Germany	
	Au	**Pd**	**Au**	**Pd**	**Au**	**Pd**	**Au**	**Pd**
Mobile telephone[1]	347	151	347	151	0.068	0.030	980	285
Desktop personal computer	30.8	12.8	30.8	12.8	0.374	0.156	250	110
CRT monitor	0.7	0.3	0.6	0.3	0.008	0.004	13	6
Large high-grade equipment	12.6	2.4	11.9	2.1	0.059	0.011	93	17
Small high-grade equipment	72.6	21.4	61.2	13.1	0.032	0.007	333	55
Low-grade equipment	2.9	0.7	2.8	0.6	0.008	0.002	44	14

[1] without battery

Table 33 shows the average concentration of precious metals in the six equipment groups in Germany measured per tonne of equipment, per device and per tonne of printed circuit boards from the devices belonging to the equipment groups. Mobile phones form the richest equipment groups with the richest printed circuit boards, but the content of precious metals in one mobile phone is lower by a factor 5 than in one personal computer. The data relevant for the substance flow analysis are the concentration of precious metals per tonne of sWEEE (column ‘average mass of PM per tonne of sWEEE’).

5. Quantification of the flows of gold and palladium

The data on the flows of sWEEE and on the gold and palladium concentrations are compiled with the STAN software for the six different equipment groups. Data are reconciled as described in chapter 3.4. This led in some cases to significant corrections probably due to the high uncertainties related to the estimation of the sWEEE generation (see chapter 4.1.1.2). The flows of collected, non-separately collected, reused and treated sWEEE are quantified (Appendix 7) and, based on it, the flows of precious metals associated with the sWEEE that were recovered, reused and discarded are calculated. Appendix 8 presents the gold flows and Appendix 9 presents the flows of palladium. The uncertainties of the results are expressed as standard deviation. In spite of the high uncertainties, the results give the order of magnitude of the mass flows of precious metals related to sWEEE.

5.1. Mobile phones

After data reconciliation as described by chapter 3.3.3, the quantity of end-of-life mobile phones generated in Germany in 2007 is assumed to amount to 1300 tonnes (standard deviation of 189 tonnes) and to contain around 450 kg of gold and 200 kg of palladium (Figure 14). Around 18% of the mobile phones are collected and around 12% end up in a process for formal treatment. Almost 5% of the mobile phones are reused. Finally, between 26 and 40 kg of gold were recovered (with a confidence interval of 95%) and between 11 and 17 kg of palladium. Between 260 and 530 kg of gold were discarded, which had in 2007 an economic value between 5.7 and 11.5 million US-dollars according to the average gold price in 2007 published by USGS (2008). The losses of palladium amounted to between 120 and 230 kg, which had in 2007 a value of 1.3 to 2.7 million US-dollars. Figure 14 illustrates the flows of precious metals associated with the management of end-of-life mobile phones in Germany in 2007 (without showing the uncertainties). The data on flows of mobile phones with the standard deviations are presented in table form in Appendix 6. Appendix 7 and Appendix 8 summarize the data on flows of precious metals and their uncertainties expressed as standard deviation.

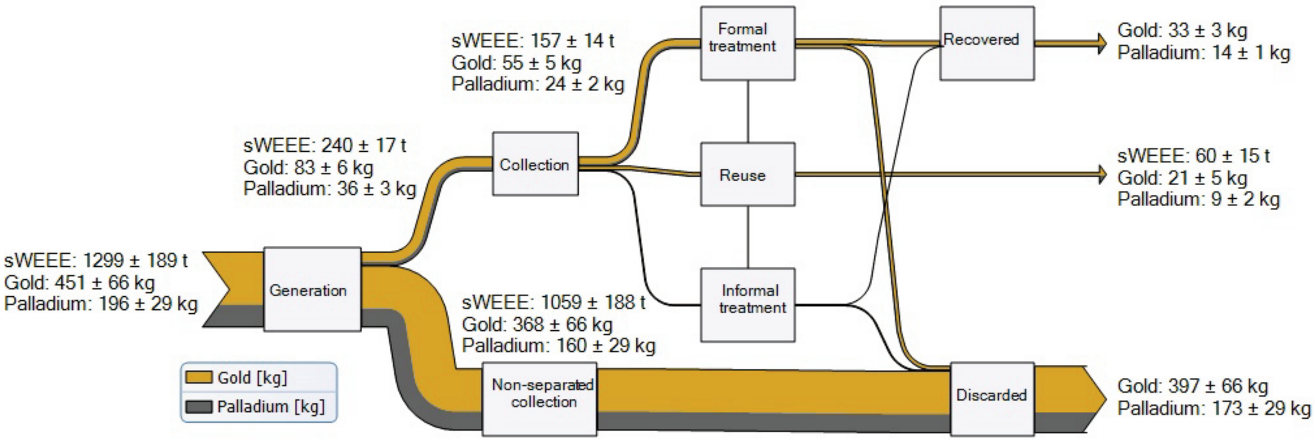

Figure 14 Flows of gold and palladium contained in end-of-life mobile phones in Germany in 2007[1]

The main source of losses of precious metals in Germany is collection, since around 82% of the end-of-life mobile phones are not separately collected but disposed of by the users. The hibernating mobile phones are not considered in this study.

In the USA, the collection rate is lower than in Germany. Around 11% of the 16 000 tonnes of mobile phones generated in 2007 were collected, the rest was disposed of (Figure 15). Around 5% of the generated mobile phones passed through the formal treatment. The reuse rate amounts to around 4%. The losses due to non-separated collection combined with the losses of precious metals during treatment caused the loss of between 2.9 and 7.5 tonnes of gold, which in 2007 had an economic value between 63 and 162 million US-dollars.

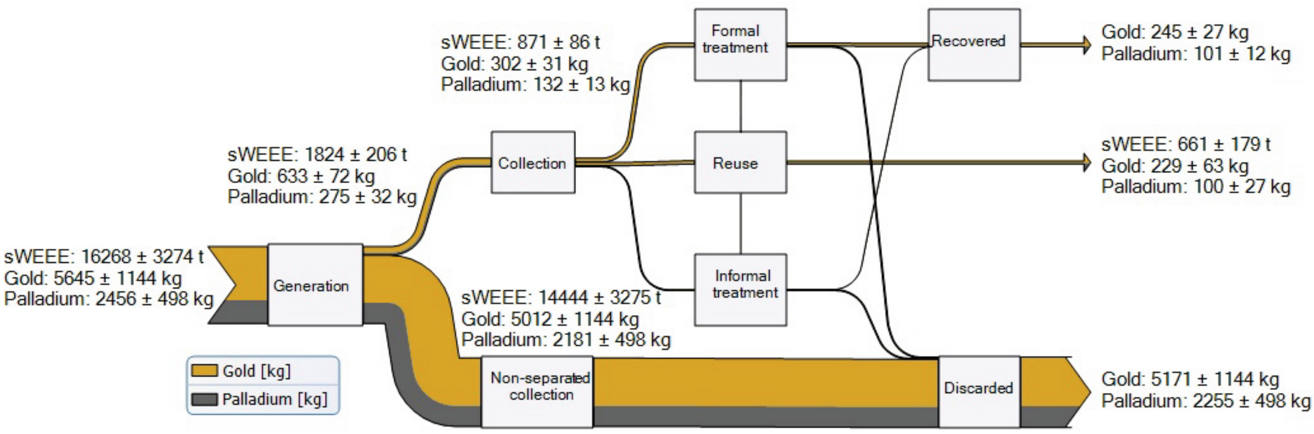

Figure 15 Flows of gold and palladium contained in end-of-life mobile phones in the USA in 2007[1]

5.2. Desktop personal computers

In Germany, between 12 000 and 14 000 tonnes of end-of-life desktop personal computers were generated in 2009. Around 76% of these computers were collected. According to the sorting analyses of Janz (2006), the majority of the non-separately collected flow of PCs consists of loose drives and components of PCs. No entire desktop personal computer was found in residual waste during the sorting analyses.

Around 62% of the generated PCs were treated by the formal sector. In total, between 120 and 180 kg of gold was recovered, which corresponds to around 37% of the gold contained in the generated computers. The losses of gold amounted in 2007 to 180 to 270 kg, which in 2007 had a value of 3.9 to 5.9 million US-dollars. Between 76 and 115 kg of palladium were lost. Figure 16 illustrates the flows of end-of-life computers and of gold and palladium associated with them in Germany in 2007.

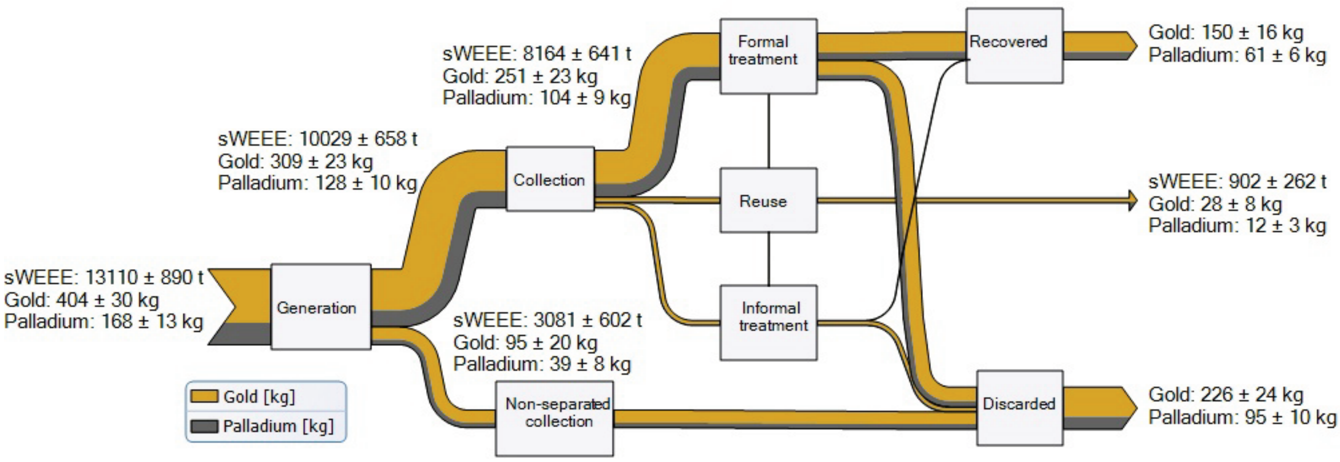

Figure 16 Flows of gold and palladium contained in end-of-life desktop personal computers in Germany in 2007[1]

The flows in the USA are illustrated in Figure 17. The generation of end-of-life desktop computers is much higher than in Germany and amounted in 2007 almost 400 000 tonnes. Around half of this WEEE (54%) was collected. The reuse rate amounts to around 15%. Almost 30% of the generated computers were treated by the formal sector. According to the assumptions, around 7% of the end-of-life computers were treated informally, which mainly means that they were exported for treatment in developing countries. In total, less than a quarter of the gold and of the palladium contained in the generated computers was recovered (around 23%). The losses of gold had a value of 110 to 215 million US-dollars, and the losses of palladium were worth 25 to 48 million US-dollars.

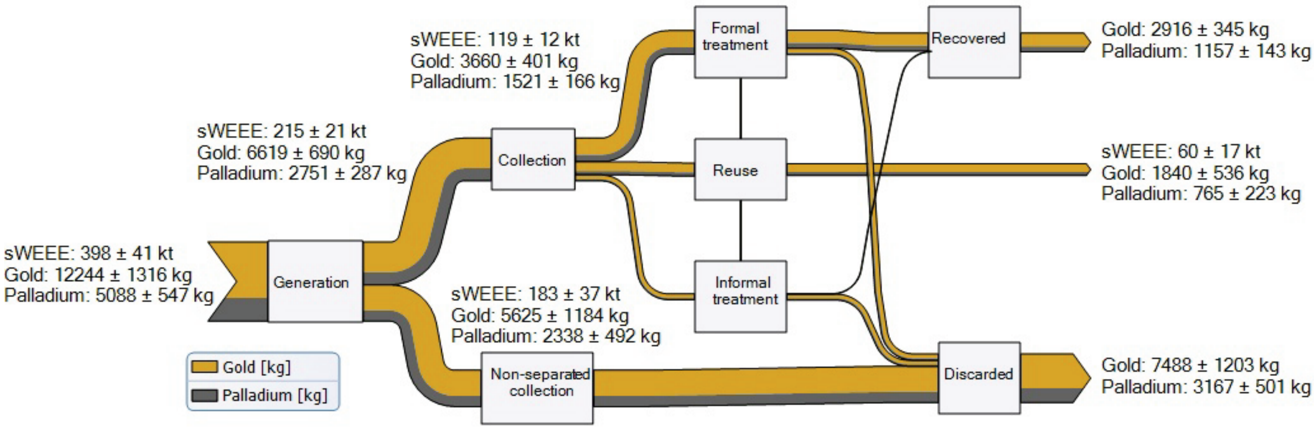

Figure 17 Flows of gold and palladium contained in desktop personal computers in the USA in 2007[1]

5.3. Cathode-ray tube monitors

In Germany, the 119 000 to 154 000 tonnes of CRT monitors (TV sets and computer monitors) generated in 2007 contained between 68 and 100 kg of gold and between 32 and 47 kg of palladium (Figure 18). Around 99% of these appliances were collected. According to the assumptions used in this thesis, around three-quarters of the monitors were treated by the formal sector. In total, around 45% of the precious metals were recovered. The losses are mainly due to inappropriate treatment by the formal and the informal sector. They amount to 33 to 52 kg of gold and 16 to 26 kg of palladium.

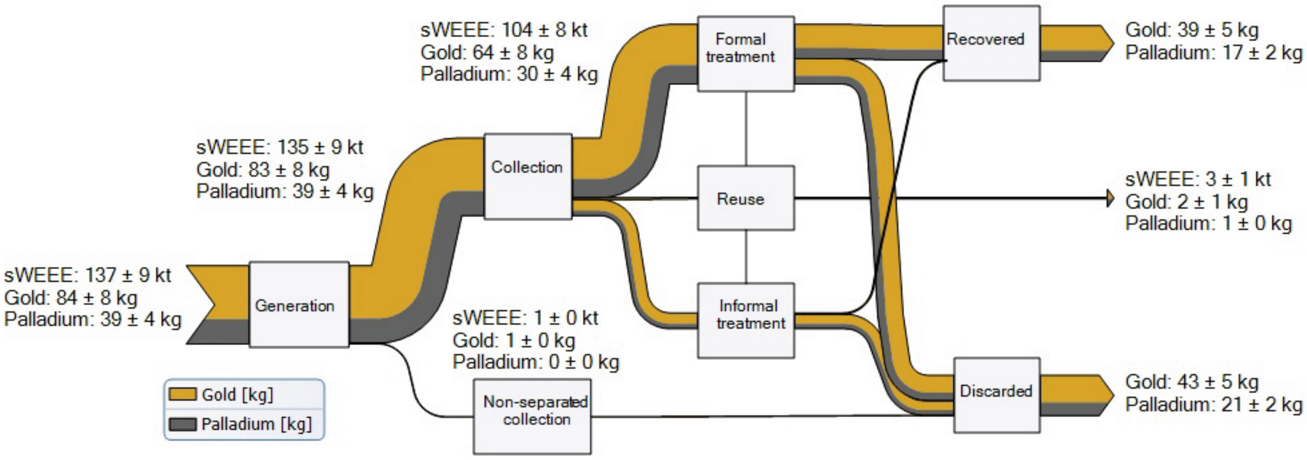

Figure 18 Flows of gold and palladium contained in end-of-life cathode-ray tube monitors in Germany in 2007[1]

In the USA, the generation of end-of-life CRT monitors amounted to around 1.5 million tonnes (Figure 19). Around 60% of this sWEEE was disposed of. Around 14% was treated by the formal sector, and 20% was exported and treated by the informal sector. The management system led to the loss of 530 to 1070 kg of gold and 270 to 550 kg of palladium.

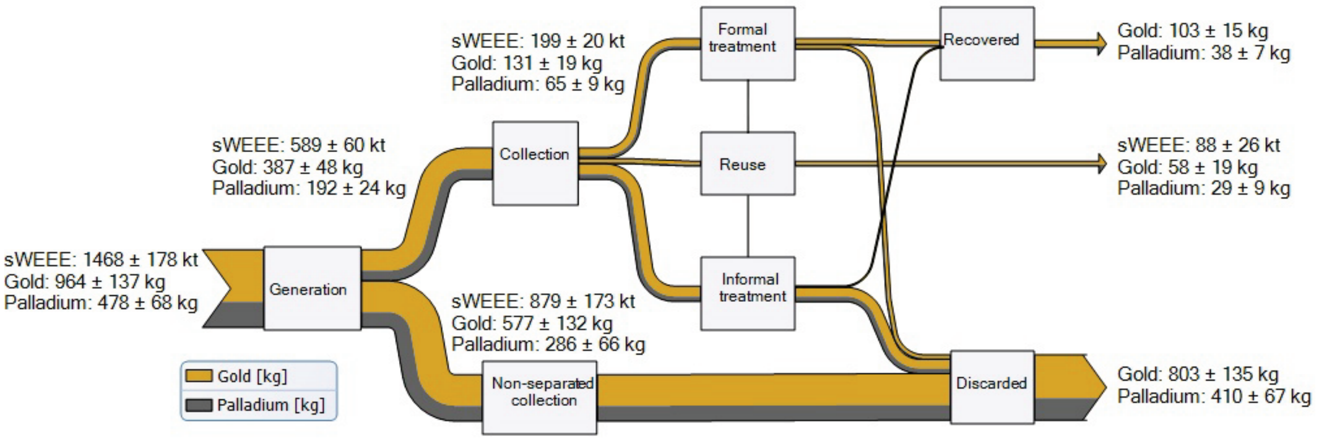

Figure 19 Flows of gold and palladium contained in end-of-life cathode-ray tube monitors in the USA in 2007[1]

5.4. Large high-grade equipment

Regarding large high-grade equipment, which includes mainly Hi-fi units, CD players, printers, video recorder, DVD players, flat displays and laptops, a very high collection rate of around 92% is achieved in Germany (Figure 20). Around 49 000 tonnes of waste equipment belonging to this equipment group were generated in Germany in 2007, containing between 470 and 690 kg of gold and between 80 and 120 kg of palladium. Around a third of these precious metals is recovered.

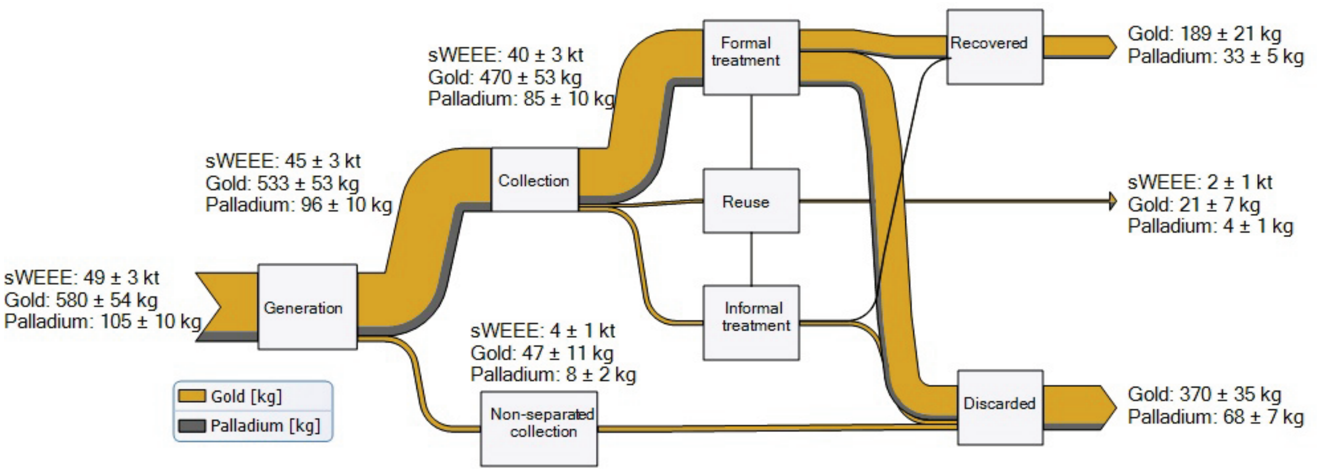

Figure 20 Flows of gold and palladium contained in large high-grade waste equipment in Germany in 2007[1]

In the USA, the collection rate is almost 60%. Between 3 and 9 tonnes of gold were contained in the 260 000 to 740 000 tonnes of large high-grade equipment that were generated in 2007 (Figure 21). Around 17% of the precious metals are recovered. The losses have an economic value of 20 to 160 million US-dollars for gold and 2 to 16 million US-dollars for palladium. The uncertainties are very large.

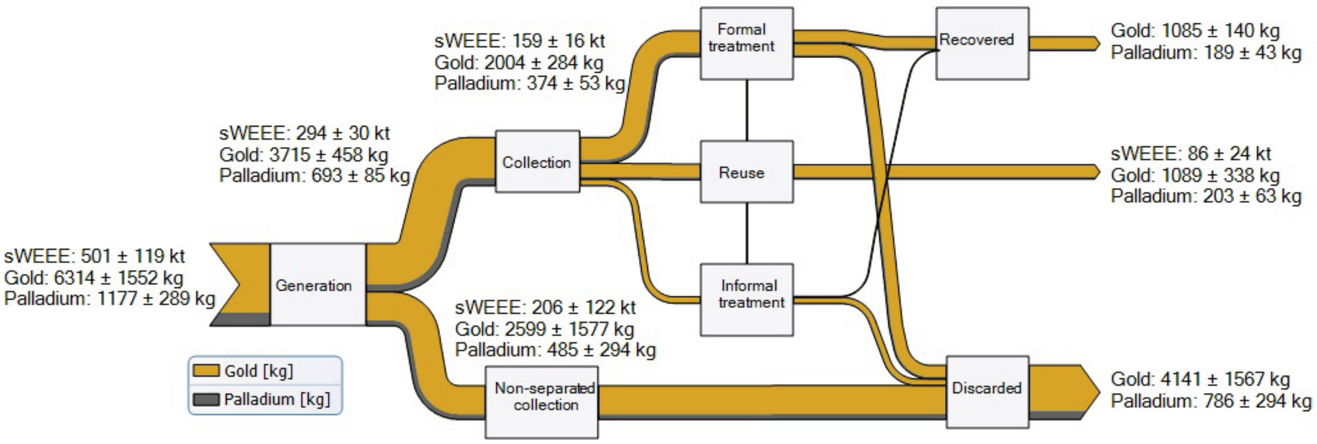

Figure 21 Flows of gold and palladium contained in large high-grade waste equipment in the USA in 2007[1]

5.5. Small high-grade equipment

The generation of small high-grade waste equipment amounted to 1160 to 1700 tonnes in Germany in 2007 and contained 67 to 108 kg of gold (Figure 22). Around 54% of this equipment was collected. The management system allowed the recovery of almost 20% of the precious metals. Between 50 and 88 kg of gold and between 11 and 19 kg of palladium were discarded.

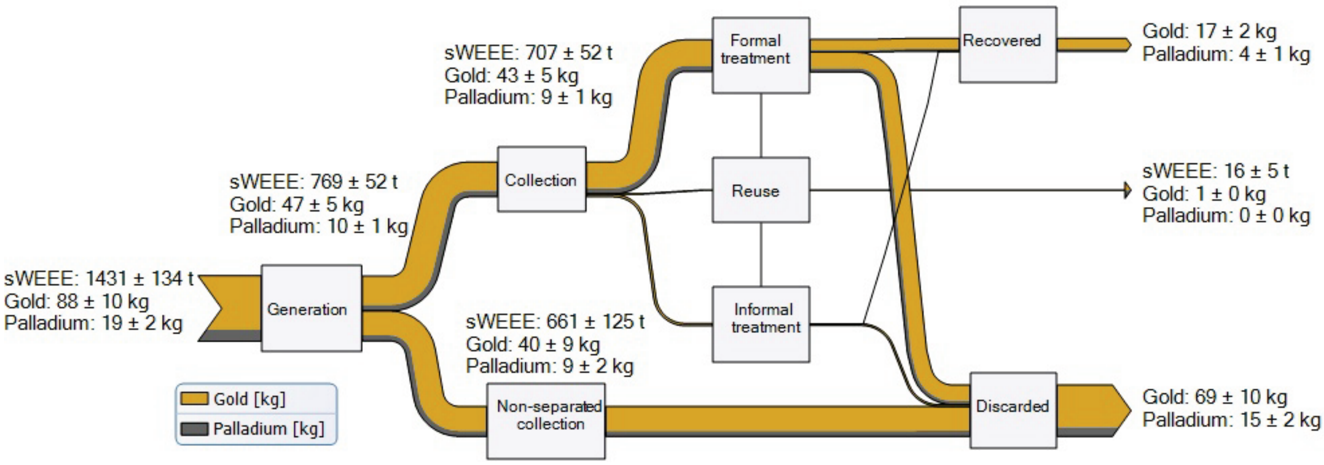

Figure 22 Flows of gold and palladium contained in small high-grade waste equipment in Germany in 2007[1]

In the USA, between 14 000 and 32 000 tonnes of small high-grade equipment were generated. Around 22% of this sWEEE was collected (Figure 23). In total, around 9% of the precious metals contained in small high-grade waste equipment were recovered, which represent 110 to 190 kg of gold and 23 to 61 kg of palladium.

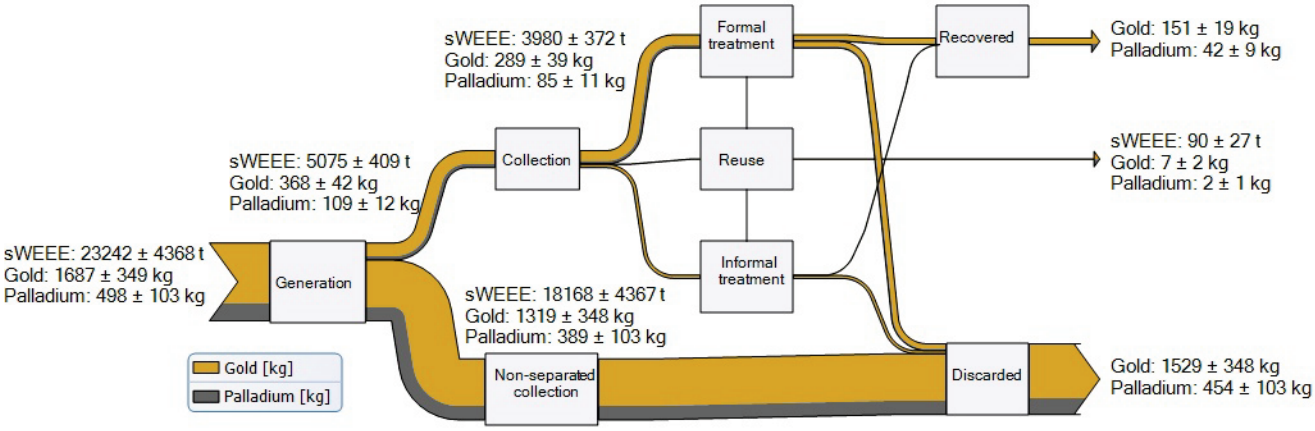

Figure 23 Flows of gold and palladium contained in small high-grade waste equipment in the USA in 2007[1]

5.6. Low-grade equipment

The mass of low-grade equipment generated in 2007 in Germany was very high: between 175 000 and 221 000 tonnes (Figure 24). Around 60% of this waste equipment was separately collected. The treatment allowed the recovery of 62 to 104 kg of gold and 12 to 24 kg of palladium, which represents around 15% of the precious metals contained in the generated waste equipment.

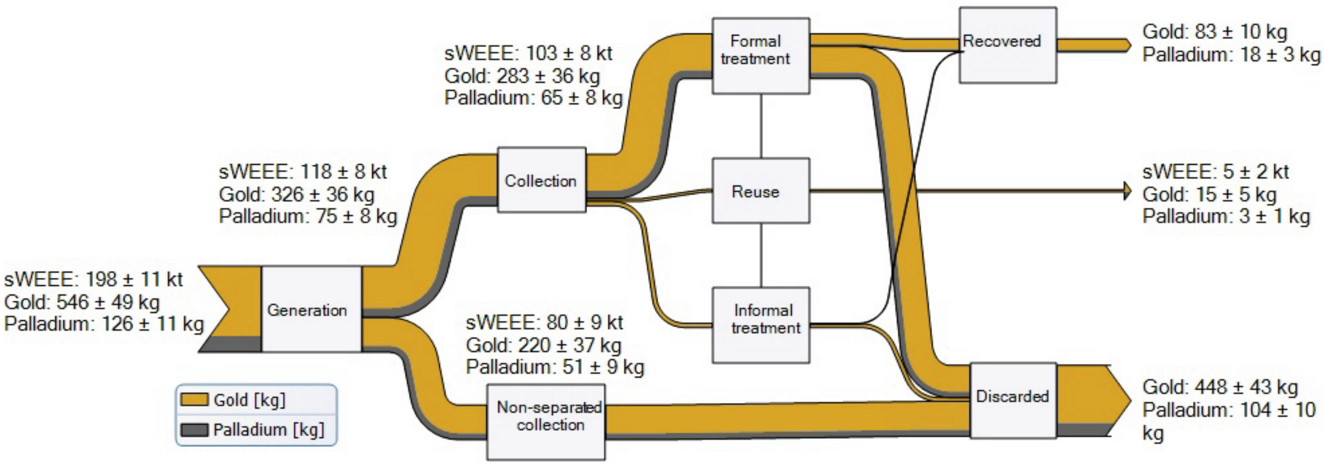

Figure 24 Flows of gold and palladium contained in low-grade waste equipment in Germany in 2007[1]

In the USA, below 1% of the 0.9 to 1.8 million tonnes of low-grade equipment generated was collected in 2007 (Figure 25). Almost no precious metals were recovered from this waste equipment, which contained between 2.3 to 5.3 tonnes of gold and 0.6 to 1.3 tonnes of palladium. The economic value of the discarded precious metals amounted to 57 to 129 million US-dollars.

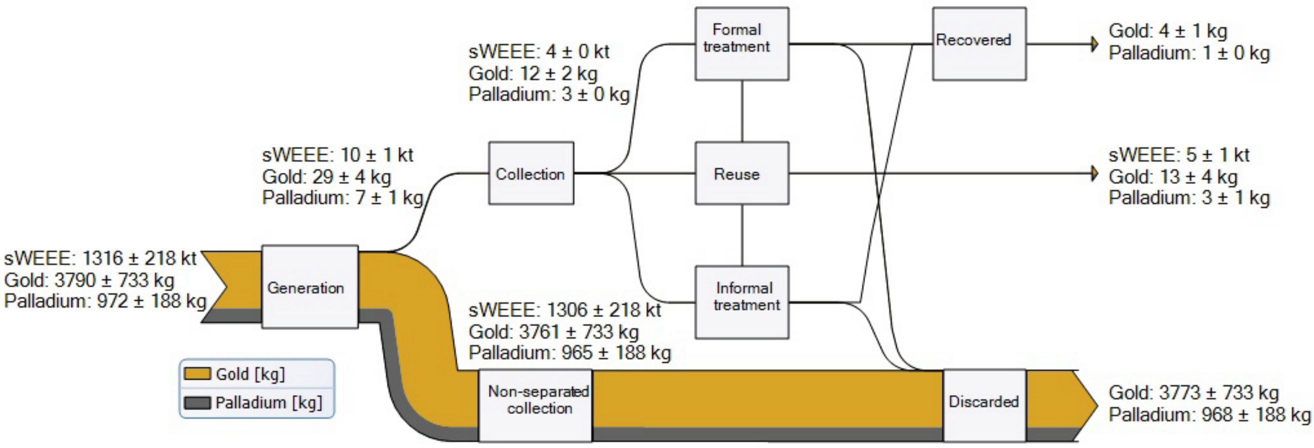

Figure 25 Flows of gold and palladium contained in low-grade waste equipment in the USA in 2007[1]

5.7. Total flows of precious metals related to sWEEE

Based on the results presented in chapter 1 for the six equipment groups, the total flows of gold and palladium related to the management of sWEEE could be calculated. The Sankey-diagrams presented in Figure 26 and Figure 27 and the data presented in Table 34 summarize the main findings. The quantitative estimations of the flows and their uncertainties are presented in detail in Appendix 10.

In total, between 370 000 and 430 000 tonnes of sWEEE were generated in Germany in 2007, containing 1.9 to 2.4 tonnes of gold and 580 to 720 kg of palladium. The generation corresponds to 4.5 to 5.2 kg of sWEEE per capita. Around 77% of this sWEEE was collected. Around 3% was reused, about 64% came to a treatment facility of the formal sector and about 10% was treated by the informal sector. Regarding precious metals, in Germany around 72% of the gold and of the palladium were discarded. In total, between 1.4 and 1.7 tonnes of gold and between 410 and 540 kg of palladium were discarded. The economic value of these discarded precious metals was 34 to 44 million US-dollars in 2007.

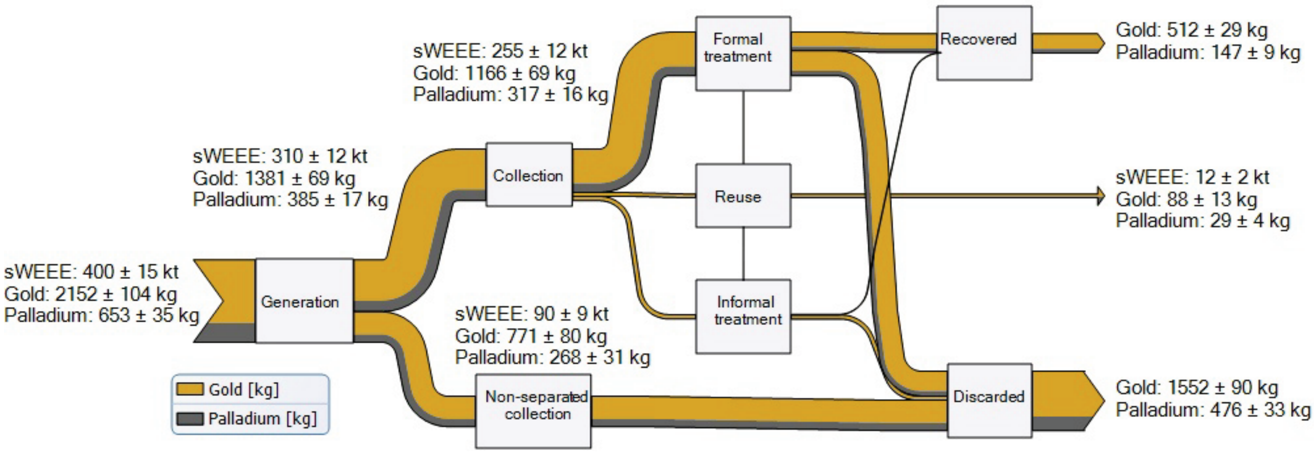

Figure 26 Total flows of gold and palladium contained in sWEEE in Germany in 2007[1]

In the USA, around 74% of the gold and the palladium contained in the 3.1 to 4.3 million tonnes of sWEEE generated in 2007 were discarded. The generation per capita amounted to 10 to 15 kg in 2007. The overall collection rate for sWEEE is much lower than in Germany. Around 30% of the generated sWEEE was collected. The 18 to 28 tonnes of gold and the 6.4 to 9.6 tonnes of palladium discarded in 2007 had a value of 466 to 714 million US-dollars.

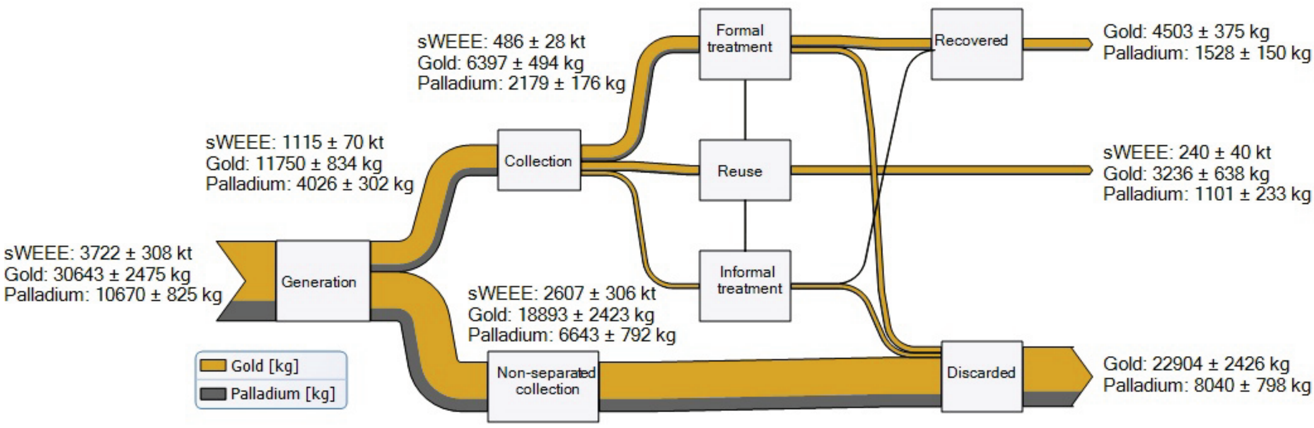

Figure 27 Total flows of gold and palladium contained in sWEEE in the USA in 2007[1]

Table 34 summarizes the indicators calculated on the basis of the mass flows determined by the SFA. In Germany, the collection rates are much higher (around 77% of the generated sWEEE is collected) than in the USA (around 30%). In contrast, in the USA 6% of the generated sWEEE is reused, whereas in Germany the reuse rate amounts to 3%. As shown by Table 24, a majority of the WEEE reused in Germany (around 70%) is managed by the informal sector. In total, it was estimated that around 64% of the generated sWEEE is treated by the formal sector in Germany. This indicator in the USA reveals that "only" 13% of the generated sWEEE is fed into a formal treatment process. Despite these differences, the discarding rates for gold and palladium are comparable in Germany and in the USA (around

72% versus around 75%). Here it must be noted that the absolute quantities of precious metals discarded are much higher in the USA than in Germany.

Table 34 Indicators on collection, reuse and treatment of sWEEE and on recovery and discard of gold and palladium associated with sWEEE in Germany and in the USA (without uncertainties – the uncertainties can be found in Appendix 10)

Country	Equipment group	Collection rate	Reuse rate	Treatment rate		Recovery rate		Discarding rate	
				Formal	Informal	Au	Pd	Au	Pd
Germany	Mobile telephone	18%	5%	12%	1%	7%	7%	88%	88%
	Desktop PC	76%	7%	62%	7%	37%	36%	56%	57%
	CRT monitor	99%	3%	76%	20%	47%	44%	51%	53%
	Large high-grade eq.	92%	4%	81%	7%	33%	32%	64%	65%
	Small high-grade eq.	54%	1%	49%	3%	20%	19%	79%	80%
	Low-grade eq.	60%	3%	52%	5%	15%	15%	82%	83%
	All groups	**77%**	**3%**	**64%**	**10%**	**24%**	**23%**	**72%**	**73%**
USA	Mobile telephone	11%	4%	5%	1%	4%	4%	92%	92%
	Desktop PC	54%	15%	30%	7%	24%	23%	61%	62%
	CRT monitor	40%	6%	14%	20%	11%	8%	83%	86%
	Large high-grade eq.	59%	17%	32%	8%	17%	16%	66%	67%
	Small high-grade eq.	22%	0%	17%	4%	9%	8%	91%	91%
	Low-grade eq.	1%	0%	0%	0%	0%	0%	100%	100%
	All groups	**30%**	**6%**	**13%**	**10%**	**15%**	**14%**	**75%**	**75%**

A more specific analysis of the losses of precious metals and their causes is provided in Figure 28 and Figure 29. The amounts of precious metals vary considerably according to the equipment groups. In Germany, the largest part of the losses is caused by the management of end-of-life mobile phones, large high-grade and low-grade equipment. In the USA, a very large amount of gold associated with personal computers is discarded. The figures show that for mobile phones and low-grade equipment in Germany and for all equipment groups in the USA, the losses of gold are due to non-separated collection of sWEEE. Other losses are caused by the treatment processes applied by the formal and by the informal sector. The treatment losses are especially high for large high-grade equipment in Germany.

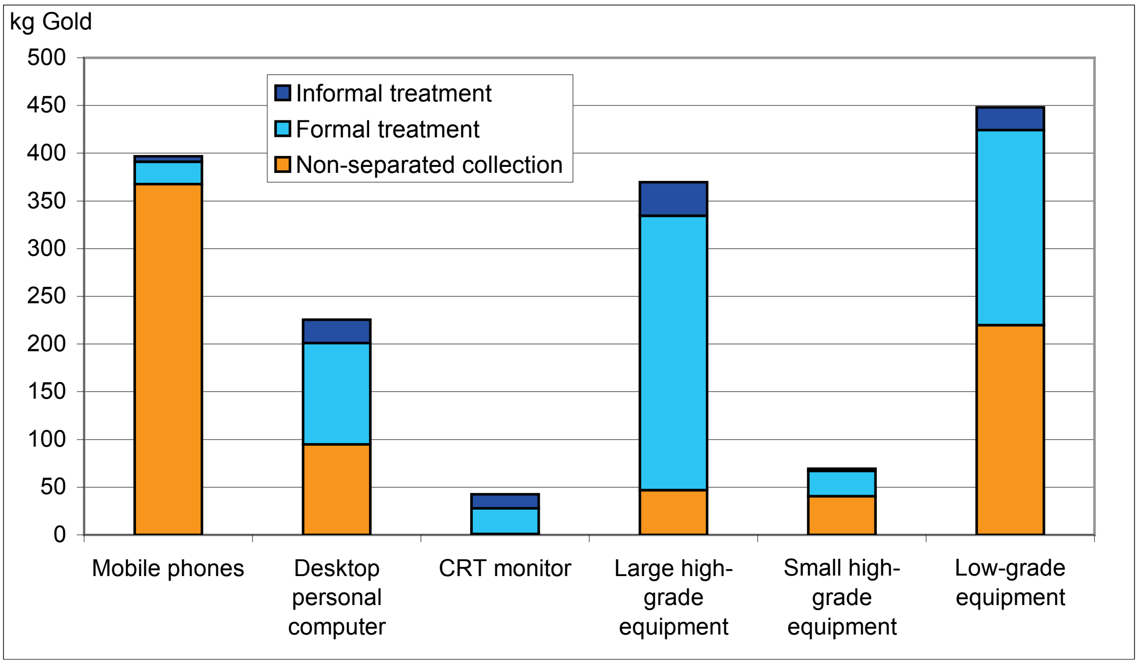

Figure 28 Quantity of gold discarded and origin of the losses in Germany in 2007

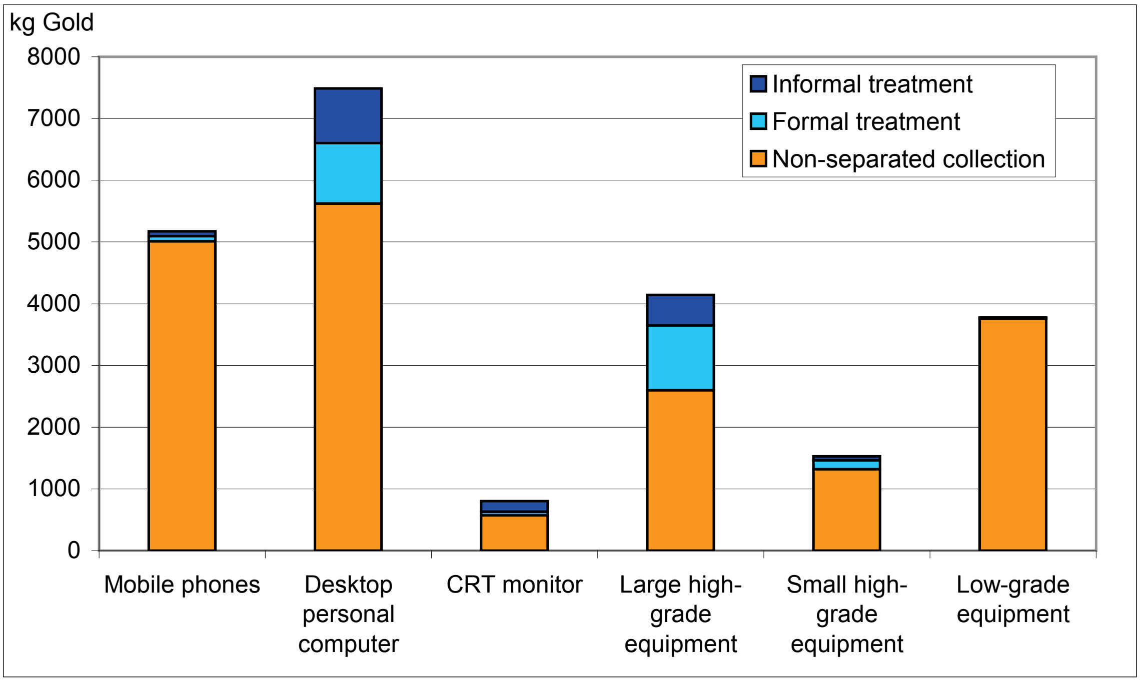

Figure 29 Quantity of gold discarded and origin of the losses in the USA in 2007

In total, about half of the losses of gold associated with sWEEE in Germany are a consequence of the non-separated collection of WEEE. In the USA, around 82% of the gold is lost because of non-separated collection. The losses caused by the formal treatment amount to about 43% in Germany and about 10% in the USA. In both countries, around 7% of the losses are due to inadequate treatment in the informal sector.

[1] The uncertainties presented in the Sankey-diagrams are the standard deviations, and not the radius of the 95%-confidence interval (1299 ± 189 tonnes means that the standard deviation of the calculated 1299 tonnes is 189 tonnes). The radius of the 95%-confidence interval of the result is assumed to be twice the standard deviation.

6. Discussion of the results of the SFA

This chapter describes how the substance flow analysis delivers results that allow a better understanding of the management of sWEEE in 2007 in Germany and in the USA and of the precious metals associated with these waste flows.

6.1. System analysis for Germany and the USA

The substance flow analysis focussed on quantifying the flows of sWEEE categorised in six equipment groups in two countries. Therefore, the following variables are taken into account to assess the management of sWEEE:

- Some characteristics of waste equipment, because the average mass, size and value of the devices vary according to the equipment groups;
- The legislative framework, as well as some economic and social factors in Germany and the USA that influence the system.

The variations of other factors, like the changing characteristics of the waste equipment over time and space, were not considered because of data gaps, so that their influence on the management of sWEEE could not be investigated in this thesis.

6.1.1. Waste generation and user discarding behaviour

More than the double quantity of sWEEE is generated per capita in the USA (around 12 kg per capita per year) compared to Germany (around 5 kg per capita per year). A comparison of the contribution of the different equipment groups to the total mass of generated sWEEE, as well as to the flows of gold and palladium, is provided by Figure 30. Both in Germany and in the USA, low-grade equipment and CRT monitors make out at least 75% of the generated sWEEE. However, the most relevant fractions for precious metals in absolute are mobile phones, personal computers, large high-grade and low-grade equipment. Mobile phones and personal computers contain over 50% of the palladium. The main differences between the German and the US flows are:

- 'Mobile phones', 'personal computers' and 'high-grade equipment' contribute to a higher mass fraction of the sWEEE in the USA (around 25%) than in Germany (around 16%);
- Consequently, the flows of precious metals per capita associated with sWEEE are higher in the USA than in Germany. The sWEEE generated by an average person in the USA in 2007 contained four times more precious metals than the sWEEE generated by an average person in Germany, although the quantity of sWEEE generated per capita is "only" higher by a factor 2.5;

- In the USA, personal computers contribute to almost half of the palladium and around 40% of the gold contained in the generated sWEEE. This is much higher than in Germany, where PCs contribute to around 19% of the gold load and around a quarter of the palladium load.

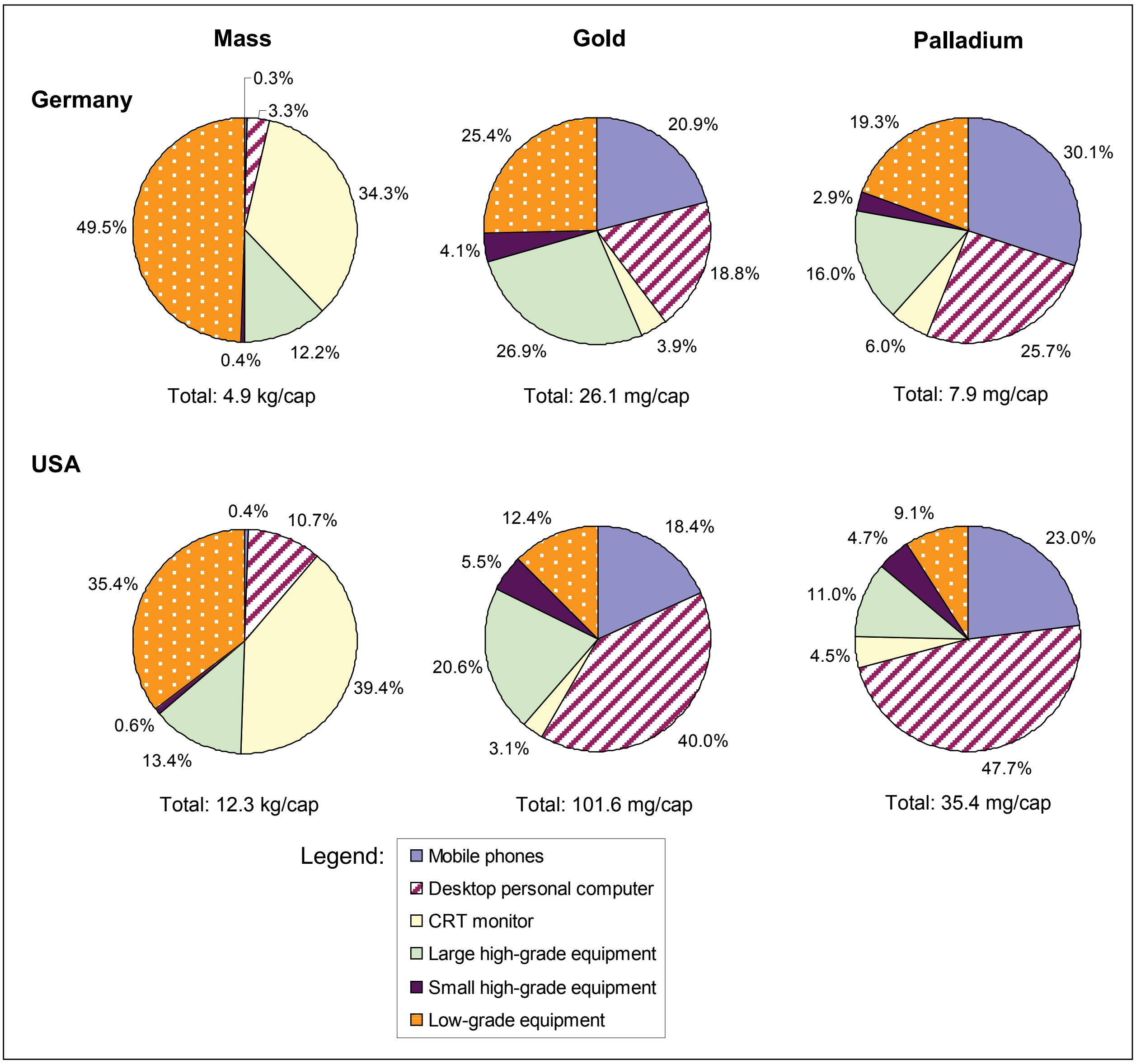

Figure 30 Comparison of the relevance of the different equipment groups in the generated sWEEE in terms of mass, quantity of gold and quantity of palladium in Germany and in the USA in 2007

For all equipment groups except low-grade equipment, the theoretical generation in Germany (see chapter 4.1.1.2) was significantly higher than the generation calculated by data reconciliation, based on the sum of the quantities of sWEEE collected separately and disposed of together with residual waste (Figure 31). The discrepancy between theoretical generation and actually collected waste flows was reported by Hagelüken (2006a), Huisman et al. (2007), Janz et al. (2009b) and Saurat & Bringezu (2008). These authors mentioned the role that the informal sector could play, for instance the export to non-OECD countries.

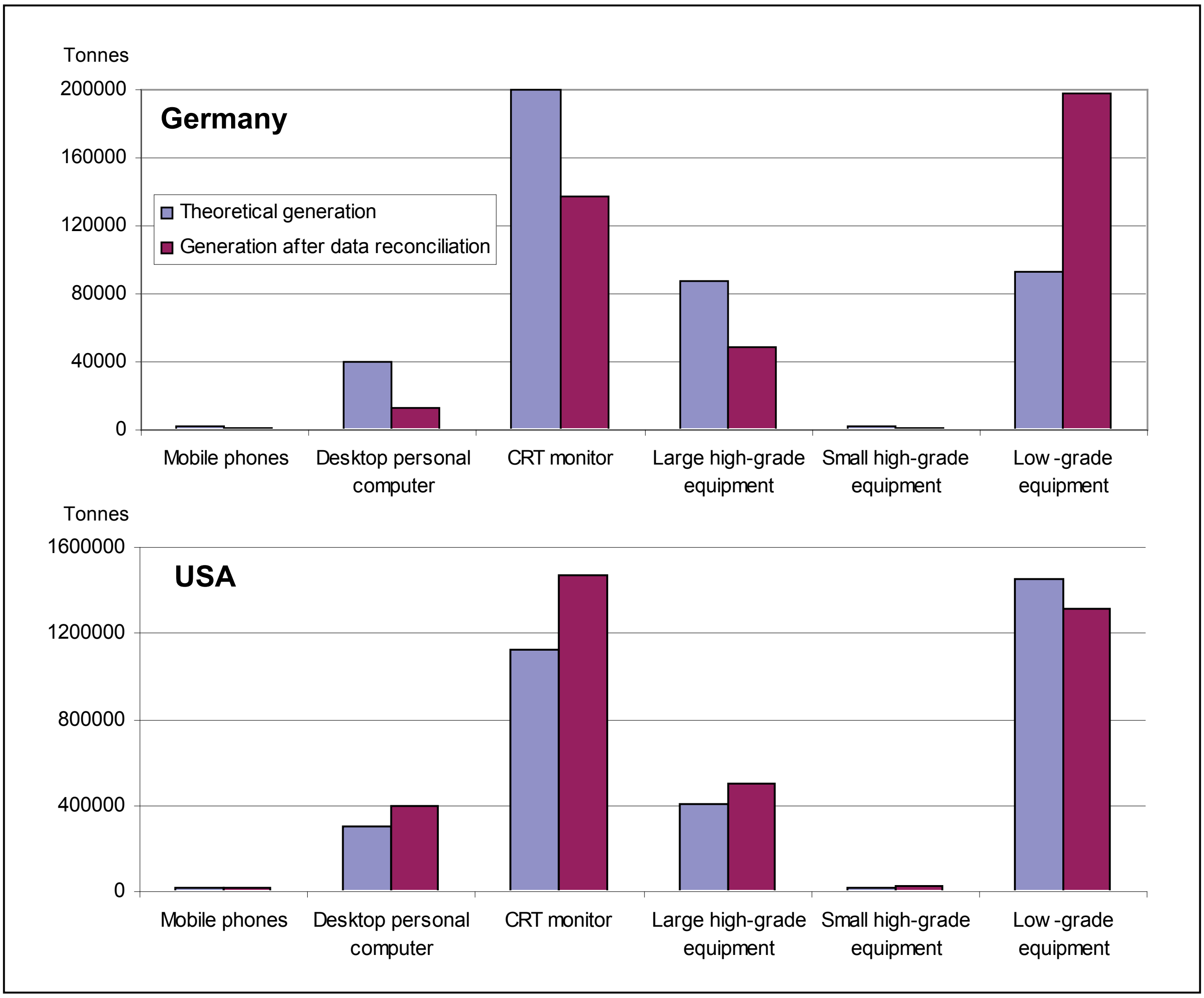

Figure 31 Comparison of the theoretical generation of sWEEE and the sum of the quantities of sWEEE collected separately and disposed of together with residual waste

The following hypotheses can be proposed to explain why, in Germany, the theoretical generation is higher than the generation determined by data reconciliation based on the quantities of separately and non-separately collected sWEEE (except for low-grade equipment):

1. The waste flows collected by the informal sector were underestimated;
2. The non-separated collection, quantified on the basis of the sorting analyses of Rotter & Janz (2006) and Janz & Bilitewski (2007), was underestimated;
3. The generation was overestimated, due to data gaps on the lifetime distribution of devices (including hibernation of unused devices), as mentioned by Wen et al. (2009).

4. The allocation of the separately collected sWEEE in the collection groups was partly erroneous, and some low-grade devices were classified as high-grade equipment.

In Germany, the overestimation of the generation is probably due to an underestimation of the average lifetimes of the EEE. This may be a consequence of the behaviour of the German users, who may have more hibernating end-of-life devices than the US users. The behaviour of the users and for instance the phenomenon of hibernation were little investigated. Up to now, the research on lifetime of appliances focused on investigating experimentally the age of end-of-life appliances delivered to WEEE collection facilities (Babbitt et al. 2009; Mueller et al. 2007; Scheidt 2007; US EPA 2007a). These reports mention that the age distribution of the end-of-life devices is not symmetrical, has a long tail, and is best described by the Weibull function. So far, studies did not take into account the unused appliances stored for a (very) long time by the last user to determine the average lifetimes, because the previous research considered only end-of-life equipment brought to a collection facility. The consideration of these unused hibernating devices would probably show that the average lifetimes were underestimated by the previous studies and also that the hibernation phenomenon of the EEE cannot be observed in the same magnitude for all equipment types. Janz et al. (2009b) shows how an underestimation of the average lifetime of WEEE can cause an overestimation of the theoretical generation of WEEE. The underestimation of the generation of low-grade waste equipment in Germany may be explained by the non-consideration of some equipment types in the estimation of the generation.

In the USA, the theoretical generation is closer to the total amount of separately and non-separately collected sWEEE (Figure 31), which can suggest that hibernation of unused devices is less common in the USA than in Germany. Many factors influence the discarding behaviour of the users, like cultural factors, which lead the German citizens to dislike discarding their unused appliances, especially the most valuable ones. This is illustrated in Figure 30, which shows that in Germany, far less sWEEE rich in precious metals is generated per capita than in the USA.

More research on the equipment lifetimes and on the factors that influence them would bring new quantitative information for a better modelling of the lifetime distribution of EEE and of the generation of WEEE (Babbitt et al. 2009). Research on waste generation allows a better understanding of the behaviour of the user and, therefore, the development of strategies and incentives for collection more adapted to the user behaviour.

6.1.2. Collection

In Germany, legislative requirements provide the main motivation for collection, reuse and treatment of WEEE. The current collection target of 4 kg per year and capita does not set incentives to increase the collection of WEEE, because this collection target was already achieved in Germany in 2000 (long before the implementation of the ElektroG), where 476 000 tonnes of electronic waste appliances were collected (BMU 2007). Moreover, the collection target is not differentiated according to the equipment types, so that it does not promote the collection of small and light devices, but the collection of heavy appliances (Rotter et al. 2006). However, the regulations define how collection should be performed and who is responsible for financing the operations, so that collection systems are in place for all types of waste equipment including the small ones. In the USA, where little legislation regulates the recycling of WEEE, collection and treatment are mainly driven by the economy and by voluntary environmental protection for equipment types with a high hazardous potential, like CRT monitors. If maximising the revenues from the production of secondary raw materials is the primary focus, mainly very high-grade equipment like mobile phones and personal computers are collected for treatment or reuse. Because there is little motivation to collect low-grade equipment, the collection rate for this equipment group is almost zero. In this sense, the different legislative frameworks explain the higher collection rates in Germany than in the USA.

Regarding non-separated collection of sWEEE, a clear correlation between average size of the WEEE and percentage of end-of-life devices disposed of by the last user was identified, as illustrated for Germany in Figure 32. To estimate the average size of the devices, quantified as the diagonal length, the data of the database described in chapter 3.3.1 were used. The smaller the device, the more likely it is to be disposed of by the last user. The economic value of the device also plays a role in the discard behaviour of the user, as well as other factors like the emotional value, or the identification of the user with the device that is not only used for its function but primarily as a “life-style companion”. Low-grade equipment is more likely to be disposed of than large high-grade equipment (Figure 32).

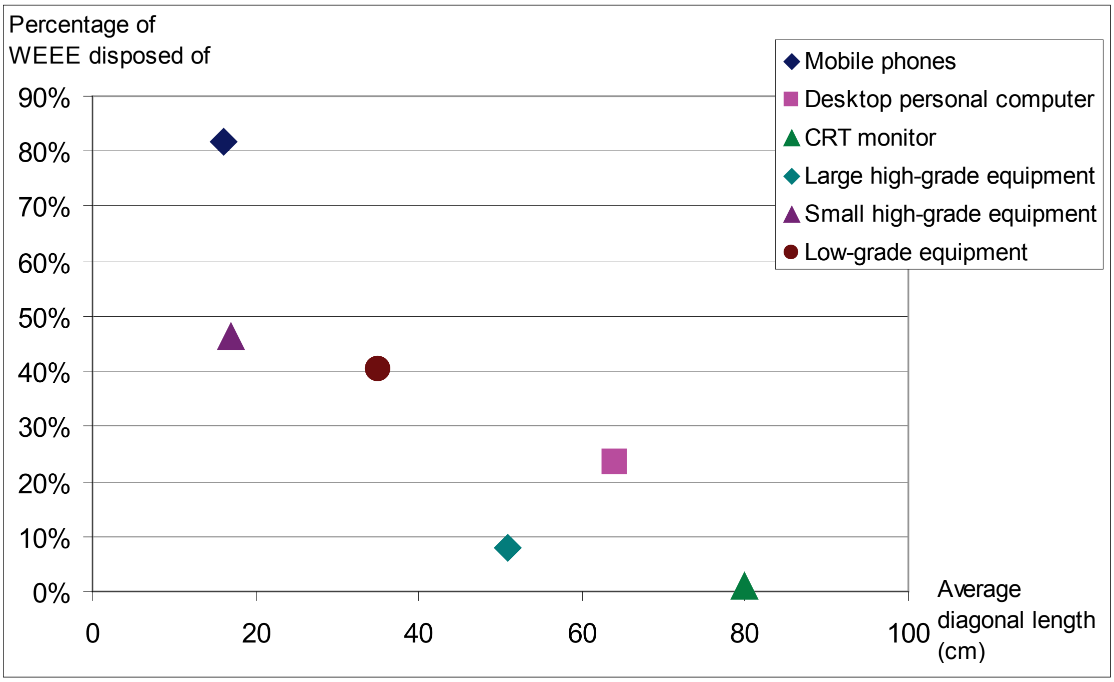

Figure 32 Correlation between the percentage of WEEE disposed of and the average diagonal length of the devices in Germany

6.1.3. Treatment and reuse

The recovery rates for precious metals depend both on the characteristics of the input and on the technology used (see chapter 4.1.4.2). The mass-oriented recovery targets defined by the WEEE Directive set incentives to apply processes that allow the recovery of the most mass-relevant materials, for instance ferrous metals and plastics. The precious metals contained in trace concentrations in the materials sent to recovery processes for plastics and ferrous metals are usually not recovered (Paper 2), so that the loss of trace metals is a trade-off for the maximisation of the recovery of mass-relevant materials. As shown in Paper 2 and by Schill (2007), the recovery targets of the WEEE Directive establish no incentive for the recovery of precious metals. In the USA, the main impulse for managing sWEEE is economic, so that the processes are optimised to recover the most economically valuable materials, which, for high-grade equipment, include precious metals. Manual processes at industrial scale are traditionally more common in the USA than in Germany.

Therefore, the obligation to achieve mass-oriented recovery targets besides the necessity to maximize the economic revenues partially explains why higher recovery rates for precious metals are achieved by the pre-processing technologies applied in the USA compared to Germany (see chapter 4.1.4.2). Figure 33 illustrates that there is a weak correlation between gold concentration in the WEEE and recovery rates achieved by the processes of the formal sector in Germany. However, the treatment technologies currently applied do not set a clear priority on recovering the precious metals of the equipment types that contain larger concentrations of precious metals.

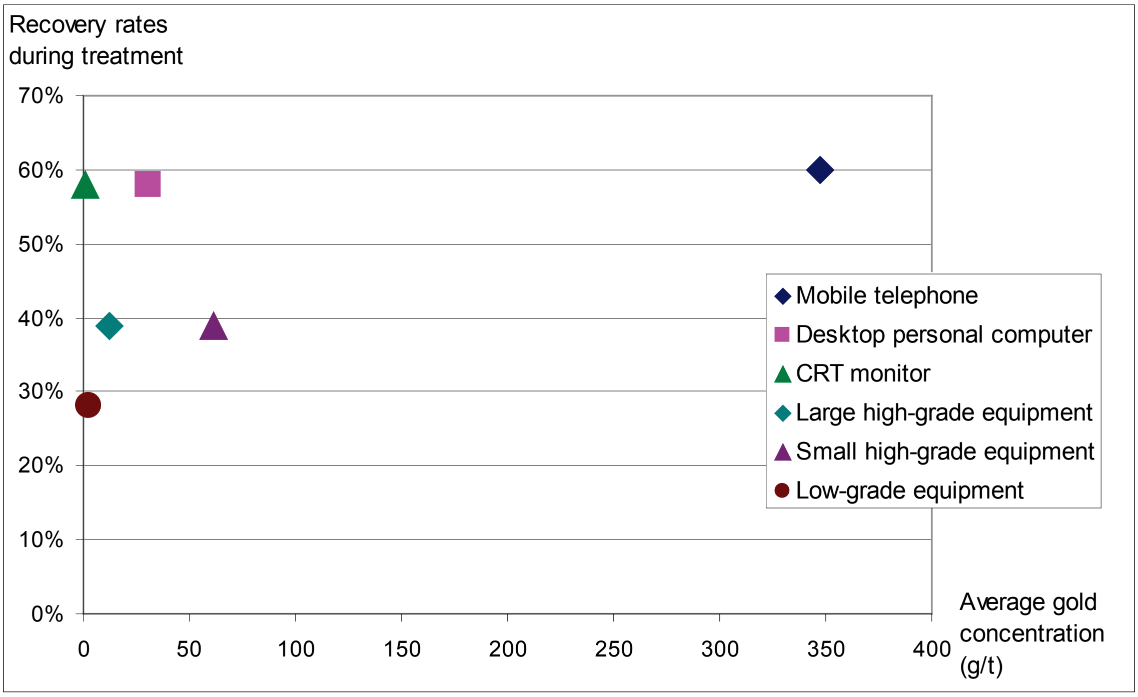

Figure 33 Correlation between the recovery rates for gold achieved by the treatment processes of the formal sector and the gold concentration in the equipment groups in Germany in 2007 (see Table 31)

According to the data and assumptions used in this research, in total 3% of the WEEE generated in Germany was reused and 6% of the WEEE generated in the USA. Around 70% of the WEEE reused in Germany is managed by the informal sector (Table 24). As described by Faulstich & Baron (2008) and Leonhardt (2007), the current management system for WEEE in Germany, especially the means used to collect and transport the collected waste, creates difficulties for the reuse of the collected WEEE.

6.2. Comparison with data from other geographical areas

The recovery rates of around 24% of the gold and the palladium contained in WEEE in Germany determined in this thesis are much lower than the recovery rates for palladium reported by Hagelüken et al. (2005) (37.6%) and Saurat & Bringezu (2008) (around 62%). The goal of these two studies was to provide a broad overview of the flows of platinum-group metals. At the time of their research, very little knowledge on the flows of precious metals in recycling facilities for WEEE was available, and since the authors did not conduct experimental research, the uncertainty of their results is very high. The rate of 24% is higher than the worldwide recycling rates for gold, palladium and silver determined by Deubzer

(2007), who assumed that 7% of the precious metals contained in low and medium grade WEEE generated worldwide was recovered, and 9% of the precious metals contained in high-grade WEEE. According to Saurat & Bringezu (2008), around 22.5 tonnes of platinum-group metals are contained in the end-of-life electronics in Europe in 2004. In this thesis, it was estimated that 580 to 720 kg of palladium were contained in the sWEEE generated in Germany in 2007. A rough extrapolation of the quantity of palladium contained in the German sWEEE to the European Union (for example proportionally to the population) would deliver a flow of palladium contained in the sWEEE significantly less than the 22.5 tonnes of Saurat & Bringezu (2008). The discrepancy may be explained by a possible overestimation of the generation of WEEE by Saurat & Bringezu (2008), as well as by differences in the methods applied and in the research assumptions.

Some authors investigated the flows of WEEE, so that their results can be compared to the results of this research. Huisman et al. (2007) quantified the percentage of theoretically generated WEEE that is collected and treated in the European Union. According to Huisman et al. (2007), between 20% and 27% of the end-of-life small household appliances, tools and toys are collected (corresponding to the equipment group 'low-grade equipment), between 30% and 35% of the CRT monitors, around 28% of the IT and telecommunication waste equipment, and around 40% of the consumer waste equipment. These collection rates are lower than the collection rates determined for Germany in this thesis (Table 34). The discrepancy can be explained by the geographical boundaries of the study (European Union versus Germany) and the method used to calculate the theoretical waste generation. Huisman et al. (2007) calculated the collection rates based on an estimation of the theoretical generation (see chapter 6.1.1 as well as Huisman et al. 2007 and Widmer et al. 2005), and did not reconcile the generation data with the collection data like in this thesis.

The investigations of Witteveen+Bos (2008) and GfK (2007) focussed on the stocks of EEE in Dutch households and their behaviour regarding disposal. Witteveen+Bos (2008) quantified the generation of WEEE and the flows of WEEE at municipal collection points, household waste recycling centres, second hand stores, regional sorting centres, retail stores, distribution centres and processing companies. Table 35 shows that the collection rates determined by Witteveen+Bos (2008), even though the WEEE is categorised in another way than in this thesis, are comparable with the results for Germany.

Table 35 Flows of WEEE separately collected, disposed of and sent to an undetermined destination in the Netherlands – modified from Witteveen+Bos (2008)

Category of WEEE	Generation kg/capita/year	Separately collected	Residual waste	Retail/ Uncertainty
Small household appliances and consumer equipment	5.1	82%	11%	7%
IT equipment	2.7	46%	22%	31%
Electrical and electronic tools	0.7	49%	51%	0%
Toys, leisure and sports equipment	0.2	10%	90%	0%

Witteveen+Bos (2008) revealed that around two-third of WEEE is recycled by the formal sector. The remaining WEEE is either disposed of with residual waste or treated through unofficial channels.

Regarding Japan, Oguchi et al. (2008) considered nine equipment types and mentions a waste product collection ratio of 2 to 56% (20% for mobile phones, 4% for desktop personal computers). Terazono & Yoshida (2008) investigated the flows of four types of WEEE (TV sets, air conditioners, refrigerators and washing machines) in Japan and exported from Japan in 2005. They found that about 50% of the 22.87 million end-of-life appliances were recovered and recycled by the producers. Regarding the flows of waste personal computers, Yoshida et al. (2009) report that around 37% of these devices were disposed and recycled in Japan in 2004, and another 37% were reused in Japan. The majority of the remaining flow, called “invisible flow” by Terazono & Yoshida (2008), was exported as second-hand equipment for reuse or as scrap. In this thesis, the “invisible flows” are the flows that do not end up in the formal sector (non-separately collected WEEE and flows to the informal sector). In Germany, around 36% of the sWEEE form the “invisible flow”. In the USA, around 87% of the generated sWEEE is not fed into a formal treatment for WEEE or reuse process. According to Shirahase et al. (2007), around 20% of the waste personal computers, containing 209 kg of gold and 285 kg of palladium, are recycled in Japan.

6.3. Impacts of the sWEEE generation expected in the future

Rotter & Janz (2006) estimated the generation of WEEE in Germany in 2003 by using the ‘batch leaching’ method, and found out that the generation of waste IT equipment will increase by 72% between 2008 and 2013, while the generation of small waste consumer equipment will increase by “only” 10%.

Table 36 presents a rough forecast of the generation of sWEEE in 2012, based on the results for 2007. Because few data on the evolution of the waste generation in the next years are available, the changes expected in Germany and in the USA were assumed to be similar. The following assumptions were made:

- The generation of end-of-life mobile phones and small high-grade equipment will double by 2012. Since the markets for these two equipment groups have grown in recent years, an increase of the waste generation is expected;
- The generation of end-of-life desktop PC will increase by 75% in five years;
- The generation of large high-grade equipment, including some IT equipment, will increase by 50%;
- The generation of CRT monitors will remain more or less stable until 2012 and decrease afterwards, as described by Chancerel (2009), as a consequence of the decrease in the sales of CRT monitors;
- The generation of low-grade equipment will increase by 10%, as mentioned by Rotter & Janz (2006).

Table 36 Generation of sWEEE expected in 2012 compared to the sWEEE generation in 2007, and expected flows of gold and palladium in 2012 associated with sWEEE

Country	Equipment group	Generation in 2007 (tonnes)	Expected growth	Generation expected in 2012 (tonnes)	Gold in 2012 (kg)	Palladium in 2012 (kg)
Germany	Mobile telephone	1 299	100%	2 598	901	392
	Desktop PC	13 110	75%	22 942	707	294
	CRT monitor	136 978	0%	136 978	84	39
	Large high-grade eq.	48 787	50%	73 181	870	157
	Small high-grade eq.	1 431	100%	2 862	175	37
	Low-grade eq.	197 998	10%	217 798	601	139
	All groups	**399 602**		**456 357**	**3 338**	**1 058**
USA	Mobile telephone	16 268	100%	32 536	11 290	4 913
	Desktop PC	397 517	75%	695 654	21 426	8 904
	CRT monitor	1 468 391	0%	1 468 391	964	478
	Large high-grade eq.	500 533	50%	750 800	9 472	1 766
	Small high-grade eq.	23 242	100%	46 485	3 374	996
	Low-grade eq.	1 316 223	10%	1 447 846	4 168	1 069
	All groups	**3 722 175**		**4 441 711**	**50 694**	**18 126**

Table 36 shows that based on the assumptions presented above, the generation of sWEEE in 2012 is expected to reach around 456 000 tonnes of sWEEE in Germany and around 4.4 million tonnes in the USA. This corresponds to an increase of 14% in comparison to 2007 in Germany, and of 19% in the USA. Table 36 also presents the expected flows of gold and palladium associated with this sWEEE. The concentrations of gold and palladium in the different equipment groups were assumed to be constant between 2007 and 2012. The flow of gold associated with the sWEEE is expected to increase in Germany by 55%, and in the USA by 65%. The greater increase of the generation of precious-metals rich sWEEE compared to the moderate increase of lower-grade waste equipment explains why the gold flow increases at a significantly higher rate than the sWEEE generation. Compared to 2007, an increase by 62% in Germany and by 70% in the USA of the flow of palladium associated with sWEEE is expected, so that the sWEEE generated in 2012 will contain around 1060 kg of palladium in Germany and around 18 tonnes in the USA.

Table 37 shows how the losses of gold are affected by the increase of the sWEEE generation presented in Table 36 if the discarding rates remain constant (that means that the discarding rates in 2012 are assumed to be equal to the discarding rates determined for 2007).

Table 37 Flow of gold discarded in 2012, assuming the generation presented in Table 36 and assuming that the discarding rates of 2012 are equal to the discarding rates of 2007

Country	Equipment group	Discarded flow of gold in 2007 (kg)	Gold discarding rate	Discarded flow of gold in 2012 (kg)
Germany	Mobile telephone	397	88%	794
	Desktop PC	226	56%	395
	CRT monitor	43	51%	43
	Large high-grade eq.	370	64%	554
	Small high-grade eq.	69	79%	139
	Low-grade eq.	448	82%	493
	All groups	**1 552**		**2 417**
USA	Mobile telephone	5 171	92%	10 342
	Desktop PC	7 488	61%	13 104
	CRT monitor	803	83%	803
	Large high-grade eq.	4 141	66%	6 211
	Small high-grade eq.	1 529	91%	3 059
	Low-grade eq.	3 773	100%	4 150
	All groups	**22 904**		**37 668**

Although the overall discarding rates remain almost constant, with this scenario the absolute quantity of gold discarded reaches around 2.4 tonnes in Germany and around 38 tonnes in the USA, which means an increase by 56% in Germany and by 64% in the USA compared to 2007. This quantity of gold had an economic value of around 52 million US-dollars in Germany and 817 million US-dollars in the USA in 2007. This shows that the relevance of sWEEE as a source of precious metals is expected to increase. Therefore, it is an acute necessity to improve the system, so that the losses of gold do not reach this level in 2012.

7. Recommendations

The substance flow analysis allows identifying and quantifying the system weaknesses and, therefore, provides a basis to formulate recommendations to improve it. In addition to the recommendations directly relating to the recovery of precious metals, some more general suggestions can be made for the use of substance flow analyses to assess waste management systems and about how to improve the data quality.

7.1. Recommendations to improve the recovery of precious metals from WEEE

Based on the SFA, some recommendations are formulated about the subsystems constituting the management system for sWEEE. Table 38 summarizes the recommendations that are developed in the chapters 7.1.1 to 7.1.4.

Table 38 Recommendations for limiting the losses of precious metals during management of sWEEE

Category	Strategy
Collect more	Define priorities and set collection objectives considering the presence of precious metals in some types of waste equipment
	Communicate with the users of WEEE and set incentives for collection
	Make different collection options available to the users
	Monitor and control the flows of collected WEEE
	Communicate with the pre-processing facilities to provide the WEEE in a way that facilitates the treatment
Reuse more	Develop an adequate infrastructure to sort the WEEE with a high reuse potential
	Reduce the decrease of the reuse value during collection and transportation
Treat better	Pre-sort the WEEE according to the ‘needs for treatment’
	Avoid the decrease of the quality of the WEEE during collection and transportation
	Set priorities for material recovery according to the composition of the different WEEE, i.e. reduce the fraction of precious metals sent to processes where precious metals are not recovered
	Develop and apply standards for treatment technologies, e.g. remove higher grade PCB before shredding
	Monitor and control the flows in and out of the treatment facilities
	Promote research to improve the treatment technologies

Category	Strategy
Send less WEEE into uncontrolled channels	Develop and enforce the regulations, e.g. the guidelines to distinguish second-hand EEE and WEEE
	Develop unified codes to facilitate the tracking of the flows of WEEE
	If possible, develop cooperation projects with the informal sector

7.1.1. Collect more

As shown by Figure 28 and Figure 29, around 50% of the losses of gold and palladium in Germany, and over 80% in the USA are a consequence of the non-separated collection of sWEEE. The correlation between size of the devices and percentage of devices disposed of by the last user was shown by Figure 32: the smaller are the devices, the more likely they are thrown into the waste bin (or stored in drawers).

Through a more extensive collection of sWEEE, substantial losses of precious metals could be prevented. Future efforts for more collection could focus on the waste equipment that is most likely to be disposed of, like for example in Germany the small end-of-life devices. The European WEEE Directive sets little **incentive to collect small devices**, since the collection targets are defined by weight and therefore are easier to achieve if the collection focuses on large appliances. The definition of separate collection targets for different groups of waste equipment would be a solution to enhance the collection of waste equipment rich in precious metals. In the USA, where the collection rates for sWEEE from households are very low in general, efforts are needed for all equipment types. Priorities for the collection can also be set up depending on the concentration of precious metals in the sWEEE, taking into account the information contained in Table 33. However, not only precious metals, but also the other hazardous and valuable materials in WEEE, like (flame-retarded) plastics, other metals, batteries etc., should be considered by developing collection strategies.

As described in chapter 2.4.2, every collection strategy has advantages and disadvantages (CIWMB 2004a, Nagel et al. 1998, Legler 2009). In order to reach as many households and businesses as possible, the **different options should be used in parallel**, so that the individuals can for example choose to take their WEEE to a municipal collection centre, to a temporary collection event at a supermarket (Melissen 2006), or to have the WEEE be picked up.

Communication and public involvement are keys for the success of the collection of WEEE (Melissen 2006). Salhofer & Isaac (2002) presented in a more general way the role of public relations to enhance separate collection of waste for recycling. Regarding separate collection of WEEE, the communication could spread the following information to the public:

- WEEE contains hazardous and valuable substances, which should not end up in the environment;
- the disposal of WEEE in residual waste might be made illegal (depending on the country);
- information on the treatment of the collected WEEE can be a motivation for giving WEEE for recycling, if people feel sure that the WEEE will be treated or reused in an environmentally-sound way.

The importance of **incentives to motivate the collection of WEEE** was shown by Most (2003). According to Most (2003), a private operator of a mobile telephone network employed the strategy of distributing coupons that entitled donors of end-of-life mobile phones to $5 off the price of a new phone or accessory, and the result was a 15 to 20 percent increase in the number of phones collected. Economic incentives for collection of end-of-life devices could also be implemented in the form of deposit systems (an amount of money paid to the distributor at purchase is returned when the end-of-life device is returned) or in the frame of leasing contracts replacing sale (the device has to be returned after being used during a certain time). Despite the effectiveness of financial incentives, such offers are rare (Most 2003).

In addition to the development of separated collection, and as long as WEEE is found in residual waste, the presence of WEEE in residual waste should also be considered by developing strategies for managing residual waste, so that some of the materials contained in the WEEE disposed of are recovered. For example, technologies could be implemented to recover precious metals contained in bottom ashes of incinerators for municipal solid waste (Bakker et al. 2007).

After collection, the transfer of the sWEEE to adequate reuse or treatment processes conditions the appropriate management of the precious metals. According to Faulstich & Baron (2008) and Leonhardt (2007), the shared responsibility defined in the German legislation (the municipalities are responsible for collection of WEEE and the producers for treatment, with a clearing house serving as a coordinating body) poses problems in practice, since the complexity of the system and the lack of transparency cause a decrease of the quality of the materials delivered to the treatment facilities. Moreover, the lack of **monitoring of the materials flows** facilitates the illegal export of the WEEE to non-OECD countries (Faulstich & Baron 2008, Leonhardt 2007).

7.1.2. Reuse if it makes sense

As explained in chapter 2.4.3, reusing WEEE has advantages regarding environmental and social aspects. For these reasons, reuse was defined as a priority in the WEEE Directive. Reuse also has disadvantages that were enumerated in chapter 2.4.3. Anyway, regarding precious metals, reuse usually helps to limit the quantity of new EEE put into the market and therefore decreasing the flow of precious metals that will be later contained in the generated sWEEE. However, reuse is no “definitive solution” for WEEE, since reused EEE becomes later WEEE again and, like WEEE coming from new EEE, needs to be collected and fed into adequate recycling processes.

As reported by Li et al. (2008), Rose & Stevels (2001) and Rifer et al. (2009), the reuse potential of WEEE discarded by consumers is limited. This potential depends on the time and efforts deployed to repair and refurbish the WEEE, as well as the origin and the type of WEEE (and, therefore, on the existence of a market for reselling the devices). The reuse activities should **focus on the types of WEEE that have a high reuse potential**, i.e. devices in a good condition and devices with a broad resale market. The reuse of WEEE should be in channels subject to regulations, in order to avoid environmental impacts and losses of resources, for example through illegal export of WEEE to developing countries. Moreover, reuse should be called into question when appliances are exported for reuse to a country with no adequate treatment infrastructure, since in a long-term perspective, this export means that the substances contained in the reused appliances will not be treated in an adequate way. Anyway, this is more a “collection issue” than a “reuse issue”, since any waste device should be collected and treated in any country, whether it has been reused or not.

One of the reasons for the higher potential for reuse of WEEE from businesses compared to WEEE from households is related to the transport of the collected WEEE. Whereas WEEE from businesses is usually packaged and transported in a way that conserves the value, most of the WEEE from households is transported in large containers, so that the waste devices or some parts are broken (Faulstich & Baron 2008, Leonhardt 2007) and the possibilities of reusing the equipment become very limited. According to a recycling company in Germany, around 10% of the WEEE could be reused before the implementation of the ElektroG. Although the ElektroG defines reuse as a priority, the means used to transport the WEEE changed and the reuse potential sank to 3% (BVSE 2007). Some forms of collection, like temporary collection events as presented by Legler (2009), are more likely to preserve the reuse value than other collection channels. **Adequate packaging and careful transport** requires time and costs money, but is a condition for making the reuse of WEEE possible.

After collection, the devices for reuse must be sorted (triage) and processed. The companies conducting reuse activities gained experience over the past years on:

- Selecting the devices appropriate for reuse according to the brand, the age, the state etc.;
- Repairing and refurbishing the selected devices;
- Selling the devices on appropriate markets.

Efforts are needed from policy-makers and other actors like the operators of collection activities, as well as more communication between the actors, in order to help the reuse companies to have access to adequate input material and develop their activities. These measures would increase the quantity of reused sWEEE as encouraged in the WEEE Directive.

7.1.3. Treat better

44% of the losses of gold during management of sWEEE in Germany occur during formal treatment (Figure 28 and Figure 29). To enable the recovery of precious metals, pre-processing has to segregate a wide range of WEEE into higher grade concentrates, without losing too much of the precious metals in other streams (Malhotra 1985). The **pre-sorting of end-of-life equipment** (also called triage) is recommended not only to separate the devices for reuse, but also to feed the WEEE in treatment processes adequate to their needs. This was stated by Rifer et al. (2009) in following terms: “Performing in-depth and accurate triage allows a product to be sorted into the highest value activity and enhances both the process efficiency and value of end-of-life electronics.” The idea of pre-sorting the end-of-life devices before treatment was mentioned by Chancerel & Rotter (2008a) and Hagelüken (2006a). Like reuse, pre-sorting of sWEEE is facilitated by a **careful transport**, since it is easier to identify and sort entire devices than broken parts.

Depending on the characteristics of the WEEE of the different equipment groups, some recommendations regarding treatment, for instance pre-processing, were formulated (Table 39). The recommendations rest mainly upon the results published in Paper 2 and by Huisman (2004). Huisman (2004) compared various end-of-life treatment options and showed that, for both economic and environmental reasons, it is preferable to feed end-of-life mobile phones directly into an appropriate pyrometallurgical process for recovery of several non-ferrous metals after removal of the battery (without further pre-processing). The recommendations take into account the technologies commonly applied in 2007. If future technological innovations enable the achievement of higher recovery rates for precious metals, obviously they should be used.

Table 39 Recommendations for pre-processing the WEEE depending on the equipment groups, in order to limit the losses of precious-metals during treatment

Group	Other substance of concern	Recommendation for pre-processing to limit the discard of precious metals
Mobile telephone	Plastics, non-ferrous metals	Direct feed into a state-of-the-art recovery process for precious metals after removal of the battery
Desktop personal computer	Ferrous metals	Manual removal of the entire printed circuit boards
CRT monitor	Lead, plastics	Removal of the printed circuit boards
Large high-grade equipment	Plastics, ferrous and non-ferrous metals	Manual dismantling or “gentle” mechanical treatment to sort out the printed circuit boards
Small high-grade equipment	Plastics, other non-ferrous metals	Direct feed into a state-of-the-art recovery process for precious metals after removal of the battery
Low-grade equipment	Plastics, other ferrous and non-ferrous metals	Advanced mechanical treatment with sorting of the printed-circuit boards

Even though the recovery of precious metals is the main focus of the recommendations, other relevant materials contained in the waste and some cost-benefits considerations were qualitatively taken into account. Despite the lack of quantitative data, it was necessary to keep in mind the trade-off between increase of the recovery of precious metals and decrease of the recovery of other materials, due to the grade-recovery function (Figure 5). To **measure the relevance of the materials and define recycling priorities**, some indicators measuring the environmental impacts of materials like the ’material intensity’ (MIT) developed by the Wuppertal Institute (Ritthoff et al. 2002), the ‘Eco-Indicator ’99’ (Goedkoop & Spriensma 2000), the ‘environmental value’ (Huisman 2003) and the ‘Fraunhofer IZM Toxic Potential Indicator’ (Middendorf et al. 2000) can be applied. Shirahase et al. (2007) provided a comparison of different weighting methods to quantify the recovery priority of metals contained in printed circuit boards, considering the amount of reserves, the amount of production, the prices and other parameters relating to the different metals. A possible option to set recycling priorities is to promote the recovery of the most mass-relevant materials, as required by the WEEE Directive. This approach was criticised in Paper 2, as well as by Huisman et al. (2007) and Reuter et al. (2005). The relevance of the materials can also be measured with an economic approach, by aiming at recovering the materials that bring the highest economic revenues.

For appliances that are very rich in precious metals, like personal computers, a manual removal of the printed circuit boards is recommended. If this is not economically feasible, like in the case of small appliances like mobile phones, it may make sense to feed the devices directly into a state-of-the-art recovery process for precious metals after removal of the battery. Paper 2 showed that the shredding of WEEE and the automatic sorting of the printed circuit boards cause losses of precious metals through dispersion over the output fractions, so that the shredding of high-grade equipment or other strong mechanical stress should be avoided for waste appliances rich in precious metals. Manual dismantling or the application of mechanical technologies that prevent the uncontrolled dispersion of the precious metals over different material fractions ("gentle" mechanical treatment) are recommended. Table 4 shows that precious metals contribute to a very small fraction of the environmental weight of low-grade sWEEE. However, the applied pre-processing should consider the precious metals, even though it should primarily focus on the management of the most relevant materials, since in Germany low-grade equipment is responsible for around 28% of the losses of precious metals.

As emphasized by Leroy (2008), "law is not the most appropriate instrument to promote state-of-the-art treatment and recycling technologies, or, worse, to lay down specific operational requirements, e.g. 'manual dismantling'. First of all, by the time law enters into force, new and better techniques have made it to the market." However, the **development of recycling standards**, as recommended by the European Commission (COM 2005) and by Leroy (2008), would help promoting efficient recycling technologies. Past and current working groups on the development of standards relating to WEEE management are listed in Appendix 4. The definition of standards should be accompanied by control measures, to make sure that the recommended technologies are really used in practice. The ability of the applied technology to recover the precious metals and other substances should be periodically **experimentally monitored**, using a method similar to the method described in Paper 2.

Research should be encouraged to develop new technologies able to recover the precious metals in the different equipment mixes more efficiently, considering the presence of other valuable and hazardous materials that also need to be handled appropriately. The overall recovery of precious metals can be improved not only by better pre-processing, but also at other steps of the treatment chain. For example, the implementation of scavenger technologies to recover the precious metals contained at trace levels in the materials entering plastic recycling facilities or production processes for secondary steel may also be options to improve the recovery rates for precious metals along the whole treatment chain.

7.1.4. Send less WEEE into uncontrolled channels

The processes to recover the precious metals used by the informal sector, especially in developing countries (see chapter 4.1.4.2), achieve lower recovery rates for precious metals and have much higher impacts on the environment than the state-of-the-art processes applied in the industrial countries. To limit the losses of precious metals, fewer waste appliances should be sent to treatment processes that are not subject to adequate regulations.

Leonhardt (2007) and GAO (2008) identified the lack of transparency in the WEEE management system and the insufficient **enforcement of the legislation** as elements making illegal practices possible. Also the complex definition of the responsibilities in Germany (Leonhardt 2007) and the narrow scope of the US hazardous waste regulations, which consider only CRTs as hazardous waste (GAO 2008), but not many types of WEEE such as computers, printers, and cell phones, facilitate the illegal export of WEEE to developing countries.

More transparency along the treatment chain would enable a better tracking of the flows of WEEE and therefore open new possibilities to control them. This would help the enforcement of the legislation inside the borders of the countries and relative to the exports of hazardous waste. The traceability of the material flows would be higher if specific codes were defined to classify WEEE. 7-digit international standard codes are usually used to describe the contents of containers shipped over sea, but no such code exists for WEEE (GAO 2008). In the European Union, unified waste codes are listed in the Annex of the European Commission Decision 2000/532/EC. Twelve of these waste codes relate to WEEE. According to Bolland (2009), these waste codes are not adequate to describe WEEE and track the flows. The **definition of internationally unified waste codes to classify WEEE** (and to distinguish it from second-hand EEE, see chapter 2.4.3) could facilitate “basic statistical tracking” of exports of WEEE (GOA 2009; Sander & Schilling 2009).

A **better transparency of the flows** in the formal sector would support the identification of the system leakages by means of which the flows of WEEE leave the formal sector for the informal sector. For example, if the total quantity of collected WEEE is significantly higher than the quantity of WEEE treated by the formal sector, this indicates that some WEEE is leaving the formal sector during the transfer of the collected WEEE to the treatment facilities. Studies like the research of Tesar & Öhlinger (2009) in Austria are useful to get an overview of the material flows entering and leaving treatment facilities. So far, such detailed studies have not been conducted in Germany or the USA.

In many cases, WEEE is dismantled manually in the informal sector, which achieves high recovery rates for precious metals, and employs many people who need an employment. These accomplishments as well as the high reuse rates should not hide the negative effects of the informal activities related to the recovery of metals on the environment, as presented in chapter 2.4.3. As emphasized by Manomaivibool (2009), strategies to solve the problems cannot be developed “without a solid understanding of the context” and an improvement of “our knowledge on physical and economic flows in the target market”. Instead of making policies to suppress the informal sector, it could be more effective to integrate it into the process chain and help it to reduce the environmental impacts to an acceptable level. The advantages of **combining the potentials** of the manual dismantling and of reuse in developing countries with the technologies used in Europe and North America to recover the (precious) metals are mentioned by the description of the project “Best of two worlds” of the StEP initiative (StEP 2009) and by the research of Kahhat & Williams (2009). However, since the informal sector is not yet ready to treat WEEE in an environmentally sound manner and, anyway, since it has to deal with the increasing generation of domestic WEEE in developing countries, the export of WEEE should be effectively prevented, in accordance with the legislation.

7.2. Other strategies to limit the discard of precious metals

Because solutions of problems within a system can also be found outside this system, two further strategies are recommended to improve the cycles of precious metals associated with WEEE. They concern the design of EEE for reuse and recycling and the limitation of the generation of WEEE.

7.2.1. Design EEE for reuse and treatment

The design of the product essentially determines the materials used in the product, the material combinations and the type of connections (screws, glue etc.). For this reason, the design of electrical and electronic equipment considerably influences the efficiency of the end-of-life process (pre-processing and recovery process). **Design-for-Recycling** aims at increasing both the quality of the recyclates and the recovery rates (Reuter and Van Schaik 2008). Various research groups developed concepts related to design for end-of-life, like Dietrich et al. (2000), Krause et al. (2006), Huisman (2003), Mathieux (2008), Meskers (2008), Reuter et al. (2005), Rifer et al. (2009), Stevels (2007) and Unger et al. (2008), as well as the project ‘DfR case studies library’ (StEP 2009).

A concrete example of design-for-recycling relates to the accessibility of printed circuit boards. The manual removal of printed circuit boards would partially prevent the losses of precious metals in side-streams (Paper 2). How easy the manual removal is, depends on product design. Design-for-recycling models to link product design to the amount and composition of the output fractions of mechanical pre-processing and to the products of the subsequent material recovery processes were developed by Van Schaik and Reuter (2004, 2007).

However, recycling-friendly designed products does not mean that the materials are actually recycled. Recyclable materials can only be recycled if adequate infrastructure, consumer attitude and appropriate business models are available to collect and treat the waste.

7.2.2. Generate less WEEE

The Waste Framework Directive (2006) of the European Union defines the “prevention or reduction of waste production and its harmfulness” as a first priority of waste policy. Among other advantages, **waste prevention** supports sustainability through minimising human and environmental health risks from waste treatment and disposal (Vancini 2000). Vancini (2000) distinguishes three types of practical actions for waste prevention: strict avoidance, reduction at source and product reuse. Reusing EEE or WEEE to avoid the necessity of treating of WEEE is a strategy for waste prevention, even though only temporarily, since in the long term it cannot be avoided that the reused equipment becomes WEEE.

Besides reuse, the generation of WEEE can be limited through following strategies (modified from Vancini (2000)):

- Avoid the purchase of EEE;
- Purchase EEE designed for a long use;
- Increase the use time of EEE by:
    - Repairing
    - Maintenance (to prevent the break-down of EEE)
    - Improvement (to modernise the EEE).
- Apply new business models that allow reducing the WEEE generation, like leasing, where for example the function “phoning during two years” is sold instead of the object “mobile phone”, which has to be returned after two years.

Prevention can only be achieved by influencing practical decisions taken at various stages of the life cycle: how a product is designed, manufactured, made available to the consumer and finally used (COM 2005). Waste prevention can conflict with the sales objectives of the EEE manufacturers and have a detrimental effect on every national economy, if the consumption process is really reduced significantly (Brunner 1996).

As emphasized by the European Commission (COM 2005), waste prevention has been the paramount objective of many waste management policies for many years, but limited progress has been made so far in transforming this objective into practical action. This will possibly change in a near future, since the revised Waste Framework Directive (2008) requires that the member states of the European Union establish waste prevention programmes by 12 December 2013 (Article 29).

7.3. Strategies to increase the data quality

In addition to the quantitative results regarding the material flows, the SFA makes possible the assessment of the quality of the available data and the identification of gaps in the data. This leads to the formulation of recommendations to improve the data quality, having in view the conduct of similar investigations in the future. Table 40 presents an overview of the quality of the data used to conduct the substance flow analysis (quantified as variation coefficient) and some recommendations to improve it.

Table 40 Quality of the data used for mapping the flows of materials and precious metals related to the management of sWEEE

Subsystem	Required data	Uncertainty*	Recommended methods for data collection	Comment
EOL equipment characterisation	Concentration of precious metals	5-20%	Periodical determination of the composition of sWEEE at material and substance level	Standards for sampling, dismantling and analysis are needed
Generation	Sales data, lifetime distribution	30%	Study of user behaviour regarding discarding of WEEE; Compilation of sales data in mass units	The market data are still too expensive for research institutions
Collection	Quantity and destination of collected sWEEE	Germany: 10% USA: 20%	Compilation of data from the operators of collection systems	A computerised system to collect and compile the data from all the operators of collection activities is needed (quantity and destination of the collected WEEE)
	Non-separately collected sWEEE	Germany: 10-20% USA: 20-30%	Periodical representative sorting analyses of residual waste and study on user behaviour regarding discarding of WEEE	Standards for sampling, sorting and classifying the residual waste are needed

Subsystem	Required data	Uncertainty*	Recommended methods for data collection	Comment
Reuse	Quantity of sWEEE sent to reuse processes	30%	Compilation of data from the reuse industry	A computerised system to collect and compile the data from all the operators of reuse activities is needed (quantity of the input and destination of all output fractions)
	Reuse rates for precious metals (mass of PM in the reused devices divided by mass of PM in input)	10%	Compilation of data from the reuse industry	Periodical monitoring of the destination of the outputs
Formal treatment	Quantity of sWEEE sent to formal treatment processes	10%	Compilation of data from the recycling industry	A computerised system to collect and compile the data from all the operators of treatment activities is needed (quantity of the input and destination of all output fractions)
	Recovery rates for precious metals (mass of recovered PM divided by mass of PM in input)	Germany: 10% USA: 20%	Experimental monitoring of treatment processes	Periodical monitoring of the concentration of precious metals in the outputs and of the destination of the outputs
Informal treatment	Quantity of sWEEE sent to informal treatment processes	20%	Compilation of data on informal treatment of WEEE gathered through observations of the informal sector	Research, in cooperation with the informal sector if possible, to quantify the flows and their destination
	Recovery rates for precious metals (mass of recovered PM divided by mass of PM in input)	10%	Experimental monitoring of treatment processes	Monitoring of the concentration of precious metals in the outputs and of the destination of the outputs

* Variation coefficient (standard deviation divided by average)

Regarding the average concentrations of precious metals in sWEEE, a clear lack of data could be identified. For example, no data is available on the precious metals in parts other than printed circuit boards. More representative data are needed on concentration of precious metals in the different equipment types (which definition needs to be standardised), as well as on the variations of the concentrations in time and space. The extrapolation of the uncertain data on concentration of precious metals spread uncertainties over the whole substance flow analysis. In addition to further analyses of sWEEE by research institutions, the manufacturers of the EEE placed on market could provide data on the content of precious metals of their appliances. These data should be compiled in a systematic way to increase the reliability of the data for the conduct of future substance flow analyses.

The generation estimates in this study were partly based on sales data that, for Germany, did not reach far enough in the past. Such datasets are traded by private companies and are very expensive, so that the majority of the research institutions cannot afford to buy them. A recommendation is to make such data available for non-commercial research projects. The use of mass units (besides the financial units) by collecting the data of the manufacturers would reduce the uncertainties. Moreover, further research on the behaviour of the users is necessary to develop better models to estimate the WEEE generation.

The systematic and computerised collection of data on material flows in and out of the collection, reuse and treatment processes is recommended. In Germany so far, the data on collection of sWEEE is more reliable than the data related to the pre-processing and recovery processes, which are to a large extent not available. In the USA, some data on the flows of sWEEE entering the recycling industry are available, but no data on collection. To collect more reliable data, a close collaboration with the operators of facilities is required. The industry frequently tends to be protectionist and to avoid releasing data because they fear negative impacts on their businesses. Efforts can be made to convince them that such cooperation is useful and to ensure them that no harm will be done to their businesses (for example through the signing of confidentiality agreements). Tesar & Öhlinger (2009) conducted the work of compiling, analysing and publishing data on the flows of sWEEE in Austria and delivered an overview of current treatment practices. Similar methods to process systematically data on WEEE flows should be applied in other countries, in particular in Germany and in the USA.

In addition, more experimental research is necessary to measure the ability of different treatment facilities to recover precious metals (see Paper 2). The investigations of further technologies would help understanding the behaviour of precious metals during pre-processing of WEEE. Monitoring periodically the flows of precious metals in the facilities is directly in the interest of the facility operators, for them to be aware of the losses caused by their treatment and to have a data basis to implement measures to reduce the losses.

The development of standardised methods is required, in order to guarantee the representativeness and the reproducibility of the data collected. The clear definition of the responsibilities regarding the gathering, compilation and analysis of the data is essential for the success of the monitoring. Cooperation is necessary between manufacturers of EEE, operators of collection, reuse and treatment facilities, public authorities as well as private and public research institutions.

7.4. SFA as assessment tool for waste management

In Paper 2, three goals of the application of SFA in waste management were identified:

- Provide data for the technical operation of waste management facilities to quantify and improve the material flows and, thus, to reduce the losses of resources during waste management,
- Improve the life-cycle of products and enable a better communication between the actors along the product life-cycle,
- Provide data for conducting further research, like for example regional, national or global analyses of material or substance flows.

The quantification of the substance flows rests upon a large amount of very different data, so that the quantification of the uncertainties and the data reconciliation are crucial to provide information on the reliability of the results. Uncertainties should always be quantified and discussed, even though they are (very) high and even though the uncertainties of the uncertainties are (very) high. Synergies could be observed by conducting the SFA: if the subsystems comply with the law of conservation of mass and no material is stored, the sum of the inputs is equal to the sum of the outputs. Therefore, if information is available on all the flows except one, the data reconciliation delivers the missing information.

The SFA has shown in this thesis its ability to highlight the strengths and the weaknesses of a waste management system regarding its ability to manage the substances considered. The SFA does not seek to be predictive, but presents a “snapshot” of the substance flows within a defined time and geographical frame. Based on the knowledge gathered on the material flows, recommendations to improve the system could be systematically formulated. Quantitative data on the material flows condition the development of improvement strategies, as expressed in a very general way by Sir William Thomson (Lord Kelvin): “If you can not measure it, you can not improve it." For Brunner & Ma (2009), goal-oriented, effective waste management is hardly feasible “if we do not know substance flows through waste management”. Kahhat et al. (2008) also stated that the development of a sustainable WEEE management system “begins with understanding the culture within which the material flows take place“.

Reuter et al. (2005) criticised some research methods of the field of industrial ecology, to which MFA and SFA belong, by saying that “industrial ecology so far has not or only partly bridged the gap between its holistic concepts and the different industrial practices”. Bridging this gap is a challenge and requires a close collaboration between the research and the industry. From the industry, data and information on the practices are required. The research community should communicate more on the importance of research on industrial ecology and on its ability to deliver very useful findings for policy-support. Discussing the reliability of the data and presenting the uncertainties are essential to increase the credibility of the studies. Unfortunately, many MFA are published without a discussion of the reliability of the data and the uncertainties of the results.

Further investigations are needed to complete the results and to quantify the flows of other substances and in other geographical areas. The recovery and discarding rates for palladium presented in Table 34 are probably similar to the recovery and discarding rates for other trace metals like tin, antimony or nickel, because these metals are recovered in the same recovery facilities. The results presented in this thesis of the flows of palladium and gold can not be transferred to quantify the flows of other materials like basis metals and plastics. The applied method is not only useful for assessing the recovery of valuable substances, but also for quantifying the amount of hazardous substances (for example mercury or brominated flame retardants) that is disposed of in an environmentally-sound way versus direct releases to the environment. In addition to the quantification of the material flows, future research can be combined with other methods like life-cycle assessment (Tukker et al. 1997) or social sciences modelling (Binder 2007), to provide more profound information for policy-making.

8. Conclusion

This investigation estimated the flows of sWEEE and the related flows of gold and palladium in the system ‘management of sWEEE’ in Germany and in the USA. A large amount of data from different sources were selected and combined. The result of the SFA showed that in Germany, around 72 % of the gold and of the palladium contained in sWEEE gets lost to the recycling economy. These losses amount to 75% in the USA. The economic value of these lost precious metals is high. Beyond the quantitative results, the SFA enabled the identification of gaps in the data and the formulation of recommendations for gathering better data in the future.

‘Non-separated collection’ and ‘losses during treatment’ are the main reasons for the losses, which vary according to the considered groups of equipment. The main losses of precious metals from WEEE are not due to the lack of available technologies, but to logistical and organisational challenges. WEEE includes numerous different types of devices that contain precious metals and other materials in different concentrations. The efforts for more efficient collection and recycling need to be differentiated according to the different equipment type. Limiting the non-separated collection of WEEE and pre-sorting the different kinds of equipment according to their characteristics before treating them with state-of-the-art technology would considerably reduce the material losses. The research showed that especially the collection of small and high-grade end-of-life devices like mobile phones needs to be improved. Since the collection target of 4 kg per year and capita defined in the WEEE directive does not promote the collection of light devices, specific collection targets and new collection channels are required for these devices. A change of the legislation would also support the implementation of more efficient recycling processes regarding the recovery of precious metals, because the mass-based recovery targets of the WEEE directive does not set incentives for the recovery of trace elements like precious metals.

Besides the development of the legislation, improving the recovery of precious metals involves raising awareness and developing economic incentives. The actors of WEEE management, which are primarily the EEE producers, the users, the operators of recycling facilities, the public authorities, the research institutions and the non-governmental organisations, need to cooperate to develop practical solutions considering the complexity of WEEE. A clear definition of responsibilities is needed, as well as an efficient monitoring of the material flows and more control to enforce the regulations.

All the equipment groups investigated in this thesis, except the CRT monitors, have higher concentrations of gold than the majority of the currently mined ores. Of course, the other materials and substances contained in WEEE should not be forgotten when designing management strategies for WEEE. The recovery of precious metals from WEEE is very relevant regarding the development of our societies towards close-loop management of materials and substances.

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Appendices

Appendix 1 Equipment types and their classification according to the WEEE Directive and to the equipment groups defined in this thesis

Equipment group	Equipment type	Category (WEEE Directive)
Personal computer	Personal computer (without monitor)	3
Mobile telephone	Mobile telephone	3
CRT monitor	Computer CRT Monitor	3
CRT monitor	TV set – CRT monitor	4
Large high-grade equipment	Beamer/ Video projector	4
Large high-grade equipment	CD player	4
Large high-grade equipment	Computer keyboard	3
Large high-grade equipment	Computer LCD Monitor	3
Large high-grade equipment	DVD player	4
Large high-grade equipment	Hi-fi unit	4
Large high-grade equipment	Laptop/ Notebook/ Notepad computer	3
Large high-grade equipment	Modem (ISDN-DSL-analog)	3
Large high-grade equipment	Printer	3
Large high-grade equipment	TV set – LCD-Monitor	4
Large high-grade equipment	Video game console	7
Large high-grade equipment	Video recorder	4
Small high-grade equipment	Camera analog	4
Small high-grade equipment	Camera digital	4
Small high-grade equipment	Computer mouse	3
Small high-grade equipment	Discman for CDs	4
Small high-grade equipment	Electronic organiser	4
Small high-grade equipment	GPS	4
Small high-grade equipment	Hand-held video game console	7
Small high-grade equipment	Joystick	7
Small high-grade equipment	MP3 player	4
Small high-grade equipment	Pocket calculator	4
Small high-grade equipment	USB memory stick	3
Small high-grade equipment	Video camera analog	4
Small high-grade equipment	Video camera digital	4
Low-grade equipment	Adapter	4
Low-grade equipment	Alarm clock	2
Low-grade equipment	Battery charger	2
Low-grade equipment	Bread Maker	2
Low-grade equipment	Coffee machine	2

Equipment group	Equipment type	Category (WEEE Directive)
Low-grade equipment	Cordless telephone	3
Low-grade equipment	Drilling machine	6
Low-grade equipment	Electric knife	2
Low-grade equipment	Electrical shaver	2
Low-grade equipment	Grinding machine	6
Low-grade equipment	Hair dryer	2
Low-grade equipment	Hand-vacuum cleaner	2
Low-grade equipment	Loudspeaker	4
Low-grade equipment	Mixer / Blender	2
Low-grade equipment	Music Keyboard	4
Low-grade equipment	Plastic-rich electrical toy	7
Low-grade equipment	Radio control vehicle	7
Low-grade equipment	Radio set	4
Low-grade equipment	Remote control	4
Low-grade equipment	Telefax	3
Low-grade equipment	Telephone	3
Low-grade equipment	Telephone answering machine	3
Low-grade equipment	Toaster	2
Low-grade equipment	Vacuum Cleaner	2
Low-grade equipment	Wall clock	2
Low-grade equipment	Watch	2

Appendix 2 Average concentration of precious metals in different equipment types (median of the reported concentrations)

Equipment type (undismantled)	Reference	Silver (g/t)	Gold (g/t)	Palladium (g/t)	Platinum (g/t)	Data reliability for this study
Mobile telephone	Hagelüken & Buchert 2008	3630	347	151	5	Very good
	Huisman 2004	1708	343	186	10	Good
	USGS 2006	3097	301	133	3	Good
Personal computer	Gmünder 2007	175	26	12		Good
Personal computer including CRT monitor	MCC 1996	189	16	3		Poor
Computer CD drive	Gmünder 2007	460	20	10		Good
Computer floppy drive	Gmünder 2007	180	10	20		Good
Computer hard drive	Gmünder 2007	280	40	30		Good
Computer CRT Monitor	Huisman 2003	11	1			Middle
DVD player	Hagelüken 2006a	115	15	4		Good
	Hagelüken 2006a	170	25	5		Good
	Huisman 2003	109	16	4		Middle
Cordless telephone	Hagelüken 2006a	1350	120	95		Good
Pocket calculator	Hagelüken 2006a	260	50	5		Good
USB memory stick	Measurements by Umicore 2008	957	182	6		Good
Adapter	Measurements by Umicore 2008	9	2	1		Good
Portable audio	Hagelüken 2006a	150	10	4		Good

[1] Evaluation criteria: sample size, sample representativeness, age

Appendix 3 Average concentration of precious metals in printed circuit boards from different equipment types (median of the reported concentrations)

Equipment type (origin of the PCB)	Reference	Silver (g/t)	Gold (g/t)	Palladium (g/t)	Platinum (g/t)	Data reliability for this study
Mobile telephone	Ernst et al. 2003	3573	368	287		Middle
	Hagelüken & Buchert 2008	5540	980	285	7	Very good
Personal computer	Angerer et al. 1993	905	81			Poor
	Gmünder 2007	1000	225	90		Very good
	Hagelüken 2006a	1000	250	110		Very good
	Huisman et al. 2007[2]	1000	230	90		Very good
	Keller 2006	775	156	99		Middle
	Kramer 1994	600	300			Middle
	Legarth et al. 1995	700	600	100	40	Middle
Computer CD drive	Gmünder 2007	2203	88	52		Very good
Computer floppy drive	Gmünder 2007	1500	112	203		Very good
Computer hard drive	Gmünder 2007	2630	415	286		Very good
Computer power supply	Gmünder 2007	373	10	17		Very good
Computer CRT Monitor	Huisman et al. 2007[2]	150	9	3		Middle
TV set – CRT monitor	Hagelüken 2006a	280	17	10		Good
	Huisman et al. 2007[2]	1600	110	41		Middle
Computer LCD Monitor	Huisman et al. 2007[2]	1300	490	99		Middle
	Measurements by Umicore 2009		123	14		Middle
TV set – LCD-Monitor	Huisman et al. 2007[2]	250	60	19		Middle
DVD player	Huisman et al. 2007[2]	700	100	21		Middle
Printer	Huisman et al. 2007[2]	350	47	9		Middle
Telephone	Ernst et al. 2003	2244	50	241		Middle
Battery charger	Ernst et al. 2003		278			Middle
Camera digital	Measurements by Umicore 2008	3057	863	42		Good
GPS	Ernst et al. 2003	5033	536	688		Middle
Hand-held video game console	Measurements by Umicore 2008	609	141	44		Good
Radio set	Huisman et al. 2007[2]	520	68	8		Good
Toy	Huisman et al. 2007[2]	365	89	18		Middle

[1] Evaluation criteria: sample size, sample representativeness, age

[2] Combination of data from different sources

Appendix 4 Past and current work on the definition of guidelines and quality specifications for WEEE management

Reference of the document	Geographical area	Members of the working group	Scope of the guideline
UNEP E-waste management manual	Worldwide	UNEP, research, secretariat of the Basel Convention	Manual for policy-making, collection, treatment of WEEE and financing
Basel Convention MPPI guidance document	Worldwide	Experts from signatories of the Basel convention, mobile phone manufacturers, secretariat of the Basel Convention	Environmentally sound management of used and end-of-life mobile phones
OECD Guidance	Worldwide	OECD Working Group on Waste Prevention and Recycling	Technical guidance for the environmentally sound management of used and scrap personal computers
VDI 2343	Germany	Recycling industry, research, NGOs	Seven parts: Basics, Logistics, Disassembly, Preparation Techniques, Recycling, Marketing, ReUse (see Brüning 2007)
LAGA M31	Germany	Environment ministries of the German states	Technical requirements for collection, reuse, treatment and transport of WEEE
RAL-GZ 728	Germany	RAL institute	Quality assurance and test specifications for the demanufacture of refrigeration equipment
WEEE Forum 2007	European Union	Recyclers	Collection, transportation, storage, handling and treatment of freezing appliances
WEEELABEX 2008	European Union	Recyclers and take-back systems	European Standards with respect to collection, treatment, recovery of WEEE and monitoring the processing companies
ÖNORM S 2106	Austria	Austrian Standards Institute in collaboration with the industry	Recovery and disposal of materials from WEEE
ÖNORM S 2107	Austria	Austrian Standards Institute in collaboration with the industry	Collection and treatment of WEEE
EcoNet-Austria	Austria	Social enterprises handling WEEE	Manual depollution and dismantling of selected WEEE
DEFRA guidance	United Kingdom	Department for Environment, Food and Rural Affairs	Definition of Best Available Treatment Recovery and Recycling Techniques according to WEEE Directive
US EPA Plug-In to eCycling	USA	US Environmental Protection Agency	National guidance for the management of “end-of-life” Electronics

Appendix 5 Generation of sWEEE in Germany and in the USA in 2007 estimated with the 'batch leaching' method

Eq. group	Equipment type	Average weight (g)[1]	Total lifetime (years)[2]	Penetration rate in Germany (per 100 inhabitants)[3]	sWEEE generation in Germany (tonnes)	Penetration rate in the USA (per 100 inhabitants)[4]	sWEEE generation in the USA (tonnes)
Mobile phones	Mobile telephone	197	6	104	2817	76	7532
	Total				**2817**		**7532**
PCs	Desktop personal computer	12154	9	45	50097	89	362511
	Total				**50097**		**362511**
CRT monitor	Computer CRT Monitor	10000	9	40	36639	70	234594
	TV set - CRT monitor	14512	15	73	62382	80	250127
	Total				**99021**		**484721**
Large high-grade eq.	Beamer/ Video projector	2000	12	2	275	2	1005
	CD player	3000	12	60	12366	50	37703
	Computer keyboard	934	12	40	2567	80	18784
	Computer LCD Monitor	3337	10	15	4127	40	40264
	DVD player	3140	12	36	7765	50	39457
	Hi-fi unit	7527	12	50	25853	50	94592
	Laptop/ Notebook computer	2815	7	12	3978	20	24256
	Modem (ISDN-DSL-analog)	134	7	29	458	29	1676
	Printer	4340	9	30	11925	50	72718
	TV set - LCD-Monitor	8600	12	10	5908	20	43232
	Video game console	1547	12	9	957	15	5834
	Video recorder	3964	12	40	10893	40	39854
	Total				**87071**		**419375**

Eq. group	Equipment type	Average weight (g)[1]	Total lifetime (years)[2]	Penetration rate in Germany (per 100 inhabitants)[3]	sWEEE generation in Germany (tonnes)	Penetration rate in the USA (per 100 inhabitants)[4]	sWEEE generation in the USA (tonnes)
Small high-grade eq.	Camera digital	144	11	24	259	40	1579
	Computer mouse	112	11	40	337	80	2464
	Discman for CDs	555	11	6	250	10	1523
	Electronic organiser	104	11	5	39	10	286
	GPS	300	11	4	90	20	1645
	Hand-held video game console	165	5	5	136	20	1996
	Joystick	408	11	5	153	20	2237
	MP3 player	50	5	15	124	20	603
	Pocket calculator	79	11	40	235	40	862
	USB memory stick	13	5	20	43	30	233
	Video camera analog	1229	11	7	645	10	3370
	Video camera digital	800	11	4	240	20	4387
	Total				**2550**		**21186**
Low-grade eq.	Adapter	802	11	130	7816	130	28597
	Alarm clock	71	10	50	294	50	1075
	Battery charger	216	12	20	297	20	1085
	Bread Maker	6600	12	10	4534	10	16589
	Camera analog	500	11	47	1761	47	6444
	Coffee machine	1000	12	50	3436	50	12571
	Cordless telephone	226	10	20	373	40	2726
	Drilling machine	2470	12	20	3394	20	12416

Eq. group	Equipment type	Average weight (g)[1]	Total lifetime (years)[2]	Penetration rate in Germany (per 100 inhabitants)[3]	sWEEE generation in Germany (tonnes)	Penetration rate in the USA (per 100 inhabitants)[4]	sWEEE generation in the USA (tonnes)
	Electric knife	750	12	10	515	10	1886
	Electrical shaver	312	12	30	642	30	2350
	Grinding machine	2522	12	10	1733	10	6340
	Hair dryer	363	12	40	998	40	3650
	Hand-vacuum cleaner	535	12	10	368	10	1346
	Loudspeaker	1635	10	100	13481	100	49324
	Mixer / Blender	891	12	40	2448	40	8955
	Music Keyboard	2200	12	2	302	2	1105944
	Plastic-rich electrical toy	230	5	100	3796	100	13889
	Radio control vehicle	656	5	20	2163	20	7914
	Radio set	868	11	100	6509	100	23814
	Remote control	92	11	200	1380	200	5051
	Telefax	4000	10	9	2968	15	18097
	Telephone	638	10	50	2629	40	7696
	Telephone answering machine	677	10	24	1340	30	6126
	Toaster	1335	12	40	3670	40	13426
	Vacuum Cleaner	6338	12	60	26126	60	95590
	Wall clock	111	12	50	381	50	1393
	Watch	33	12	70	161	70	587
	Total				**93513**		**1454882**
Total	**All equipment groups**				**335068**		**2740142**

[1] The data on the weight of the devices are collected in the database presented in chapter 3.3.1 (see also Paper 1)

[2] Assumptions based on the results presented in Table 11
[3] Data from Destatis (2008) and BITKOM (2007)
[4] Data from BITKOM (2007)

Appendix 6 Estimation of the average concentration of gold and palladium in the different equipment groups

Eq. group	Equipment type	Average weight (g)[1]	Mass fraction of printed circuit boards[1]	PM concentration in the printed circuit boards (g/t)[2]		sWEEE generated in Germany (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)		sWEEE generated in the USA (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)	
				Au	Pd		Au	Pd	Au	Pd		Au	Pd	Au	Pd
CRT monitor	Computer CRT Monitor	10000	5.0%	17	10	36639	31.1	18.3	0.9	0.1	234594	199.4	117.3	0.9	0.5
	TV set - CRT monitor	14512	4.7%	10	3.4	62382	29.6	10.1	0.5	0.0	250127	118.7	40.4	0.5	0.2
	Total					**99021**	**61**	**28**	**0.6**	**0.3**	**484721**	**318**	**158**	**0.7**	**0.3**
Large high-grade eq.	Beamer/ Video projector	2000	10.0%	100	20	275	2.7	0.5	10.0	0.5	1005	10.1	2.0	10.0	2.0
	CD player	3000	4.4%	100	20	12366	54.4	10.9	4.4	0.3	37703	165.9	33.2	4.4	0.9
	Computer keyboard	934	2.2%	50	20	2567	2.8	1.1	1.1	0.1	18784	20.7	8.3	1.1	0.4
	Computer LCD Monitor	3337	6.9%	123	14	4127	35.0	4.0	8.5	0.1	40264	256	29.2	8.5	1.0
	DVD player	3140	14.8%	100	21	7765	114.9	24.1	14.8	0.6	39457	584.0	122.6	14.8	3.1
	Hi-fi unit	7527	15.3%	68	8	25853	269.0	31.6	10.4	0.3	94592	984.1	115.8	10.4	1.2
	Laptop/ Notebook computer	2815	17.5%	500	100	3978	348.1	69.6	87.5	2.9	24256	2122	424.5	87.5	17.5
	Modem (ISDN-DSL-analog)	134	30.0%	100	20	458	13.7	2.7	30.0	1.6	1676	50.3	10.1	30.0	6.0
	Printer	4340	6.5%	50	9	11925	38.8	7.0	3.3	0.1	72718	236.3	42.5	3.3	0.6
	TV set - LCD-Monitor	8600	9.2%	60	19	5908	32.6	10.3	5.5	0.2	43232	238.6	75.6	5.5	1.7
	Video game console	1547	19.6%	100	20	957	18.8	3.8	19.6	0.6	5834	114.4	22.9	19.6	3.9
	Video recorder	3964	19.1%	50	10	10893	104.0	20.8	9.6	0.5	39854	380.6	76.1	9.6	1.9
	Total					**87071**	**1035**	**187**	**11.9**	**2.1**	**419375**	**5164**	**963**	**12.6**	**2.4**

Eq. group	Equipment type	Average weight (g)[1]	Mass fraction of printed circuit boards[1]	PM concentration in the printed circuit boards (g/t) [2]		sWEEE generated in Germany (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)		sWEEE generated in the USA (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)	
				Au	Pd		Au	Pd	Au	Pd		Au	Pd	Au	Pd
Small high-grade eq.	Camera digital	144	15.0%	863	42	259	38.0	1.8	146.7	1.2	1579	231.7	11.3	146.7	7.1
	Computer mouse	112	8.2%	100	20	337	2.8	0.6	8.2	0.2	2464	20.2	4.0	8.2	1.6
	Discman for CDs	555	4.4%	200	20	250	2.2	0.2	8.8	0.1	1523	13.4	1.3	8.8	0.9
	Electronic organiser	104	15.5%	500	60	39	3.0	0.4	77.5	1.3	286	22.2	2.7	77.5	9.3
	GPS	300	30.0%	536	688	90	14.5	18.6	160.8	11.3	1645	264.5	339.6	160.8	206.4
	Hand-held video game console	165	21.5%	141.3	44	136	4.1	1.3	30.4	0.6	1996	60.6	18.9	30.4	9.5
	Joystick	408	7.3%	100	20	153	1.1	0.2	7.3	0.1	2237	16.3	3.3	7.3	1.5
	MP3 player	50	30.0%	500	100	124	18.5	3.7	150.0	6.1	603	90.5	18.1	150.0	30.0
	Pocket calculator	79	13.4%	n/a	n/a	235	11.8	1.2	50[3]	5[3]	862	43.1	4.3	50.0	5.0
	USB memory stick	13	n/a	n/a	n/a	43	7.7	0.3	181.7[3]	5.9[3]	233	42.4	1.4	181.7	5.9
	Video camera analog	1229	26.5%	100	20	645	17.1	3.4	26.5	1.0	3370	89.3	17.9	26.5	5.3
	Video camera digital	800	17.0%	863	42	240	35.2	1.7	146.7	0.4	4387	643.6	31.3	146.7	7.1
	Total					**2550**	**156**	**33**	**61.2**	**13.1**	**21186**	**1538**	**454**	**72.6**	**21.4**
Low-grade eq.	Adapter	802	1.5%	n/a	n/a	7816	15.6	7.8	2[3]	1[3]	28597	57.2	28.6	2.0	1.0
	Alarm clock	71	0.9%	30	8	294	0.1	0.0	0.3	0.0	1075	0.3	0.1	0.3	0.1
	Battery charger	216	6.2%	50	10	297	0.9	0.2	3.1	0.2	1085	3.4	0.7	3.1	0.6
	Bread Maker	6600	4.3%	30	8	4534	5.8	1.6	1.3	0.1	16589	21.4	5.7	1.3	0.3
	Camera analog	500	5.0%	30	8	1761	2.6	0.7	1.5	0.1	6444	9.7	2.6	1.5	0.4

Eq. group	Equipment type	Ave-rage weight (g)[1]	Mass fraction of printed circuit boards[1]	PM concentration in the printed circuit boards (g/t) [2]		sWEEE generated in Germany (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)		sWEEE generated in the USA (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)	
				Au	Pd		Au	Pd	Au	Pd		Au	Pd	Au	Pd
	Coffee machine	1000	0.3%	30	8	3436	0.3	0.1	0.1	0.0	12571	1.1	0.3	0.1	0.0
	Cordless telephone	226	23.9%	70	15	373	6.2	1.3	16.7	0.5	2726	45.6	9.8	16.7	3.6
	Drilling machine	2470	0.2%	30	8	3394	0.2	0.1	0.1	0.0	12416	0.7	0.2	0.1	0.0
	Electric knife	750	0.9%	30	8	515	0.1	0.0	0.3	0.0	1886	0.5	0.1	0.3	0.1
	Electrical shaver	312	2.2%	30	8	642	0.4	0.1	0.7	0.0	2350	1.6	0.4	0.7	0.2
	Grinding machine	2522	0.4%	30	8	1733	0.2	0.1	0.1	0.0	6340	0.8	0.2	0.1	0.0
	Hair dryer	363	0.1%	30	8	998	0.0	0.0	0.0	0.0	3650	0.1	0.0	0.0	0.0
	Hand-vacuum cleaner	535	1.7%	30	8	368	0.2	0.1	0.5	0.0	1346	0.7	0.2	0.5	0.1
	Loudspeaker	1635	8.4%	30	8	13481	34.0	9.1	2.5	0.2	49324	124.3	33.1	2.5	0.7
	Mixer / Blender	891	0.7%	30	8	2448	0.5	0.1	0.2	0.0	8955	1.9	0.5	0.2	0.1
	Music Keyboard	2200	9.5%	30	8	302	0.9	0.2	2.9	0.0	1105944	3152	840.5	2.9	0.8
	Plastic-rich electrical toy	230	2.1%	30	8	3796	2.4	0.6	0.6	0.0	13889	8.8	2.3	0.6	0.2
	Radio control vehicle	656	3.2%	30	8	2163	2.1	0.6	1.0	0.1	7914	7.6	2.0	1.0	0.3
	Radio set	868	20.5%	68	8	6509	90.7	10.7	13.9	0.4	23814	332.0	39.1	13.9	1.6
	Remote control	92	15.0%	30	8	1380	6.2	1.7	4.5	0.3	5051	22.7	6.1	4.5	1.2
	Telefax	4000	15.0%	70	15	2968	31.2	6.7	10.5	0.4	18097	190.0	40.7	10.5	2.3
	Telephone	638	21.9%	50	20	2629	28.8	11.5	11.0	1.5	7696	84.3	33.7	11.0	4.4
	Telephone answering machine	677	21.8%	70	15	1340	20.4	4.4	15.3	0.7	6126	93.5	20.0	15.3	3.3

Eq. group	Equipment type	Average weight (g)[1]	Mass fraction of printed circuit boards[1]	PM concentration in the printed circuit boards (g/t) [2]		sWEEE generated in Germany (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)		sWEEE generated in the USA (tonnes)	Flows of PM in the generated sWEEE (kg)		Average PM concentration in the generated sWEEE (g/t)	
				Au	Pd		Au	Pd	Au	Pd		Au	Pd	Au	Pd
	Toaster	1335	2.8%	30	8	3670	3.1	0.8	0.8	0.1	13426	11.3	3.0	0.8	0.2
	Vacuum Cleaner	6338	0.6%	30	8	26126	4.7	1.3	0.2	0.0	95590	17.2	4.6	0.2	0.0
	Wall clock	111	0.2%	30	8	381	0.0	0.0	0.1	0.0	1393	0.1	0.0	0.1	0.0
	Watch	33	1.2%	30	8	161	0.1	0.0	0.4	0.0	587	0.2	0.1	0.4	0.1
	Total					**93513**	**258**	**60**	**2.8**	**0.6**	**1454882**	**4189**	**1075**	**2.9**	**0.7**

[1] The data on the weight of the devices are collected in the database presented in chapter 3.3.1
[2] See data in Appendix 3, completed with assumptions
[3] See data in Appendix 2

Appendix 7 Flows of sWEEE in Germany and in the USA in 2007 (tonnes)

Country	Input of subsystem	Mobile phones		Desktop personal computer		CRT monitor		Large high-grade equipment		Small high-grade equipment		Low-grade equipment	
		Flow	Std Dev	Flow	Std Dev	Flow	Std Dev	Flow	Std Dev	Flow	Std Dev	Flow	Std Dev
Germany	Generation	1 299	189	13 110	890	136 978	8 734	48 787	3 054	1 431	134	197 998	11 392
	Collection	240	17	10 029	658	135 489	8 729	44 835	2 954	769	52	118 227	8 214
	Non-separated collection	1 059	188	3 081	602	1 489	297	3 952	783	661	125	79 771	8 664
	Reuse	66	16	1 002	290	3 853	1 150	1 973	586	17	5	6 062	1 885
	Formal treatment	157	14	8 164	641	103 746	8 332	39 567	2 940	707	52	102 512	8 192
	Informal treatment	16	3	863	171	27 889	5 238	3 294	652	45	9	9 653	1 974
	Reused sWEEE	60	15	902	262	3 468	1 039	1 776	529	16	5	5 456	1 703
USA	Generation	16 268	3 274	397 517	40 767	1 468 391	177 652	500 533	118 976	23 242	4 368	1 316 223	218 239
	Collection	1 824	206	214 894	21 193	588 978	59 759	294 487	30 130	5 075	409	10 001	1 233
	Non-separated collection	14 444	3 275	182 623	36 826	879 413	172 758	206 046	122 277	18 168	4 367	1 306 222	218 237
	Reuse	735	199	66 374	18 823	97 976	29 243	95 933	27 021	100	30	5 001	1 210
	Formal treatment	871	86	118 816	11 609	199 100	19 777	158 843	15 565	3 980	372	4 000	395
	Informal treatment	218	44	29 704	5 952	291 903	53 691	39 711	7 946	995	197	1 000	199
	Reused sWEEE	661	179	59 736	16 978	88 178	26 419	86 340	24 421	90	27	4 501	1 095

Appendix 8 Flows of gold associated with sWEEE in Germany and in the USA in 2007 (kg)

Country	Input of subsystem	Mobile phones		Desktop personal computer		CRT monitor		Large high-grade equipment		Small high-grade equipment		Low-grade equipment	
		Au flow	Std Dev	Au flow	Std Dev	Au flow	Std Dev	Au flow	Std Dev	Au flow	Std Dev	Au flow	Std Dev
Germany	Generation	451	66	404	30	84	8	580	54	88	10	546	49
	Collection	83	6	309	23	83	8	533	53	47	5	326	36
	Non-separated collection	368	66	95	20	1	0	47	11	40	9	220	37
	Reuse	23	6	31	9	2	1	23	8	1	0	17	6
	Formal treatment	55	5	251	23	64	8	470	53	43	5	283	36
	Informal treatment	6	1	27	6	17	4	39	9	3	1	27	7
	Recovered	33	3	150	16	39	5	189	21	17	2	83	10
	Reused	21	5	28	8	2	1	21	7	1	0	15	5
	Discarded	397	66	226	24	43	5	370	35	69	10	448	43
USA	Generation	5 645	1 144	12 244	1 316	964	137	6 314	1 552	1 687	349	3 790	733
	Collection	633	72	6 619	690	387	48	3 715	458	368	42	29	4
	Non-separated collection	5 012	1 144	5 625	1 184	577	132	2 599	1 577	1 319	348	3 761	733
	Reuse	255	69	2 044	595	64	21	1 210	376	7	2	14	4
	Formal treatment	302	31	3 660	401	131	19	2 004	284	289	39	12	2
	Informal treatment	76	15	915	194	192	43	501	122	72	17	3	1
	Recovered	245	27	2 916	345	103	15	1 085	140	151	19	4	1
	Reused	229	63	1 840	536	58	19	1 089	338	7	2	13	4
	Discarded	5 171	1 144	7 488	1 203	803	135	4 141	1 567	1 529	348	3 773	733

Appendix 9 Flows of palladium associated with sWEEE in Germany and in the USA in 2007 (kg)

Country	Input of subsystem	Mobile phones		Desktop personal computer		CRT monitor		Large high-grade equipment		Small high-grade equipment		Low-grade equipment	
		Pd flow	Std Dev	Pd flow	Std Dev	Pd flow	Std Dev	Pd flow	Std Dev	Pd flow	Std Dev	Pd flow	Std Dev
Germany	Generation	196	29	168	13	39	4	105	10	19	2	126	11
	Collection	36	3	128	10	39	4	96	10	10	1	75	8
	Non-separated collection	160	29	39	8	0	0	8	2	9	2	51	9
	Reuse	10	2	13	4	1	0	4	1	0	0	4	1
	Formal treatment	24	2	104	9	30	4	85	10	9	1	65	8
	Informal treatment	2	0	11	2	8	2	7	2	1	0	6	2
	Recovered	14	1	61	6	17	2	33	5	4	1	18	3
	Reused	9	2	12	3	1	0	4	1	0	0	3	1
	Discarded	173	29	95	10	21	2	68	7	15	2	104	10
USA	Generation	2 456	498	5088	547	478	68	1177	289	498	103	972	188
	Collection	275	32	2751	287	192	24	693	85	109	12	7	1
	Non-separated collection	2 181	498	2338	492	286	66	485	294	389	103	965	188
	Reuse	111	30	850	247	32	10	226	70	2	1	4	1
	Formal treatment	132	13	1521	166	65	9	374	53	85	11	3	0
	Informal treatment	33	7	380	81	95	22	93	23	21	5	1	0
	Recovered	101	12	1157	143	38	7	189	43	42	9	1	0
	Reused	100	27	765	223	29	9	203	63	2	1	3	1
	Discarded	2 255	498	3167	501	410	67	786	294	454	103	968	188

Appendix 10 Flows of sWEEE (tonnes) and flows of gold and palladium (kg) associated with sWEEE in Germany and in the USA in 2007

Country	Input of subsystem	Total flow of sWEEE		Flow of gold		Flow of palladium	
		Flow	Std Dev	Au flow	Std Dev	Pd flow	Std Dev
Germany	Generation	399 602	14 705	2 152	104	653	35
	Collection	309 588	12 363	1 381	69	385	17
	Non-separated collection	90 014	8 728	771	80	268	31
	Reuse	12 974	2 303	97	14	32	5
	Formal treatment	254 854	12 066	1 166	69	317	16
	Informal treatment	41 760	5 638	118	13	35	4
	Recovered	11 677	2 080	512	29	147	9
	Reused	3 722 175	308 278	88	13	29	4
	Discarded	1 115 258	70 213	1 552	90	476	33
USA	Generation	2 606 916	306 285	30 643	2 475	10 670	825
	Collection	266 118	44 058	11 750	834	4 026	302
	Non-separated collection	485 611	27 721	18 893	2 423	6 643	792
	Reuse	363 530	54 602	3 595	707	1 224	259
	Formal treatment	239 506	39 797	6 397	494	2 179	176
	Informal treatment	399 602	14 705	1 758	234	623	88
	Recovered	309 588	12 363	4 503	375	1 528	150
	Reused	90 014	8 728	3 236	638	1 101	233
	Discarded	12 974	2 303	22 904	2 426	8 040	798

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