E-waste: collect more, treat better

Tracking take-back system performance
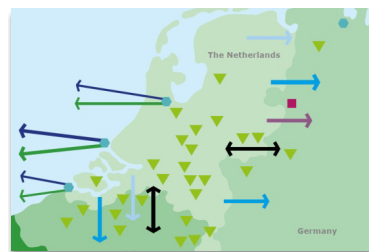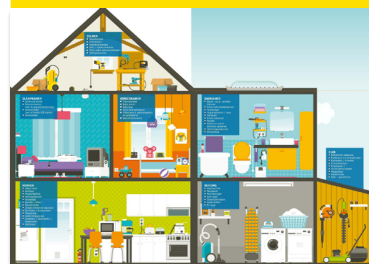for eco-efficient electronics recycling

Feng Wang

Delft University of Technology

Design for Sustainability Program

This dissertation establishes a methodology for evaluating the performance of take-back and treatment systems for end-of-life electronics (e-waste). First, a comprehensive classification is developed to fully understand the complex characteristics of e-waste. A multivariate model is then created to quantify e-waste generation for mapping e-waste flows and tracking the collection efficiency. A multidisciplinary approach is taken to assess the technical performance of e-waste treatment infrastructures, as well as environmental, economic and social impacts associated with them. The results from the model development and case studies demonstrate that the constructed methodology is effective to identify working priorities and intervention measures for improving system performance.

The research conducted represents up-to-date knowledge of both scientific research and implementation experience in the field of global e-waste management. The outcomes can be used to facilitate the progress of upgrading take-back and treatment systems to improve eco-efficiency, for more collection and better treatment in both developed and developing countries.

Feng Wang

DfS **Publication no. 25**

E-waste: collect more, treat better

Tracking take-back system performance for eco-efficient electronics recycling

Feng Wang

E-waste: collect more, treat better

Tracking take-back system performance for eco-efficient electronics recycling

Proefschrift

ter verkrijging van de graad van doctor

aan de Technische Universiteit Delft,

op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben

voorzitter van het College voor Promoties

in het openbaar te verdedigen op 21 maart 2014 om 10:00 uur

door

Feng WANG

Master of Science in Chemistry

Geboren te Daye, China

Dit proefschrift is goedgekeurd door de promotor:

Prof. Dr. Ir. A.L.N. Stevels

en de copromotor:

Dr.ir. J. Huisman

Samenstelling promotiecommissie:

Rector Magnificus	Voorzitter
Prof. Dr. Ir. A.L.N. Stevels	Technische Universiteit Delft, promotor
Dr.ir. J. Huisman	Technische Universiteit Delft, copromotor
Prof.dr.ir. J.C. Brezet	Technische Universiteit Delft
Prof.dr.ir. J.M.P. Geraedts	Technische Universiteit Delft
Prof.dr. P.C. Rem	Technische Universiteit Delft
Prof. Dr.-Ing. Vera Susanne Rotter	Technische Universität Berlin
Dr. Thomas Marinelli	Philips International B.V.

Table of Contents

Preface

First of all, I would like to express my ultimate gratitude to Prof. Zhu Xiaodong in Nanjing University. Without your kind recommendation and generous support in 2006, my academic and learning trip to the west would have never materialized.

Ab, being your last Ph.D. student, I have had the privilege of getting endless help and care from you and Annet. Thanks for all the words of wisdom to help me through so many unexpected situations. It is a great honor to be your last apprentice, and I hope I have not destroyed your reputation to a large extent.

When coming to my gratitude for you, Jaco, any words seem pale and insignificant. Seven years ago, a coincidental discussion at a lecture has unfolded my research journey in e-waste with you (and that is exactly the unexpected but wonderful charm of life). It is a great honor to be your first graduating Ph.D., and it is not an easy task for anyone to foster a Ph.D. without solid funding from the very beginning. Thanks for all your altruistic efforts to raise funds and find projects for me year by year. I also appreciate our sparkling discussions all these years spanning from politics and the environment to society and religion. Arranging for me to travel around the world to see and explore is your unique way of teaching. It is a lifetime treasure for me to learn and work with you under a fair, democratic and inspiring environment.

Ruediger, thank you for providing me with a free working environment and for allowing me to boldly choose my own working locations, topics and projects. I really appreciate your effort in pulling our team together in this organic but flexible "family" manner. It also has been a great pleasure to work with the rest of the UNU team: Claudia, Daniel, Deepali, Kees, Otmar, Romona, Sunghee and Wesley.

Thanks to Mr. Fang Ankong, Gu Liyong and Stephan van Ooyen in Chiho-Tiande, Nils and Eelco in Philips (the Netherlands and China), Ellen and Kees in Statistics Netherlands, Stephanie in the U.S. EPA and Wecycle for providing resources, information, help and funding to support my studies. Elaine, thanks a lot for proof-reading this dissertation.

Jan (Zanen), it was a challenging but unforgettable working experience with you in China, and thanks for all the patient tutoring and assistance to get me through the tough period. Nils (de Caluwe), thanks for all the help and discussion, and I hope you are having a good life in Singapore. Kees (Baldé), I have greatly enjoyed collaborating with you in both CBS and UNU. I like our shared tastes in, and discussions about, music, and I hope your band will be big again in the near future.

Summary

Waste electrical and electronic equipment, or e-waste, is an emerging and fast-growing solid waste stream with complex and heterogeneous characteristics. In the past 20 years, policy-makers and producers across the world have created specialized "take-back and treatment systems" to collect e-waste from final users and process it in recycling and disposal facilities. The fundamental goal of this dissertation is to develop methods to evaluate the performance of these e-waste take-back and treatment systems. The research outcomes will be instrumental to identifying improvement options and intervention measures for enhancing system performance in a more eco-efficient direction.

The main subjects investigated in this dissertation include the collection schemes and treatment infrastructures within the take-back and treatment system, founded on a thorough understanding of e-waste characteristics. The performance assessment in this dissertation covers the technical aspects (collection quantity and treatment efficiency), as well as the social aspects (environmental and economic impacts). This will guarantee the validity of the results in both theoretical analysis and applications for daily management.

The general research goal is differentiated into four interconnected parts: 1) a comprehensive analysis of e-waste characteristics; 2) a method to determine quantity of e-waste generation and efficiency of collection scheme; 3) a method to assess the technical, environmental and economic performance of treatment infrastructures and system optimization under specific socio-economic conditions; and 4) an evaluation of the occupational impacts associated with e-waste treatment. Accordingly, separate methods and case studies are developed and applied in different chapters.

Chapter 4 classifies Electrical and Electronic Equipment (EEE) and e-waste according to different representative criteria in order to fully understand its characteristics. Nine generic categories are identified by combining the individual classification results with five separate criteria (product type, average weight, potential market value, environmental gain from recycling and toxic potential in the end-of-life treatment). Differentiated requirements for end-of-life management in each category are analyzed, such as the collection methods, treatment technologies and toxic control measures. The results can greatly improve the operational and managerial efficiency of these systems, while setting priorities for the most critical categories with high impacts.

Chapter 5 develops a multivariate input-output analysis to enhance the current approach of e-waste estimates. This proposed method applies multiple variables and available data points to improve data quality by maximizing the use of best available data from product sales, stock and

lifespan in historical and present years. The result from a Dutch case study demonstrates the significance of applying consolidated data to improve the reliability of e-waste estimates. This method can lead to more accurate assessments of the collection efficiency of established collection schemes and help identify uncontrolled flows as system leakages.

Chapter 6 analyses the basic structure and configuration of the e-waste treatment chain. Three sequential treatment stages with their requisite arrangements and alternative techniques are investigated in detail: toxic removal, pre-processing and end-processing. Various end-of-life scenarios can be constructed by connecting different treatment alternatives to these three stages. In order to reach the optimal technical performance to recover all materials, a high recovery rate in each treatment stage is required.

Chapter 7 further examines the socio-economic conditions influencing the implementation of treatment technologies. Combining the theoretical analysis and developing experience from pilot projects, it is observed that socio-economic conditions (labor cost, legislation, treatment standards, availability of investment, etc.) greatly influence the feasibility and selection of pre-processing (dismantling versus mechanical separation) and end-processing techniques (state-of-the-art treatment versus low-tech, or substandard treatment). Exclusively for developing countries, a philosophy called "Best-of-2-worlds" (Bo2W) has been proposed. The Bo2W integrates technical and logistical "best" pre-processing practices in developing countries to manually dismantle e-waste and "best" end-processing practices to treat hazardous and complex fractions in international state-of-the-art facilities. This is regarded as a pragmatic and environmentally-responsible solution before establishment of high-tech end-processing facilities is made feasible in emerging economies.

Chapter 8 develops a method to assess occupational impact from e-waste treatment. It incorporates the occupational and indoor environment into the existing framework of Life Cycle Assessment. The fundamental element of Risk Assessment is also integrated into the method to understand the impact severity by comparing with relevant health standards. A case study of the treatment of LCD monitors demonstrates that the impact severity in the occupational environment for workers is much greater than the impact in observed the outdoor environment, experienced by the general public. This method can facilitate the implementation of essential environmental, health and safety measures in facilities in order to lower health risks for workers.

Chapter 9 provides recommendations for specific stakeholders, including legislators, recyclers, operators and managers of take-back and treatment systems, and producers. Potential research topics that are extended further from this dissertation are listed for future development.

The research conducted in this dissertation represents up-to-date knowledge of both scientific research and implementation experience in the field of e-waste management at the global scale. It can play a significant role in understanding the nature of e-waste problems and identifying critical gaps for improvement. The research outcomes can facilitate the progress of upgrading take-back and treatment systems eco-efficiently for more collection and better treatment in both developed and developing countries.

Chapter 1: Introduction

1.1 Background

1.1.1 Complexity of e-waste and the need for systematic classification

With the ever-advancing development of technology in today's society, electrical and electronic equipment (EEE) have become indispensable to all aspects of people's daily lives. It is estimated that more than 660 types of electronic appliances are currently sold in the global marketplace (Huisman et al., 2012). These products have a variety of attributes, such as price, function, size, inner structure, components and material composition.

When consumers no longer want them, used electronics are removed from households and dwellings. At the time of disposal, these products become waste, which is commonly referred to as "e-waste," "e-scrap," or WEEE (Waste Electrical and Electronic Equipment). The quantity of e-waste has been increasing exponentially, with a global annual growth rate of 4 percent, due to fast technological development and ever-shortening product lifespans (Lundgren, 2012). From the perspective of proper waste management, collection schemes are needed to aggregate e-waste from individual consumers before sending waste appliances to professional facilities for treatment. Because of heterogeneous and complex characteristics, e-waste should preferably not be collected and treated together with the common solid wastes such as municipal waste, metal or plastic scraps. Conventional waste handling methods such as landfills, municipal incinerators and metal recyclers cannot fulfill the treatment requirements necessary to recover all e-waste materials and minimize environmental impacts.

E-waste is a category that is distinguished from other types of solid wastes in the following ways: 1) it covers a wide spectrum of electrical and electronic products with distinct characteristics; 2) it contains recyclable materials (e.g. non-precious metals such as iron, steel, copper, aluminum, etc.; and precious metals such as gold, silver, palladium, platinum, etc.; plastics; and glass); 3) it contains hazardous substances with the potential for toxicity (e.g. lead, mercury, cadmium, batteries, brominated flame retardants, chlorofluorocarbons and other coolants with high potentials for environmental impact).

Consequently, e-waste should be handled separately from other solid wastes. The characteristics of electrical and electronic products vary widely in terms of type, material composition and volume; there is no "one size fits all" model in terms of technical solutions (Stevels, 2012). Differentiation is needed for managing distinct e-waste categories in the following aspects:

> ➢ **Policymaking:** e-waste categories with disproportionate environmental and resource impacts should be managed as priorities.
> ➢ **Collection**: separate collection modes and logistic arrangements are needed for e-waste categories of different sizes and volumes.
> ➢ **Treatment**: treatment technologies need to be dedicated to e-waste categories of different sizes and material compositions (to enable material recovery and to reduce environmental impacts).
> ➢ **Health and safety measures**: occupational protection and emissions control measures are needed specifically for e-waste categories with high potentials for toxicity.
> ➢ **Financing**: most products have a positive end-of-life value from recyclable materials, but they can simultaneously contain materials with negative value (such mercury and lead-glass). Most e-waste categories have a financial deficit between collection and appropriate treatment. Cost of collection and treatment varies significantly by product type, due to different sizes, material compositions and volumes.

To summarize, e-waste is a very complex and heterogeneous waste stream, containing numerous types of products, components and materials. The characteristics of different e-waste categories predominantly determine the differentiation in the configurations of their take-back and treatment systems. Research can play a unique role in identifying and specifying the characteristics of e-waste, according to separate and diverse criteria related to waste management. The present work entails a comprehensive qualitative and quantitative analysis of the function, material composition, value and potential environmental impact of different product types and resulting waste streams. Then numerous types of products are grouped into categories to reduce the complexity of end-of-life management. E-waste will prove to be an emerging and evolving waste type, and research can track its dynamic characteristics as they develop over time. With priority-level e-waste streams, the knowledge gained from conducting e-waste analyses will assist in identifying categories with the most resource potential, market value and environmental impact.

1.1.2 E-waste take-back and treatment systems

In the past 20 years, there has been a substantial increase in attention and initiatives dedicated to managing e-waste on the global scale. This trend has been driven by a quickly growing quantity of e-waste, as well as severe environmental challenges associated with managing it. Policymakers and producers around the world have created specialized systems for collecting and processing e-waste, also known as "take-back systems" or "take-back and treatment systems." Such take-back and treatment systems are generally regarded as "formal" systems. They comply with relevant policies and treatment standards for reducing the environmental impacts from e-waste. These formal take-back and treatment systems are distinguished from informal systems, such as improper collection, uncontrolled export, substandard recycling and the dumping of residuals and leftovers. There are also complementary streams for treating e-waste (such as metal scrap recycling, refurbishment and collection businesses), which do not cause significant pollution but are not reported to the formal systems.

A take-back and treatment system includes two major activities: collection from the final users and treatment (processing it in treatment facilities). There are multiple modes for accomplishing

collection, such as fixed collection points (in municipal sites, schools, stores etc.), door-to-door collection, and special drop-off events. These collection modes are generally combined, and involve different stakeholders in arranging the collection channels and logistics (e.g. governments, municipalities, retailers, producers and consumers). After collection, aggregated e-waste streams are transported to qualified treatment facilities for recycling and disposal of hazardous materials.

Recycling materials from e-waste requires well-built systems that are able to efficiently separate, refine and upgrade different types of materials while minimizing associated environmental impacts. Materials with the potential for toxicity need to be separated and disposed of safely to reduce their environmental impacts. Every stage of the treatment system produces an output material and/or an intermediate stream which is used as an input in a subsequent process, contributing to the treatment and recovery of various materials present in e-waste (Castro, 2005). The technological efficiency of a treatment system is determined by the quality of its input streams as well as the separation and treatment of preceding processes.

E-waste take-back systems began in the developed world, particularly in Europe. The Member States of the European Union (EU) began transposing the EU Waste Electrical and Electronic Equipment (WEEE) Directive into national law in 2003. The directive requires original equipment manufacturers (OEMs) to be responsible for the collection and treatment of end-of-life electronics. An updated version of this directive was adopted in 2012 for transposition in 2013. In recent years, developing countries have begun to follow this lead at a rapid pace. In the pursuit of establishing national take-back and treatment systems, Japan, South Korea and China have developed laws to make e-waste collection and treatment mandatory. North America has also experienced a rapid increase in e-waste legislative activity within the past three years. As of 2013, 25 US states and six (out of 10) Canadian provinces have already passed legislation mandating electronics recycling systems (Gallo, 2013).

Despite the efforts to formalize the collection and treatment of e-waste, there is still a large portion of the e-waste stream that is not fully controlled. For instance, 3.4 million tons of e-waste (TVs, computers and consumer equipment) was ready for management in the US in 2011, but only 25 percent of it was collected and recycled by formal systems (US EPA, 2013). In Europe, around 34 percent of e-waste generated in 2008 was treated by producers' take-back systems (Huisman, 2010). The rest of the e-waste in these countries still ends up in municipal incinerators, landfills or is collected by scrap dealers for refurbishment, recycling or export. When exported to developing countries, these e-waste streams are usually recycled by crude and substandard means due to a lack of technology, infrastructure, resources and trained workforces. Activities such as acid leaching and open burning have caused tremendous environmental hazards to local environments. More specifically, the health of workers has been directly and intensely influenced (Babu et al., 2007; Cobbing, 2008).

Developing countries in the early stages of establishing take-back and treatment systems (such as China and Nigeria) face considerable challenges from informal collectors and backyard recyclers. Existing trading and recycling networks formed by the informal sector usually make it difficult for the formal system to collect sufficient e-waste. With limited investment and administrative resources, it is challenging to construct comprehensive collection networks and

full-scale, high-tech treatment facilities. Therefore, priority has to be allocated to the most important working areas (such as products with high impacts, critical treatment infrastructure), while considering the efficiency of work. The informal sector is not only an issue for developing countries. E-waste issues are globally linked, due to transboundary shipment of e-waste between different regions and continents.

From a geographical perspective, developed and developing countries face different challenges with e-waste. In developing countries, it is important to find the best solutions for collection and treatment while incorporating the informal sector. Furthermore, local situations are often characterized by low labor costs, intricate trading networks and a lack of sufficient investment, technological know-how and environmental policies. Consequently, technological solutions need be properly matched with socio-economic conditions. Such solutions are not necessarily the most advanced from a purely technical perspective, but they reach a balance between the environment, the economy and technology. It usually takes time and effort to gradually grow and develop effective systems. In this dissertation, the relationship between technological implementation and societal factors will be addressed chiefly as a basis of research. Smart and effective solutions can be identified by following the concept of eco-efficiency, which seeks the highest environmental gains for the lowest costs (more resource conservation, less environmental damage and less cost) (Huisman, 2003; Stevels, 2007). In developed countries, collecting more e-waste while curbing the leakage of e-waste for illegal export is expected to be the main target for take-back schemes. For treatment, an optimal balance between treatment efficiency (by increasing the quality of liberated material) and material refinery efficiency also needs to be identified due to high labor costs.

From experiences of take-back and treatment systems in both developed and developing countries, one commonly shared goal is to divert e-waste flows towards qualified treatment facilities through collection channels. With improvement over time, take-back and treatment systems need to collect more e-waste to prevent leakage and treat it with better performance in regards to resource efficiency, the environment and the economy. As an additional goal, the operation of take-back and treatment systems needs to be cost-effective. All past experience has shown that the management of take-back and treatment systems has been much more complicated than was anticipated (Sinha-Khetriwal et al., 2006; Nnorom and Osibanjo, 2008; Gallo, 2013).

Effective collection programs can prevent e-waste from flowing into unwanted channels such as landfills, municipal incinerators and export. The established system usually has to compete with parallel systems in order to harvest most of the e-waste being generated in society. Thus, cost-effective approaches need to be applied in order to reach optimal levels for both resource efficiency and environmental quality. These approaches include constructing new treatment facilities or contracting with existing recyclers, following the designed treatment route. High efficiency in recovering materials with low environmental impacts and low costs is required for eco-efficient treatment systems. Treatment activities should have emission control measures to reduce the impact on the environment, ecology and the general public. In treatment facilities, it is critical to guarantee the health and safety of workers who are under daily exposure to e-waste and its potential hazards. There are many categories of environmental impacts associated

with e-waste and its treatment processes. A systematic analysis of all environmental impact categories can indicate the overall impact of a treatment system. At the same time, specialized studies of health and safety issues in the workplace can shed light on how to improve conditions for the most vulnerable people of concern (workers).

1.1.3 Scientific basis of this dissertation

The establishment of e-waste take-back and treatment systems is primarily driven by relevant laws. The performance of such systems needs to comply with concrete policy targets in most cases. Although it is reasonable that policymakers and producers are responsible for addressing e-waste issues, they often lack the knowledge and practical experience required to create efficient take-back and treatment systems (Gregory et al., 2008). In order to close the knowledge gap, science and engineering studies can play a leading role in investigating the characteristics of e-waste streams, and researchers must also learn from existing systems. This is a necessary, but not totally sufficient, precondition. It is also vital to build a connection between the technical knowledge of systems and societal influences. This will help policymakers and system architects identify critical working areas, and develop both effective technical solutions and policies.

The system for collecting and treating e-waste is highly intricate, with a great variety of processes and stakeholders involved (Figure 1.1). This complex system can be observed as two separate layers of sub-systems: (1) the internal technical system including collection channels and treatment infrastructure; and (2) the external societal system responsible for adopting innovations and managing the technical system with legal frameworks and standards, shaping market structure and conditions, reducing environmental impacts, providing financing and improving public awareness. The performance of a take-back and treatment system mainly depends on the settings of the technical sub-system, such as the configuration of collection points and activities, treatment facilities and technologies. The main stakeholders involved in the technical sub-system are e-waste collectors (municipalities, retailers, logistic companies, etc.) and recyclers. The societal system provides a conditional framework, which influences the planning, design and organization of the technical system. The societal system shapes the architecture of the technical system through a series of socio-economic factors such as take-back policies and instruments, economic rules, market dynamics and environmental standards. There is a wider range of stakeholders involved in the societal sub-system, including system managers and operators of the take-back systems, policymakers, producers, academics, users and the general public.
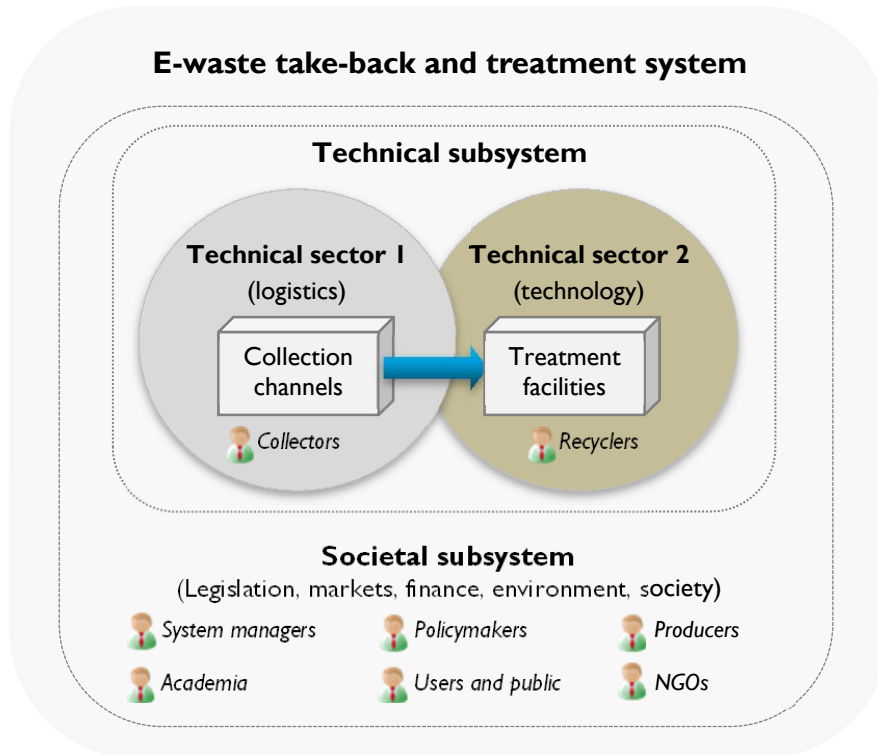
Figure 1.1 Technical and societal subsystems within an e-waste take-back and treatment system

Basically, the technical sub-system is established with expectations from the societal system for lowering the environmental impact of e-waste and/or improving its resource efficiency. These expectations can be substantiated by relevant policy targets and environmental standards. Because e-waste is an emerging and dynamic waste stream, it takes time and effort for the technical system (logistic arrangement and the recycling industry) to gradually adjust to this new waste type and evolve efficient solutions. This development usually entails approaches such as "trial and error," "learning by doing," pilot projects, technical innovation and optimization of management. With such steady growth of the technical system, the gap between actual performance and the original targets can be closed. Consequently, the process is iterative in that expectations and policy goals can also change along with the development of the technical sub-system. With each cycle of development, the quality and performance of the system will continuously increase.

A useful approach for bridging the technical and societal sub-systems is to compare the actual performance of the technical sub-system with societal expectations. Figure 1.2 illustrates a brief roadmap of the system's development by comparing the status quo of the present system with best-case scenarios. This status quo analysis will identify the gaps between the current performance of the technical sub-system and the expected goals, standards and benchmark scenarios defined by the societal sub-system. From a progressive angle, a take-back and

treatment system can be gradually optimized and improved to reach maturity, with better performance regarding the environment and resource efficiency. Consequently, improved performance of the system will also result in a change of costs due to the investment in logistics, manpower and infrastructure needed to manage e-waste flows.

Two major criteria indicate the performance of the technical sub-system: collection amount and treatment efficiency (two axes of the primary coordinate system in Figure 1.2). These two criteria reflect the functional performance of the technical sub-system. Furthermore, two major criteria indicate the performance of the societal sub-system: environmental impact and the economy (two axes of the secondary coordinate system in Figure 1.2). These two criteria represent the feasibility of implementing such systems under social requirements and market rules. Scenarios with good performance in all of these four dimensions can be established as the ultimate objective of the system.

As this best-case scenario rarely happens in one large quantum leap, the development process for constructing this optimum system can be assisted by research. Scientific research can play a significant role in understanding and evaluating the performance of e-waste take-back and treatment systems. This research mainly studies the collection efficiency of take-back schemes and the treatment quality of recycling facilities. The performance research should cover the basics of the technical sub-system, including system coverage (of e-waste categories), mass balances and recycling efficiency. In addition to the technical aspects, the economic and environmental impacts of established systems need to be evaluated. This will help to identify the optimum equilibrium between money invested and environmental gain (or impact prevented). Evaluation of the baseline system can also help to identify leakages of flows and other gaps. This will allow for further improvement by comparing relevant policy targets, standards and benchmarking scenarios. A strong scientific basis will lead to effective policymaking and system operations based on objective fact finding and analysis used to determine intervention areas and to develop plans.

In previous studies, the analysis of e-waste take-back and treatment systems was not conducted in the comprehensive layout, which is presented in Figure 1.1. Existing research either covers a specific topic of the system (such as collection or recycling), or it focuses on a specific aspect (technology, the environment or the economy). Therefore, the established methods and tools are too fragmented to provide a systematic overview of the e-waste complexity and the implemented systems. This will make the research outcomes only valid or successful in a certain aspect. In the practical world, all the important elements in technology, the environment, the economy and other socio-economic conditions collectively contribute to the success of a system. The uniqueness of the present dissertation is to take a multidisciplinary approach by examining and analyzing the interaction and influences among different technical and societal factors. As a result, the conclusions and lessons learned will have a bigger chance of providing feasible and practical solutions to contribute to the development of e-waste take-back and treatment systems in society for all stakeholders.
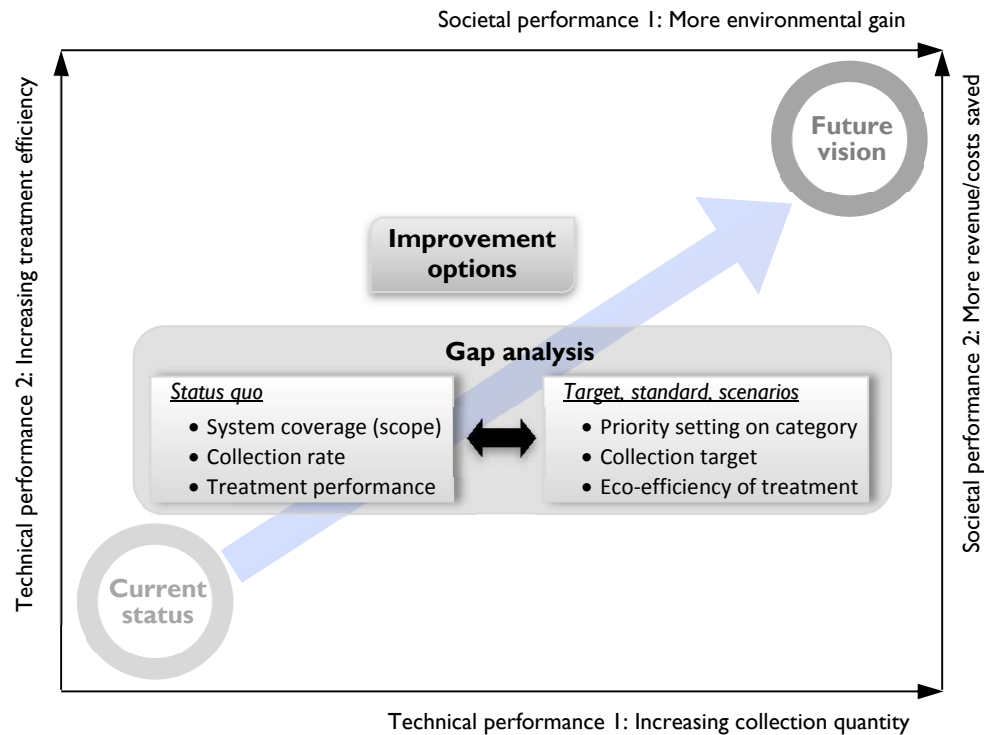
Figure 1.2 Gap analysis to identify improvement options for enhancing the present take-back and treatment system

1.2 Research goal and questions

The fundamental goal of this dissertation is:

To develop methods for evaluating the performance of e-waste take-back and treatment systems in order to identify potential areas for improvement and generate options for enhancing eco-efficiently regarding technology, the environment and the economy.

In order to better deal with the complexity of e-waste categories, those with the most impact will have to be recognized as priorities. For collection, the outcome of this categorization will be useful for identifying the quantity and destinations of e-waste flows, particularly for those that have not been captured by the established system. The evaluation of the treatment system will be functional, as it will examine whether the current treatment technologies and settings are optimal from the environmental and economic perspectives. Starting with such an analysis, technical optimization can be identified for the adaption of specific treatment processes and measures, better selection of machinery and equipment, and the integration of more compatible processes.

The general research goal is further delineated by the following research questions:

1. Which categories of e-waste should be given the highest priority?

E-waste is a very complicated type of solid waste that contains numerous types of products, components and materials. It is important to possess a more thorough understanding of its heterogeneous characteristics. From a managerial point of view, this understanding is needed to better classify e-waste (such as by average weight, volume, resource potential and potential environmental impact). Classification will help to determine whether the take-back and treatment system has processed the waste category with the most impact potential. The enhanced method for classifying e-waste into categories and setting priority categories will be discussed in Chapter 4.

2. What is the best way to determine e-waste generation and collection efficiencies of take-back systems?

This question refers to the mapping of e-waste quantities and various e-waste flows in society. This mapping will enable a comparison to be made between policy targets and actual collection performance and make clear the magnitude of non-collected e-waste streams. When assessing the collection efficiency of take-back systems, it is critical to have an accurate estimation of the overall e-waste quantity generated by all users. Development of an enhanced methodology for improving the accuracy of e-waste estimates will be discussed in Chapter 5.

3. How should the technical, environmental and economic performance of treatment systems for e-waste be assessed, and where can treatment systems be optimized, given specific socio-economic conditions?

This research question focuses on the assessment of the technical performance of e-waste treatment systems, as well as the impact on the economy and the environment. It extends the conventional technical analysis of treatment systems by examining the compatibility of implemented technologies with socio-economic conditions. It helps to identify areas for improvement that will drive e-waste treatment systems in a more eco-efficient direction. This topic will be discussed in Chapters 6, which covers the theoretical analysis, and in Chapter 7, which covers specific case studies.

4. What is the best method for evaluating occupational impacts associated with e-waste recycling?

The presence of hazardous substances in e-waste is well recognized in existing research, but a comprehensive knowledge of the effects of these substances and the resulting risks associated with different treatment options is fragmented. This research question investigates the health and safety impacts of hazardous substances in e-waste. Workers are potentially the most vulnerable to high-dose exposures from, and long-term effects of, pollutants. Necessary methods, the approach for data acquisition and results will be discussed in Chapter 8.

1.3 Research approach and methodologies applied

Due to the complexity of e-waste and e-waste take-back and treatment systems, it is difficult to apply a single methodology to all the research questions proposed. Therefore, multiple

disciplines and methods are required to study the diversity of topics in this complex system. The main dimensions for evaluating system performance in this dissertation include technology, the economy and the environment. To begin, specific disciplines and methods are applied to individual dimensions because of the uniqueness of each dimension. For instance, the activities associated with e-waste collection are fundamentally different from the follow-up treatment processes. The methods used to evaluate environmental impacts are different from those used by a cost analysis. After all the dimensions are studied individually, they need to be analyzed together, because they influence each other. A multidisciplinary approach is taken due to the complexity of e-waste, and this allows for a holistic overview of the collective outcome of all three dimensions.

Before addressing the research questions, a literature review of e-waste management will be conducted in Chapter 2. This will present the relevant research on development and improvement in the area of e-waste take-back and treatment systems. Similarly, a review of the management history of e-waste during the past 20 years in different regions of the world will be outlined in Chapter 3. This will help to validate the relevant research topics based on real-world experiences.

In order to set up a fundamental basis for evaluating the performance of e-waste take-back and treatment systems, it is necessary to thoroughly comprehend the characteristics of e-waste. In Chapter 4, a thorough inventory of all electrical and electronic product types placed in the global market will be compiled using a statistical coding system as the starting point. Then, the available indicators used to represent the characteristics of e-waste will be listed. Based on these criteria, all types of electrical and electronic products will be grouped into different categories qualitatively and quantitatively. Classification will help identify priority products for collection, resource potential, market value and potential toxicity. Finally, a comprehensive classification of e-waste will be presented based on these criteria. These classifications can be used to determine if a take-back system has covered the most critical product categories and allows for harmonization and comparison of results between different countries. The methods and results of the e-waste classification in Chapter 4 have been validated by research projects carried out in several European countries (The Netherlands, Italy and Belgium).

The first step in evaluating the collection efficiency of take-back systems is to compile the quantities collected from all take-back channels. A parallel and challenging task is to accurately estimate the overall e-waste quantity generated by society. Then the magnitude of "leakage," or uncollected e-waste, from the take-back system can be determined. In order to define the research focus, a brief overview of the current methods for e-waste estimation will be discussed in Chapter 5. The approach with the most potential for improvement will be selected as the target method for research (Input-Output Analysis). Then methodological improvements and approaches for improving data quality will be studied collectively in order to enhance the current practices in e-waste generation modeling. After the theoretical options for improvement are offered, the proposed model for e-waste generation will be validated and tested in a case study with concrete and comprehensive datasets. The outcome of this work will enhance the accuracy and reliability of estimating total e-waste quantities from both scientific and administrative perspectives.

E-waste treatment systems seek to both control environmental impacts and recover materials. These two major tasks are commonly fulfilled by a cluster of interconnected recyclers or facilities. It is critical to start by understanding the fundamental configuration of a treatment system (or treatment chain). In view of this, the sequential stages of a treatment chain are analyzed in detail, and technological alternatives in each stage are presented in Chapter 6. This will deconstruct a treatment chain into three interdependent stages for the purpose of analysis: toxic removal, pre-processing and end-processing. In theory, various treatment scenarios can be constructed by combining technical options from each stage along the treatment chain.

After the theoretical analysis of the treatment chain, a case study from developing countries will be employed in Chapter 7 to demonstrate the influence of technology, the economy and the environment on determining technological options for treatment. Treatment scenarios are established based on the previous theoretical setup of treatment chains. Detailed mass balance data will be collected for different scenarios, derived from dismantling trials. Then the technical, environmental and economic performance of these treatment scenarios is evaluated, taking market dynamics and socio-economic conditions into account. The result will provide insights on how to select the best route for treatment by balancing different criteria. In addition to theoretical calculations, the experience of carrying out pilot project for e-waste treatment solutions in developing countries will be summarized and analyzed. This will corroborate the theoretical findings and the conditions needed for success in implementing technologies in real-world socio-economic contexts.

The environmental impact associated with e-waste treatment is a major social concern. Conventional Life Cycle Assessment (LCA) can provide a good indication of the overall impact scores. However, its methodology has not been developed for evaluating the impact on both an occupational and local scale. This dissertation will integrate the basic conception of Risk Assessment into the framework of LCAs in order to assess the occupational health impacts on workers. This will help to improve the understanding of both the severity and acceptance of these impacts at different geographical scales. With a detailed scrutiny of the characterization step in LCA, additional models for the dispersion of pollutants in occupational environments will be added to the conventional LCA procedure. Occupational thresholds for pollutants will be introduced as a baseline to illustrate the severity of the impacts of pollutants. Based on the models and procedures developed, a case study will be conducted to practice the proposed approach.

To briefly summarize the research approach in this dissertation, Table 1.1 displays the application of methods and tools as they relate to different topics. Input-output analysis will be applied to model the dynamics of product flows in society in order to appraise the quantity of e-waste generated. Material flow analysis will be applied to track the mass balances of products, components and substances in different treatment systems. A general cost analysis will serve to classify e-waste according to the market value of embedded secondary materials. Cost analysis will be applied to model the technical cost accrued during treatment processes. Life cycle assessment will be applied to characterize the toxic potential of different e-waste categories and to assess the environmental impacts associated with e-waste treatment processes. The basic

concept of, and elements from, Risk Assessment will be integrated with LCA to quantify the severity of specific treatment activities.

In order to serve the research approach of this dissertation, some existing tools are applied directly: material flow analysis and cost analysis. Some methods and tools are adapted or improved to better fit the scope of research and topics from separate chapters. In Chapter 4, an advanced and multivariate input-output analysis (IOA) will be developed from the existing two-variable IOA method to improve the accuracy of e-waste estimates. In Chapter 8, the conventional Life Cycle Assessment is adapted to assess health impacts in the occupational environment. In addition, a Risk Assessment will be included in the Life Cycle Impact Assessment stage of LCA to evaluate the level of risk associated with a specific impact score.

Table 1.1 Chief methods and tools applied in the different dimensions and topics in this dissertation

Method/ tool	Classification of e-waste	Evaluate collection efficiency	Technical performance of treatment system	Economic performance of treatment system	Environmental performance of treatment system
Input-output Analysis (product)		√			
Material flow analysis (substance)			√		
General/process-based cost analysis	√			√	
Life Cycle Assessment	√				√
Risk assessment					√

1.4 Scope and system boundary

Each chapter addresses different types of electrical and electronic products for separate research topics. All types of electrical and electronic products are analyzed and classified in Chapter 4, in order to sketch a comprehensive overview of their characteristics. In Chapter 5, all categories of e-waste are analyzed in the case study of the Netherlands. A specific focus in this chapter is to obtain the lifespan and quantities of these e-waste products. In Chapter 7, desktop computers are used to evaluate the performance of various treatment scenarios, as they are easily dismantled, complex in structure and material composition, and they contain valuable components and materials. In Chapter 8, LCD (liquid-crystal display) monitors are used as a case study to investigate the health impacts to workers during treatment processes. LCD monitors were selected because they contain mercury in their backlights, which can be easily released during treatment, causing severe health damage.

12

In addition to the focus on product categories, another important focus of this dissertation is the variation of product characteristics as they change over time. This dissertation will stress the importance of tracking the dynamic changes of product weights, lifespans, volumes and even material compositions.

The central area of research for this dissertation is e-waste take-back and treatment systems. Therefore, it focuses exclusively on managing the "formal" system (established by producers or governments), including collection systems and contracted recycling facilities. The informal sector and trading networks are not specifically included in this dissertation. The reason for this is that the informal system is difficult to study with the same academic principles and methodologies applied in this dissertation. Nevertheless, the methods and tools developed here can be still relevant and useful for studying informal collection and backyard e-waste recycling.

The geographical scope covered in this dissertation encompasses both developed countries and developing countries. This will demonstrate the diversity of take-back and treatment systems of e-waste and make the methods and outcomes of this dissertation more applicable to a wider breadth of socio-economic and cultural contexts.

The research described in this dissertation was carried out during 2009 and 2013 and has been supported by two major projects. The section that discusses e-waste characterization (Chapter 4) and the chapter on developing models for estimating e-waste quantities (Chapter 5) are from the project titled "The Future Flows in the Netherlands" (2011-2012). This project applied statistical sources, consumer surveys, market investigation and interviews with recyclers to map e-waste flows in the Netherlands. The content from Chapters 6 and 8 (which analyze e-waste treatment systems and identify optimal treatment routes, respectively) are supported by the project named "the Best-of-2-worlds" (2007-2011). This project aimed to explore the possibility of, and approaches to, establishing a network of global treatment infrastructures as a technical solution for developing countries, combining deep-level manual dismantling and state-of-the-art refineries.

In this dissertation, the term "technology," as in "e-waste treatment technology," does not only refer to technical installations or machinery (as technical hardware). It also reflects broader dimensions such as the scientific and technical knowledge (formal qualifications and experienced-based knowledge), the management methods used to link technical hardware and know-how and physical goods or services (Hillebrand et al., 1994). Based on these criteria, this dissertation defines technologies as not limited to hardware, but also including skills, processes, technological optimization, system integration and network development as potential treatment solutions for e-waste.

Re-use is a very important topic in the end-of-life management of electrical and electronic products. Re-use ranks higher than recycling in the waste hierarchy, and in most cases leads to greater environmental benefits. Re-use affects product lifespans, the amount of obsolete products, collection and trading networks, and the economic performance of the treatment chain as a whole. However, re-use is a different topic from e-waste take-back and treatment. This dissertation mainly focuses on the final stage of the e-waste life cycle, after re-used

products have been disposed and are ready for treatment. This takes place when a refurbished product finishes its service term from the last user. Therefore, the mechanism of, and influences on, re-use are not exclusively analyzed in this dissertation.

1.5 Structure of this dissertation

The structure of this dissertation closely follows the research approach described in the previous section. Figure 1.3 illustrates the arrangement of chapters. The contents of the chapters are described in further detail as follows:

Chapter 1 presents an overarching picture for the whole dissertation, including a brief background of e-waste and its management, research questions and the general research approach. The objectives, scope, system boundaries and target audiences of this dissertation are also introduced here.

Chapter 2 presents a comprehensive literature analysis of current e-waste-related research. The emphasis is devoted to research progress on e-waste take-back and treatment systems. Research gaps will be identified based on a critical analysis of the literature.

Chapter 3 provides an overview of global e-waste take-back and treatment system initiatives throughout the past 20 years. Key research topics relevant to daily management and system improvement are summarized. Combined with the gap analysis made in Chapter 2, the research topics for this dissertation are confirmed.

Chapter 4 presents a comprehensive sketch of the characteristics of e-waste. All types of electrical and electronic equipment (EEE) are compiled, based on international statistics codes of goods and commodities. EEE, or e-waste items, are classified into categories based on their original function, material composition, average weight, resource potential and potential for toxicity. Built from these separate categorization results, a comprehensive and multi-purpose classification is compiled to address different dimensions of take-back and treatment systems.

In Chapter 5, a sophisticated input-output model will be developed to enhance the accuracy of e-waste estimates. This multivariate model can make the best use of all available datasets and consolidate and improve data quality for product sales, stocks and lifespans. This consequently improves the quality of collection efficiency calculations for take-back systems. A case study from the Netherlands, which mapped national e-waste flows, is applied in order to practice and validate the proposed method.

In Chapter 6, a detailed analysis of the structure of the e-waste treatment chain is made, taking each stage of the process into account. In this way, various end-of-life scenarios for electronics can be constructed based on different technological alternatives in each treatment stage. The technical performances of treatment scenarios are briefly discussed in this chapter.

Chapter 7 extends the performance evaluation of treatment systems from the technical perspective (Chapter 6) into the realms of the economy and the environment. Methods for carrying out such assessments are proposed and improved upon. This approach is validated by a case study assessing a series of dismantling trials of major home appliances and IT products.

Based on the findings of this case study, more eco-efficient routes for e-waste treatment are proposed for developing countries. The experience of developing pilot projects further underscores the key factors necessary for technological improvements to be implemented under specific cultural and societal conditions.

Chapter 8 focuses on the methodology used to evaluate health impacts on workers in the occupational environment. The basic element of Risk Assessment is integrated with the conventional LCA framework in order to better understand the severity and risks for a specific activities and processes. Additional environmental models and steps for gathering data are proposed in order to make such evaluations feasible. A case study of LCD monitor recycling is applied to examine and verify the proposed method.

Chapter 9 presents recommendations for take-back and treatment system performance improvements. Tangible advice is provided for individual stakeholders. Relevant research topics for future model development, data gathering and project implementation are also proposed.

Chapter 10 summarizes the findings and outcomes from the research presented in this dissertation.

```
                    ┌─────────────────────┐
                    │    Introduction     │
                    │     (Chapter 1)     │
                    └─────────────────────┘
                              ↓
    ┌──────────────────────────────────────────────────┐   Status quo analysis
    │  ┌──────────────────┐   ┌──────────────────┐      │          and
    │  │ Literature review│↔  │ Experience review│      │   problem definition
    │  │   (Chapter 2)    │   │   (Chapter 3)    │      │
    │  └──────────────────┘   └──────────────────┘      │
    └──────────────────────────────────────────────────┘
                              ↓
    ┌──────────────────────────────────────────────────┐   Modeling
    │  ┌──────────────────────┐                         │   Theoretical analysis
    │  │ Classification of    │                         │   Empirical study
    │  │ e-waste (Chapter 4)  │──┐                      │
    │  └──────────────────────┘  │                      │
    │  ┌──────────────────────────┐  │                  │
    │  │ E-waste quantity and     │  │                  │
    │  │ collection efficiency    │──┼──┐               │
    │  │      (Chapter 5)         │  │  │               │
    │  └──────────────────────────┘  │  │               │
    │  ┌───────────────────────────────────────────┐    │
    │  │          Treatment performance            │    │
    │  ├───────────────┬──────────────┬────────────┤    │
    │  │Treatment chain│Performance   │Occupational│    │
    │  │ (Chapter 6)   │evaluation    │impact      │    │
    │  │               │(Chapter 7)   │(Chapter 8) │    │
    │  └───────────────┴──────────────┴────────────┘    │
    └──────────────────────────────────────────────────┘
                              ↓
                    ┌─────────────────────┐
                    │   Recommendations   │
                    │     (Chapter 9)     │
                    └─────────────────────┘
                              ↓
                    ┌─────────────────────┐
                    │     Conclusions     │
                    │    (Chapter 10)     │
                    └─────────────────────┘
```

Figure 1.3 Structure of this dissertation

This dissertation is relevant not only to the scientific community in the field, but also to people who are concerned about, and connected to, the daily work of e-waste take-back and treatment. Each chapter addresses different audiences interested in specific applications of these scientific findings. Such audiences include policymakers, operators and managers of take-back systems, recyclers and producers.

Table 1.2 displays the main content and target audiences of each chapter. The primary audiences include researchers who study the magnitude and characteristics of e-waste flows, the treatment performance of facilities, and the environmental policies that improve system performance. Policymakers will learn the methods for developing effective e-waste take-back legislation and define appropriate collection targets, treatment standards and even financial schemes. The operators and managers of take-back and treatment systems can also benefit greatly from this dissertation. The worldwide management experience of these actors will provide them with insights that will be helpful for aligning the activities of various stakeholders and enforcing the system's rules and regulations. The results of e-waste classification will help

them to streamline and simplify registration and reporting. Recyclers can improve their operations by making use of the findings regarding improved system eco-efficiency and workplace safety. Producers can better understand the complexity of e-waste collection and treatment systems. These findings can also be useful for product designers and producers' take-back programs.

Table 1.2 Overview of dissertation contents and reader's guide

Chapter	Section	Key content	Target audience(s)
2	2.2 2.3	Review of e-waste related research Research related to take-back and treatment systems	Researchers of e-waste management
3	3.1 3.2	Global practice of e-waste management Case study: Managing e-waste in EU and China	Policymakers, operators of take-back systems, researchers
4	4.1 4.2 4.3	Criteria for EEE/e-waste classification Classification of e-waste by separate criteria Integrated classification with all criteria combined	Researchers of e-waste management Researchers of e-waste flows System operators
5	5.2 5.3	Multivariate model for e-waste estimation Case study: quantify e-waste flows in the Netherlands	Researchers of e-waste flows and quantities, policymakers Idem
6	6.2	Structure of treatment chain and various scenarios	Researchers of e-waste recycling
7	7.2 7.3	Performance evaluation of treatment Case study: technology development in China & India	Researchers of e-waste recycling Policymakers, recyclers
8	8.3 8.4	Assess occupational impact with LCA Case study: treatment of LCD monitors	Researchers of Risk Assessment and Life Cycle Assessment (LCA)
9	9.1 9.2 9.3 9.4 9.5	Implications for developing effective legislation Improvement options for recycling industry Improvement options for developing countries Recommendations for stakeholders Recommendations for future research	Policymakers Recyclers Policymakers and recyclers in developing countries Policymakers, recyclers, producers, system operators Researchers

1.6 Research outcome

The outcome of this dissertation can contribute to a better understanding of the heterogeneous characteristics of e-waste, the methods for evaluating performance of its take-back and treatment systems, and it will pinpoint solutions for improving system performance. More research outcomes from this dissertation include:

- Thorough understanding of the characteristics of e-waste and a comprehensive classification of e-waste in order to set managerial priorities for take-back and treatment systems;
- Multivariate method of advanced input-output analysis used to enhance the accuracy of estimating e-waste quantity;
- Better understanding of the structure of, and alternate scenarios for, the e-waste treatment chain;

- Methods for identifying eco-efficient treatment routes under specific socio-economic conditions;
- Improvement of LCA methodology to include occupational health impacts and risks assessments.
- Recommendations for policymakers, operators and managers of e-waste take-back and treatment systems, producers and recyclers.

1.7 References

Babu, B. R., et al. (2007). "Electrical and electronic waste: a global environmental problem." Waste Management & Research **25**(4): 307-318.

Castro, B. (2005). Design for resource efficiency. Department of Industrial Design. Delft, the Netherlands, TU Delft. **PhD thesis**.

Cobbing, M. (2008). Toxic tech: not in our backyard, uncovering the hidden flows of e-waste.

Gallo, D. T. (2013). Broad Overview of E-Waste Management Policies in the U.S., U.S. Environmental Protection Agency.

Gregory, J., et al. (2008). E-waste Take-Back System Design and Policy Approaches. Solving the E-Waste Problem (StEP) White Paper. Bonn, Germany, United Nations University.

Hillebrand, W., et al. (1994). Strengthening technological capability in developing countries: lessons from German technical cooperation, German Development Institute.

Huisman, J. (2003). The QWERTY/EE Concept, quantifying recycability and eco-efficiency for end-of-life treatment of consumer electronic products. Delft, the Netherlands, Delft University of Technology. **PhD thesis**.

Huisman, J. (2010). WEEE recast: from 4kg to 65%: the compliance consequences, UNU Expert opinion on the EU WEEE Directive. Bonn, Germany, United Nations University.

Huisman, J., et al. (2012). The Dutch WEEE Flows. Bonn, Germany, United Nations University, ISP-SCYCLE.

Lundgren, K. (2012). The global impact of e-waste: Addressing the challenge. Geneva, Switzerland, International Labour Organization.

Nnorom, I. C. and O. Osibanjo (2008). "Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries." Resources, Conservation and Recycling **52**(6): 843-858.

Sinha-Khetriwal, D., et al. (2006). "Legislating e-waste management: progress from various countries." elni Review **1+2**: 27-36.

Stevels, A. (2007). Adventures in ecodesign of electronic products 1993-2007. Delft, the Netherlands, Delft University of Technology.

Stevels, A. (2012). The present recast of the WEEE Directive. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

US EPA (2013). Municipal solid waste in the United States: 2011 facts and figures, United States Environmental Protection Agency.

Chapter 2: Literature review on take-back and treatment of e-waste

E-waste management is a highly complex topic that involves a great variety of tasks ranging from the prevention, characterization, collection, treatment and disposal of residuals. The movement of end-of-life electronic products is not confined by national borders or economic regions. Global trading networks of e-waste, and different treatment practices in developed and developing countries, further complicate the situation. Therefore, it is a big challenge to identify and implement best practices, or at least acceptable practices, for all regions. Due to this intrinsic complexity, an integrated approach is required to understand and manage global e-waste streams, as is a thorough understanding of the pertinent technical, environmental, social, economic, legal and regulatory issues involved. Throughout the past two decades, scientific research on e-waste management has played an important role in underpinning sensible policymaking and managerial decision-making. Most of the studies conducted were driven by political and social interests in order to better understand e-waste streams and determine effective measures for managing them. This research forms a solid and factual basis for legislation and management, as opposed to a collection of beliefs and opinions from earlier period (1995-2005).

This chapter provides a literature review of e-waste management research for publications dated before July 2013, with a special focus on performance assessments of take-back and treatment systems. The beginning of this chapter will discuss e-waste background information and e-waste characteristics. A systematic analysis of the current e-waste issues is also presented. Then a comprehensive overview of current e-waste research is introduced, structured according to separate research topics. As discussed in Chapter 1, the major research interest of this dissertation is the performance of "formal" e-waste take-back and treatment systems. Therefore, the analysis of literature is limited to three dimensions: the characterization and classification of e-waste, the quantification of collection efficiencies and the assessment of treatment performances. This division of topics is made according to the complexity of e-waste streams and two major tasks of the take-back and treatment systems.

The research topic of this dissertation was chosen to fill the gaps from previous research. These issues are expected to generate new knowledge of topics related to e-waste management to facilitate the formulation of sensible e-waste management for policymakers, system architects and managers of take-back and treatment operations.

Chapter 3 will relate practical experiences from take-back and treatment systems in different countries. A critical analysis of this development will add value to the research topics identified in Chapter 2.

2.1 Introduction

2.1.1 Definition and characteristics of e-waste

E-waste is generally defined as waste or end-of-life electrical and electronic equipment (EEE), which has ceased to be of any value to its original owner and has been discarded (Widmer et al., 2005). E-waste encompasses a broad and growing range of electronic devices as well as embedded components and substances (OECD, 2001; Puckett et al., 2002). The definition of "waste" also includes used or obsolete electronics destined for re-use, refurbishment, resale and recycling. Because of international shipping, reusable electronics that can be refurbished into new products are not regarded as e-waste, but as commodities (Salehabadi, 2013). However, used equipment destined for re-use will eventually become waste after it is consumed by its final user. Because there is simply a delay of time before re-used electronics become obsolete and require treatment, this topic falls outside scope of this dissertation. The full focus will be on take-back and treatment systems for e-waste that has been discarded by its last owner.

In general, the definition of e-waste in existing literature is similar to "discarded electrical and electronic devices." But there is no standard or widely accepted description for all relevant products, and the scope of e-waste (for mandatory take-back and treatment) varies greatly by country. Due to the extensive use of EEE in all aspects of modern life, there are an enormous number of products with different functions, types and brands (more than 660 types, as mentioned in Chapter 1). These products come from such differing sectors of society as medicine, transportation, education, health and personal care, food, communication, security and society at large (Schluep et al., 2009). In order to establish proper e-waste management strategies, the first step is to identify the entire catalogue of equipment– currently available products, as well as those from past markets. So far there is very little literature that focuses on a comprehensive and chronological compilation of all EEE types. Without an exhaustive inventory, further identification of critical equipment for e-waste management is hampered. Furthermore, systematic classification of all EEE and e-waste can support the present research and improve efficiencies in registration and reporting for compliance schemes.

E-waste is heterogeneous not only because of its variety of primary functions, but also because of different product sizes, weights and material compositions. E-waste covers a wide spectrum of product weights ranging from less than 100 grams (lamps and small IT equipment), up to more than 80 kilograms (professional appliances) (Huisman et al., 2008). Regarding material compositions, modern electronics can contain up to 60 different elements (Schluep et al., 2009). Many of these materials are recoverable, which allows for the extraction of virgin materials, and they usually have positive market values. Recoverable materials generally include all types of metals, plastics and glass. In contrast, other materials have high potential for toxicity and other environmental impacts, and these materials are regarded as hazardous if they are improperly disposed (Sepúlveda et al., 2010). The concentrations of these recyclable and potentially toxic materials vary greatly from product to product (Matsuto et al., 2004; Oguchi et al., 2011; Oguchi et al., 2012). This situation demands that e-waste treatment accomplish two tasks: recover materials and control the potential for toxicity and emissions. There is a natural difference between the methods used to process products in "bulk waste streams" for general material

recycling and the specialized processes used to recover specific materials and components and/or capture hazardous materials. The methods used to accomplish these two goals will vary from product to product. It is therefore useful to classify e-waste items by their "treatment priorities," according to their specific characteristics. In the existing literature, analysis of e-waste characteristics is rather sporadic and selective, and it does not cover all product types. The topic of e-waste classification will be further explored and discussed in Chapter 4.

2.1.2 The e-waste problem

Regarding the complexity of e-waste characteristics, the "e-waste problem" has three main dimensions:

1) **Growing diversity and increasing quantities**. E-waste is one of the fastest-growing waste streams. The global amount of e-waste will increase from 20 million tons in 1998 to an estimation of 50 million tons in 2014 and 2015 (Widmer et al., 2005; StEP Initiative, 2010). This phenomenon is caused by continuous technological innovation, product miniaturization, rapid replacement and lower sale prices caused by improved economies of scale in production in both developed and developing countries (Kuehr, 2012). E-waste is usually regarded as a special type of solid waste (sometimes as hazardous waste), so this substantial volume of obsolete equipment poses a great challenge to waste management (EEA, 2003). The immature recycling industry and non-existence of professional treatment facilities in developing countries are the main barriers to handling emerging e-waste streams around the globe.

2) **Environmental concerns and chemical hazards**. Many types of EEE contain substantial amounts of hazardous substances such as heavy metals (e.g., mercury, lead, cadmium, chromium, etc.), halogenated compounds (chlorofluorocarbon/CFC, polychlorinated biphenyls/PCB, polybrominated diphenyl ethers/PBDEs, etc.), and others like toner and radioactive substances. If improperly managed, these substances can cause significant harm to human health and the environment (Tsydenova and Bengtsson, 2011). In addition to the direct emissions from hazardous substances contained in e-waste, uncontrolled disposal and crude recycling activities can generate secondary and tertiary emissions (Schluep et al., 2009). Hazardous reagents can be used and toxic substances can be formed through such processes (Sepúlveda et al., 2010), such as the cyanide and aqua regia used in the backyard leaching of circuit boards.

3) **Resource potential**. Apart from the substances with potential toxicity, e-waste contains a variety of recyclable materials with great resource potentials. Such materials include ferrous and non-ferrous metals, precious metals, glass and various forms of plastics. Inefficient recycling of these materials will lead to a loss of secondary resources and indirectly increase mining for primary material production.

These three dimensions pose challenges to e-waste management systems. In order to reduce the potential environmental impact of e-waste and preserve resources, policymakers and producers around the world have created specialized systems to collect and process e-waste, known as "take-back and treatment systems" (Gregory et al., 2008). The rest of this chapter will present an overview of the existing literature that discusses e-waste flows and evaluates the performances of established take-back and treatment systems.

2.2 Literature overview of e-waste handling systems

This section first presents an overarching analysis of the existing research related to e-waste management with an emphasis on e-waste handling systems. It addresses all aspects of informal and formal systems for handling e-waste. Next, the literature analysis focuses on the performance evaluation of take-back and treatment systems. Progress in e-waste take-back and treatment research is reviewed for current methods, tools and body of knowledge, along with the limits to further development.

2.2.1 Overview

Based on the different types of e-waste handling systems, research on e-waste management can be generally divided into two separate groups: 1) status quo analyses and upgrades of the existing (autonomous or informal) e-waste handling systems; and 2) assessments and developments of specialized take-back and treatment systems. Both groups of research study the collection and treatment of discarded electronic products. The autonomous or informal system is mainly driven by the economic value of discarded electronics. The scope of products that can be collected is rather selective, and treatment costs are usually low. The formal system, on the other hand, mostly originated from the introduction of national regulations and legislation. The formal system focuses both on environmental quality and resource efficiency in the pursuit of reaching optimal eco-efficiency. The activities of the formal system aim to minimize the loss of e-waste to unwanted waste channels such as landfills, backyard recycling, etc.

The autonomous e-waste handling system is often characterized as "informal," "complementary," uncontrolled" or even "cherry-picking." Such systems are usually beyond the administration of formally established systems and legislation. Informal systems exist in both developed and developing counties, and they engage in the collection, import, export and recycling of e-waste (Widmer et al., 2005; Eijsbouts, 2008; Chi et al., 2011; Huisman et al., 2012). Informal systems mainly serve to extract valuable elements from e-waste, and environmental considerations can be greatly compromised in the process. These autonomous system can also be destinations, such as municipal channels (landfills and incinerators), which lack specialized treatments, metal scrap collection facilities and recycling facilities (which do not register or report to formal systems). Formal take-back and treatment systems, by contrast, have established collection channels and treatment facilities for responsibly processing e-waste. They minimize environmental impacts and improve resource efficiencies. Formal systems are usually established in order to comply with national take-back legislation and/or to fulfill producers' responsibilities. In reality, the informal system and formal take-back and treatment systems are interlinked and influence each other in many ways, such as by competing for access to e-waste and by shaping market conditions.

Figure 2.1 presents an overview for the division of research topics and corresponding academic disciplines in these two separate e-waste handling systems. It shows that a variety of disciplines are involved with, and contributes to, effective e-waste management.

There are three layers of research work relating to formal take-back and treatment systems: the technical development of collection channels and treatment networks, the comprehensive

assessment of system performance and policy development. To develop collection channels and logistics, the disciplines of environmental management and social science are applied to examine the best reverse logistic plans, collection quantities and user behaviors. To develop treatment solutions, the disciplines of environmental engineering and science, metallurgy, mechanics and materials science are usually applied to investigate specific treatment processes and their effectiveness. In order to evaluate the established take-back and treatment system as a whole, environmental science is usually applied to map system flows between e-waste generation and various e-waste destinations. Combined with environmental engineering, economics and social sciences, environmental science is also used to evaluate the technical, economic, environmental and social impacts of formal systems. For the purpose of legislative development, policy studies, law and environmental management can assess the implementation of legislation and propose methods for improving it.

There are also three layers of research relating to informal systems: transboundary shipment, collection and treatment. Transboundary shipment is reviewed by legal and policy studies, which analyze the implementation and development of national legislation and international conventions that control illegal shipment. Social science, geology, economics and environmental science have been applied to map shipment routes and quantities, as well as the specific mechanisms for trade. Environmental management and social science research has been applied to investigate the societal background, collection networks, market mechanisms and flows of e-waste (Eugster and Fu, 2004; Geering, 2007). There are a great number of environmental and social studies that investigate the environmental hazards and damage associated with substandard recycling in typical sites of developing countries.

Although the research topics that investigate these two systems appear separate in Figure 2.1, the knowledge from each is relevant to the other. For instance, a study of e-waste generation can provide baseline figures for the flows in both formal and informal systems. Sections 2.2.2 and 2.2.3 will separately analyze the progress of research in both of these systems.
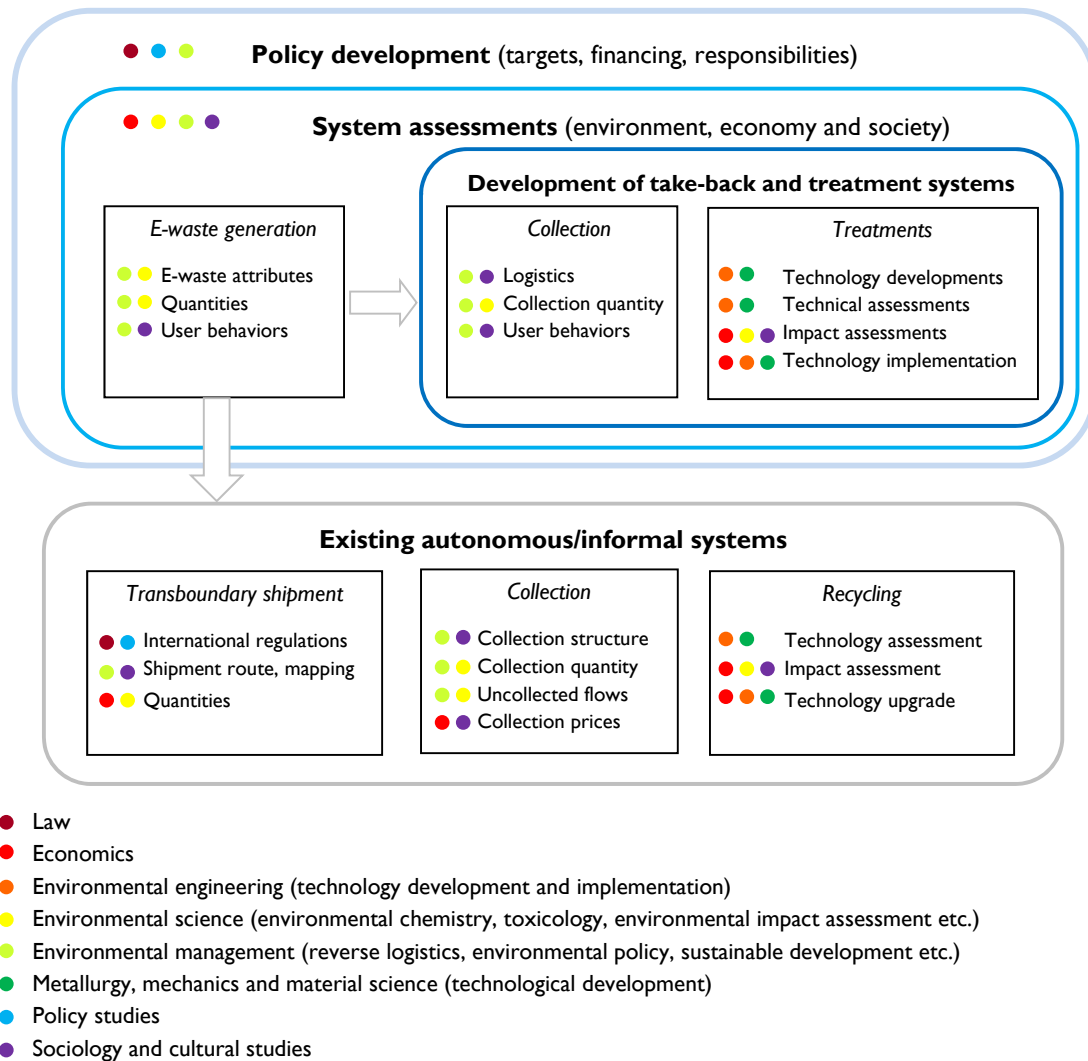
Figure 2.1 Existing e-waste management research and corresponding academic disciplines

2.2.2 Research on take-back and treatment systems

Research related to formal take-back and treatment systems can be divided into the following three areas: the technological development of the take-back and treatment systems (technical aspect), the systematic performance evaluation of established systems (which addresses the environmental, economic and social aspects) and policy development related to e-waste management (which address legislative and societal aspects).

The development-oriented studies conduct experiments, pilot projects and tests on innovative approaches and techniques to establish efficient collection schemes and treatment technologies. As an emerging waste type, e-waste is still relatively new for most solid waste collectors and recyclers. There are many of technological studies that focus on developing optimal reverse

logistics, efficient treatment techniques and machines and facilities for different types of e-waste and embedded materials. The fundamental basis for this technical development has come from logistics, metallurgy, mechanics, chemistry and physics. Most pre-processing studies focus on the development of processes that liberate materials from waste products, especially by mechanical size reduction and sorting. Pre-processing studies have also helped define different product categories by their distinct end-of-life characteristics: large household appliances, small household appliances and consumer equipment, IT equipment, monitors and screens, cooling and freezing appliances, and lamps. End-processing research focuses on technological developments, innovation in refineries and the treatment of fractions such as printed circuit boards (Hagelüken, 2006; Veit et al., 2006; Sheng and Etsell, 2007; Yoo et al., 2009; Zheng et al., 2009; Long et al., 2010; Zhou and Qiu, 2010; Yamane et al., 2011), Li-ion and Ni–MH batteries (Xin et al., 2009; Li et al., 2010; Huang et al., 2011; Provazi et al., 2011), CRT lead-glass (Andreola et al., 2005; Andreola et al., 2008; Chen et al., 2009; Mostaghel and Samuelsson, 2010), etc.

Assessment-oriented studies explore models and indicators to evaluate the performance of take-back and treatment systems. From technical, environmental, economic and societal perspectives, these studies map e-waste sources and flows in society and evaluate collection rates and treatment efficiencies. Such comprehensive assessments require the fundamental knowledge of, and methods from, environmental science, engineering and management, economics and social sciences. This type of research helps to identify operational equilibrium and determines how the environment can be best served while minimizing cost (eco-efficiency). It can draw comparisons between systems to identify the best one and identify gaps and areas for improvement. The result of this type of research is also instrumental for comparing actual system performance with expected policy targets and for checking compliance with e-waste take-back legislation.

Part of the research on take-back and treatment systems is driven by policy development, and it is indispensable to keeping track of and improving the implementation of domestic e-waste-related legislation. Such studies evaluate collection rates and treatment efficiencies for mandated systems and assess their associated impacts on the environment, the economy and society. As a result, appropriate financial planning and policy instruments for efficient management of e-waste streams can assist in policy development. For instance, the WEEE Review study is a comprehensive report that evaluates the implementation of the WEEE EU Directive between 2003 and 2007 (Huisman et al., 2008). The study appraised the environmental impact, technical and administrative costs, and stakeholder responsibilities as a result of legislation implementation. It also proposed suggestions for further policy adjustments and improvements. Similar research has also been carried out in Switzerland (Khetriwal et al., 2009), Japan (Tasaki et al., 2005; Aizawa et al., 2008; Yoshida et al., 2009; Yoshida and Yoshida, 2012) and South Korea (Chung and Murakami-Suzuki, 2008).

2.2.3 Research on informal systems
Research on informal e-waste take-back and treatment systems mainly focuses on three major topics: collection networks and quantities, trans-boundary shipments and treatment performances. These studies make an effort to track illegal and complementary flows and

streams, together with the economic and social drivers behind them. This type of work has been supported by social sciences (law, economics, sociology, anthropology and policy studies) and environmental sciences (environmental chemistry, toxicology and environmental impact assessment). Apart from quantifying the flows, there is also a substantial amount of research that investigates the methods by which uncontrolled e-waste is eventually processed. Technical and environmental studies have produced assessments of the recycling efficiencies, environmental impacts, ecological damage and health risks associated with substandard treatment of e-waste.

An increase in the amount of discarded products that are processed by the existing autonomous or informal system correlates directly to a decrease in collections by the formal take-back system. Complementary collection streams, trading and export, pose financial and market challenges for established take-back and treatment systems. International trading networks and multiple recycling destinations can create loopholes that further undermine domestic "formal" systems, creating marketplace competition. The existence of informal or non-contract recyclers can be more cost-effective than the formal recyclers, but informal or non-contract recyclers may cause resource losses and environmental damage. Studies have emerged from many countries, both developing and developed, to analyze the competition between formal and informal systems (Yang and Lu, 2005; Eijsbouts, 2008; Yang et al., 2008; Yoshida et al., 2009). A typical study is the comprehensive mapping of e-waste flows in a specific country from their sources of origin to their final treatment destinations (Oguchi et al., 2008; Yoshida et al., 2009; Steubing et al., 2010; Huisman et al., 2012; Magalini et al., 2012; Yoshida and Yoshida, 2012; Wielenga et al., 2013). Such national studies are further supported by transboundary research on interregional trading networks and e-waste quantities (Terazono et al., 2004; Tong and Wang, 2004; Lepawsky and McNabb, 2010; Yoshida and Terazono, 2010; Miller et al., 2012; Salehabadi, 2013). Numerous studies have investigated the pollution and ecological damage resulting from unsophisticated e-waste treatment in global dumping sites such as the major international destinations for e-waste in Guiyu, China; Taizhou, China; and Bangalore, India (Puckett et al., 2002; Brigden et al., 2005; Wong et al., 2007; Wong et al., 2007; Cobbing, 2008; Leung et al., 2008; Ha et al., 2009; Xing et al., 2009; Gu et al., 2010; Sepúlveda et al., 2010; Gao et al., 2011).

Policy-oriented studies help to define optimal regulations and instruments for managing e-waste for specific countries and regions. These studies assess proper policy targets for collection and treatment, as well as the allocation of responsibilities and concrete tasks for stakeholders; they define cost-effective financing plans by comparing best-case principles with policy alternatives. Policy-oriented research requires knowledge from policy analysis, program evaluation, sociology, philosophy, economics, geography, law, political science, environmental planning and public administration.

2.2.4 Summary
The review of e-waste-related research indicates its multidisciplinary nature, drawing from such diverse disciplines as environmental studies (science, engineering and management), metallurgy and material sciences, economics and social sciences. This trans-disciplinary synthesis is a result of the comprehensive knowledge required to understand the multifaceted issues that govern e-waste at a societal level (Lawhon et al., 2010). At the technical level, a single academic discipline may suffice for the analysis of a specific objective or research goal. However, sustainable

management of e-waste under a social context should consider a broader range of impacts and consequences for the environment, society, and the economy. These three main considerations have the potential to conflict with each other at the seams where different value systems and societies meet. Therefore, in order to find a balance for optimal management, interpretations and collaboration from multidisciplinary studies are critical. This variety of disciplines can guide the data-gathering, analysis and help draw conclusions throughout the research processes.

This dissertation's main research focus is the assessment of established take-back and treatment systems. This work is primarily derived from environmental science and engineering, combined with the basic knowledge of economics, management and other social sciences. A multidisciplinary approach will help develop proper policies and strategies for establishing take-back systems – either from scratch, or by improving the performance of existing systems. Although the research on informal sectors will provide relevant information on complementary streams, the methodology for researching and the approach to studying the performance of formal systems is still relatively independent. Also, the technical development of collection channels, reverse logistics and new treatment technologies are beyond the scope of assessing existing systems, and so these topics do not fall within the focus of this dissertation.

The literature review for the remaining part of this chapter will further elaborate on three major topics: 1) the definition and classification of e-waste; 2) the methods for evaluating e-waste collection rates; and 3) the methods for evaluating the technical, environmental and economic performance of treatment systems. This will directly answer the three questions: 1) Which categories of e-waste should be given the highest priority? 2) How much e-waste has been formally collected and treated, compared with the total amount produced by society? 3) What is the optimal and most eco-efficient treatment technology for specific types of e-waste. This will again contribute to the ultimate goal of e-waste management: collect more and treat better.

2.3 Review of research evaluating the performance of e-waste take-back and treatment systems

In order to evaluate the performance of established take-back and treatment systems, it is critical to assess the scope of the products involved, collection rates and treatment efficiencies. Therefore, this chapter will elaborate on the methods used to appraise the collection and treatment systems. It starts with a literature analysis to characterize various e-waste categories in order to identify managerial priorities. Then, it summarizes the studies calculating collection efficiency of take-back system and compliance schemes. A special focus is given to the methods used to estimate e-waste generation. Finally, the research evaluating the performance of treatment processes is reviewed, including the technical performance of material recovery and the associated environmental and economic impacts.

2.3.1 Research on characterization and classification of e-waste

E-waste possesses generic characteristics, such as original product types and functions, average weight, material composition, etc. But many country or region-specific characteristics exist such as quantity, value, (product) lifespan, market purchase pattern and disposal behaviors. Before

constructing a take-back and treatment system for e-waste, it is good have a comprehensive characterization and classification of e-waste to fully understand this type of solid waste.

Considering the complexity of e-waste, it is useful to classify it into groups of products that pose similar risks to the environment and/or possess similar resource potentials. This work will facilitate separate management and disposal of different categories, which will improve operational and administrative efficiencies in registration, monitoring and reporting. Existing studies and policies have adopted different approaches to classifying EEE and e-waste. The most recognized classification of EEE is Annex I of the EU WEEE Directive (European Union, 2003). In this legislation, EEE is classified into 10 product categories mainly according to their original use function, such as large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lamps, tools, etc. However, this function-based classification approach cannot perfectly segregate products according to their environmental and economic impacts. For instance, in the category of large household appliances, CFC-containing cooling and freezing equipment is expected to have a higher impact than other equipment in the same category. As a result, treatment technologies are quite different for these products, even though they are in the same functional category. In practice, e-waste streams are collected, sorted and treated in a manner that is different from these 10 regulated categories. One study, upon reviewing this directive, has proposed classifying EEE into six categories based on their end-of-life characteristics in the European take-back schemes (Huisman et al., 2008). The classification proposed by this study was adopted by the new/recast EU WEEE Directive in 2012. In this report, the central conception of product evaluation is described as QWERTY, which was developed to determine environmentally weighted recycling scores, as opposed to weight-based recycling scores for EEE (Huisman, 2003; Huisman et al., 2003). It takes into account the "environmental value" of secondary materials and the environmental burden of all materials during end-of-life treatment. Accompanying the environmental analysis, the cost analysis of treatment processes provides extra information about the economic performance of products. By combining and balancing environmental and economic priorities, the concept of eco-efficiency can be applied to identify the categories of e-waste. This analysis indicates that it is even necessary to define separate targets for collection and treatment by category, due to the potential for distinct impacts. Nevertheless, the analysis in this study is based on managerial experiences and data from European treatment facilities. Further justification (research outside of Europe) is required to analyze the characteristics of EEE as well as the societal backgrounds that might affect treatment techniques in different countries.

In addition to the European studies, Dahmus and Gutowski (2007) have proposed a method for classifying EEE according to its material recycling potential. The indicator "material mixing" was created to evaluate the collective effect from the number of recyclable materials and their concentrations in a product. One case study plotted the material mixing of various products against their market values and actual recycling rates in the United States. The results showed an apparently remarkable reduction in the recyclability of products, primarily due to greater material mixing. However, this research only assessed 20 products, and it needs to be extended to more EEE. Furthermore, the recycling rates of products greatly depend on the collection

schemes and treatment technologies available, which may lead to distinct conclusions in different countries. Oguchi et al. (2011) and Oguchi et al. (2012) have classified 21 types of products according to the presence of secondary metal resources and toxic metals. The main criteria for classification were the concentration of the target material and the total amount of that material that was contained in relevant types of end-of-life EEE within Japan per annum. In addition, the average weight and annual generation of waste EEE were used to classify 48 types of waste EEE by their physical characteristics. These two studies have provided valuable insights into the material compositions of various EEE and contributed to the systematic classification of e-waste. However, the quantity of obsolete EEE in Japan does not indicate much about the generation of e-waste in other countries, because the income levels, market patterns and demographics vary by country. Country-specific indicators need to be used in order to analyze the universal characteristics of obsolete EEE to obtain the widest-possible application for a method of classification.

In pursuit of a comprehensive and objective understanding of e-waste, proper selection of criteria or indicators is essential. The literature has shown that indicators such as material composition and concentration and product weight are almost universally constant. This is a result of globalization; products from major manufacturing countries like China are produced similarly. But such universal characteristics can change over time due to technological innovation, product design and legislation (such as the EU RoHS Directive to reduce hazardous substances in EEE). However, indicators such as product sales, price, lifespan and the quantity of obsolete EEE vary by specific regions and countries. Therefore, these indicators may not necessarily provide a consistent overview of e-waste in different markets and regions. Furthermore, introducing the economic value or environmental potential for a specific material or product can shed more light on its associated impact.

To completely summarize the existing research on the topic of defining e-waste and its classification, more work is required. This desk research can provide background knowledge for further analysis, streamline comparisons and set priorities. Systematically classifying EEE products by end-of-life characteristics, as opposed to product type, can provide support for efficient management. An overview of all available indicators facilitates an evaluation of the physical, environmental and economic characteristics of EEE and e-waste. Categorizing by universally constant indicators provides an objective and unbiased understanding of EEE, which does not change with geography or culture. These indicators need to reflect the fundamental characteristics of e-waste that influence the strategy of waste management.

This topic will be discussed in more detail in Chapter 4.

2.3.2 Research on e-waste quantities and collection efficiencies

Evaluating the collection efficiencies of established collection systems requires both the quantities of formally collected e-waste and the total amount of e-waste generated. The overall quantity reflects the scale of the e-waste problem and provides a baseline for understanding the distribution of e-waste flows by region. Total e-waste quantity is also associated with the scale, quality and cost of treatment infrastructure.

It is fundamentally more difficult to measure the overall amount e-waste generated than it is to compile the quantities collected by formal take-back systems. The mechanisms of e-waste generation are connected to a series of social and economic factors such as income level, demographic structure, household characteristics, miniaturization and technological development, availability of collection schemes and consumer disposal habits (Young, 2008; Robinson, 2009; Huisman et al., 2012). Therefore, models and estimations of e-waste quantities need to consider such influential factors for dynamic analyses.

Various studies have quantified regional and national e-waste generation based on different models and assumptions. Several studies presume that the quantity of e-waste output is the total number of products in stock divided by the average product lifespan (van der Voet et al., 2002; Robinson, 2009; Chung et al., 2011; Araújo et al., 2012). More advanced studies consider that the probability of EEE becoming obsolete (or the lifespan for a group of products) is a mathematical function rather than a constant (Melo, 1999; Babbitt et al., 2009; Oguchi et al., 2010; Polák and Drápalová, 2012). Combining lifespan distribution with historical sales data, such models for e-waste estimation apply what is called the "distribution delay" method (TemaNord, 2009), the "market supply" model (Walk, 2004) or "survival analysis" (Wen et al., 2009; Gutiérrez et al., 2010). Alternatively, e-waste quantities can be estimated with lifespan distributions and historical stock data (Müller et al., 2009). One straightforward but data-demanding method is the "time-step" model, which requires continuous stock data from two neighboring years and product sales numbers from the evaluation year (EEA, 2003; Elshkaki et al., 2005; Yu et al., 2010).

By applying these methods, studies have provided essential e-waste data for the very first time in Chile (Steubing et al., 2010), China (Yang et al., 2008), Brazil (Araújo et al., 2012), Europe (Huisman et al., 2008; TemaNord, 2009; Gutiérrez et al., 2010), Hong Kong (Chung et al., 2011), India (Jain and Sareen, 2006; Dwivedy and Mittal, 2010), Japan (Oguchi et al., 2008), the Philippines (Peralta and Fontanos, 2006) and the United States (Kang and Schoenung, 2006; Gregory et al., 2009). Despite these developments, there are still many unresolved issues regarding both the maturity of estimation models and the reliability of results.

First of all, these applied studies focus on different product types predefined by specific research goals. Consistent and uniform definitions of e-waste and its associated product types can greatly facilitate interregional comparisons and streamline estimates. Harmonization between different countries and regions can help to identify the global generation of e-waste as well as the quantity of interregional flows. Secondly, the data used in these studies were not always obtained by statistically robust methods (low sampling sizes, lack of representation, little or no data processing), and the hierarchy of data quality needs to be understood and analyzed. The sensitivity of estimates related to the quality of data inputs needs to be assessed and discussed. Finally, the impacts from economic, market and technological dynamics cause fluctuations in e-waste generation. For instance, economic recessions delay the purchase of new products and obsolescence of old products, and sales of products grow quickly when new technologies are introduced (LCD TVs, smart phones etc.). As a result, estimation models are expected to simulate complicated situations with advanced modeling. These modeling techniques need to capture the dynamic changes in both current and past product lifespans and stocks. Extra efforts

vis-à-vis data gathering and processing can help determine model parameters by providing more accurate information.

Accurate estimates of e-waste quantities will provide information for collection systems as well as the recycling industry. The scale of the e-waste streams will determine the feasibility and profitability of installing treatment technologies, recycling networks and other infrastructure. This topic will be further addressed in Chapter 5.

2.3.3 Research on the effectiveness of e-waste treatment

After it is collected, e-waste is processed in different treatment facilities that recycle valuable resources and treat hazardous materials. E-waste treatment technologies and facilities can be divided into three sequential stages: toxic removal, pre-processing and end-processing (Schluep et al., 2009). Toxic removal serves to "de-pollution" prior to further treatment. The next step, pre-processing, liberates and separates different materials. Sometimes toxic removed during pre-processing, because these procedures are usually conducted at the same treatment site or facility. End-processing is the final stage in refining, upgrading or treating material for re-sale, re-application or disposal. Based on the particular treatment goal, performance assessment varies by treatment stage. After the analysis for each stage is complete, it is also necessary to conduct an overarching assessment for the performance of the whole treatment chain. This is needed to manage and optimize the overall performance for a whole treatment chain and to create optimum connections between stages.

The importance of toxic removal has been emphasized by the EU WEEE Directive (European Union, 2003) and others (Kang and Schoenung, 2005; Babu et al., 2007). However, the efficiency of toxic removal in current treatment practices has been seldom studied. One Austrian study has explicitly investigated the removal of components containing hazardous substances from small e-waste items (Salhofer and Tesar, 2011). This study assessed the performance of de-pollution on the basis of removal rates of hazardous substances. A comprehensive list was established to enumerate the contents of hazardous substances and their presences in various small e-waste components. The removal rate was calculated as the ratio between the weight of a specific substance removed in a treatment facility and its gross weight present in the input material. The results from this study showed that components containing hazardous substances are only partly removed during treatment. This implies that substantial quantities of hazardous substances are forwarded to subsequent treatment processes and will inevitably cause significant dispersion of pollutants. It has been discussed that low removal rates of "easily" releasable pollutants (such as mercury from LCD-backlights and cadmium from batteries) can pose great health risks for workers in shredding plants. High removal rates of hazardous but valuable components such as circuit boards and batteries can greatly improve their overall recovery rates.

Compared to toxic removal, there are far more studies that assess the performances of pre-processing techniques and facilities. It is commonly recognized that manual dismantling and mechanical separation are the two major pre-processing options. As a frequent pre-processing technique in both automobile and e-waste recycling, the technical settings and characteristics of mechanical separation have been summarized by many researchers (Cui and Forssberg, 2003;

Castro, 2005; Chancerel et al., 2009; Makenji and Savage, 2012; Reuter et al., 2013). The sequence to, and characteristics of, manual dismantling are also well documented (Lambert and Gupta, 2004; Gmünder, 2007; Duflou et al., 2008; Wang et al., 2008). Various studies have tried to compare the differences in performance between manual dismantling and mechanical separation (Gmünder, 2007; Meskers et al., 2009). Several studies also elaborate on methods for pre-processing different types of e-waste including CRT TVs and monitors (Aanstoos et al., 1997; Schluep et al., 2009), LCD TVs and monitors (Böni and Widmer, 2011; Salhofer et al., 2011), cooling and freezing appliances (Scottish Environmental Protection Agency, 2002; Ruan and Xu, 2011; Keri, 2012) and IT equipment (Gmünder, 2007). Criteria for performance comparisons include liberation rates, economic performance, environmental performance and synthesis indicators such as eco-efficiency and exergy. Liberation or separation rate based on the weight percentage of target material(s) separated from e-waste is the most straightforward indicator. This can be calculated by simply tracking the mass balance throughout a treatment process. But different pre-processing techniques have distinct environmental and economic consequences, which essentially determine the applicability of technologies. For instance, pre-processing techniques have different start-up costs (for installing machines), operational costs (labor and energy) and revenues (from different qualities of separation outputs between mechanical separation and manual dismantling). Therefore, environmental and economic models have been established to evaluate the societal impact of different pre-processing techniques (Huisman, 2003; Gregory et al., 2006 ; Dahmus et al., 2008; Achillas et al., 2013). Additionally, standard LCA methodologies cannot properly describe quality losses during recycling, because this degradation cannot be measured by mass alone (Castro et al., 2007). Therefore, exergy has been proposed as an indicator for evaluating the contamination by impurities arising from the imperfect liberation of materials by mechanical separation (Castro, 2005; Castro et al., 2007).

The focus of the end-processing stage is to recycle and treat fractions or materials liberated from the previous two stages: toxic removal and pre-processing. A variety of studies have researched the technological developments of treatments for specific materials or components including base metals (Schluep et al., 2009), lead-glass (Mostaghel and Samuelsson, 2010; Nnorom et al., 2011), printed circuit boards (Veit et al., 2006; Cui and Zhang, 2008; Hou et al., 2010; Duan et al., 2011; Yamane et al., 2011), liquid crystal displays (Williams and McDonnel, 2012), batteries (Espinosa and Mansur, 2012) and plastics (Nnorom and Osibanjo, 2008; Wäger et al., 2009; Makenji and Savage, 2012). These assessments mainly examine the technical capabilities necessary to treat or recycle specific materials. Analyses include detailed schemes of the treatment processes, mass balances of target materials and comparisons between alternative technologies. These studies also evaluate the environmental and economic impacts of the end-processing stage.

Although the three treatment stages may take place in many different parts of the world, their performance is interlinked. The performance of one recycling chain is determined by the outcomes from each treatment stage, so the impacts from each stage need to be assessed separately. Most existing research regards the e-waste treatment chain as a black box; this research only records the mass balances in and out of treatment systems. This approach is common in conventional MFA (material flow analysis) and LCA (life cycle assessment) studies, as

it can greatly reduce the workload and cost of extensively gathering data on details of each process and facility. However, an aggregated score for a whole system does not always make clear the advantages and weaknesses of each stage. In order to possess a clear overview of the performance of the whole chain, each treatment stage needs to be analyzed separately, with clear documentation of the details of the treatment process. Regarding the variety of technologies and facilities available for each stage of treatment, assessments should also extend from analyzing the existing technologies to comparing different treatment scenarios. This will serve to justify the application of the selected technologies and identify potential areas for improvement. The analysis thus far has focused on the technological details with less discussion on the impacts and compatibilities of the assessed technologies in the context of society. These external factors can be interpreted by assessing the environmental, economic and social impacts of a specific technology.

Methods with individual or combined indicators exist for assessing performance in different areas (such as technology, the economy and the environment). The most basic approach, mass balance analysis, has been extensively used to study the losses and gains of substances, materials, components and products as they move through the treatment processes. Mass balance analysis forms the fundamental structure for methods like Material Flow Analysis (MFA), Substance Flow Analysis (SFA) and Input-output Analysis. Weight-based analysis is very functional for indicating the ability of a system to recover a specific type of substance or material but it is insufficient for determining the priorities and quality of the treatment system or the actual economic and environmental impacts; the disparities between the environmental and economic impacts of different materials cannot be reflected simply by weight-based indicators. In the next step, economic and environmental metrics are introduced to address the economic and environmental performance of treatment processes and systems (Gregory et al., 2006 ; Dahmus et al., 2008; Lim and Schoenung, 2010; Manfredi et al., 2011; Wäger et al., 2011). To find the optimal balances and trade-offs between investments and environmental impacts a synthetic indicator such as eco-efficiency is applied (Huisman et al., 2003; Stevels, 2007). This is necessary because neither the best environmental performance nor maximum profit is feasible (these options are too costly on the one hand and too polluting on the other). Adopting extreme scenarios based on singular criteria should be avoided, and equilibrium is needed among separate dimensions of concern. The methods and approaches used to define optimal technology for the best technical and societal performance will be further analyzed in Chapters 6 and 7.

2.3.4 Research on global approaches to e-waste take-back and treatment

Existing literature applies methods for evaluating the technical performance of e-waste take-back and treatment systems in disciplines related to the environment and technology. Such methods are applied to studies based on established take-back and treatment systems in specific countries.

The WEEE Review study is by far the most comprehensive study of those in countries with nationally legislated e-waste take-back and treatment systems (Huisman et al., 2008). It studies the technical, environmental, economic and social aspects of e-waste systems being implemented in all European Member States. Many studies based in individual countries aim to evaluate the domestic implementation of take-back and treatment systems, including studies in the

Netherlands (Eijsbouts, 2008; Huisman et al., 2012), Italy (Magalini et al., 2012), Belgium (Wielenga et al., 2013), Switzerland (Hischier et al., 2005; Wäger et al., 2009; Wäger et al., 2011) and Germany (Deubzer, 2011). Several studies from Japan analyze the collection and recycling performances of established systems (Tasaki et al., 2005; Aizawa et al., 2008; Yoshida and Yoshida, 2010; 2012).

For countries without national legislation and formal take-back systems, research mainly focuses on mapping national e-waste flows and exploring possible methods for management. This research is carried out by comparing the status-quo figures in the target countries with those from countries with established systems and legislation (mainly European countries). Such studies come from the United States (Kang and Schoenung, 2005; Huisman et al., 2006; Kahhat et al., 2008), India (Sinha-Khetriwal et al., 2005; Khetriwal et al., 2009; Manomaivibool, 2009), China (Yang et al., 2008; Yu et al., 2010; Zeng et al., 2013), Thailand (Kojima et al., 2009) and Nigeria (Osibanjo and Nnorom, 2007; Nnorom and Osibanjo, 2008).

These studies follow e-waste flows as they move through different collection channels to their treatment destinations. The main differences between countries are the distinct patterns and distribution channels of domestic e-waste flows, as they are determined by local socio-economic and cultural factors. Additionally, the scope of products and research interests are rather different in each country. Separate studies are needed to identify the most important and influential e-waste categories in specific countries and to track their flows within different handling systems and between actors. Evaluation methods can be shared among these countries, but the results may vary drastically by country.

Another significant difference is the range of treatment technologies adopted by different countries. Treatment technologies for each stage need to be analyzed according to distinct market and societal conditions in each country. Technical performance needs to match local factors such as labor costs, scale of investment, environmental standards and other requirements. So far, treatment technology assessments have only been applied to machinery and efficiencies, and they are simply based on the analysis of mass balances. A broader technological assessment extends to environmental, economic and social impacts. As a result, different treatment technologies can be selected for different countries, and the feasibility of implementing specific technologies can be understood. For a clear analysis of treatment technologies in developing countries, existing barriers and problems have been clearly identified, such as limited availability of technology, knowledge, investments and environmental protection measures. However, a few solutions have been proposed to solve these problems. Chapter 7 will focus on treatment solutions for developing countries based on technical and societal analyses.

To summarize, establishing e-waste take-back and treatment systems should be differentiated for each e-waste category as well as the socio-economic conditions in a specific country. Assessment of system performances can apply similar methodologies and research approaches to a variety of countries. But the result of defining e-waste scopes, domestic e-waste quantities and flows, collection schemes and optimal technologies can greatly vary. Such assessments need to consider country-specific conditions to obtain reliable outcomes.

2.4 Gap analysis and synthesis

For managers and developers of e-waste take-back and treatment systems, the primary task is to comprehensively understand the physical, chemical, environmental and societal characteristics of the e-waste stream with which they work. The literature previously reviewed offers a sporadic analysis, which only emphasizes common household, consumer and IT appliances. An exhaustive listing of all past and the present EEE will complete the picture. A systematic inventory and categorization of products by primary product category creates efficient collection and treatment. This can also reduce the administrative burden of registering, reporting and monitoring more than 660 types of products. Chapter 4 will conduct a thorough analysis of all EEE and make an effort to classify them by separate end-of-life characteristics such as average product weight, material composition, economic value and environmental impact. This work is not only a synthesis of existing product analyses, but also an improvement for the holistic overview of the complicated e-waste stream. The result will prepare a basis for systematic management of e-waste and enable international comparisons of system implementation and best practices.

Besides examining the characteristics of e-waste, it is also important to estimate the quantities of e-waste that are generated, collected and treated in different destinations. The literature shows that current models and procedures for estimating e-waste generation are far from mature. These approaches are based on simple methods with limited variables and poor data quality. These models pose a barrier to proper evaluation of the scale of the e-waste problem, and they hinder accurate appraisals of the collection efficiencies of take-back systems. Based on the existing models and experiences in studies from various countries, Chapter 5 will develop a multivariate analysis with consideration to data quality in order to improve e-waste estimation methods. This improvement will allow estimation models to more accurately apply to different situations with different data availability, and it will improve the quality of data inputs. This will improve the scientific understanding of the mechanisms behind e-waste generation and provide more reliable data for e-waste management.

The structure and settings of treatment chains are more intricate and diverse than collection systems. Treatment chains have multiple stages and a great variety of possible technologies in each stage. A complete e-waste treatment chain is formed by a set of (technically and geographically) independent but interlinked stages. An elaborate map of all the technical configurations in each treatment stage will help to present treatment scenarios. However, most studies related to e-waste treatment emphasize technological development or analyze individual processes. Assessing a treatment chain requires both a holistic overview of the entire system and a separate examination of each treatment stage as well as an examination of their interrelationship. Taking these complex factors into account, Chapter 6 presents both generic and detail-oriented analyses of treatment chains and their sequential stages. The result will help to construct a comprehensive treatment system with a thorough understanding of the technical performance in each stage.

As argued before, most studies assessing treatment technologies are based on mass balances, but these weight-based indicators (such as recycling rates) are not the only criteria for selecting an appropriate technology. Environmental impact, economic viability and social acceptance

determine the applicability of a technology. Due to dynamic socio-economic conditions, the impacts of technology need to be modeled dynamically; the selection of optimal technologies is based on both technological and societal relevance. Starting from this theoretical observation, Chapter 7 mainly explores a treatment solution for developing countries, where clean and affordable treatment of e-waste is in great demand due to lacking investment and infrastructure. This treatment solution combines the best technical routes in each treatment stage while seeking the best match for geographical and socio-economic factors. This will place the technological analysis in a more detailed context and shed light on the societal perspective in order to present a more realistic overview of the applicability of different technical solutions.

One main focus of existing studies related to the environmental impacts of e-waste has been to investigate pollution at informal recycling sites. These studies provide valuable information about the current environmental quality of the areas that were investigated. However, such measurements of the severity of pollution have not been linked to specific recycling processes, and so the results are a collection of many different activities and local conditions. LCA has been widely applied, and it is the accepted tool for research that assesses the impact of one specific process. Despite the standardized procedure and comprehensive categories of impact, the results are still rather aggregated and general for only indicating the overall impact on a global scale. One important impact category of e-waste treatment is its damaging health effects. This topic has not been sufficiently studied, especially with regard to the most exposed groups: those who work with e-waste and those who live close to e-waste treatment plants. Chapter 8 will extend the scope of LCA studies to the occupational environment. Additional models and data acquisition steps are introduced to integrate the occupational environment into the general framework of LCA. This integration will improve understanding emissions' impact on human health. It will also advise next steps for lowering the health risks for e-waste workers, to be used when designing or adjusting specific treatment process.

2.5 Conclusions

The development of e-waste take-back and treatment systems requires multidisciplinary research in order to understand the complexity of the e-waste problem and develop measures to lower environmental impacts and increase resource efficiency. This chapter has mapped the e-waste management research with a special focus on the assessment of e-waste take-back and treatment systems.

Existing research provides valuable insight into the characteristics and treatment solutions for a number of popular electrical and electronic equipment items, but it lacks a thorough understanding of the e-waste stream and its associated issues. Furthermore, an understanding of the magnitude of e-waste flows is significant for evaluating, planning and managing take-back and treatment systems, yet sophisticated methods for accurate estimation of e-waste generation are still inadequate. A great variety of treatment scenarios are available for each stage of e-waste treatment, and these alternatives need to be understood better. Treatment scenarios can be modeled by connecting alternatives from each stage in the treatment chain. Together with mass balances analysis, treatment systems' environmental and economic impacts need to be researched further. The results can indicate the applicability of technologies in different regions and societies. Furthermore, pragmatic treatment solutions are urgently needed in developing

countries. Effective treatment solutions should be technically feasible and consider local societal conditions. Environmental assessments need to incorporate human health risks for workers and nearby residents to the treatment plants into the current LCA framework.

The research gaps identified in this chapter are based on a literature analysis. Chapter 3 will present a review of managerial experiences on the global scale from currently operational take-back systems. By examining the reality of experiences in implementing take-back systems, these research topics will be further examined and validated in Chapter 3. Consequently, precise directions for research can be formulated as the main focus of this dissertation.

2.6 References

Aanstoos, T., et al. (1997). <u>Disassembly process far a cathode ray tube</u>. Electronics Manufacturing Technology Symposium, 1997., Twenty-First IEEE/CPMT International, IEEE.

Achillas, C., et al. (2013). "Depth of manual dismantling analysis: A cost–benefit approach." <u>Waste Management</u>.

Aizawa, H., et al. (2008). "Current results and future perspectives for Japanese recycling of home electrical appliances." <u>Resources, Conservation and Recycling</u> **52**(12): 1399-1410.

Andreola, F., et al. (2005). "Glass-ceramics obtained by the recycling of end of life cathode ray tubes glasses." <u>Waste Management</u> **25**(2): 183-189.

Andreola, F., et al. (2008). "Recycling of CRT panel glass as fluxing agent in the porcelain stoneware tile production." <u>Ceramics International</u> **34**(5): 1289-1295.

Araújo, M. G., et al. (2012). "A model for estimation of potential generation of waste electrical and electronic equipment in Brazil." <u>Waste Management</u> **32**(2): 335-342.

Babbitt, C. W., et al. (2009). "Evolution of Product Lifespan and Implications for Environmental Assessment and Management: A Case Study of Personal Computers in Higher Education." <u>Environ Sci Technol</u> **43**(13): 5106-5112.

Babu, B. R., et al. (2007). "Electrical and electronic waste: a global environmental problem." <u>Waste Management & Research</u> **25**(4): 307-318.

Böni, H. and R. Widmer (2011). Disposal of flat panel display monitors in Switzerland, final report. St. Gallen, Switzerland, EMPA, SWICO Recycling.

Brigden, K., et al. (2005). Recycling of Electronic Waste in China and India: Workplace and Environmental Contamination, Greenpeace Report, Greenpeace International.

Castro, B. (2005). Design for resource efficiency. <u>Department of Industrial Design</u>. Delft, the Netherlands, TU Delft. **PhD degree**.

Castro, M. B. G., et al. (2007). "Exergy losses during recycling and the resource efficiency of product systems." <u>Resources, Conservation and Recycling</u> **52**(2): 219-233.

Chancerel, P., et al. (2009). "Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment." <u>Journal of Industrial Ecology</u> **13**(5): 791-810.

Chen, M., et al. (2009). "Lead recovery and the feasibility of foam glass production from funnel glass of dismantled cathode ray tube through pyrovacuum process." <u>Journal of Hazardous Materials</u> **161**(2–3): 1109-1113.

Chi, X., et al. (2011). "Informal electronic waste recycling: A sector review with special focus on China." <u>Waste Management</u> **31**7: 731-742.

Chung, S.-S., et al. (2011). "Generation of and control measures for, e-waste in Hong Kong." <u>Waste Management</u> **31**(3): 544-554.

Chung, S.-W. and R. Murakami-Suzuki (2008). "A comparative study of e-waste recycling systems in Japan, South Korea and Taiwan from the EPR perspective: implications for developing countries." <u>Kojima. Chiba</u>.

Cobbing, M. (2008). Toxic tech: not in our backyard, uncovering the hidden flows of e-waste.

Cui, J. and E. Forssberg (2003). "Mechanical recycling of waste electric and electronic equipment: a review." Journal of Hazardous Materials **99**(3): 243-263.

Cui, J. and L. Zhang (2008). "Metallurgical recovery of metals from electronic waste: a review." Journal of Hazardous Materials **158**: 228–256.

Dahmus, J. B., et al. (2008). Modeling the economic and environmental performance of recycling systems. ISEE 2008. IEEE International Symposium on Electronics and the Environment.

Dahmus, J. B. and T. G. Gutowski (2007). "What gets recycled: an information theory based model for product recycling." Environmental Science and Technology **41**: 7543-7550.

Deubzer, O. (2011). E-waste management in Germany. Bonn, Germany, United Nations University.

Duan, H., et al. (2011). "Examining the technology acceptance for dismantling of waste printed circuit boards in light of recycling and environmental concerns." Journal of Environmental Management **92**(3): 392-399.

Duflou, J. R., et al. (2008). "Efficiency and feasibility of product disassembly: A case-based study." CIRP Annals - Manufacturing Technology **57**(2): 583-600.

Dwivedy, M. and R. K. Mittal (2010). "Estimation of future outflows of e-waste in India." Waste Management **30**(3): 483-491.

EEA (2003). Waste from electrical and electronic equipement WEEE - quantities, dangerous substances and treatment methods. Copenhagen, Denmark, Environmental European Agency, European Topic Centre on Waste.

Eijsbouts, R. J. J. (2008). Research into complementary waste streams for e-waste in the Netherlands. Breda, the Netherlands, Witteveen+Bos.

Elshkaki, A., et al. (2005). "Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics." Energy **30**(8): 1353-1363.

Espinosa, D. C. R. and M. B. Mansur (2012). Recycling batteries. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Eugster, M. and H. Fu (2004). e-Waste Assessment in P.R. China, A case study in Beijing. St.Gallen Switzerland, Beijing China, Empa, Technology and Society Laboratory.

European Union (2003). Waste Electrical and Electronic Equipment Directive (2002/96/EC). Brussels, Belgium, Official Journal of the European Union L37.

Gao, S., et al. (2011). "Polybrominated diphenyl ethers in surface soils from e-waste recycling areas and industrial areas in South China: Concentration levels, congener profile, and inventory." Environ Toxicol Chem **30**(12): 2688-2696.

Geering, A. (2007). Modelling of existing e-waste collection systems in China, a case study based on household surveys in the Taizhou prefecture, Master Thesis. Swiss Federal Institute of Technology (ETH)/Swiss Federal Laboratories for Materials Testing and Research (Empa), Zurich/St. Gallen Switzerland.

Gmünder, S. (2007). Recycling - from waste to resource: assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Zurich / St.Gallen, Switzerland, Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Testing and Research (EMPA). **Master thesis**.

Gregory, J., et al. (2006). Process-Based Cost Modeling: Understanding the economics of technical decisions. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment. Scottsdale, AZ, USA**:** 138-143

Gregory, J., et al. (2008). E-waste Take-Back System Design and Policy Approaches. Solving the E-Waste Problem (StEP) White Paper. Bonn, Germany, United Nations University.

Gregory, J. R., et al. (2009). "Evaluating the Economic Viability of a Material Recovery System: The Case of Cathode Ray Tube Glass." Environ Sci Technol **43**(24): 9245-9251.

Gu, Z., et al. (2010). "Characteristics of organic matter in PM2.5 from an e-waste dismantling area in Taizhou, China." Chemosphere **80**(7): 800-806.

Gutiérrez, E., et al. (2010). "A competing risks approach for time estimation of household WEEE disposal." Waste Management **30**(8-9): 1643-1652.

Ha, N. N., et al. (2009). "Contamination by trace elements at e-waste recycling sites in Bangalore, India." Chemosphere **76** (1): 9-15.

Hagelüken, C. (2006). Improving metal returns and eco-efficiency in electronics recycling. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, IEEE 2006.

Hischier, R., et al. (2005). "Does WEEE recycling make sense from an environmental perspective?: The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE)." Environmental Impact Assessment Review **25**(5): 525-539.

Hou, S., et al. (2010). "Electrostatic Separation for Recycling Waste Printed Circuit Board: A Study on External Factor and a Robust Design for Optimization." Environmental Science & Technology **44**(13): 5177-5181.

Huang, K., et al. (2011). "Enhancement of the recycling of waste Ni–Cd and Ni–MH batteries by mechanical treatment." Waste Management **31**(6): 1292-1299.

Huisman, J. (2003). The QWERTY/EE Concept, quantifying recycability and eco-efficiency for end-of-life treatment of consumer electronic products. Delft, the Netherlands, Delft University of Technology. **PhD thesis**.

Huisman, J., et al. (2003). "Quotes for environmentally weighted recyclability (QWERTY): concept of describing product recyclability in terms of environmental value." International Journal of Production Research **41**(16): 3649-3665.

Huisman, J., et al. (2008). Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Bonn, Germany, United Nations University.

Huisman, J., et al. (2006). Where did WEEE go wrong in Europe? Practical and academic lessons for the US. Electronics and the Environment, 2006. Proceedings of the 2006 IEEE International Symposium on, IEEE.

Huisman, J., et al. (2012). The Dutch WEEE Flows. Bonn, Germany, United Nations University, ISP-SCYCLE.

Jain, A. and R. Sareen (2006). "E-waste assessment methodology and validation in India." Journal of Material Cycles and Waste Management **8**: 40-45.

Kahhat, R., et al. (2008). "Exploring e-waste management systems in the United States." Resources, Conservation and Recycling **52**(7): 955-964.

Kang, H.-Y. and J. M. Schoenung (2005). "Electronic waste recycling: A review of U.S. infrastructure and technology options." Resources, Conservation and Recycling **45**(4): 368-400.

Kang, H.-Y. and J. M. Schoenung (2006). "Estimation of future outflows and infrastructure needed to recycle personal computer systems in California." Journal of Hazardous Materials **137**(2): 1165-1174.

Keri, C. (2012). Recycing cooling and freezing appliances. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Khetriwal, D. S., et al. (2009). "Producer responsibility for e-waste management: Key issues for consideration–Learning from the Swiss experience." Journal of Environmental Management **90**(1): 153-165.

Kojima, M., et al. (2009). "Difficulties in applying extended producer responsibility policies in developing countries: case studies in e-waste recycling in China and Thailand." Journal of Material Cycles and Waste Management **11**(3): 263-269.

Kuehr, R. (2012). Global e-waste initiatives. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Lambert, A. F. and S. M. Gupta (2004). Disassembly modeling for assembly, maintenance, reuse and recycling, CRC press.

Lawhon, M., et al. (2010). "Solving/understanding/evaluating the e-waste challenge through transdisciplinarity?" Futures **42**(10): 1212-1221.

Lepawsky, J. and C. McNabb (2010). "Mapping international flows of electronic waste." The Canadian Geographer / Le Géographe canadien **54**(2): 177-195.

Leung, A. O., et al. (2008). "Heavy metals concentrations of surface dust from e-waste recycling and its human health implications in southeast China." Environ Sci Technol **42**(7): 2674-2680.

Li, L., et al. (2010). "Recovery of cobalt and lithium from spent lithium ion batteries using organic citric acid as leachant." Journal of Hazardous Materials **176**(1–3): 288-293.

Lim, S.-R. and J. M. Schoenung (2010). "Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays." Journal of Hazardous Materials **177**(1–3): 251-259.

Long, L., et al. (2010). "Using vacuum pyrolysis and mechanical processing for recycling waste printed circuit boards." Journal of Hazardous Materials **177**(1–3): 626-632.

Magalini, F., et al. (2012). Household WEEE Arising in Italy. Bonn, Germany, United Nations University.

Makenji, K. and M. Savage (2012). Mechanical methods of recycling plastics from WEEE. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Manfredi, S., et al. (2011). "Environmental assessment of different management options for individual waste fractions by means of life-cycle assessment modelling." Resources, Conservation and Recycling **55**(11): 995-1004.

Manomaivibool, P. (2009). "Extended producer responsibility in a non-OECD context: The management of waste electrical and electronic equipment in India." Resources, Conservation and Recycling **53**(3): 136-144.

Matsuto, T., et al. (2004). "Material and heavy metal balance in a recycling facility for home electrical appliances." Waste Management **24**(5): 425-436.

Melo, M. T. (1999). "Statistical analysis of metal scrap generation: the case of aluminium in Germany." Resources, Conservation and Recycling **26**: 91-113.

Meskers, C. E. M., et al. (2009). Impact of pre-processing routes on precious metal recovery from PCs. Proceedings of European Metallurgical Conference EMC.

Miller, T. R., et al. (2012). Characterizing Transboundary Flows of Used Electronics: Summary Report, Massachusetts Institute of Technology, Material Systems Laboratory.

Mostaghel, S. and C. Samuelsson (2010). "Metallurgical use of glass fractions from waste electric and electronic equipment (WEEE)." Waste Management **30**: 140–144.

Müller, E., et al. (2009). Assessment of e-waste flows: a probabilistic approach to quantify e-waste based on world ICT and development indicators. R'09 World Congress. Davos, Switzerland.

Nnorom, I. C. and O. Osibanjo (2008). "Electronic waste (e-waste): Material flows and management practices in Nigeria." Waste Management **28**(8): 1472-1479.

Nnorom, I. C. and O. Osibanjo (2008). "Sound management of brominated flame retarded (BFR) plastics from electronic wastes: State of the art and options in Nigeria." Resources, Conservation and Recycling **52**(12): 1362-1372.

Nnorom, I. C., et al. (2011). "Global disposal strategies for waste cathode ray tubes." Resources, Conservation and Recycling **55**(3): 275-290.

OECD (2001). Extended producer responsibility: a guidance manual for governments. Paris, France, Organisation for Economic Co-operation and Development.

Oguchi, M., et al. (2008). "Product flow analysis of various consumer durables in Japan." Resources, Conservation and Recycling **52**(3): 463-480.

Oguchi, M., et al. (2011). "A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources." Waste Management **31**(9–10): 2150-2160.

Oguchi, M., et al. (2010). "Lifespan of Commodities, Part II." Journal of Industrial Ecology **14**(4): 613-626.

Oguchi, M., et al. (2012). "Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes." Science of The Total Environment(0).

Osibanjo, O. and I. C. Nnorom (2007). "The challenge of electronic waste (e-waste) management in developing countries." Waste Management and Research **25** (6): 489–501.

Peralta, G. L. and P. M. Fontanos (2006). "E-waste issues and measures in the Philippines." Journal of Material Cycles and Waste Management **8**(1): 34-39.

Polák, M. and L. Drápalová (2012). "Estimation of end of life mobile phones generation: The case study of the Czech Republic." Waste Management(In Press).

Provazi, K., et al. (2011). "Metal separation from mixed types of batteries using selective precipitation and liquid–liquid extraction techniques." Waste Management **31**(1): 59-64.

Puckett, J., et al. (2002). Exporting harm, the high-tech trashing of Asia. Seattle, USA, The Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC).

Reuter, M. A., et al. (2013). Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Paris, France, United Nations Environment Programme.

Robinson, B. H. (2009). "E-waste: An assessment of global production and environmental impacts." Science of The Total Environment **408**(2): 183-191.

Ruan, J. and Z. Xu (2011). "Environmental friendly automated line for recovering the cabinet of waste refrigerator." Waste Management **31**(11): 2319-2326.

Salehabadi, D. (2013). Transboundary Movements of Discarded Electrical and Electronic Equipment. Solving the E-Waste Problem (StEP) Green Paper. Bonn, Germany, United Nations University.

Salhofer, S., et al. (2011). Recycling of LCD Screens in Europe - State of the Art and Challenges. Glocalized Solutions for Sustainability in Manufacturing. J. Hesselbach and C. Herrmann, Springer Berlin Heidelberg: 454-458.

Salhofer, S. and M. Tesar (2011). "Assessment of removal of components containing hazardous substances from small WEEE in Austria." Journal of Hazardous Materials 186 1481–1488.

Schluep, M., et al. (2009). Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling - from E-waste to resources. Bonn, Germany, United Nations Environment Programme & United Nations University.

Scottish Environmental Protection Agency (2002). Guidance on the recovery and disposal of controlle substances contained in refrigerators and freezers. Bristol, UK.

Sepúlveda, A., et al. (2010). "A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India." Environmental Impact Assessment Review 30(1): 28-41.

Sheng, P. P. and T. H. Etsell (2007). "Recovery of gold from computer circuit board scrap using aqua regia." Waste Management & Research 25(4): 380-383.

Sinha-Khetriwal, D., et al. (2005). "A comparison of electronic waste recycling in Switzerland and in India." Environmental Impact Assessment Review 25(5): 492-504.

StEP Initiative (2010). Annual report. Bonn, Germany, Solving the E-waste Problem Initiative.

Steubing, B., et al. (2010). "Assessing computer waste generation in Chile using material flow analysis." Waste Management 30(3): 473-482.

Stevels, A. (2007). Adventures in ecodesign of electronic products 1993-2007. Delft, the Netherlands, Delft University of Technology.

Tasaki, T., et al. (2005). Effective assessment of Japanese recycling law for electrical home appliances: four years after the full enforcement of the law. Electronics and the Environment, 2005. Proceedings of the 2005 IEEE International Symposium on.

TemaNord (2009). Method to measure the amount of WEEE generated - Report to Nordic council's subgroup on EEE waste. Copenhagen, Denmark, Nordic Council of Ministers.

Terazono, A., et al. (2004). "Material cycles in Asia: especially the recycling loop between Japan and China." Journal of Material Cycles and Waste Management 6(2): 82-96.

Tong, X. and J. Wang (2004). "Transnational Flows of E-Waste and Spatial Patterns of Recycling in China." Eurasian Geography and Economics 45(8): 608-621.

Tsydenova, O. and M. Bengtsson (2011). "Chemical hazards associated with treatment of waste electrical and electronic equipment." Waste Management 31(1): 45-58.

van der Voet, E., et al. (2002). "Predicting future emissions based on characteristics of stocks." Ecological Economics 41(2): 223-234.

Veit, H. M., et al. (2006). "Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy." Journal of Hazardous Materials 137(3): 1704-1709.

Wäger, P., et al. (2009). Recycling of plastics from waste electrical and electronic equipment (WEEE) – Tentative Results of a Swiss Study. Proceedings of R'09 World Congress. Davos, Switzerland.

Wäger, P. A., et al. (2011). "Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up." Science of The Total Environment 409(10): 1746-1756.

Walk, W. (2004). Appraoches to estimated future quantities of waste electrical and electronic equipment (WEEE). Proceedings of the Eletronics Goes Green 2004. Berlin, Germany: 263-268.

Wang, F., et al. (2008). Economic conditions for formal and informal recycling of e-waste in China. Electronics Goes Green. Berlin, Germany.

Wen, L., et al. (2009). "Review of recycling performance indicators: A study on collection rate in Taiwan." Waste Management 29(8): 2248-2256.

Widmer, R., et al. (2005). "Global perspectives on e-waste." Environmental Impact Assessment Review 25(5): 436-458.

Wielenga, K., et al. (2013). (W)EEE Mass balance and market structure in Belgium, study for Recupel, Brussels, Belgium, Recupel.

Williams, K. S. and T. McDonnel (2012). Recycling liquid crystal displays. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Wong, C. S. C., et al. (2007). "Trace metal contamination of sediments in an e-waste processing village in China." Environmental Pollution **145**(2): 434-442.

Wong, M. H., et al. (2007). "Export of toxic chemicals – A review of the case of uncontrolled electronic-waste recycling." Environmental Pollution **149**(2): 131-140.

Xin, B., et al. (2009). "Bioleaching mechanism of Co and Li from spent lithium-ion battery by the mixed culture of acidophilic sulfur-oxidizing and iron-oxidizing bacteria." Bioresource Technology **100**(24): 6163-6169.

Xing, G. H., et al. (2009). "Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China." Environ Int **35**(1): 76-82.

Yamane, L. H., et al. (2011). "Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers." Waste Management **31**(12): 2553-2558.

Yang, J. and B. Lu (2005). E-waste flow and recycling situation in China. Proceedings of the Second Workshop on E-waste, Tokyo, Japan.

Yang, J., et al. (2008). "WEEE flow and mitigating measures in China." Waste Management **28**(9): 1589-1597.

Yoo, J.-M., et al. (2009). "Enrichment of the metallic components from waste printed circuit boards by a mechanical separation process using a stamp mill." Waste Management **29**(3): 1132-1137.

Yoshida, A., et al. (2009). "Material flow analysis of used personal computers in Japan." Waste Management **29**(5): 1602-1614.

Yoshida, A. and A. Terazono (2010). "Reuse of secondhand TVs exported from Japan to the Philippines." Waste Management **30**(6): 1063-1072.

Yoshida, F. and H. Yoshida (2010). "Japan, the European Union, and waste electronic and electrical equipment recycling: key lessons learned." Environmental Engineering Science **27**(1): 21-28.

Yoshida, F. and H. Yoshida (2012). An environmental and economic analysis of e-waste recycling based on the Japanese experience - focusing on flow estimation. Electronics Goes Green 2012. Berlin.

Young, D. (2008). "When do energy-efficient appliances generate energy savings? Some evidence from Canada." Energy Policy **36**(1): 34-46.

Yu, J., et al. (2010). "Managing e-waste in China: Policies, pilot projects and alternative approaches." Resources, Conservation and Recycling **54**(11): 991-999.

Yu, J., et al. (2010). "Forecasting Global Generation of Obsolete Personal Computers." Environ Sci Technol **44**(9): 3232-3237.

Zeng, X., et al. (2013). "Perspective of electronic waste management in China based on a legislation comparison between China and the EU." Journal of Cleaner Production **51**(0): 80-87.

Zheng, Y., et al. (2009). "A novel approach to recycling of glass fibers from nonmetal materials of waste printed circuit boards." Journal of Hazardous Materials **170**(2–3): 978-982.

Zhou, Y. and K. Qiu (2010). "A new technology for recycling materials from waste printed circuit boards." Journal of Hazardous Materials **175**(1–3): 823-828.

Chapter 3: Implementation experiences of e-waste take-back systems

The previous chapter (Chapter 2) provided an overarching review of literature pertaining to e-waste management and assessments of e-waste take-back and treatment systems. A collection of research topics for development has been identified in order to obtain more information about the characteristics of e-waste, system flows and the impacts of different treatment activities. Five major critical topics requiring further methodological and data development include: 1) a comprehensive and thorough understanding of the e-waste stream and its associated issues; 2) accurate methods for estimating the quantity of e-waste generated; 3) a greater understanding of the structure and features of the e-waste treatment chain and alternative treatment techniques; 4) a better evaluation of the technical, environmental and economic performance of e-waste treatment systems, in order to identify pragmatic and effective treatment solutions for different regions; and 5) a method for evaluating the occupational health impacts of e-waste treatment.

With the literature analysis established, the present chapter will examine the proposed research topics and separate them by their level of real-world relevance. First, an overview of global e-waste management practices will be summarized in order to understand the trends followed by e-waste policies, guiding principles, modes for management and practical experiences from various regions and countries. Next, two extreme case studies will be presented to examine e-waste management experiences in Europe and China, two places with distinct socio-economic conditions. Both the commonly shared agenda, as well as country-specific items, can be identified for research and management.

Analysis from these case studies provides a historical perspective on the progress and evolution of critical topics in e-waste. It brings useful insights to the dynamic interaction and cyclical nature of progress between scientific research and practical developments in field work. Research topics with real-world relevance to daily management practices can be confirmed to further validate the critical research topics introduced in the scientific analysis in Chapter 2. These topics are expected to generate new knowledge and facilitate the formulation of sensible managerial paradigms and instruments for policy makers, system architects and managers on both regional and global scales.

3.1 Global practices in e-waste management

3.1.1 General background

E-waste has been a critical topic since the 1990s, both on a regional and global level. With rapid technological innovation and development, the amount of obsolete electronic equipment has grown substantially (first in developed countries). This situation has created pressure in industrialized countries for landfill sites and managers of solid waste. Along with this trend, the amount of e-waste that is exported from developed countries to developing countries has significantly increased. There has been growing attention paid by NGOs (Non-governmental Organizations) to the improper handling of e-waste and its resulting impacts (Puckett et al., 2002; Brigden et al., 2005; Cobbing, 2008). Media coverage of this issue has also increased (Carroll, 2008; CBS, 2008; Elgin and Grow, 2008). Such reports have graphically documented threats to the health and safety of workers, as well as the environmental contamination at common e-waste destinations with substandard treatment practices such as Guiyu town in China, New Delhi and Bangalore in India, and the Agbogbloshie site near Accra, Ghana (Luther, 2010). As a result of both illegal import and domestic generation, emerging economies face great challenges from rising quantities of e-waste (Widmer et al., 2005; Schluep et al., 2009).

There has been an increase in the number of domestic and international policies and pieces of legislation to reduce the environmental impacts from end-of-life electronics. The most prominent example of an international initiative to combat illegal transboundary e-waste shipments was the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (in force since 1992). The Convention also requires that exporting countries ensure that hazardous wastes are managed in an environmentally sound manner in the countries to which they are exported (Widmer *et al.*, 2005). At the domestic level, there are a great variety of pieces of legislation in place to control the environmental impacts of e-waste products throughout the entire life cycle, during product design, manufacturing, consumption and end-of-life management.

For e-waste management, many countries have instituted "take-back" laws, which mandate separate collection and environmentally sound treatment of e-waste. The reasons behind product take-back initiatives can be traced to economic and ecological concerns (Nnorom and Osibanjo, 2008). A primary concern is that electronic products contain hazardous materials, which can be released into the environment at landfills, municipal waste incinerators or through illegal export to developing countries. In addition to these environmental motivations, recycling of secondary materials contained in e-waste is economically attractive. With the latest concerns regarding resource scarcities and preservation of critical metals (Kooroshy *et al.*, 2010), efficient recovery of valuable materials from e-waste has become a top priority for policymakers in recent years.

Most of these national take-back and treatment policies and pieces of legislation are based on the principle of extended producer responsibility (EPR). EPR states that producers' responsibilities for products extend to the post-consumer stage of a product's life cycle, especially to the take-back, recovery and final disposal of obsolete products (Lindhqvist, 2000;

OECD, 2001). Driven by a widespread recognition of the EPR principle, producers have been motivated to improve the eco-design of their products and even establish take-back systems (McKerlie *et al.*, 2006; Sander *et al.*, 2007; Zoeteman *et al.*, 2010; Lifset *et al.*, 2013). As a consequence, operational and financial responsibilities have been partly or fully shifted to producers in the EU, Japan and China (European Union, 2003; China State Council, 2009; Yoshida and Yoshida, 2009).

3.1.2 System operation

Separate collection and responsible treatment of e-waste has been discussed for almost 20 years. In several countries this has resulted in national legislation to establish management systems to mandate collection and treatment (Stevels *et al.*, 2013). At the present time, take-back and treatment systems for e-waste are operated at the regional or national level. There is no universal model for implementation, due to different policy targets, administrative priorities and socio-economic conditions around the world. A great variety of operational models and system architectures exist, with many different targets and standards, product scopes, means for collection, treatment technologies, financial schemes, monitoring systems and reporting routines.

Legislation and targets

A legal framework can provide explicit rules of conduct and operating standards for obligatory implementation of the expected policy targets. Due to the complexity of this task, a high level national prioritization, appropriate policy targets, detailed plans for implementation, coordination among stakeholders and performance monitoring are crucial for effective enforcement of the established legislation.

Take-back and treatment systems began operating in several European countries during the end of last century. The Netherlands was the first country in Europe to adopt and implement take-back legislation. The Dutch take-back approach assigns costs, relies on a national system of municipal collection points and employs profit-oriented companies to process e-waste (Gutowski et al., 2005). With the enactment of the WEEE Directive in the EU in 2003, all European Member States were required to establish systems for collecting and treating e-waste at the national level by 2005. Based on the EPR principle, the WEEE Directive mandated that producers take financial responsibility for the collection, transportation and treatment of e-waste. As a result of this directive, many types of systems are in operation throughout Europe. But there was no consensus on the best approach for constructing such systems; they take different forms and operate in significantly diverse contexts (Fredholm, 2008). Performance in achieving the expected collection and treatment targets vary greatly by country.

Japan was the first country in Asia to introduce a system with South Korea following soon thereafter. Singapore, Australia and Thailand are still in deliberation. China introduced its e-waste recycling law in 2009. The basic principles are in place but details have yet to be specified. Several states and provinces in the USA and Canada have introduced e-waste legislation, while legislation is under consideration in other countries such as Brazil and Mexico.

Based on the way in which product categories are defined, policy targets and actual performance for official treatment quantities vary by country as well. Most countries with national e-waste

legislation do not have an explicit target of how much e-waste is required to be collected. The only exception is that in the old and new versions of the EU Directive, collection rates targets have been issued for EU Member States. Despite efforts to collect as much e-waste as possible for treatment in official recycling systems, approximately 70% of the e-waste generated in the EU currently escapes the system via export or other unknown treatment channels. Similar figures apply to non-EU countries that have take-back and treatment systems and identical situations (Yoshida *et al.*, 2009; Huisman *et al.*, 2012; Magalini *et al.*, 2012); collection performance still needs to be improved. Studies from many countries have demonstrated that established take-back systems have failed to capture a majority of domestic e-waste streams (Eijsbouts, 2008; Magalini *et al.*, 2012; Yoshida and Yoshida, 2012; Wang *et al.*, 2013). E-waste in these countries is still largely collected and traded by the informal sector and complementary streams, where treatment quality is not guaranteed. Therefore, the fundamental goal of formal collection systems are to aggregate e-waste and direct it towards the most responsible and eco-efficient treatment channels in order to prevent them from ending up in undesirable destinations.

Product scope

The scope of product types designated for specialized waste collection and treatment applied by national pieces of legislation vary greatly by country. For instance, the EU regulated ten distinct product categories in the old WEEE Directive, which almost covered all types of EEE in the market (European Union, 2003). The product scope was adjusted to include six categories in the new Directive (European Union, 2012) and was amended to group e-waste by its end-of-life attributes for waste management. In North America this is typically defined on a state-by-state basis and mainly limited to Information and Communication Technology (ICT) products and TVs. Japan has defined four product categories: TVs, air conditioners, refrigerators and washing machines. Similar to the Japanese scope, China has defined five types of products, adding computers (laptops and desktops) to the list. Due to limited infrastructure, financing or managerial resources, managerial priority has first been given to the products with the most environmental and economic impacts in each country's specific context. This has resulted in a differentiation in the way in which product scopes are interpreted around the world.

Collection methods

Collection methods involve different stakeholders for taking back obsolete products from consumers. Common options include permanent drop-off sites at municipal collection points or other public places, special collection events, collection sites at retail stores, regular curbside pick-up and on-demand pick-up (Gregory *et al.*, 2008).

Usually these methods can be applied in some combination, and selecting methods for collection is up to the stakeholders who are responsible. For instance, in Switzerland, all electronics retailers are required to accept waste products that are dropped off by consumers free of charge. In Portugal and the Netherlands, retailers are required to accept waste products from consumers if the products were originally purchased in the same store, or if consumers are buying a similar new product (NEPSI, 2002).

Collection efficiency depends on the type and size of products, geographical arrangement and coverage of collection channels, availability and convenience for users, competition from informal sectors, consumer awareness, public education and even proper publicity. Therefore, it is important to compile collection results from all established channels, and seek opportunities for improvement based on system leakages (products that are not properly collected).

Treatment

Treatment is the final activity in the take-back systems to reduce environmental impacts and improve resource efficiency. Different levels of development in treatment infrastructures have been implemented around the globe. They range from unsophisticated informal treatment with no formal infrastructure present to advanced recycling industries with high technological and environmental standards. The development of treatment infrastructures and technical know-how has become one of the key objectives of take-back systems. This will lead to better control of potentially toxic components in the pursuit of recovering valuable materials and preventing health and safety risks to workers. From experiences implementing systems in both industrialized and developing regions, barriers are primarily defined by the unavailability of investment or technical proficiency, a lack of EHS (Environment, Health and Safety) standards in treatment facilities, a strong influence from the informal sector, cherry-picking (of valuable materials) and a lack of sufficient feedstock supply from formal collection channels (Schluep *et al.*, 2009).

System management

The establishment and operation of e-waste take-back and treatment systems can be the responsibility of diverse entities that serve to coordinate and arrange the activities of different stakeholders while enforcing system rules and regulations (Gregory *et al.*, 2008). System management can include establishment; collection and spending of treatment fees; contracting logistics companies, municipalities and scrap companies for collection; contracting recycling companies for treatment, registration and reporting; and advertising to increase public awareness. Entities that are tasked with managing e-waste take-back and treatment systems on the global scale include governments, third party organizations (TPOs) and individual producers.

Governments can be in the central position of introducing e-waste legislation and also establishing specific collection channels, treatment facilities and financing schemes, as well as supervising system operations. Separate governmental organizations can be assigned to tasks such as legislating, operating, financing and monitoring. Systems operated by governments can have the advantage of combining managerial resources from governments, municipalities, customs, national statistics and registration. This government-centric approach has been implemented by countries like China, where strong governmental influence and central administrations are already in place.

A more popular approach to managing e-waste take-back and treatment systems is to use a third party organization or Producer Responsibility Organization (PRO). PROs are a collective industry effort to establish and manage e-waste programs (these organizations can sometimes include governments), in order to help its members fulfill their legal and financial responsibilities

related to e-waste. Collective PRO schemes can potentially achieve greater economies of scale than systems in which producers operate individually. Systems set up by PROs (also referred to as compliance schemes) vary greatly from country to country in terms of product scope, market coverage (consumer markets vs. business-to business-markets), operational models (collection channels, arrangement of logistics and contracted recyclers), numbers of participating members, brand coverage (own-brand or all-brands of waste), registration and monitoring. The European Union is a typical example of a system that allows for flexibility and diversity in the implementation of EPR and compliance schemes. More than 140 compliance schemes were counted in 27 EU Member States in 2008 (Huisman *et al.*, 2008). This resulted in great differences in collection and treatment performance, operational costs and environmental consequences, and also created greater administrative burdens for reporting and harmonization.

Apart from collective schemes, some producers have established individual product stewardship programs. In systems guided by the principle of Individual Producer Responsibility (IPR), each producer establishes infrastructure for recovery or hires service providers to take back and treat its own products.

Besides the costs associated with take-back system organizing and set-up, costs arising from the construction of reverse logistics and treatment facilities (known as technical costs), as well as the costs of management and administration, need to be covered by specific financing schemes. This guarantees the sustained operation of collection channels and treatment plants and allows formal systems to maintain an economic advantage over their informal competitors. The central challenge facing system architects and managers is to determine how much money is needed to achieve the expected environmental goal.

By comparing the operational approaches and models from various e-waste take-back and treatment systems currently in operation (Switzerland, Sweden, the Netherlands, Norway, Belgium, Canada and the USA), one study has shown that the breadth of the e-waste system is so large that there is no obvious correlation between architectural choices and observed performance (Fredholm, 2008). System components include the channels and methods for taking back or collecting obsolete products from consumers, the configuration of treatment facilities and system management practices. There are more differences between existing systems than there are similarities. Furthermore, existing e-waste take-back and treatment systems vary significantly not only in system architectures, but also in their operating contexts. Contextual factors (such as population density, the amount of e-waste ready for waste management, level of economic development, labor costs, public awareness and presence of the informal sector) fundamentally influence the performance of e-waste take-back and treatment systems.

Despite the many differences mentioned, one shared goal among all countries is to increase collection volumes and improve treatment efficiencies. In most situations, many different operational modes and methods are available to be selected and tested. For policymakers and system architects aiming to establish the optimal system for their region, it is important to evaluate the performance of existing systems and use this information to drive improvement.

3.1.3 Key topics for system improvement

Since the e-waste problem is regarded as a pressing environmental issue for the whole of society, governments are usually in the best position to establish legislation and coordinate stakeholders. Driven by the EPR principle, producers around the world are also responsible for establishing take-back and treatment systems. However, by their nature, both governments and producers often lack knowledge and practical experience in collecting and treating e-waste. Many take-back and treatment systems were built without thoroughly understanding the existing (informal) system, market mechanisms and the fundamental limits of technology (Manomaivibool, 2009). In Europe, producers initially perceived e-waste take-back as an extra cost burden and tried to pass it on to consumers. As a result, the beginning stages of most take-back and treatment systems have been rather cumbersome. Implementation has been a learning process, and scientific research has gradually provided valuable insights regarding the characteristics of e-waste, system flows, treatment technologies and impact assessments. Research has enhanced understanding among stakeholders. Systems currently in place are in different stages of growth and maturity in different countries.

Establishing e-waste take-back systems has been primarily a policy issue with a strong emphasis on reducing the environmental impacts for society. The leading questions related to the scope of e-waste are: "What type of e-waste, and how much of it, should be collected and treated?" For treatment, the main challenge is to determine which technology can achieve high efficiencies in material recovery and toxic control. In the financial domain, a lot of attention has been paid to the questions of "who has to pay what" and "on what basis should payments be made (market share, return share and so on)," rather than addressing the challenge of how to reduce the overall cost of system operations. This situation has led to rule-making that does not deliver enough environmental gain for the amount money spent. In Europe (Huisman *et al.*, 2006), environmental effectiveness has become the primary issue, whereas in Japan cost is the primary concern (Yoshida and Yoshida, 2010).

"Collect more and treat better" has been identified as the central goal for most countries with e-waste legislation and systems (Huisman *et al.*, 2008; Nnorom and Osibanjo, 2008; Wang *et al.*, 2013). It is therefore relevant to understand the status-quo of e-waste system performance as a baseline for benchmarking expected goals. Such systems evaluations can identify the cause and effect relationship between specific pieces of architecture in a system and the resulting performance change in e-waste collection and treatment. Consequently, these evaluations identify critical areas for improvement by adjusting system configurations.

The experiences and issues previously mentioned demonstrate the need for a more holistic approach to e-waste management, with due consideration given to the relevant technical, environmental, economic, social and legislative issues. Comparing the performance of systems without acknowledging the differences in the systems' characteristics and contexts can lead to ill-suited conclusions and recommendations.

The steps and priorities for developing take-back systems vary by country, and the following two sections will briefly introduce two case studies on the e-waste managerial experience in Europe and China. To a certain extent e-waste management in these two regions share many

similarities in general principles, but the operational models vary greatly. This can be attributed to different demographic, political, socio-economic and social circumstances (Zeng *et al.*, 2013). Europe and China could be considered two extreme cases in the spectrum of possibilities and administration styles, while other countries could end up somewhere in between. The learning trajectories and essential topics from the EU and China are summarized in the following sections.

3.2 Case studies of e-waste management in Europe and China

3.2.1 Case study 1: E-waste management in Europe

To address the rapidly growing amount of e-waste flowing into municipal waste streams, the European Union Waste Electrical and Electronic Equipment Directive (2002/96/EC) came into force on 27 January 2003. Prior to the enactment of this directive, there were a number of national initiatives to develop producer responsibility legislation and establish take-back and treatment systems in countries such as Austria, the Netherlands, Switzerland, Norway and Sweden (Leroy, 2012). The first draft of this directive was originally conceived in 1995, essentially in response to growing concerns of the toxic characteristics of e-waste. The initial goal was to ensure that e-waste was collected and treated in an environmentally sound manner (Huisman *et al.*, 2008). After the first draft in 2005, the WEEE Directive expanded its objectives to prevent the generation of e-waste, and to promote re-use, recycling and other forms of recovery, while also improving environmental performance related to e-waste treatment (Van Rossem *et al.*, 2006).

The WEEE Directive emphasizes the principle of EPR, that producers should be responsible for organizing collections for e-waste that are separate from other waste, and finance its treatment. This is envisaged to be an incentive for producers to implement eco-design strategies to reduce environmental impacts and improve the recyclability of their products. The WEEE Directive classified e-waste into ten major categories (based on waste products' original shapes and functions), which covered almost all EEE for household and business use. A collection target for products in all ten categories was stipulated: that member states must collect four kilograms per year per capita by the end of 2006. Additionally, re-use, recycling, and recovery rates between 50 and 80 percent (by category) should be achieved by the end of 2006. An inventory of hazardous substances and components was listed for obligatory removal during treatment (European Union, 2003).

Several years after implementation of the WEEE Directive, three studies were contracted by the European Commission with the goal of investigating the legal, technical and administrative enforcement practices implemented by member states in compliance with the directive (Savage, 2006; Sander *et al.*, 2007; Huisman *et al.*, 2008). The results from these three reports all found that better national compliance schemes were needed to collect more e-waste and treat it better in terms of environmental impacts, resource efficiency and operational costs. These reports also indicated that the levels of enforcement were not uniform among member states. The targets described in the framework of the WEEE directive were minimum requirements, and member states had the flexibility to formulate their own approaches and national laws. As a result, transposition of the directive looked rather different among the 27 EU countries in terms of timelines, definitions of key terms, take-back models, financing schemes and reporting

procedures (Stewart, 2012). Despite the effort to separately collect e-waste through specialized take-back systems, the problem of complementary flows and illegal exports persisted. For instance, only 40 percent of large appliances that were discarded were properly collected and treated in 2005; for medium-sized products, this rate was only 25 percent. Considering the disparities in e-waste generation between member states, the "one size fits all" collection target of four kilograms per capita per year was regarded as too static and conservative. For treatment, fulfillment of the recycling and recovery targets was too weight focused, but not from the basis of reducing environmental impacts and improving recovery efficiencies. Too little emphasis was put on the actual treatment performances of facilities, and further improvements can still be made in pre-processing efficiencies and upgrades of secondary material streams (Stevels, 2012).

In the meantime, the role of design in reducing the potential environmental impacts of products has been overestimated, and no obvious progress has been made in the field of eco-design in Europe. The original concept – that through better product design (for recycling) and the interaction between designers and recyclers, the cost and complexity of recycling schemes would be reduced – has failed in practice. There has been no fundamental environmental change in the product design paradigm or increase in practices to significantly improve the recyclability of products. For treatment technologies, mechanical size reduction and automatic sorting is the predominant technique used to pre-process waste products. However, economies of scale and costs to the recycling industry are underestimated. Cost management to lower the overall economic burden of take-back and treatment systems has been implemented by EU Member States in many different ways. Despite the complex characteristics and configurations found in the end-of-life stages, no information feedback loops emerged between the treatment industry and designers to formulate better products.

To address the issues of system performance, the European Commission proposed a recast of the Directive for amendments in 2008. After the recast process, the new WEEE Directive (2012/19/EU) was published in July 2012. The original e-waste classifications – ten application-oriented categories – were updated to become six collection-oriented categories. A new collection target replaced the previous weight-based target (4 kg/capita); starting in 2016, Member States will be required to collect 45 percent of the average weight of EEE placed on the market in the three preceding years. These targets will increase in 2019 to 65 percent of the average weight of EEE placed on the market in the three preceding years, or 85 percent of WEEE generated in the territory of that Member State (European Union, 2012). The new collection targets should ensure that around 10 million tons, or roughly 20 kg per capita per annum, are expected to be separately collected from 2019 onwards (European Commission, 2012). Another improvement in the new directive was the harmonization of national registration and reporting requirements, with more integration and better consistency under a uniform format. Administrative burdens are expected to decrease significantly.

The recast process demonstrates that there is no "one size fits all" policy or single best solution that is suitable to all countries, which have different socio-economic and political conditions. The old 4 kg/capita collection target is a characteristic example, as it did not consider specific market conditions and different magnitudes of e-waste generation in individual Member States. For instance, current e-waste generation in member states varies from 9kg/capita (in Bulgaria and

Romania) to 21-27 kg/capita (in Austria, Belgium, Germany and Sweden) (Stevels, 2012). A uniform collection target is not a properly scaled goal for each country. The gap between the actual collections and the regulated targets needs to be closed by additional measures to improve collection quantities. This disparity also shows that while the basic elements of the solutions are similar, diverse approaches have been employed to tackle the same objective: efficient and effective management of e-waste. However, common standards and harmonization between national and international pieces of legislation are still essential for reducing managerial burdens and improving efficiency (Khetriwal *et al.*, 2011).

One very important lesson from the European experience comes from the cycle of learning resulting from the interaction with scientific research. Stevels (2012) evaluated the trends in approaches to e-waste management in Europe between 1996 and 2006. Key principles, product scopes, environmental priorities and applied technologies have all gradually evolved over time due to developments in technology, managing experience, awareness and stakeholder collaboration. For instance, the starting point of managing e-waste in the 1990s was to simply solve the waste issue, but priorities later changed to focus on optimizing waste management and saving resources in 2006. Environmental concerns have evolved from waste prevention and toxic control to a range of topics including toxicity, resource efficiency, energy preservation, health and safety.

Europe's experiences make clear that it is essential to keep legislation, standards and policy instruments dynamic and responsive to the latest developments. The e-waste issue is primarily environmental, with many challenges in resource efficiency and toxicity. These problems need to be solved by a combination of the appropriate treatment technologies, policy instruments, better eco-design for products, prevention and improved system organization (both in terms of management and costs). Scientific research can play a very important role throughout this learning process by evaluating the current status of policies and identifying performance gaps. This fact-based approach will allow the respective producers, recyclers and governments to create better methods to increase the performance of national e-waste systems.

3.2.2 Case study 2: E-waste management in China

In China, the e-waste situation is fundamentally different from the EU. E-waste is generally regarded as a valuable secondary resource for re-use and material recycling rather than a waste issue, as it is in Europe. A huge role is played by the informal sector, which engages in import door-to-door e-waste collection, refurbishment and backyard recycling. Most end-of-life home appliances in China are already handled by the informal sector through established trading networks. Due to imperfect environmental performance in the informal sector, formal take-back and treatment systems are being planned by the government. Therefore, the main challenge facing the Chinese e-waste management system is to figure out how to reduce adverse effects from the informal sector while establishing a formal sector with a competitive advantage and reasonable environmental and economic performance.

Unlike in Europe, e-waste management in China did not start with legislation; two pilot projects were initiated to gain practical insights to determine the best means for collection and treatment technologies. After these two pilot projects, detailed articles for implementing the e-

waste legislation were laid down in 2012. In China, the demand for secondary resources and regulatory frameworks contribute to industrial scaling-up and increased interest among companies in investing in e-waste processing (Bogaert *et al.*, 2008).

E-waste treatment in China was characterized by the prevalence of informal or backyard treatments, which caused substantial damages to local environments and the health of workers (Puckett *et al.*, 2002). Therefore, between 2003 and 2006 the National Development and Reform Commission (NDRC) of China initiated a pilot project in four target cities to explore the critical technologies and equipment that had the potential to mitigate this problem. E-waste treatment facilities for major home appliances were constructed in the pilot cities. These plants were planned and financed by both governments and private companies.

Despite the successful construction of these treatment facilities, very little progress was made on the collection channels to supply sufficient e-waste to them. This was because no regulatory framework for a compatible collection system was established. As a result, the facilities suffered serious deficits due to high operational and maintenance costs arising from insufficient feedstock of e-waste and a lack of treatment subsidies for specific products. When the project was implemented, e-waste was mainly collected by informal, door-to-door collectors and it became difficult to collect e-waste for reasonable prices without the proper take-back channels. The main lesson from this project is that a sufficient supply of e-waste is essential for the success of advanced treatment facilities. Merely constructing treatment facilities, without preparing a complete recycling and supply chain, will lead to discontinuous operation and insufficient performance. It was concluded that proper financing schemes to cover the deficits from formal recycling are essential to running the systems as effective businesses.

With these lessons learned, the Chinese government unfolded a new pilot program between July 2009 and December 2011, calling it the *household appliance "old for new" program*. This program was prepared with two objectives in mind: 1) stimulate domestic purchases of new home appliances to create a thriving national economy in a period of global economic recession; 2) explore a possible model for e-waste take-back that would provide consumers with an economic incentive to return their e-waste to formal channels. The new rule stipulated that consumers who bought one new home appliance and handed in one unit of e-waste to the retailer/formal collector would receive a 10 percent discount off the price of the new equipment and the remaining value from the returned e-waste. Contracted collectors received subsidies for collection logistics. Recyclers also received subsidies, based on product type. The data (MOC, 2011) shows that this program has had substantial successes in selling new products and getting back old appliances from consumers. By 11 May 2011, after 20 months of implementation, 49.9 million units of obsolete home appliances were collected from consumers and 48.1 million units of new appliances were sold (for 27 billion USD).

The main lesson from this pilot project is that, provided with sufficient collection subsidies, the formal sector can collect large quantities of e-waste within a short period of time and stay competitive with the informal sector. When a recycling deficit is assisted by a recycling subsidy with an abundant supply of e-waste, formal recyclers can sustain their operations and make a profit. But the success of the program was heavily dependent on a high level of subsidy. For

instance, when one new TV is sold and an old TV is collected, the subsidies issued can add up to 41-68 USD per item. This generous subsidy has created unrealistic market hype that will be impossible to sustain for a long period of time. As soon as the subsidy stops, consumers are quite likely to sell their waste appliances to the informal sector again. Defining optimal subsidy levels while maintaining high collection rates and properly allocating responsibilities still needs to be researched and discussed.

As a result of these two pilot projects, a national e-waste law has been enforced in China since January 2011 (Regulation on Management of the Recycling and Disposal of Waste Electrical and Electronic Equipment). It can be regarded as equivalent to the EU WEEE Directive and is a pivotal piece of national legislation for e-waste management in China. It stipulates that e-waste should be separately collected by multiple channels and recycled collectively. A specialized fund has been set up to subsidize the formal collection and recycling of e-waste. Producers and importers of electronic products are required to contribute to this fund. In July 2012, the Chinese government released the details of the China E-waste Fund Management Measures, which specifies the amount of treatment fees, means and frequency of fee collections, fund contributors and list of eligible recyclers (China Ministry of Finance *et al.*, 2012; China Ministry of Finance *et al.*, 2012). As of 2013, five types of products were regulated, and their producers were taxed for subsidies (computers, refrigerators, air conditioners, washing machines and TVs), according to their estimated treatment and managerial costs. This product list will be updated in the future if more products with high environmental impacts and social relevance are identified. A standard and certification system for e-waste recycling and disposal enterprises has been established to monitor and ensure safe processing of e-waste. But there is no detailed article in this law that defines specific collection or recycling targets and its outcome in different provinces has yet to be evaluated.

3.3 Discussion

European and Chinese practices in managing e-waste demonstrate that there is no universal or single ideal e-waste policy that can be replicated globally to solve the problem for all countries. But the overall goals are rather identical: collect more e-waste through take-back systems and treat it better with high eco-efficiency (Huisman *et al.*, 2008; Wang *et al.*, 2013). This will aggregate diverse e-waste streams into organized channels and responsible treatment destinations.

In Europe, a top-down approach was adopted with performance requirements centralized by the legislative framework. In China, the approach to tackle the e-waste issues has been much more straightforward and pragmatic through "learning by doing," and it chiefly focuses on the technical work of collection and treatment. This is because influences from the informal sector in developing countries are not negligible. The national legislation in China was only introduced eight years after pilot project testing, investigating and consulting with stakeholders. But while Europe still allows flexibility in legislation implementation and enforcement for each Member State, China has applied a very centralized approach in which the government coordinates the operation, management and monitoring of the national take-back and treatment system. There is much less flexibility and incentive for producers to establish their own recovery networks and

infrastructures. Also, regional differences have not been reflected in the Chinese take-back and treatment system.

Despite these different starting points and system architectures, the implementation experiences in both Europe and China highlight the importance of dynamic learning cycles. Both cases show the importance of developing systems into maturity. For proper management, e-waste flows need to move from a state of chaos and autonomy to a more organized state with specialized systems. This transition is inevitable when building up a fully efficient and sophisticated end-of-life industry with more high-tech treatment and reducing the prevalence of low-tech practices. Such development should incorporate the informal sector without destroying it, which will retain the advantages of high collection efficiency and repair levels. This demands that formal systems develop efficient means for collection and state-of-the-art treatment facilities. Throughout this process, policies and intervention instruments that generate positive outcomes are likely to have side effects. These adverse impacts should be closely monitored and measured. According to the latest developments and newly acquired knowledge, legislation and policy instruments should be constantly updated and adjusted for incremental improvements.

Scientific and engineering research has played an important part in forming the knowledge base and contributing to the learning experience. It can provide objective and independent information to close the knowledge gap, facilitating discussions relating to politics and system construction. Due to the complexity of the topics, many answers are needed from the technical, economic, social and legislative perspectives. Based on a review of these case studies, a couple of key questions are recapitulated below.

Based on the scope of e-waste definitions and national priorities, interpretations vary by country. Although it is idealistic to compile an exhaustive catalogue of all e-waste, limited resources often limit such ambitious management plans. In most cases, setting priorities can greatly reduce workloads by allocating managerial resources to products with the potential for the most impact. The key question becomes, "What type of e-waste should be given priority and based on what criteria?" According to the literature review, few studies actually attempt to systematically categorize e-waste and provide criteria for prioritizing e-waste types to ease the complexity of daily management. Because of this, an extensive analysis of the societal, environmental and economic impacts of all existing e-waste types is necessary to improve research.

The second topic for e-waste management is to determine how much e-waste is out there in society and how much should be formally collected. The former part of the question can be answered by modeling the generation, consumption and disposal of e-waste flows. The latter part of the question depends on the existing collection system and extent of intervention from new collection channels. From the managerial perspective it is rather important, but also difficult, to map all the sources and destinations of e-waste in society. It requires extensive fact finding, data gathering, modeling and analysis to fully understand current e-waste flows in specific regions, and also include consumer behaviors and social structures. The literature review showed that the methods and procedures for quantifying e-waste in society is not yet sophisticated enough to generate reliable and comparable results. Uniform methods and processes for calculating this need to be developed to increase the accuracy of results and

reduce computational complexities. This will greatly improve understanding of the e-waste system for managers of compliance schemes and policymakers.

The third pending question is: "What kind of treatment technology can best recycle materials in e-waste and also capture embedded toxic substances?" This question is related to technological innovations in both developing/new treatment techniques and to identifying the best existing technologies for application. Technological analysis should not only assess the performance of physical and chemical processes in facilities, but also measure their potential impacts on investment, the economy and social acceptance. In light of the literature review, it makes sense to conduct more contextual assessments of existing treatment techniques. This would examine their applicability to specific market conditions and social contexts. It requires extending the weight-based technical analysis to include a more societal analysis, including the environmental and economic impacts of a specific facility, country or market period.

Finally, the informal and backyard recyclers in developing countries are still influential parties that pollute and are not to be neglected. Qualitatively, it is clear that most substandard techniques cause environmental problems. But there is little quantitative assessment of the actual treatment process, especially regarding damage to the health of workers and nearby residents. Including an occupational assessment in the general framework of the environmental impact assessment will guide improvements and upgrades of informal recycling practices when formalizing the informal sectors. This can greatly reduce health risks to backyard workers. Such assessment can also assist the formal treatment industry to comply with specific health standards and develop in a more environmentally friendly manner.

Related to these basic questions of take-back and treatment systems, other topics include the allocation of responsibilities among stakeholders, possible financing models, best managerial approaches and legislative instruments for achieving targets and the role of eco-design in reducing problems from the source. These questions refer to intervention profiles for execution, and a sensible discussion can only be built upon a solid base of knowledge.

3.4 Conclusions

Developed countries have passed most of the e-waste legislation that has been enacted around the world today. Developing countries are gradually catching up with these legislative and managerial developments because of their substantial increase in e-waste quantities and presence of the informal sector. Although basic principles are shared, there is no universal legislation or practice that can be directly copied from country to country. In order to develop an effective legislative framework, each country should assess its own market dynamics and socio-economic conditions while taking note of the experiences from other countries. Establishing an e-waste take-back and treatment system requires substantial amounts of time and effort to grow and find the optimal approach. But the common denominator is that policymakers and system managers need to increase the amount of e-waste collected through take-back systems and treat it better via the recycling industry. This reaffirms the importance for researchers to assess the current performance of take-back and treatment systems. The following points are the main areas for the remaining chapters of this dissertation:

- Characterizing and classifying e-waste, and setting managerial priorities for specific categories of e-waste, will help to solve the scoping issue (Chapter 4). This is extremely helpful for countries with limited resources, where managing all e-waste categories is not possible.

- Accurate accounting and understanding the e-waste flows (especially for e-waste generation) can provide a baseline for planning and managing collection systems with clear targets and measurements (Chapter 5). This is instrumental in identifying gaps and loopholes for uncontrolled e-waste flows and treatment. Effective intervention schemes can be implemented to reduce system leakages and improve collection volume.

- A systematic analysis of treatment technologies with consideration of market and socio-economic dynamics will deepen knowledge of the treatment system (Chapter 6). This will help to identify tailored treatment techniques for various categories of e-waste in different countries, when accompanied by the proper incentives. It will also improve treatment efficiencies and guide investments in the recycling industry. Understanding the differences between developed and developing countries will help bridge the technical and knowledge gaps, while improving e-waste treatment around the globe through the transfer of knowledge and international cooperation (Chapter 7).

- Evaluating the health impacts to workers will greatly help to understand the environmental mechanism between emissions and health consequences within the occupational environment (Chapter 8). This will guide improvements to substandard treatment processes for better environmental, health and safety measures.

3.5 References

Bogaert, S., M. Van Acoleyen, I. Van Tomme, L. De Smet, D. Fleet and R. Salado (2008). Study on RoHS and WEEE Directives, ARCADIS & RPA.

Brigden, K., I. Labanska, D. Sanyillo and M. Allsopp (2005). Recycling of Electronic Waste in China and India: Workplace and Environmental Contamination, Greenpeace Report, Greenpeace International.

Carroll, C. (2008). High Tech Trash. National Geographic. USA.

CBS (2008). Following the Trail of Toxic E-Waste. USA, CBS (60 Minutes). CBS Broadcasting, Inc.

China Ministry of Finance, China Ministry of Environmental Protection, China National Development and Reform Commission and China Ministry of Industry and Information Technology (2012). "Announcement on the first list of e-waste recycling companies eligible for receiving treatment subsidy"关于公布第一批废弃电器电子产品处理基金补贴企业名单的通知 (财综[2012]48 号). Bejing, China.

China Ministry of Finance, China Ministry of Environmental Protection, China National Development and Reform Commission, China Ministry of Industry and Information Technology, China General Administration of Customs and State Administration of Taxation of the People's Republic of China (2012). Management measures on the collection and use of recycling funding on waste electrical and electronic equipment (废弃电器电子产品处理基金征收使用管理办法). Beijing, China.

China State Council (2009). Regulation on Management of the Recycling and Disposal of Waste Electrical and Electronic Equipment (废弃电器电子产品回收处理管理条例). Beijing, State Council of the People's Republic of China. **No.551**.

Cobbing, M. (2008). Toxic tech: not in our backyard, uncovering the hidden flows of e-waste.

Eijsbouts, R. J. J. (2008). Research into complementary waste streams for e-waste in the Netherlands. Breda, the Netherlands, Witteveen+Bos.

Elgin, B. and B. Grow (2008). E-Waste: The Dirty Secret of Recycling Electronics. Business Week. USA.

European Commission. (2012). "Recast of the WEEE Directive (official webpage)." from http://ec.europa.eu/environment/waste/weee/index_en.htm.

European Union (2003). Waste Electrical and Electronic Equipment Directive (2002/96/EC). Brussels, Belgium, Official Journal of the European Union L37.

European Union (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) (Recast), Official Journal of the European Union L 197. **Volume 55**.

Fredholm, S. (2008). Evaluating Electronic Waste Recycling Systems: The influence of physical architecture on system performance, Massachusetts Institute of Technology.

Gregory, J., F. Magalini, R. Kuehr and J. Huisman (2008). E-waste Take-Back System Design and Policy Approaches. Solving the E-Waste Problem (StEP) White Paper. Bonn, Germany, United Nations University.

Gutowski, T., C. Murphy, D. Allen, D. Bauer, B. Bras, T. Piwonka, P. Sheng, J. Sutherland, D. Thurston and E. Wolff (2005). "Environmentally benign manufacturing: observations from Japan, Europe and the United States." Journal of Cleaner Production **13**(1): 1-17.

Huisman, J., F. Magalini, R. Kuehr, C. Maurer, S. Ogilvie, J. Poll, C. Delgado, E. Artim, J. Szlezak and A. Stevels (2008). Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Bonn, Germany, United Nations University.

Huisman, J., A. Stevels, T. Marinelli and F. Magalini (2006). Where did WEEE go wrong in Europe? Practical and academic lessons for the US. Electronics and the Environment, 2006. Proceedings of the 2006 IEEE International Symposium on, IEEE.

Huisman, J., M. van de Maesen, R. J. J. Eijsbouts, F. Wang, C. P. Baldé and C. A. Wielenga (2012). The Dutch WEEE Flows. Bonn, Germany, United Nations University, ISP-SCYCLE.

Khetriwal, D. S., R. Widmer, R. Kuehr and J. Huisman (2011). "One WEEE, many species: lessons from the European experience." Waste Management & Research **29**(9): 954-962.

Kooroshy, J., C. Meindersma, R. Podkolinski, Michel Rademaker, T. Sweijs and S. d. Goede (2010). Scarcity of Minerals: A strategic security issue. The Hague, The Netherlands, The Hague Centre for Strategic Studies.

Leroy, P. (2012). The WEEE Forum and the WEEELABEX project. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Lifset, R., A. Atasu and N. Tojo (2013). "Extended Producer Responsibility." Journal of Industrial Ecology **17**(2): 162-166.

Lindhqvist, T. (2000). Extended producer responsibility in cleaner production: Policy principle to promote environmental improvements of product systems, International Institute for Industrial Environmental Economics (Internationella miljöinstitutet), Univ.

Luther, L. (2010). Managing Electronic Waste: Issues with Exporting E-Waste. USA, Congressional Research Service.

Magalini, F., J. Huisman, R. Mosconi and A. Gobbi (2012). Household WEEE Arising in Italy. Bonn, Germany, United Nations University.

Manomaivibool, P. (2009). "Extended producer responsibility in a non-OECD context: The management of waste electrical and electronic equipment in India." Resources, Conservation and Recycling **53**(3): 136-144.

McKerlie, K., N. Knight and B. Thorpe (2006). "Advancing Extended Producer Responsibility in Canada." Journal of Cleaner Production **14**(6–7): 616-628.

MOC. (2011). "The sales of home appliance 'old for new' program exceeds 180 billion RMB." Retrieved 18 November, 2011, from http://jdyjhx.mofcom.gov.cn/website/webNews!view.shtml?_id=164659417.

NEPSI (2002). Financing and Infrastructure Model Characteristics. Knoxville, USA, National Electronics Product Stewardship Initiative (NEPSI).

Nnorom, I. C. and O. Osibanjo (2008). "Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries." Resources, Conservation and Recycling **52**(6): 843-858.

OECD (2001). Extended producer responsibility: a guidance manual for governments. Paris, France, Organisation for Economic Co-operation and Development.

Puckett, J., L. Byster, S. Westervelt, R. Gutierrez, S. Davis, A. Hussain and M. Dutta (2002). Exporting harm, the high-tech trashing of Asia. Seattle, USA, The Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC).

Sander, K., N. Tojo and J. Vernon (2007). "The Producer Responsibility Principle of the WEEE Directive."

Savage, M. (2006). Implementation of Waste Electric and Electronic Equipment Directive in EU 25, AEA Technology, Institute for Prospective Technological Studies.

Schluep, M., C. Hagelüken, R. Kuehr, F. Magalini, C. Maurer, C. Meskers, E. Mueller and F. Wang (2009). Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling - from E-waste to resources. Bonn, Germany, United Nations Environment Programme & United Nations University.

Stevels, A. (2012). The present recast of the WEEE Directive. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Stevels, A., J. Huisman, F. Wang, J. Li, B. Li and H. Duan (2013). "Take back and treatment of discarded electronics: a scientific update." Frontiers of Environmental Science & Engineering: 1-8.

Stewart, R. (2012). EU legislation relating to electronic waste: the WEEE and RoHS Directives and the REACH regulations. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Philadelphia, USA, Woodhead Publishing Limited.

Van Rossem, C., N. Tojo and T. Lindhqvist (2006). "Lost in transposition? A study of the implementation of individual producer responsibility in the WEEE Directive." Report commissioned by Greenpeace International, European Environmental bureau.

Wang, F., R. Kuehr, D. Ahlquist and J. Li (2013). E-waste in China: a country report. Bonn, Germany, United Nations University.

Widmer, R., H. Oswald-Krapf, D. Sinha-Khetriwal, M. Schnellmann and H. Böni (2005). "Global perspectives on e-waste." Environmental Impact Assessment Review 25(5): 436-458.

Yoshida, A., T. Tasaki and A. Terazono (2009). "Material flow analysis of used personal computers in Japan." Waste Management 29(5): 1602-1614.

Yoshida, F. and H. Yoshida (2009). "Japan, the European Union, and Waste Electronic and Electrical Equipment Recycling: Key Lessons Learned." Environmental Engineering Science 27(1): 21-28.

Yoshida, F. and H. Yoshida (2010). "Japan, the European Union, and waste electronic and electrical equipment recycling: key lessons learned." Environmental Engineering Science 27(1): 21-28.

Yoshida, F. and H. Yoshida (2012). An environmental and economic analysis of e-waste recycling based on the Japanese experience - focusing on flow estimation. Electronics Goes Green 2012. Berlin.

Zeng, X., J. Li, A. L. N. Stevels and L. Liu (2013). "Perspective of electronic waste management in China based on a legislation comparison between China and the EU." Journal of Cleaner Production 51(0): 80-87.

Zoeteman, B., H. Krikke and J. Venselaar (2010). "Handling WEEE waste flows: on the effectiveness of producer responsibility in a globalizing world." The International Journal of Advanced Manufacturing Technology 47(5): 415-436.

Chapter 4: Classification of EEE and E-waste

E-waste, as a category, describes a wide spectrum of obsolete products. Electronic products have heterogeneous characteristics such as size, weight, material composition, remaining function and value. This heterogeneity creates difficulty for end-of-life management, because combined treatment of different products can lead to resource losses and contamination from incompatible materials (Castro, 2005). Due to the diversity of product types, it is inefficient to establish specific collection channels and treatment facilities for each. In practice, take-back and treatment systems need to aggregate similar types of e-waste and implement category-specific recycling technologies for optimum efficiency by employing economies of scale (Goosey, 2012). This same principal applies to e-waste related legislation and management and will reduce administrative burdens. For these reasons, a systematic classification of e-waste can improve understanding of all e-waste products. It also can help to set priorities for managing critical product categories from an environmental, economic and social perspective.

The previous two chapters presented a literature review and the e-waste managerial experience, both of which made clear the importance of understanding e-waste characteristics and prioritizing management of categories with the most impact. This chapter analyzes the properties of waste products entering the waste stream and proposes methods for classifying e-waste in order to obtain a thorough understanding of this complicated waste category.

4.1 Criteria for classification of electrical and electronic equipment

E-waste is different from any other type of solid waste; it has multiple properties and a great variety of product types and complex material compositions. Large amounts of ferrous and base metals, precious metals and plastics are contained in e-waste as embedded materials, which can serve as secondary resources to be recycled. But hazardous and toxic materials present in e-waste can cause adverse environmental impacts if they are not properly controlled. From the perspective of functionality, e-waste has a big re-use potential both at the product and component levels (from detachable assemblies and modules). Due to the presence of various properties, it is logical to classify e-waste based on individual properties as well as by considering the characteristics together.

In order to understand the connection between products and end-of-life management strategies, the basic properties of EEE can be separated into two classes:

1) **Intrinsic properties** are the functional, physical and chemical characteristics of a product such as exterior and interior structure, weight, size, energy efficiency, product function and material composition. These product properties are preliminarily determined by functionality requirements and initial design. They usually do not change dramatically over time, space or with changes in social context.

2) **Extrinsic properties** include product price, quantities of sales, qualities of stock and lifespan. These properties often vary and are dependent on social and market conditions.

Table 4.1 summarizes key properties of EEE under these two classes and their influences on end-of-life management after products become obsolete. The first column of the table divides the properties of EEE into dimensions and criteria. The second column provides key measurements (units or indicators) associated with the property criteria. The third column lists the influence of this property on end-of-life management. The last column briefly summarizes the determining factors that influence the property.

The intrinsic properties have comparatively more influence on the technical construction of end-of-life management systems than extrinsic properties. For instance, product collections need to be tailored to the sizes and weights of obsolete products. The set-ups of pre-processing and end-processing technologies are influenced by the size and material composition of products. These properties have been pre-defined as functionality requirements and are universally consistent.

In contrast, exterior properties may vary greatly between countries and users, which are determined by local socio-economic factors. The types of products sold in a region are relevant to the region's lifestyle, climate, culture and economy. For instance, product sales and lifespans are related to income levels and consumer behaviors in a specific country. Combined with socio-economic conditions, these properties shape the scale of the e-waste problem and the overarching patterns that shape collection and treatment channels (such as informal sectors) in specific regions.

The main goal of this chapter is to categorize EEE and e-waste by their ubiquitous properties, which are independent from specific geographical and social contexts. Therefore, the analysis focuses on the intrinsic properties of EEE (i.e., weight, size and material composition). Extrinsic properties such as product sales, market saturation levels, stock amounts and lifespans are not applied as classification criteria in this chapter, considering their great variations across regions. The next section further explores indicators to quantitatively classify e-waste based on intrinsic properties.

Table 4.1 Overview of EEE properties and their influences on end-of-life management

Product property		Unit or indicator	Influences on end-of-life management	Mainly determined by
Intrinsic property	Weight and volume	kg/unit m³/unit	- Arrangement of collection - Pre-processing technologies	Product functionality and product design
	Material composition (recyclables)	- kg/kg - kg/unit - material value - Envi. impact score	- Material separation and refinery technologies - Recycling revenue and cost	
	Material composition (toxics)	- kg/kg - kg/unit - Envi. impact score	- Requirements for separation and detoxification - Cost of the recycling facilities	
Extrinsic property	Product price	€/unit	Incentive for re-use	- Product design - Production cost - Marketing strategy
	Quantity of product sales and stock	Units (or pieces)	Scale of take-back system treatment facilities	- Product function - Market conditions - Socio-economic status
	Product lifespan	Years	Expected time until product is discarded and the quantities of e-waste generated	- Product design - Technology cycle - User behavior - Socio-economic status

4.1.1 Product weight and volume as criteria

Collection is the step prior to treatment; during collection, e-waste is transported from users to treatment facilities. Users (especially household consumers) are geographically scattered, and collection requires logistical planning to aggregate obsolete equipment into concentrated streams. During this process, the size and weight of equipment play an important role in determining the means and efficiency of collection.

Small equipment can easily be stored indoors for a relatively long period of time (e.g., mobile phones and lamps in drawers, closets or storage rooms). When discarded, this type of waste can also be easily mixed with other waste streams such as municipal waste, plastic waste or metal scraps. If higher collection rates are expected for this category, more incentives are necessary to motivate consumers to hand in small equipment. Moreover, these small items are highly portable, and people can bring them to collection points without much effort. This can potentially reduce logistic costs for collection systems, but consumer motivation may decrease if collection points are far away. Due to the small size and low weight of small equipment, large quantities are needed for sufficient volumes, to reach the economies of scale needed for systematic recycling.

Contrarily, large or bulky equipment usually contains a large amount of recyclable material per unit. This partially offsets the cost of take-back and treatment systems. Large-size equipment takes up considerable space, and it is rarely stored in the built environment when it becomes obsolete (e.g., dishwashing machines and refrigerators). Swift removal and logistic arrangements are necessary due to the low mobility associated with heavy and large equipment. Despite this,

large or bulky equipment can easily be separated from other items and wastes in the return stream.

The size of equipment also determines the selection of optimal treatment technologies, especially in pre-processing. Manual dismantling can keep components intact and well sorted. But manual dismantling is not efficient for large numbers of small equipment unless special requirements are compulsory, such as obligatory removal of circuit boards and batteries. Batch recycling by mechanical methods to separate materials is more cost-efficient in countries with high labor costs. This method can process much higher quantities of e-waste than manual dismantling. But mechanical separation requires substantial capital investments for machines and the large amounts of energy used during operation. The separation rate of mechanical recycling is usually lower than manual dismantling, due to imperfect separation of mixed materials. Heavy equipment creates barriers for manual dismantling as well, due to difficulties in operating and handling these items on normal dismantling tables (e.g., washing machines and refrigerators). Here, mechanical separation can be more convenient and avoid workplace accidents.

In this chapter, average weight (kg/unit) is used as an indicator to represent the size of a specific product. This method is better than using volume (such as liter or m³) because volume is not easy to measure or communicate. Usually, there is a weight distribution for a specific type of equipment. Average weight represents the mean value of all sampled weight data, and the standard deviation indicates the level of variation from the average value.

4.1.2 Content of recyclable materials as a criterion

The majority of materials contained in EEE can be recycled when efficiently separated from other materials in the same equipment. Recyclable materials in EEE and its components can be generally grouped into the following types: base metals, precious metals, plastics and glass. Due to trace concentrations in EEE, rare earth metals and other less common metals can also be found (e.g., gallium, barium, rhodium, tantalum and bismuth). This topic is beyond the scope of this dissertation.

Base metals in EEE include metals (such as iron, steel, aluminum, copper, zinc, magnesium, lead and tin) and their alloys. Precious metals (such as silver, gold and palladium) are often found in circuit boards, chips and connectors. There is a great variety of plastics used in EEE that contain additives. Metals and plastics are the main economic drivers for e-waste recycling, and the main challenge lies in liberating target materials in sufficiently pure forms. This requires a careful compromise between avoiding cross contamination and preventing treatment losses. In theory, it is physically impossible to achieve 100 percent recovery for all materials due to entropy increases as defined by the second law of thermodynamics. In practice, full recovery of materials is limited by factors such as the intrinsic properties of the separation processes, imperfect liberation from pre-processing, loss of materials in end-processing and the degradation of recyclables in different recycling stages.

Weight metrics for specific materials are the most straightforward indicators (i.e., kg/unit, kg/kg or percentage) for evaluating the content of recyclable materials in EEE. However, only using weight-based indicators does not fully reflect the economic and environmental differences

between materials (Stevels, 2007). Extra indicators are needed to demonstrate the levels of importance of different materials and thus establish the real priority products.

Material price (i.e., €/kg) is the indicator used to show the financial value of both primary and secondary materials present in EEE. This can help to identify the most cost-effective equipment for recycling. Although most of the materials in EEE can be recycled, this does not necessarily mean that they have positive market values. Material prices only reflect the relationship between material supply and demand at a specific point of time, and they are rather dynamic over time. For instance, lead glass contained in CRT can be recycled and reproduced into new glass, but it has had little market value since the rapid decline in demand for CRT TVs and monitors in 2007. Finally, material price does not directly indicate material recyclability, but it does give an indication as to which materials global and regional markets prefer to recycle.

A third indicator is the environmental impact of material production. The value of this indicator is relatively constant and uninfluenced by market dynamics. It helps to indicate what equipment shall be recycled first, in order to have the most environmental gain by avoiding primary production. One quantitative method, Life Cycle Assessment (LCA), is an effective tool for evaluating the environmental impacts of different materials throughout their life cycles. In this chapter, the impact indicator from the "ReCiPe" method is applied to evaluate the impact of material production. ReCiPe is a life cycle impact assessment method that transforms the long list of Life Cycle Inventory results (for example, emissions and resources consumed) into a number of indicator scores. These indicator scores express the relative severity of a product on an environmental impact category (ReCiPe, 2009). The endpoint indicator in ReCiPe (expressed as point or "pt") is used to show the magnitude of the impact.

Table 4.2 provides a 2012 snapshot of both the market prices and the environmental impacts of primary production for the selected materials. Overall, the data shows that primary production of each material has an economic value (as defined by the market) that is different from its environmental impact. For instance, one gram of gold is the economic equivalent of 26 kg of aluminum and 6.7 kg of copper; it is the environmental equivalent of 1.4 kg of aluminum and 3.1 kg of copper. In general, both market price and environmental impact indicators have similar orders of magnitude, but there is no strict correlation between market prices and environmental impact of production. The disparity between these two indicators mainly suggests that they represent different pieces of information: market prices indicate the temporal relationship between supply and demand, and the environmental impact of production accounts for energy use and emissions during material extraction and refining. These environmental impacts may not be fully reflected in the economic indicator, because market prices fluctuate over time. Therefore, when evaluating recyclable materials, these two indicators should be applied separately in addition to the weight-based analysis.

Table 4.2 Market prices (2012) and environmental impacts of primary production for selected recyclable materials

Metals	Material price (€/kg)	Environmental impact (pt/kg)	Plastics	Material price (€/kg)	Environmental impact (pt/kg)
Iron	0.4	0.2	**ABS**	1.5	0.4
Aluminum	1.6	1.1	**PS (EPS)**	1.1	0.4
Copper	6.2	0.5	**PC**	2.2	0.7
Silver	778.8	16.6	**PE (HD)**	0.9	0.3
Gold	41725.8	1540.6	**PVC**	0.5	0.2
Palladium	16085	9832	**PMMA**	2.2	0.7

4.1.3 Content of hazardous materials and human toxicity potential as a criterion

Hazardous materials are materials that possess the potential to adversely affect the environment, or the safety and health of human beings. Since the implementation of regulations like the RoHS Directive 2002/95/EC (Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment) in the EU, the concentrations of six substances in EEE have been substantially reduced in new products. The environmental hazards associated with EEE mostly pose a threat during the end-of-life phase of the lifecycle. If the waste stream containing these hazardous materials is not properly treated, there is a risk that hazardous materials will be released into the environment. While some substances are harmless in nature, the recycling process might lead to significant pollution (e.g., uncontrolled acid leaching of precious metals in circuit boards). This is regarded as secondary pollution from e-waste (Schluep et al., 2009). The following table gives a selection of the most common toxic substances in e-waste (EMPA, 2013), including halogenated compounds, heavy metals and other materials such as toner and radioactive substances.

The table shows that most halogen-related materials are contained in plastics (such as flame retardants and cable insulation), so flame retardant (FR) products containing plastics and PVC need to be treated separately. Although CFCs have been phased out of cooling and freezing equipment since 1993 (Kim et al., 2006), old models are still likely to appear in waste streams due to time delays in disposal, and precaution still needs to be used with old appliances. Most heavy metals appear in circuit boards, batteries and screens, so methods for controlling toxics should be applied when treating CRT and LCD screens (monitors and TVs), mercury-containing lamps, products containing substantial amounts of batteries and circuit boards.

Toxic control should be the first priority in end-of-life management of these products due to their potential to cause severe damage to human beings and the environment. For products that do not contain these materials or have very low concentrations, priority in treatment is given to material recycling.

Table 4.3 Hazardous materials contained in e-waste

Substance	Occurrence in e-waste
Halogenated compounds	
- PCB (polychlorinated biphenyls)	Condensers, Transformers, TV enclosures,
- TBBA (tetrabromo-bisphenol-A); PBB (polybrominated biphenyls); PBDE (polybrominated diphenyl ethers)	Flame retardants for plastics (thermoplastic components, cable insulation, TV enclosures); TBBA is presently the most widely used flame retardant in printed wiring, TV enclosures; Boards and casings, housing of CRT screens
- Chlorofluorocarbon (CFC)	Cooling and freezing units, Insulation foam
- PVC (polyvinyl chloride)	Cable insulation
Heavy metals and other metals	
- Arsenic	Small quantities in the form of gallium arsenide in light emitting diodes
- Barium	Getters in CRT
- Beryllium	Power supply boxes which contain silicon controlled rectifiers and x-ray lenses
- Cadmium	Rechargeable Ni-Cd batteries, fluorescent layers (CRT screens), printer inks and toners, photocopying machines (printer drums)
- Chromium VI	Data tapes, floppy-disks
- Lead	CRT screens, batteries, printed wiring boards, solders
- Lithium	Li-batteries
- Mercury	Fluorescent lamps, some alkaline batteries and mercury wetted switches
- Nickel	Rechargeable Ni-Cd batteries or Ni-MH batteries, electron gun in CRT
- Selenium	Older photocopying-machines (photo drums)
- Zinc sulphide	Interior of CRT screens, mixed with rare earth metals
Others:	
- Toner Dust	Toner cartridges for laser printers / copiers
- Radioactive substances - Americium - Asbestos	Medical equipment, fire detectors, active sensing elements in smoke detectors Older appliances such as electric heaters, coffee pots, toasters and irons

To summarize the analysis from this section, there are multiple properties of e-waste that can serve as criteria for classification. As most intrinsic properties are independent from social contexts, they can provide a basis for uniform classification in most countries. The first grouping systems for e-waste are original size, and content of recyclable and hazardous materials. These physical properties are the main factors that determine the technical set-ups of take-back and treatment systems. The following section will classify all e-waste types by the three intrinsic properties. The outcome will allow for a useful agenda for e-waste legislation, management, investment and industrial development.

4.1.4 Product type on the basis of application as a criterion

It is natural to classify e-waste according to the product's original type and function. The main challenge lies in capturing all currently and formerly manufactured products, as well as all products that are expected to be manufactured in the future. The system of commodity codes in international statistics is a good source for compiling such information because it is publicly available, transparent, covers all commodities past and present and it is consistent across

countries. In addition, these records provide consistent past and present sales figures for all products. However, commodity codes were created for the purpose of registering products for global shipment; this system was not specifically designed for managing e-waste. Adjustments are needed before commodity codes can be used to categorize EEE and e-waste.

This dissertation will use codes and information from the European Prodcom (Production Statistics Database for the domestic statistics on the production of manufactured goods) and CN (Combined Nomenclature Database for the external trade statistics of goods) to compile all EEE-related information (Wang et al., 2012). Relevant statistical codes were selected for the period from 1993 to 2011 from the Eurostat Ramon database (Eurostat, 2011). Applying European statistical codes does not limit this analysis to the EU because the coding systems are compatible and can be traced back to their international counterparts (such as Harmonized System Codes).

As a result, around 250 Prodcom codes are identified as relevant to EEE every year. After chronologically organizing all the descriptions and coding information, they are arranged into 11 primary and 55 secondary (more specific) product categories. These ten primary categories were defined in the old EU WEEE Directive (2002/96/EC) (European Union, 2003). From the legislation perspective, it is essential to link the ten major categories from the old WEEE Directive with the six categories from the recast version (2012/19/EU) to establish compatibility between them and improve monitoring in the EU (European Union, 2012). For each primary category, subcategories are created to further specify the function and properties of specific products. Products with similar functions, material compositions, average weights and treatment priorities are grouped under the same subcategory.

Table 4.4 lists the result of the classification by product type. The ten primary categories cover the entire list of EEE, and they are broken down into 55 subcategories to further specify product functions. Under 55 subcategories, 660 products are listed. In this way, the 55 subcategories classify all possible EEE and link them to primary product categories and collection categories. The 17 subcategories used by the WEEE Forum and the 2007 WEEE Review study are also compatible with this list (Huisman et al., 2008; WEEE Forum, 2012). This classification follows the format of the ten product categories from the old WEEE Directive (European Union, 2003); this product type based list can be easily transferred to the six collection categories defined in the new WEEE Directive (European Union, 2012).

Table 4.4 Classification of electrical and electronic equipment by product function

Primary category	Subcategory	Number of product types
0. Prof. household equipment	0-01 Professional (PROF) household Central Heating 0-02 PROF PV solar panels	9 1
1. Large household appliances (LHHA)	1-01 PROF Heating & Ventilation (excl. cooling) 1-02 LHA Dishwashing (dishwashers) 1-03 LHA Kitchen (large furnaces, ovens, cooking equipment) 1-04 LHA Washing (washing machines & combined dryers) 1-05 LHA Drying (wash dryers, centrifuges) 1-06 LHA Room (large room heating & ventilation, hoods) 1-07 C&F Combi (combined fridge-freezers for food, wine, ice, etc.) 1-08 C&F Fridge (fridges for food, wine, etc.) 1-09 C&F Freezer (freezers for food, ice, etc.) 1-10 C&F Air conditioner (HH installed air conditioners) 1-11 C&F Other (dehumidifiers, heat pump dryers, etc.) 1-12 PROF C&F (Prof. air conditioners, cooling displays, etc.) 1-13 SHA Microwaves ((combined) microwaves, excl. grills)	18 1 6 2 2 19 1 3 1 13 3 15 2
2. Small household appliances (SHHA)	2-01 SHA Other (small ventilators, irons, clocks, adapters, etc.) 2-02 SHA Food (kitchens, food processors, frying pans, etc.) 2-03 SHA Hot water (coffee, tea, hot water, etc.) 2-04 SHA Vacuum cleaners (excl. professional ones) 2-05 SHA Personal Care (tooth brushes, hair, razors, etc.)	26 56 15 4 28
3. IT and telecom equipment (IT)	3-01 IT Small (other small IT, including components & accessories) 3-02 IT Desktop PCs (excl. monitors, accessories) 3-03 IT Laptop PCs (laptops, notebooks, netbooks, tablets) 3-04 IT Printers (printing & imaging, scanners, MFS, faxes) 3-05 IT Phones (telephones & equipment, DECT phones) 3-06 IT Mobile phones (mobile phones, smart phones, pagers) 3-07 PROF IT (large IT, servers, routers, data storage, copiers) 3-08 SCREENS CRT monitors (cathode ray tube monitors) 3-09 SCREENS Flat Display Panel Monitors (LCD, LED monitors)	19 1 4 10 7 3 8 1 4
4. Consumer equipment (CE)	4-01 SHA CE (other, headphones, adapters, remote controls) 4-02 SHA Portable Audio/Video (MP3, e-readers, navigators, etc.) 4-03 SHA Radio & HiFi (audio sets, components, etc.) 4-04 SHA Video (VCR, DVD(R), Blue Ray, Decoders, etc.) 4-05 SHA Speakers 4-06 SHA Cameras (camcorders, photo & digital still cameras) 4-07 SCREENS CRT TVs 4-08 SCREENS Flat Display Panel TVs (LCD, LED, PDP)	5 13 17 15 3 4 1 9
5. Lighting equipment	5-01 SHA Lamps (pocket, Christmas, halogen) 5-02 LAMPS CFL (compact fluorescent, retro & non-retro) 5-03 LAMPS TL (straight tube fluorescent lamps) 5-04 LAMPS Special (Hg, high & low pres. Na, other prof. lamps) 5-05 LAMPS LED (incl. retrofit lamps, HH LED luminaries) 5-06 SHA Luminaries (HH incandescent fittings) 5-07 PROF Luminaries (offices, public space, industry)	3 2 2 4 2 11 2
6. Electrical & electronic tools	6-01 Small tools (saws, drills, cleaning, garden, etc.) 6-02 PROF Tools (Professional tools, excl. dual use)	83 36
7. Toys, leisure and sports equipment	7-01 SHA Toys (small toys, vehicles, small music) 7-02 SHA Game Consoles (video games and consoles) 7-03 LHA Leisure (large exercise, music instr. & sunbeds)	3 4 17
8. Medical devices	8-01 SHA Medical (small HH thermo-, blood pressure meters) 8-02 PROF medical (hospital, dentist, diagnostics, etc.)	52 47

9. Monitoring and control instruments	9-01 SHA Monitoring (alarm, heat, smoke, security, ex. screens) 9-02 PROF Monitoring (Prof. M&C, garage, diagnostic, etc.)	28 7
10. Automatic dispensers	10-01 PROF Dispensers (non-cooled vending, coffee, tickets, etc.) 10-02 PROF Dispensers (cooled vending, bottles, candy, etc.)	4 3

4.2 Classification of e-waste based on individual criterion

Both qualitative and quantitative criteria can be the basis for classifying EEE and e-waste. These criteria reflect specific characteristics for electrical and electronic products, which are usually independent from each other. This section will classify EEE and e-waste into groups with identical features or properties based on individual criterion. The result will illustrate the results of categorizing by groups such as material recycling, the environment and the economy.

As a first step, generic material compositions for representative product types in each product subcategory are compiled from the literature. Based on the composition data, e-waste is then quantitatively classified by its content of recyclable and hazardous materials, potential material value, environmental gain from recycling and human toxicity potential in the end-of-life phase.

4.2.1 Classification of e-waste by material composition

The last section, classifying by product type, separated e-waste into 11 categories and 55 subcategories. This provides a good basis for further identifying priorities based on various end-of-life characteristics. Although it is logical to categorize e-wastes according to their original product types, e-waste collection and recycling systems are not dedicated to singular product types. In practice, products with similar intrinsic properties (size, weight and material composition) are aggregated in the same stream for efficient treatment.

In order to quantitatively evaluate the properties of EEE, the next step is to identify material compositions by subcategory. Representative product types have been selected from the 660 types for each product subcategory, as introduced in Table 4.4 of Section 4.2.1. Their average weights and material compositions are compiled in Table 4.5. The data for the average product weights were retrieved from a national e-waste study conducted in the Netherlands (Huisman et al., 2012). Material compositions of computers, various small household appliances and consumer equipment (CE) were collected from several product disassembly sessions in China and the Netherlands (Gmünder, 2007; Wang et al., 2008). A variety of sources provide the material compositions of large household appliances, IT products and lighting equipment (Huisman, 2003; Townsend et al., 2004; Hikwama, 2005; Apple Inc., 2008; Cui and Zhang, 2008; Huisman et al., 2008; Chancerel et al., 2009; Hendrickson et al., 2010; Mudgal et al., 2011; Oguchi et al., 2011; Salhofer et al., 2011; Welz et al., 2011; Oguchi et al., 2012; ELC, 2013). As a result, material compositions of major products in the ten primary categories have been collected, except for medical devices, monitoring and control instruments and automatic dispensers, due to an absence of relevant data. It is important to note that the material compositions of products from the same product group vary among brands and designs. Material compositions could even change gradually over time (the change of cooling agents in refrigerators over time is one example). The representativeness of this data is dependent on the size and location of the sampling, and the uncertainty of data is rather high. To simplify the

analysis, this section only uses average product properties without further investigating the disparities between different sampling results.

In Table 4.5, materials with the highest concentrations in a product are highlighted. There is a high diversity of product weights, metal and plastic compositions and toxic contents among different EEE. Large household appliances are heavy and have a high proportion of metals (more than 50 percent), especially ferrous metals. Small household appliances are much lighter and are more than 45 percent plastic in most subcategories. IT (Information Technology) and CE (Consumer Electronics) products have much more precious metals (from circuit boards) than other product categories. Lighting equipment is very lightweight but contains a substantial amount of glass and hazardous substances such as mercury. For electrical tools, leisure equipment, entertainment and toys, monitoring and control instruments and dispensing machines, there is a big weight difference between professional and household models. Substantial amounts of hazardous materials are embedded in some product categories. Examples include: CRT TV and CRT monitors (more than 60 percent of the product is lead glass); laptops (14.4 percent of which are battery by weight on average); and mobile phone batteries, which can account for more than 20 percent of the total mobile phone weight. Furthermore, even products in the same primary category cannot be always grouped together for collection and treatment, due to different weights and material contents; for example, characteristics may vary greatly between the household and professional models. Such differences need to be considered for EEE and e-waste classification, with support from detailed product and composition data.

Recovering valuable materials is the main driver for the recycling industry, which is dependent on material purity. EEE and e-waste can be grouped by their content of recoverable substances:

Base metal dominant group

Large household appliances (heating appliances, dishwashers, furnaces, washing machines, clothes dryers, cooling and freezing equipment, air conditioners, microwaves etc.); small household appliances with metal casings (toasters, audio systems, digital video disc/DVD players); household luminaries and tools.

Precious metal dominant group

IT equipment (desktop and laptop computers, mobile phones, mp3 players, telephones etc.); and consumer equipment with high-grade circuit boards (DVD players, cameras etc.).

Plastics dominant group

Small household appliances with plastic casings (coffee machines, vacuum cleaners, shavers); IT equipment with plastic casings (accessories, printers, telephones); consumer equipment with plastic casings (cameras, calculators); toys and game consoles.

Glass dominant group

Lamps (most lamps except light-emitting diode/LED lamps), CRT monitors and TVs (leaded glass).

From this grouping, it can be seen that base metal dominant products are mainly large household appliances and products with metal casings. The precious metal dominant group contains consumer and IT products with medium or high-grade circuit boards. Most consumer equipment, small household appliances and toys contain substantial amounts of plastic. Products in the glass-dominant group are mainly lamps and CRT screens (although the recovery of leaded glass is no longer favored by the market). This result is heavily dependent on the e-waste stream that was sampled and may be very sensitive to different brands, product models and designs (from different historical periods).

Grouping by material is not strictly exclusive, meaning that one product can belong to more than one group. For instance, a desktop PC can be dominant in both iron/steel and precious metals. Recycling of both metals does not pose a conflict if materials are well separated during the pre-processing stage. However, separating one material can always lead to the loss of another material, especially during the shredding process and in metallurgical refineries. In these cases, priority has to be given to materials that will receive higher market prices, materials that fall into a specific area of focus (for recycling) or materials governed by relevant legislation.

Table 4.5 Average weight and material composition of representative products by category

Representative product in each subcategory		Average weight (kg)	Material composition								Specific hazardous content
			Common metals (%)			Precious metals (mg/kg, PPM)			Plastics (%)	Others (%)	
			Fe	Cu	Al	Ag	Au	Pd			
0-01	Central heating	N/A	N/A								
0-02	PV panels	N/A	N/A								
1-01	Prof. heating	30.9	83.3	2.9	6.1	-	-	-	6.1	1.6	
1-02	Dishwasher	43.3	68.4	2.5	0.8	0.06	0.02	-	12.6	15.7	
1-03	Furnace	45.2	81.9	1.1	1.9	2.4	-	-	0.7	14.4	
1-04	Washing machine	72.9	52.1	1.9	3.1	0.19	0.06	-	6.8	36.1	
1-05	Washing dryer	47.8	70.0	3.3	2.1	0.19	0.06	-	15.9	8.7	
1-06	Room heating	10.4	11.0	-	79.0	-	-	-	10.0	-	
1-07	Combined fridge and freezer	69.5	61.7	3.4	2.5	-	-	-	27.8	4.6	CFCs
1-08	Refrigerator	41.8	50.0	4.0	3.0	-	-	-	40.0	3.0	CFCs
1-09	Freezer	44.4	47.6	4.5	0.2	-	-	-	32.2	15.5	CFCs
1-10	Air conditioner	28.0	54.4	15.6	9.4	-	-	-	15.7	4.9	CFCs
1-11	C&F other	9.8	N/A								CFCs
1-12	Service cabinet	141.4	63.7	6.4	-	0.3	0.08	-	15.6	14.3	CFCs
1-13	Microwave	25.2	69.3	15.3	-	-	-	-	9.7	5.7	
2-01	Clothes iron	1.2	19.1	7.3	-	2.3	0.5	-	45.5	28.1	
2-02	Toaster	3.3	55.9	4.1	6.3	8.0	2.7	-	24.1	9.6	
2-03	Coffee machine	1.9	11.9	5.5	1.4	0.3	0.1	-	65.8	15.4	
2-04	Vacuum cleaner	5.9	26.2	7.4	4.1	0.1	0.05	-	51.8	10.5	
2-05	Shaver	0.6	32.3	1.9	-	3.6	1.2	-	45.6	19.9	Battery
3-01	Keyboard (PC)	0.8	7.4	4.3	0.1	3.7	0.4	0.9	86.9	1.3	
3-02	Desktop PC	8.8	70.1	3.5	6.2	120	29	10	15.8	4.4	
3-03	Laptop PC	3.2	19.5	1	2.4	151	86	27	25.8	51.3	Mercury
3-04	Printer	10.3	35.5	3.2	0.2	5.2	2.8	1.6	45.8	15.3	Cartridge
3-05	Telephone	0.5	1.9	7.4	0.8	302.4	-	-	57.3	35.	
3-06	Mobile phone	0.1	1.3	10.2	0.5	1151	455	91	37.7	50.3	Battery
3-07	Prof. IT	40.0	N/A								
3-08	CRT monitor	22.0	4	3.2	-	14.4	0.6	2.4	18.8	74	Lead glass
3-09	FPD monitor	5.5	40.9	2.1	5.2	48.6	16.2	-	36.2	15.6	Mercury
4-01	Calculator	0.1	5.4	3.1	11.0	100.1	21.2	2.8	58.9	21.6	
4-02	Mp3 player (iPod)	0.3	10.0	3.7.	31.6	378.8	104.7	61.3	2.7	55.7	Battery
4-03	Audio amplifier	3.7	52.8	6.6	3.8	19.0	2.9	3.8	21.3	15.5	
4-04	DVD player	3.5	64.2	8.0	3.2	112.7	23.8	3.2	11.8	12.8	
4-05	Speaker	2.5	19.5	1.8	6.5	5.5	0.6	-	10.1	62.1	
4-06	Camera	0.3	10.3	5.0	5.6	296.2	72.2	18.5	46	33.1	Battery
4-07	CRT TV	33.2	10.3	3.7	2.6	12.0	0.5	2.0	22.8	60.6	Lead glass, FR plastics
4-08	FPD TV	14.7	46.9	3.8	4.7	58.2	24.5	15.3	24.2	20.4	
5-01	Halogen lamp	0.1	-	-	12.8	-	-	-	37.2	50.0	
5-02	Compact fluorescent lamp	0.1	-	-	1.6	-	-	-	25.1	73.4	Mercury

5-03	Straight tube fluorescent lamp	0.1	-	-	2.5	-	-	-	-	97.5	Mercury
5-04	High-intensity discharge lamp	0.2	-	-	29.7	-	-	-	-	70.3	
5-05	LED lamp	0.1	14.6	0.6	44.7				13.1	27.0	
5-06	Household luminary	0.5	81.0	19.0	-	-	-	-	-	-	
5-07	Prof. luminary	2.7	-	0.5	55.6	-	-	-	39.8	4.2	
6-01	Drilling machine	2.5	43.0	21.4	11.0	-	-	-	22.8	1.8	Battery
6-02	Lawn mower	7.8	57.1	2.2	3.5	-	-	-	36.4	0.8	
7-01	Toy	0.2	5.3	4.8	0.2	-	-	-	76.6	13.1	
7-02	Game console	0.2	5.4	3.0	3.0	-	-	-	63.7	24.9	Battery
7-03	Music equipment	80.0	N/A								
8-01	Small medical	0.2	N/A								
8-02	Prof. medical	5.5	N/A								Radioactive substances
9-01	Small monitoring	0.2	N/A								
9-02	Prof. monitoring	68.6	N/A								
10-1	Prof. dispenser (non-cooled)	44.1	N/A								
10-2	Prof. dispenser (cooled)	92.2	N/A								CFCs

"N/A" denotes: Composition data is not available for this type of product;

"-" denotes: The concentration of the material is very low or not detected for this type of product;

Data in orange shade indicates the material having the highest concentration by weight for a specific product.

4.2.2 Classification of e-waste by potential material value

To go one step further from the weight-based analysis of material content, an economic metric is introduced to understand which equipment has the most recycling value. The method is to simply multiply the mass content (weight percentage) of a certain product by the unit price of the primary material (€/kg):

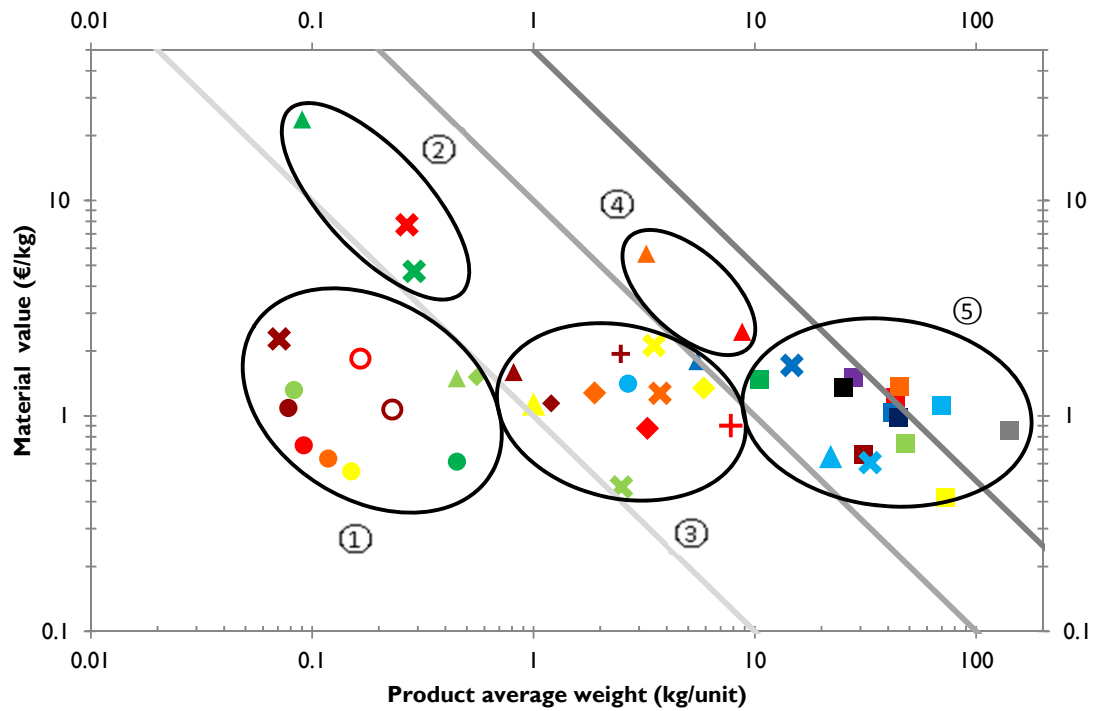$$P = \sum_{i=1}^{n} p_i * (m_i / M) \tag{4.1}$$

In this formula, P is the total material value per kilogram of a product (€/kg), which can be regarded as the material value density of a product; m_i is the weight of the material i in the product (kg); p_i is the unit price of primary material i (€/kg); n is the total number of materials in a product; and M is the average weight of a product (kg).

This material value density P only represents the total value for all materials contained in a product. It is the maximum value of a product in theory, under the assumption that all materials are finally recovered without any loss in weight or grade. The calculation does not include the actual recycling efficiency of treatment processes or the actual scrap value of obsolete products. Furthermore, this formula only covers material values, and does not include the cost of toxic control during treatment or the potential economic consequences of toxics.

The market values of primary materials in 2012 (base metals (LME, 2012), precious metals (Kitco, 2012), steel (MEPS, 2012), plastics (Plasticker, 2012)) have been obtained from a variety of sources. Combined with the material composition data for representative EEE, the material values per product are calculated according to Eq.(4.1).

Figure 4.1 projects product weights (X-axis) and their material value densities (Y-axis) for representative EEE. It shows that there is a wide range of average weights (from 0.09 to 141 kg/unit) and material values (from 0.4 to 23.8 €/unit) among these products. Large and heavy equipment tends to have a relatively low value density due to the intensive use of ferrous metals, while some consumer electronics have exceptionally high value densities because of the precious metals contained in their high-grade circuit boards (products such as mobile phones, mp3 devices and digital cameras). Lighting appliances are low in both product weight and value density. Other small household appliances and consumer electronics have a wide range of product weights and value densities, which complicates categorization.

Figure 4.1 Classification of e-waste by average weight (X-axis) and material value density of product (Y-axis)

In this figure, products are classified in the following groups: Group A1: Low weight, low value; Group A2: Low weight, high value; Group A3: Medium weight, medium value; Group A4: Medium weight, high value; Group A5: High weight, medium value. The diagonal reference lines represent absolute value for products with the same market value per unit.

At the product level, material values range between €1 and €50 per unit. Large household appliances have product values between €20 and €60 per unit due to their heavy weight. Most small household appliances, IT equipment and consumer electronics have product values between €1 and €20 per unit. From this perspective, collecting one heavy appliance is more profitable than collecting one small appliance. For instance, even though the value density of a mobile phone is 57 times higher than a washing machine, one needs to collect 15 mobile phones to reach the value of one washing machine. Because of this, collecting large quantities of lightweight appliances is essential for the scale and revenues of recycling systems.

As demonstrated in Figure 4.1, various EEE can be grouped into the following five categories for weight and material value (method A). These properties also indicate possibilities for the designs and plans of take-back and treatment systems.

Group A1: Low weight, low value (collect + control hazards)

The products in this group have low material values (< €1/kg) and low weights (< 1 kg), and overall their value per product is less than €1. Typical products are lamps, toys and small IT equipment. It is difficult to realize value in this group because a large number of products need to be collected, which is greatly dependent on collection methods and consumer awareness. In reality, these products are usually lost in waste bins or stored temporarily due to their low value and small size. In order to prevent pollution from this category, specialized collection schemes should be prioritized for environmentally critical products in this group (such as mercury-containing lamps).

Group A2: Low weight, high value (collect + realize value)

The products in this group have relatively high material values (> €4/kg) from the precious metals, but their average weight is low (< 0.5 kg). Overall, the value per product is typically higher than €1. Typical products are small appliances with high-grade circuit boards (mobile phones, cameras and mp3 players). This group is economically attractive for recycling, but can be easily mixed with other waste streams or stored instead of recycled. In order to get high economic returns from this group of products, high collection rates are needed to accumulate sufficient tonnage for treatment systems. Due to high material values, and frequently re-use value, strong incentives should be provided to consumers for efficient collection. Apart from collection, investment in sorting and treatment technologies is also necessary to recover valuable materials from this group of products. Pre-processing techniques are required to liberate circuit boards without losing precious metals. End-processing technologies should be in place to refine the precious metals efficiently.

Group A3: Medium weight, medium value (treatment)

The products in this group have medium material values (between €1 and €2.5/kg) and medium weights (between 1 and 10 kg). Overall, the value per product is between €1 and €10. Typical products are small household appliances and IT equipment. This group contains plastics and common metals, and sometimes includes medium and high grade circuit boards. The removal of circuit boards in the pre-processing phase will help to prevent the loss of precious metals in follow-up treatment. The main target materials for

recycling in this group are plastics and base metals, which require good separation during pre-processing.

Group A4: Medium weight, high value (realize value, avoid secondary or informal streams)

The products in this group have high material values (between €2.5 and €6/kg) and medium weights (between 3 and 9 kg). Overall, values per product in this group are between €10 and €50. Typical products are desktop and laptop computers. This group contains high grade circuit boards, which significantly contribute to the total material value. Removal of circuit boards in the pre-processing phase will greatly improve the recovery rates of precious metals. Due to relatively high re-use and material values, this group of products is very likely to be traded and treated by the informal sector. Therefore, take-back and treatment systems need to plan effective schemes to prevent the products in this category from ending up in secondary or informal systems to prevent lost material value and environmental damage.

Group A5: High weight, medium value (avoid in secondary stream)

The products in this group have medium material values (between €0.9 and €2.5/kg) and high weights (> 10 kg). Overall, the value per product in this group is more than €10. Typical products are large household appliances and heavy screens; pick-up services or other logistic arrangements are necessary to transport this type of waste. The treatment process mainly focuses on reducing the size of these bulky appliances, and common metals are the target materials for recycling. But there are still materials of environmental concern in this group. Extra care needs to be given to lead glass in CRT screens and plastics containing flame retardants. Flat panel TVs need to be taken care of due to their mercury lamps. Cooling and freezing equipment containing CFCs also needs to be processed with caution. Due to potential re-use and material value, these products can be of interest to the informal sector, which ignores the aforementioned hazardous materials. In order to strengthen the management of this group, these products should avoid treatment through secondary or informal streams.

To summarize, value density has been selected to demonstrate the presence of valuable or recyclable materials in these five groups. In practice, high value densities suggest that specific investments to realize the value of a product through sophisticated collection and treatment could be useful. Products with low value densities may not be favored by recyclers, but management needs to be in place for products with substantial environmental impacts. The hazardous content in products is usually not reflected by material value. Therefore, the followings section will further explore the differences in environmental impacts between products.

4.2.3 Classification of e-waste by environmental gain on recycling

Environmental impacts can take place during all stages in the lifecycle of a product. The impacts during production are predominately determined by the material composition of the product. The impacts during the use phase are mainly influenced by products' functions and user behaviors. The impacts during the end-of-life phase are influenced by diverse factors such as

consumer disposal behaviors and the performance of recycling facilities. So it is reasonable to focus the analysis on the specific phases, since an aggregated score is not informative enough. As the main interest of this dissertation is e-waste management, the use phase of electronic products is not included in the analysis.

In order to understand the impacts of production, the material composition of each product has been translated into a corresponding "environmental load" created during primary material production. This translation is a part of the LCA procedure; impacts from all materials present in the product are added together. The impact of each material is retrieved from the Idemat database (Idemat, 2013). ReCiPe is used as the indicator for Life Cycle Impact Assessment (LCIA), and the result is expressed as a "Recipe point." To simplify the calculation, the environmental impact assessment of materials in products only accounts for the level of impact during the "cradle to entry gate" time period (including raw material extraction and refining). Manufacturing processes such as injection molding and assemblies, therefore, are excluded from the analysis. The weights of materials in products are regarded as the domain impact for the phase during raw material extraction and refining.

The results of the classification have been illustrated in Figure 4.2. Generally, the result is very close to the outcome from classifying by material value, as presented in the last section. This also confirms the findings in Section 4.1; that there is a certain correlation between the market values and environmental impacts of primary material production. However, when compared to the market value classification in Figure 4.1, products containing materials with low market values (such as lead glass) are positioned differently in relation to the environmental impact. This is because there are different impact categories in LCA. Material production involving substantial energy consumption is more likely to have strong correlations to the market values of such metals because energy prices are usually reflected in the economy. Some metals (such as lead and mercury) also affect other environmental impact categories during primary production, such as human toxicity and eco-toxicity (Norgate et al., 2007). The impacts from these categories may not be properly reflected in economic terms. This explains why the aggregated LCA score does not always correlate with the economic value of a material.

E-waste can be classified into the following categories, according to the environmental impacts of material production (method B):

Group B1: Low weight, low impact

> The products in this group have low environmental impacts (< 1 point/kg) and low weights (< 1 kg). Overall, the value per product is lower than 1 point. Products in this group are mainly lightweight lamps, small household appliances and consumer equipment.

Group B2: Low weight, high impact

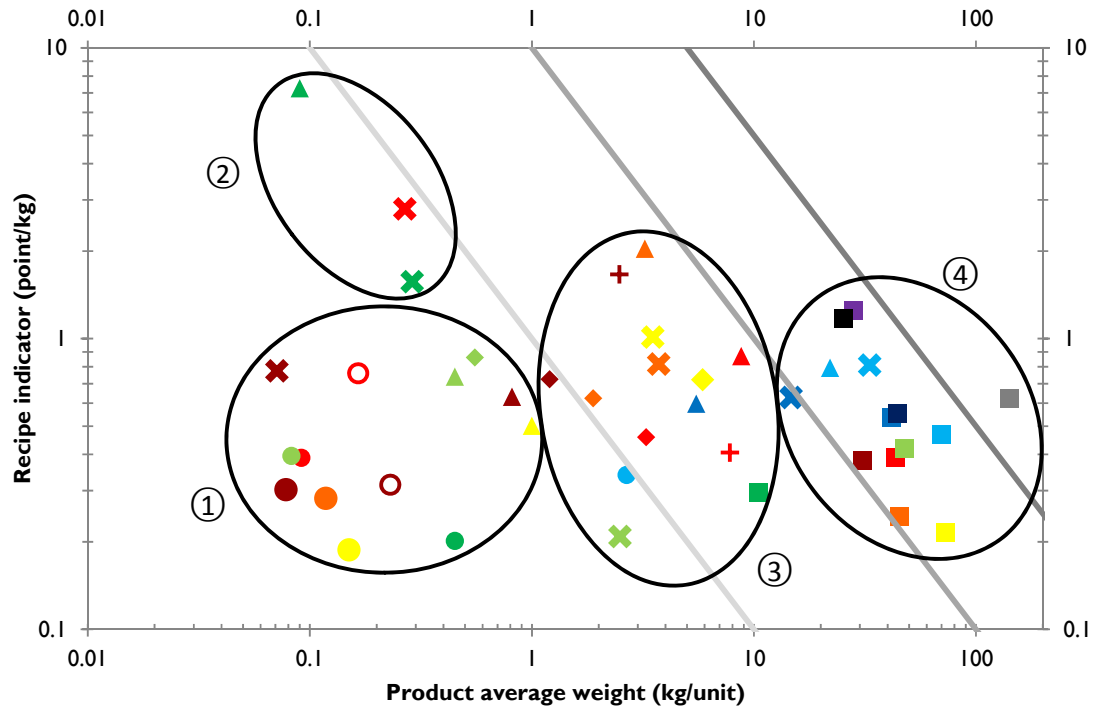> The products in this group have relatively high environmental impacts (> €1/kg) due to precious metals, but average weights are low (< 0.5 kg). Products in this group are mainly small IT and consumer equipment that contain high-grade printed circuit boards. Due to the presence of precious metals, the environmental impacts of material production per product are higher than for other types of equipment.

Group B3: Medium weight, medium impact

The products in this group have medium environmental impacts (between €0.2 and €1.0/kg) and medium weights (between 1 and 10 kg). Overall, the environmental impacts per product in this group are between 1 and 10 points. Products in this group are mainly medium-weight small household appliances and IT and consumer equipment, which contain large amounts of ferrous metals and plastics.

Group B4: High weight, medium impact

The products in this group have medium environmental impacts (between €0.1 and €1.0/kg) and high weights (> 10 kg). Overall, the environmental impact per product in this group is more than 10 points. Products in this group are mainly heavy large household appliances and IT products.

Figure 4.2 *Classification of e-waste by average weight (X-axis) and environmental impact of material production (Y-axis)*

In this figure, products are classified in the following groups: Group B1: *Low weight, low impact;* Group B2: *Low weight, high impact;* Group B3: *Medium weight, medium impact;* Group B4: *High weight, medium impact. The diagonal lines represent absolute values for products with the same environmental impact for production per unit.*

The environmental impacts of producing all materials in a product suggest the potential environmental gain that can be attained if the product is fully recycled. There is essentially no difference between the classification results in Section 4.2.3 (potential material value per product) and the classification results in the present section. The only exception is that the fourth group (medium weight, high value), including laptop and desktop computers, in Section 4.2.4 has been moved to the "medium weight, medium impact" group in this section. This may have been caused by the currently high market prices of precious metals, while their environmental impacts during production are comparatively milder. Overall, it implies that the environmental impacts from primary material production are reflected in the market prices. But there is still a fundamental difference between applying economic values and environmental metrics. Certain impact categories (i.e. toxicity) may not be fully represented by their economic value, especially when such impacts are not precisely priced, such as energy consumption and global warming potential. Besides the (positive) environmental gains from material recycling, there are also side effects and negative environmental impacts from such activities. The next section will discuss the negative environmental impacts of products in their end-of-life phase.

4.2.4 Classification of e-waste by potential for human toxicity in the end-of-life phase

In addition to the production phase, hazardous substances contained in e-waste are of substantial concern during the end-of-life phase. Although the actual environmental impacts depend on the method of treatment and disposal, embedded hazardous materials are the major cause of primary environmental pollution. There is a great variety of impact categories associated with the hazardous materials in e-waste including global warming, ozone depletion, acidification, eutrophication, ecotoxicity and human toxicity. It is obvious that cooling and freezing equipment containing CFCs will have significantly greater effects on global warming and ozone depletion than other appliances. This section mainly focuses on the impact category of human toxicity, which directly affects human beings.

In order to exclude different treatment scenarios, toxic potential is understood to be the maximum environmental impact of a product. This is based on the assumption that all hazardous materials in a product are directly discharged into the environment without capture or treatment. This is the worst-case scenario, which assumes the consequences of no e-waste toxic control whatsoever. This framework is slightly different from the conventional LCA approach, in which actual emissions from a system are accounted for. The potential for toxicity can lead to actual environmental damage through unsafe handling during treatment (such as substandard treatment) or when toxic materials are not properly cared for after recycling. The potential for toxicity in this section mainly refers to the potential for a material to be toxic to humans, and the impact category of eco-toxicity is not included in the analysis.

This analysis only considers adverse impacts resulting from direct releases into the environment. By-products and emissions from the improper treatment of equipment are not included, as they are considered secondary pollution and subject to specific treatment processes. Recyclable materials are also excluded in this toxicity calculation based on the assumption that they are not a negative influence on the environment. Due to the availability of data, only the concentrations of lead, cooling agents, mercury and toxic metals in circuit boards (lead, chromium, cadmium,

antimony and barium) are used in the calculation. The concentrations of other types of hazardous materials are either missing in the literature or lacking in the toxicological data (materials such as PVC, cadmium, hexavalent chromium and various flame retardants).
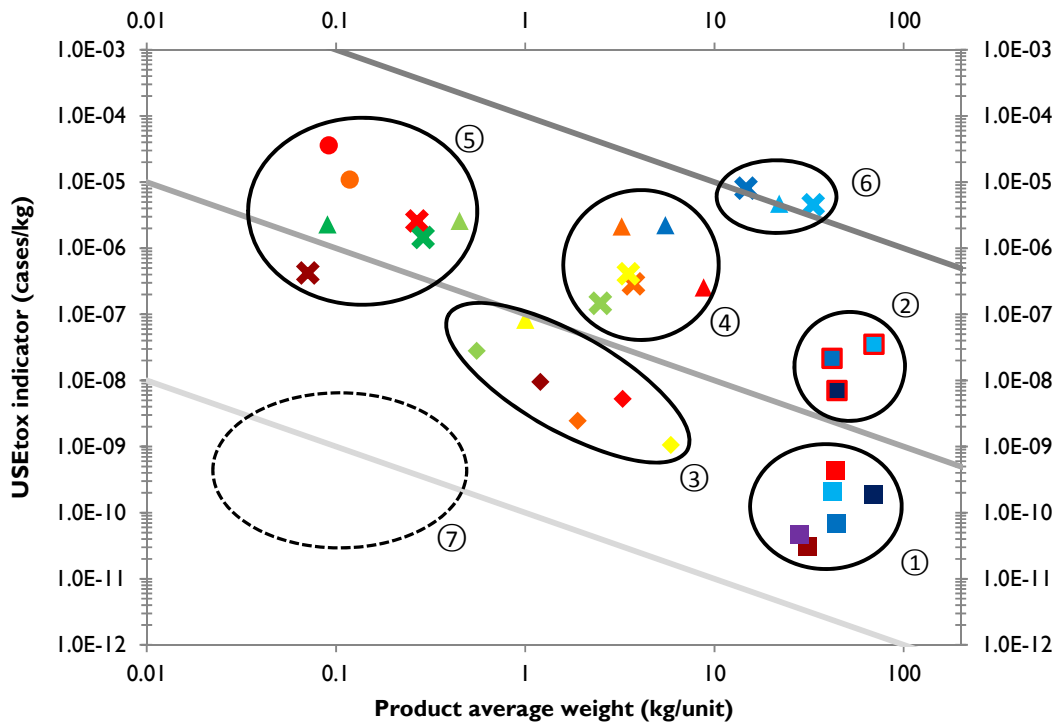
The model and database from USEtox is used in the LCIA (Rosenbaum et al., 2008) because it takes into account the pathways and fates of toxic materials in various areas of the environment. During the impact assessment, it is presumed that all solid materials in the products are released into natural soil, while CFCs and mercury are released into the air. In USEtox, the impact of one product is calculated with the following formula:

$$HTP = \sum_{x=1}^{n} CTU_x \cdot m_x \qquad (4.2)$$

In this formula, HTP is its Human Toxicity Potential of a product, which arises from its n types of embedded hazardous materials. CTU_x is the Comparative Toxic Unit, which expresses the impacts on human health of a hazardous materials. CTU stands for cases/kg-emitted, which denotes the number of cases of people who get sick (both from cancer and non-cancer sicknesses), per kilogram of material released to specific areas of the environment (such as urban air, natural soil, sea water, etc.). m_x is the weight of hazardous material x in a product (in kilograms).

Many sources provide average concentrations of lead (Oguchi et al., 2011) , mercury (Böni and Widmer, 2011; Welz et al., 2011) and CFCs (Horie, 2004; Mudgal et al., 2011) in all types of EEE. The material concentrations of other hazardous materials listed in Table 4.3 are not available in the literature due to a lack of sampling data or very low concentrations. The CTU of hazardous materials come from the USEtox Excel datasheet (USEtox, 2010). These datasets are calculated according to Eq.(4.2) and the resulting classifications are illustrated in Figure 4.3. In this figure, the average weights per product are reflected on the X-axis; the Y-axis represents the potential for human toxicity per kilogram of product, which suggests its "density" of toxicity. The diagonal line suggests the overall impact per unit of a product, and products on the same diagonal line have the same magnitude of environmental toxicity.

Figure 4.3 Classification of e-waste by average weight (X-axis) and environmental impact of hazardous materials with the most potential for human toxicity (Y-axis)

In this figure, products are classified in the following groups: Group C1: *High weight, low impact;* Group C2: *Medium weight, high impact;* Group C3: *High weight, medium impact;* Group C4: *Medium weight, high impact;* Group C5: *Low weight, high impact;* Group C6: *High weight, high impact;* Group C7: *Low weight, low impact.*

E-waste can be classified into the following seven categories, according to the environmental impacts of hazardous materials (method C). It shows that more clusters emerge from this classification than the market value or material production classifications. Furthermore, these groups are more segregated than the groups in previous classifications. This may be caused by different types of hazardous or toxic materials present in products.

Group C1: High weight, low impact

This group of products has high weight and the lowest potential for toxicity due to low concentrations of lead and non-CFC refrigerants. The toxic potential is low per unit of product (the absolute term) and also per kilogram of product (the relative term). Products in this group include large household equipment items such as professional heaters, air conditioners, dishwashers, and non CFC-containing refrigerators, freezers and combined fridges and freezers. The refrigerant in this group is HFC-134a (1,1,1,2-Tetrafluoroethane), which is a replacement for CFC-12 (Dichlorodifluoromethane) and has a much lower likelihood to deplete the ozone. From a toxic perspective, no significant caution is required for treating this product group.

Group C2: High weight, medium impact

This group of products is heavy but has a high toxic potential compared to products in Group 1. Products in this group are cooling and freezing appliances produced before 1993, which used CFC-12 as refrigerants. CFC-12 has a higher likelihood to deplete the ozone and contributes more to global warming than refrigerants such as HFC-134a (Kim et al., 2006). Other old cooling equipment items using refrigerants similar to CFC-12 also belong to this group (i.e. Bromodifluoromethane/FC-22B1). The hazardous substances in this group do not pose acute toxic threats to human health during the use and treatment phases but they will cause climate change if they are not controlled properly. This is one of the positive effects of international conventions (i.e. the Montreal Protocol), legislation and eco-designs that phase out hazardous substances over time. CFCs in products in this group need to be captured.

Group C3: Medium weight, medium impact

Products in this group are lightweight and have relative low toxic potentials. These products are small household appliances such as shavers, toasters and coffee machines. Most of the potential for toxicity in this group comes from circuit boards, but will not be a threat to human health if the circuit boards are separated for state-of-the-art treatment.

Group C4: Medium weight, medium impact

Products in this group are medium in weight and have a medium potential for toxicity. They are mainly medium-sized IT products (such as desktops and laptop computers) and consumer equipment items (DVD players, speakers and audio amplifiers). Most environmental impacts in this group arise from circuit boards. The impact from circuit boards in this group is higher than in Group C3 due to the higher content of toxic metals. However, similar to group C3, the toxic potential will not be realized if the circuit boards are treated properly.

Group C5: Low weight, high impact

Products in this group are lightweight and have a high potential for toxicity. They are mainly small-sized consumer equipment items such as calculators, mp3 players, cameras, telephones, mobile phones and mercury-containing lamps. The greatest impacts in this group come from circuit boards and mercury, but no substantial environmental risk will arise if the circuit boards are separated and treated.

Group C6: High weight, high impact

Products in this group are heavy and have a high potential for toxicity. They are mainly heavy TVs and monitors with substantial amounts of mercury or lead (glass). Mercury is usually found in screen backlights, and it needs to be treated properly; workers should avoid breaking and inhaling it during treatment. Lead glass is also hazardous and workers should minimize their contact with it and work with a respirator. These two hazardous materials can cause substantial damage to workers' health under long-term exposure.

Group C7: Low weight, low impact

Products in this group are lightweight and have a very low potential for toxicity. Although no products fall into this group in the graph due to data scarcity, they are theoretically likely to be non-mercury lamps and small toys.

Table 4.6 summarizes the results of classification by toxic potential in the end-of-life phase. This is measured under the worst-case scenario: if all the hazardous materials contained in e-waste are released directly into the environment. This shows the maximum damage these materials could cause to human health. The outcomes suggest that the product group with the most toxic potential is screens (CRT TVs and monitors and flat-panel TVs). Therefore, lead and mercury in obsolete products need to be captured and treated properly, and workers should avoid being exposed to such materials in the occupational environment. The group with the second-highest potential to damage human health is CFC-containing refrigerators and freezers. When released into the environment, CFCs will cause ozone depletion and global warming, and indirectly influence human health. Although CFCs are no longer used as a refrigerant, refrigerators produced before 1993 may still appear in the waste stream. This old cooling and freezing equipment needs to be properly sorted and treated separately. Other products with high potentials for toxicity but low weights are small-sized consumer equipment items that contain batteries and circuit boards and mercury-containing lamps. Singling out batteries and circuit boards would be the main method for reducing the environmental impact of small consumer equipment items. For mercury-containing lamps, safe collection to minimize breakage during transportation is essential to reduce mercury emissions. Specialized treatment plants are needed to extract the mercury from such lamps, and safe disposal for mercury is also required. For medium-sized IT and consumer equipment items, treating circuit boards and batteries are also the main objectives for reducing environmental impacts. Categories like non-CFC-containing large household equipment, toys and non-mercury lamps do not require specific action to reduce the potential for toxicity from embedded materials during treatment.

Certain products shown in the classifications in the other sections of this chapter are not shown in this section or in Figure 4.3. For instance, product subcategories like kitchen furnaces and ovens (1-03), washing machines (1-04), drying machines (1-05) and room heaters (1-06) are not

included in this analysis. This is due to a lack of data and low concentrations of hazardous materials present in these product subcategories. These products can be regarded as having low potentials for toxicity. Extending the analysis to include more hazardous materials will make the general picture more complete. This requires substantial waste sampling and chemical analysis of material compositions.

Table 4.6 Classification of e-waste by toxic potential during end-of-life phase

Category	Products	Average weight	Toxic potential (TP)		Specific action needed for treatment
			TP/kg	TP/unit	
C1	Large household equipment (non-CFCs)	High	Low	Low~ Medium	N/A
C2	Cooling and freezing equipment with CFCs	High	Medium	Medium~ High	CFCs need to be captured and treated
C3	Small household appliances	Medium	Medium	Low~ Medium	Circuit boards and batteries need to be separated from products and treated properly
C4	Medium-sized IT and consumer equipment	Medium	Medium	Medium~ High	
C5	Small-sized consumer equipment; Mercury-containing lamps	Low	High	Medium~ High	Lamps with mercury should be collected carefully and properly treated; Workers should avoid exposure to mercury
C6	Screens (CRT and Flat panel TVs and monitors)	High	High	High	Mercury and lead glass should be separated and treated; Workers should avoid exposure to mercury and lead dust
C7	Non-mercury lamps Small toys	Low	Low	Low	N/A

4.3 Synthesis of classification by combined criteria

Section 4.2 demonstrates that EEE can be classified according product function, material composition, material value, environmental impact of material production and potential for toxicity from embedded hazardous materials. Regarding product types, EEE and e-waste can be generally classified into ten major product categories and 55 subcategories. Regarding market values of product materials, e-waste can be classified into five groups. Regarding environmental gain on recycling, e-waste can be classified into four groups. Regarding the potential for toxicity, e-waste can be classified into seven groups.

Comparing the grouping results shows a certain level of overlap between different criteria and properties, because products characteristics are mainly determined by their material compositions. It is then possible to consolidate the separate classifications into composite groups. This will greatly help to improve the efficiency of e-waste take-back and treatment

systems by taking into account the technical, economic and environmental characteristics of different e-waste types. Multiple stakeholders such as policymakers, producers, statistical bureaus, customs, e-waste collectors and recyclers will all benefit from such classification. The consolidated results from classification are listed in Table 4.6 as the final seven categories.

These seven categories are:

1. Cooling and freezing equipment with CFCs
2. Products with screens
3. Large household equipment without CFCs
4. Professional equipment
5. Small household appliances
6. IT and consumer equipment
7. Lamps with mercury

The results from this grouping are identical to the EEE categories in the new/recast EU WEEE Directive (Annex III). The only difference is that Category 4 presented in this dissertation is included in the "large equipment" category in the EU WEEE Directive. The reason for listing it as an independent category is that specialized arrangements are always needed to collect obsolete professional equipment. For instance, removal and collection of (household) central heating systems, PV solar panels, professional IT equipment and large dispensers in buildings are usually carried out by installation companies, service providers or contractors. This type of collection is different from the collection of normal large household appliances in Categories 1-3.

Heavy appliances also require logistic arrangements for their bulky size, and their main valuable materials for recycling are ferrous metals. Due to their heavy weight, batch and mechanical pre-processing could greatly improve the efficiency of material separation. For Categories 1-3, these appliances contain hazardous materials, and toxic control during treatment should be a priority for CFCs (Category 1: cooling and freezing appliances produced before 1993); lead glass, mercury and plastics with flame retardants (Category 2: screen products); and circuit boards and ink cartridges (Category 4: professional equipment). For Category 3, most large household appliances without CFCs do not require toxic control due to little or no presence of hazardous materials.

For medium-weight appliances, well-designed and convenient collection channels need to be in place for consumers to hand in their waste products without difficulty. Most small household appliances in Category 5 contain plastics with small motors or circuit boards. Therefore, plastics are the main target for material recycling, and there is no substantial potential for toxicity from hazardous materials. In Category 6, some IT products contain batteries and medium/high grade circuit boards, which need to be segregated from the products and properly treated to prevent pollution. For medium-weight appliances, manual dismantling can be combined with mechanical separation in order to achieve the best separation efficiency.

Lightweight appliances are very easily disposed of in household waste bins and then treated together with municipal wastes and other waste streams. Consequently, specialized and

convenient collection points for small appliances are very useful for preventing these appliances from ending up in municipal incinerators or landfills. Due to size limitations, it is not economically feasible to fully manually dismantle waste appliances for pre-processing. Therefore, mechanical batch separation is preferable. Two types of small appliances require caution during handling to prevent pollution: IT and consumer equipment items containing batteries and (medium and high-grade) circuit boards (Category 6); and mercury-containing lamps (Category 7). Revenues from recycling small appliances may not cover operational costs due to the low market value of embedded materials. Therefore, subsidies or external financing is necessary to facilitate sufficient collection, treatment and break-even revenues.

In many instances, setting priorities is essential for improving management efficiency because establishing a system that targets all appliances is not always feasible. Therefore, when toxic control is the primary goal of e-waste management, special attention needs to be paid to products containing substantial amount of CFCs, lead (glass), mercury, circuit boards, batteries and plastics containing flame retardants. When material recycling is prioritized, products containing high-grade circuit boards (with high concentrations of copper and precious metals) and rechargeable batteries can be selected as targets. Manual dismantling may be preferable to single out the high-value fractions and prevent value losses throughout the recycling process. When the goal is to reduce the size of the waste stream and avoid the landfill, effort should be made to establish effective collection channels to collect the heaviest and largest number of products.

For all categories of e-waste, there remains the issue of cost and financing take-back and treatment systems. In order to collect e-waste from consumers, collection points, take-back schemes, arrangement of reverse logistics and storage all require substantial investment to construct collection channels and networks and sometimes even educating the public to improve awareness. For treatment, there are costs associated with investing in land, machinery, labor and overhead. The requirements for collecting and treatment technologies vary among different e-waste categories. Material values also differ greatly between categories, and they do not always cover the costs of establishing take-back and treatment systems. For instance, the logistic costs of taking back large household appliances are relatively high per unit, and the revenues from recycling these products (e.g. washing machines) cannot cover all costs associated with collection and treatment. IT equipment products such as desktop computers are more likely to profit from recycling due to their high density of material value. Therefore, when calculating costs and soliciting investments, it is useful to systematically accounting for all potential revenues and expenses.

Table 4.7 Consolidation of e-waste classifications and indications for end-of-life management

Category	Classification criteria			Typical products	Indication for collection	Indication for material recycling (treatment)	Indication for toxic control (treatment)
	Weight	Envi.	Value				
1. C&F with CFCs	High	High	Medium	CFCs containing freezing and cooling equipment	Pick-up collection or logistic arrangement is necessary	- Batch and automatic treatment - Target materials: metals and plastics	Capture and disposal of CFCs
2. Screens	High	High	Medium	CRT TVs and monitors; flat panel TVs			Lead glass, mercury, and FR plastics
3. LHHA without CFCs	High	Low	Medium	Most LHHA and dispensers without CFCs			No specific action
4. Prof. equipment	High	High	Medium	Central heating, PV panels, large IT (servers, routers, copiers), prof. luminaries, tools, medical equipment	Specialized collection or logistics are needed (i.e. installation companies)		PWB, ink cartridges
5. SHHA	Low - Medium	Low	Medium	Small household appliances, lamps without mercury, small toys and games	Collection points or return schemes at retailers/public places are necessary for easy disposal by consumers	Target materials: plastics	No specific action
6. IT and CE	Low - Medium	High	Medium-High	IT and CE with high-grade circuit boards (mobile phones, cameras, laptop and desktop computers, printers etc.)		Separate PWB and batteries in pre-processing	Eco-efficient treatment of PWB and batteries
7. Lamps with mercury	Low	High	Low	Mercury-containing lamps	- Separate collection with strong user incentives - Avoid mixing with other waste streams	External financing is necessary for covering costs for mercury capturing and disposal	Capture and treatment of mercury

CE: Consumer equipment; C&F: Cooling and freezing equipment; FR: Flame retardant; LHHA: large household appliance; IT: Information technology; Prof.: Professional; PWB: Printed wiring board; SHHA: Small household appliance.

4.4 Conclusions

The analysis in this chapter illustrates the complex nature of electrical and electronic equipment and the resulting e-waste when it becomes obsolete. This waste stream has multiple attributes like product function, size, weight, embedded value and toxic materials. All of these properties influence the establishment and performance of products' end-of-life management. This chapter classifies EEE and e-waste according to the following individual criteria: product type, material composition, potential market value, environmental gain on recycling and toxic potential during

end-of-life treatment. By consolidating these individual classifications, a comprehensive classification of e-waste groups the enormous number of e-waste types into nine generic categories. This system can provide guidance for customized management of different e-waste categories. Each category requires different collection methods, treatment technologies, measures for toxic control and investment. The present analysis allows policymakers, system managers, producers and researchers to draw meaningful conclusions for design, financing, planning and management of e-waste take-back and treatment systems.

4.5 References

Apple Inc. (2008). Environmental Report of iPod nano.

Böni, H. and R. Widmer (2011). Disposal of flat panel display monitors in Switzerland, final report. St. Gallen, Switzerland, EMPA, SWICO Recycling.

Castro, B. (2005). Design for resource efficiency. Department of Industrial Design. Delft, the Netherlands, TU Delft. **PhD degree**.

Chancerel, P., et al. (2009). "Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment." Journal of Industrial Ecology **13**(5): 791-810.

Cui, J. and L. Zhang (2008). "Metallurgical recovery of metals from electronic waste: a review." Journal of Hazardous Materials **158**: 228–256.

ELC (2013). Material composition of lamps, European Lamp Companies Federation.

EMPA (2013). "Hazardous substances in e-waste." Retrieved 14 April 2013, from http://ewasteguide.info/node/219.

European Union (2003). Waste Electrical and Electronic Equipment Directive (2002/96/EC). Brussels, Belgium, Official Journal of the European Union L37.

European Union (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) (Recast), Official Journal of the European Union L 197. **Volume 55**.

Eurostat (2011). RAMON Metadata Server (Prodcom and Combined Nomenclature codes), Eurostat.

Gmünder, S. (2007). Recycling - from waste to resource: assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Zurich / St.Gallen, Switzerland, Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Testing and Research (EMPA). **Master thesis**.

Goosey, M. (2012). The materials of WEEE. Waste electrical and electronic equipment (WEEE) handbook. V. Goodship and A. Stevels. Cambridge, UK, Woodhead Publishing Limited.

Hendrickson, C. T., et al. (2010). "Reducing environmental burdens of solid-state lighting through end-of-life design." Environmental Research Letters **5**.

Hikwama, B. P. (2005). Life Cycle Assessment of a Personal Computer. Faculty of Engineering and Surveying, University of Southern Queensland. **Master thesis**.

Horie, Y. A. (2004). Life Cycle Optimization of Household Refrigerator-Freezer Replacement. Center for Sustainable Systems. Ann Arbor, University of Michigan. **Master thesis**.

Huisman, J. (2003). The QWERTY/EE Concept, quantifying recycability and eco-efficiency for end-of-life treatment of consumer electronic products. Delft, the Netherlands, Delft University of Technology. **PhD thesis**.

Huisman, J., et al. (2008). Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Bonn, Germany, United Nations University.

Huisman, J., et al. (2012). The Dutch WEEE Flows. Bonn, Germany, United Nations University, ISP-SCYCLE.

Idemat (2013). Idemat online database, TU Delft.

Kim, H. C., et al. (2006). "Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost." Energy Policy **34**(15): 2310-2323.

Kitco (2012). Past historical material price of London Fix (gold, silver, platinum, palladium), Kitco Metals Inc.

LME (2012). Primary metal prices data 2004 - 2012 (non-ferrous metals, steel, precious metals), London Metal Exchange.

MEPS (2012). MEPS Steel prices online, Management Engineering & Production Services International Ltd.

Mudgal, S., et al. (2011). Preparatory study for eco-design requirements of EuPs: Lot 1 Refrigerating and freezing equipment. Paris, France, BIO Intelligence Service S.A.S.

Norgate, T. E., et al. (2007). "Assessing the environmental impact of metal production processes." Journal of Cleaner Production **15**(8–9): 838-848.

Oguchi, M., et al. (2011). "A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources." Waste Management **31**(9–10): 2150-2160.

Oguchi, M., et al. (2012). "Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes." Science of The Total Environment(0).

Plasticker (2012). Constantly updated price overviews - based on offers from the plasticker material exchange. Kaarst, Germany, New Media Publisher GmbH.

ReCiPe (2009). "Quick introduction into ReCiPe LCIA Methodology." from http://www.lcia-recipe.net/.

Rosenbaum, R., et al. (2008). "USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment." The International Journal of Life Cycle Assessment **13**(7): 532-546.

Salhofer, S., et al. (2011). Recycling of LCD Screens in Europe - State of the Art and Challenges. Glocalized Solutions for Sustainability in Manufacturing. J. Hesselbach and C. Herrmann, Springer Berlin Heidelberg**:** 454-458.

Schluep, M., et al. (2009). Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling - from E-waste to resources. Bonn, Germany, United Nations Environment Programme & United Nations University.

Stevels, A. (2007). Adventures in ecodesign of electronic products 1993-2007. Delft, the Netherlands, Delft University of Technology.

Townsend, T. G., et al. (2004). RCRA toxicity characterization of computer CPUs and other discarded electronic devices, Department of Environmental Engineering Sciences, University of Florida.

USEtox (2010). UNEP/SETAC model for the comparative assessment of chemicals released to air, water and soil and their toxic effects on the human population and ecosystems

Wang, F., et al. (2012). A systematic and compatible classification of WEEE. Electronics Goes Green. Berlin, Germany.

Wang, F., et al. (2008). Economic conditions for formal and informal recycling of e-waste in China. Electronics Goes Green. Berlin, Germany.

WEEE Forum (2012). WEEE Forum Key Figures 2006 -2011. Brussels, Belgium, WEEE Forum.

Welz, T., et al. (2011). "Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis." Environmental Impact Assessment Review **31**(3): 334-343.

Chapter 5: Modeling e-waste generation for more effective collection

Collection is the first step in e-waste take-back and treatment systems. Collection aggregates obsolete products from users in various locations, thus creating waste streams suitable for industrial treatment. The amount of formally collected e-waste influences the scale of, and investments needed for, recycling facilities, as well as the overall impact on the environment and the economy. Collection efficiency for a specific type of product is mainly determined by the arrangement of collection points, service, logistics, public awareness and consumers' willingness to return. In order to calculate the collection efficiency of a take-back scheme, it is instrumental to obtain both the amount of e-waste collected and the overall amount of e-waste generated.

It is important to accurately estimate the overall quantity of e-waste generated by society. First, this number will provide policymakers with a baseline to effectively set collection targets. Second, "leakage" or "unaccounted" flows from the take-back system can be identified per e-waste category. These figures can be used to track the quantity and destinations of uncontrolled e-waste in complementary streams, and interventions to deal with these problematic channels can be planned accordingly. Finally, the overall quantity of e-waste can indicate the capacity and investments required to establish take-back schemes and treatment infrastructures.

Due to socioeconomic conditions and complexities in discarding behavior, it is difficult to accurately estimate the overall quantity of e-waste produced in a society. This chapter explores the methods used to model e-waste generation and the efficiency with which it is collected. A multivariate analysis is proposed to improve current e-waste estimates, which maximally uses all data points and improves the data quality of the model's variables. This practice is essential for creating a scientific basis for the development of take-back schemes and logistics involved with collection. The method will also help evaluate take-back and treatment systems that are already in operation. This task is particularly relevant for countries where legislation requires that certain collection targets be achieved.

5.1 Definition of collection efficiency

5.1.1 Introduction
Regarding the collection of e-waste, the main interest of policymakers and managers of take-back systems is the overall volume of e-waste that is generated. Closely linked to this, the amount of e-waste collected (collection efficiency) and its treatment (both through formal and informal channels) are also essential data for e-waste management. Collection efficiency can be evaluated on an absolute weight basis or a relative percentage basis. These indicators can be the basis for collection targets in e-waste take-back legislation. According to the EU WEEE Directive

and the recast WEEE, three indicators to evaluate collection rates have been proposed or implemented (European Union, 2003; 2012). The description, advantages and disadvantages of these three targets are listed in Table 5.1 (Magalini et al., 2012). This table summarizes the methods for evaluating, and discussions surrounding, proper collection targets for e-waste in the EU and elsewhere.

The weight-based target (such as 4 kg per capita (kg/ca.), as introduced in the original EU WEEE Directive) is an indicator that is easy to calculate and simple for policy implementation. However, it does not account for regional differences; if the identical target were implemented in both low and high-income countries, the results would be misleading. Furthermore, a target stresses the overall tonnage of e-waste collected, but it does not regulate based on product type or waste category. For example, a low collection rate of lamps can be easily compensated for by collecting more washing machines. Achieving the same weight-based target for all appliances can lead to quite different environmental outcomes.

The indicator based on product sales (e-waste collected in proportion to product sales) is also easy to calculate because products placed on the market are usually registered at national statistics bureaus or tax offices. However, this method is less applicable in certain market situation such as emerging or phase-out markets. For instance, in the early years of light-emitting diode (LED) TVs, there will be few discarded products relative to quickly growing LED TV sales. In such a case, using a percentage of sales to define an e-waste collection target is not logical. Conversely, due to market replacement, there are far more obsolete cathode ray tube (CRT) TVs compared to the rapidly diminishing sales of this product, so collection targets based on CRT TV sales will also be inadequate.

In comparison, an indicator based on discarded products takes market and socio-economic dynamics into account. The major challenge with this indicator lies in accurately estimating future e-waste generation, which cannot be obtained by directly measuring. Therefore, it is necessary to develop the methodology for calculating e-waste generation by taking multiple influencing factors into account. Considering the advantages and disadvantages of indicators, this chapter will consider the various methods available and develop a more advanced approach to improve e-waste generation estimates.

Table 5.1 Overview of indicators for evaluating e-waste collection efficiency

Indicator	Unit	Advantage	Disadvantage
1. Average weight of e-waste collected per capita (discarding-based absolute indicator)	kg/ca.	Easy to calculate	- It does not distinguish between different product types - It does not consider the differences between regions or countries - Static and absolute indicator
2. Collected e-waste versus products put on the market (sales-based relative indicator)	%	Easy to calculate because products put on the market are usually registered in statistics	- Not suitable for emerging market or phase-out markets - Static indicator that does not update with the change in e-waste generation - Not accurate when sales data are incomplete and average product weights are not representative
3. Collected versus generated e-waste (discarding-based relative indicator)	%	Synchronized with dynamics of the market, technological leaps, consumer behaviors and e-waste generation	Difficult to estimate e-waste generation accurately due to complex discarding behavior, lack of reliable estimation models and data

This section has briefly introduced the indicators currently used to evaluate e-waste collection efficiency. These indicators are based on different criteria to check collection performance against an absolute or relative baseline. The indicator based on the total quantity of discarded e-waste effectively reflects collection results for a specific time and socioeconomic context. The following section will discuss the details of indicators based on e-waste generated.

5.1.2 Collection efficiency calculation

Most discarded products come from within the built environment. Although discarded products might have no value for their final users, they may not directly become waste due to re-use demand from other users (within or outside of the country). A multitude of collection channels exist such as trading in at shops, commercial take-back plans, municipal collection points or dustbins, donation for re-use and informal collection. Following collection, a great variety of treatments exist such as refurbishment for re-use, specialized formal treatment, municipal incineration, disposal in landfills, informal recycling and export (for re-use or recycling). For the waste or discarding-based indicator (the third indicator in Table 5.1), the collection efficiency of a specific channel or destination can be defined by:

$$R = Q_x / W_{total} \qquad (5.1)$$

Q_x is the quantity of e-waste collected within a specific time range, which is collected and treated in channel x; and W_{total} is the overall quantity of e-waste discarded by users within this time period.

It is critical to note that in this definition, Q_x refers to the quantity that has been actually processed in channel x, which is not necessarily equal to the quantity that is reported as the amount of e-waste collected. For example, it is estimated 65 percent of EEE placed on the

European market in 2008 was separately collected, but potentially more than half of this was improperly treated and illegally exported (European Union, 2012). This collection data regarding the final disposal phase was not properly reported. Only the EEE that enters the desirable treatment channel is counted as effective.

Regarding data collection and analysis, Q_x is relatively easy to quantify when e-waste is the only waste type processed in a certain channel (i.e. contracted e-waste recyclers). It can be obtained from a direct mass balance survey of the specific channel. However, difficulties arise when multiple waste types are processed by one channel (i.e. municipal incinerators and landfills), or when e-waste is handled by informal or illegal channels (such as non-contract recyclers or exporters). Precise estimates of Q_x in these channels require extensive sorting analysis, surveys and mapping of material flows. Even though the main focus is the quantity of e-waste handled by take-back systems, it is instrumental to understand how much e-waste is collected and treated through other channels. This is essential for diverting flows to formal take-back systems, reducing improper waste shipments and improving treatment quality.

In addition to the incompleteness of data, as discussed above, time-dependent factors also make it more difficult to estimate the overall amount of e-waste generated W_{total}. Factors like historical and present product sales, technological innovations, consumer behaviors and available collection schemes influence the generation of e-waste over time. E-waste generation measurements need to capture such dynamics to properly arrange collection and recycling systems.

5.2 Modeling e-waste generation

5.2.1 Current approaches to quantifying e-waste generation
A number of methods for quantifying e-waste generation are discussed in the current e-waste research and literature. Generally, these methods can be classified into four groups: disposal-related analysis, time series analysis (projections), factor models (using determinant factors for correlation) and Input-Output Analysis (IOA) (Walk, 2004; Beigl et al., 2008; Chung, 2011). **Disposal related analysis** uses e-waste figures obtained from collection channels, treatment facilities and disposal sites. It usually requires empirical data from parallel disposal streams to estimate the overall generation. **Projection models** forecast the trend of e-waste generation by extrapolating historical data into the future. **Factor models** are based on hypothesized causal relationships between exogenous factors, like population size and income level, versus e-waste generation (Beigl et al., 2008; Huisman, 2010). Factor modeling is the least-explored method so far due to complex anthropological effects, high uncertainty in long-term patterns and considerable requirements for advanced modeling techniques. **Input-Output Analysis** (IOA) quantitatively maps the sources, pathways and final sinks of material flows, and so far it is the most frequently used method. This chapter explores the applications of and improvements to the Input-Output Analysis approach, due to its higher level of detail and accuracy, as compared to the other methods. The IOA method delivers e-waste estimations at the product level for the past and the future. It contributes to the work of quantifying e-waste flows and developing e-waste take-back and treatment systems.

Socioeconomic systems move products into society (via sales), where they accumulate in the built environment (stock). When products reach the end of their lives after a certain period of time (lifespan), they flow out of the system as e-waste (van der Voet et al., 2002; Brunner and Rechberger, 2004). IOA models quantitatively describe the dynamics, magnitude and interconnections of three basic variables: product sales, stocks and lifespans, as well as e-waste generation (Walk, 2004).

Table 5.2 summarizes the variables and datasets needed for IOA e-waste generation estimates in the existing literature. It shows that all existing IOA methods use different types of data for the three defined variables (sales, stock and lifespan). Furthermore, it can be seen that current IOA models commonly use two variables from the three defined pillars (sales, stock and lifespan) for computation. These models still have relatively low degrees of freedom, and few variables can lead to errors when the formula or data quality are insufficient. Therefore, this chapter will propose an improved approach that incorporates more variables and data points into the IOA method in order to enhance the quality of e-waste estimation. All IOA variations will be compared and discussed in detail with a case study in Section 5.3.

Table 5.2 Required variables and datasets for e-waste estimates in existing IOA models

Estimation models	Variables and data requirements						Key references and applications
	Sales		**Stock**		**Lifespan**		
	Cont.*	Dis.*	Cont.	Dis.	Age distribution	Average lifespan	
A. Time Step model		√	√				(Oguchi et al., 2008; Yu et al., 2010; Araújo et al., 2012)
B-i. Market Supply model (Distribution Delay)	√				√		(Melo, 1999; Yang et al., 2008; TemaNord, 2009)
B-ii. Market Supply model (Simple Delay)		√				√	(van der Voet et al., 2002)
B-iii. Market Supply model (Carnegie Mellon method)	√					√	(Kang and Schoenung, 2006; Peralta and Fontanos, 2006; Dwivedy and Mittal, 2010; Steubing et al., 2010)
C. Stock and Lifespan model			√		√		(Müller et al., 2009; Walk, 2009; Zhang et al., 2011)
D. Leaching model			√			√	(van der Voet et al., 2002; Robinson, 2009; Chung et al., 2011; Araújo et al., 2012)

Note: "Cont." means that continuous datasets from the current year and all historical years are required for calculation; "Dis" means that discrete data (mainly in the current evaluation year) are sufficient for calculation.

These four IOA models use different variables and data points, which are briefly summarized below:

Model A. Time Step model: E-waste quantity is calculated from product sales and change of stock within a period. This method is represented by Eq.(5.2).

$$W(n) = POM(n) - [S(n) - S(n-1)] \qquad (5.2)$$

Where $W(n)$ is the e-waste generation in year n; $POM(n)$ is product sales in year n; and $S(n)$ and $S(n-1)$ are the quantities of appliances in stock for sequential years n and $n-1$ respectively (Araújo et al., 2012).

Model B. Market Supply model: E-waste quantity is calculated from time-series product sales from all historical years with their respective rates of obsolescence in the evaluation year. The method is represented by Eq.(5.3).

$$W(n) = \sum_{t=t_0}^{n} POM(t) \cdot L^{(p)}(t,n) \qquad (5.3)$$

Where $W(n)$ is the quantity of generated e-waste in evaluation year n; $POM(t)$ is the product sales in any historical years t prior to year n; t_0 is the initial year that a product was put on the market; $L^{(p)}(t,n)$ is the discard-based lifespan profile for the batch of products sold in historical year t, which reflects its probable obsolescence rate in evaluation year n (discarded equipment in percentage to total sales in year n) (Melo, 1999; Murakami et al., 2010; Oguchi et al., 2010).

Model C. Stock and Lifespan model: E-waste is calculated from time-series stock data from all historical years with their lifespan distributions. The method is represented by Eq.(5.5) with Eq.(5.4) being the initial condition. In these two formulas, historical sales data can be indirectly calculated by known stock and lifespan data.

For the initial year t_0:
$$W(t_0) = POM(t_0) - S(t_0) = POM(t_0) \cdot L^{(p)}(t_0, t_0) \qquad (5.4)$$
For the evaluation year n:
$$W(n) = POM(n) - S\big[(n) - S(n-1)\big] = \sum_{t=t_0}^{n} POM(t) \cdot L^{(p)}(t,n) \qquad (5.5)$$

Model D. Leaching model: E-waste is calculated as a fixed percentage of the total stock divided by the average product lifespan. It is represented by Eq.(5.6), and $L^{(av.)}$ is the average lifespan, which represents the most likely timeframe within which a product becomes obsolete. It can be calculated from the mean value of the lifespan distribution function.

$$W(n) = S(n) / L^{(av.)} \qquad (5.6)$$

In various national e-waste studies, the applications of these two-variable IOA models in e-waste estimates are rather straightforward. The common approach is to select an estimation method based on available data and follow the corresponding algorithm. The main drawback of applying these two-variable models lies in the underestimation of the influence of low-quality data. In these studies, data have often been considered an external problem, independent from mathematical modeling. As a result, the estimates are extremely sensitive to data quality, especially in cases with assumed or non-validated lifespan profiles (Jain and Sareen, 2006). Unrealistic assumptions, oversimplification of market conditions, variable uncertainty and insufficient validation of model parameters can substantially decrease the reliability of the estimated results (Beigl et al., 2008; Murakami et al., 2010; Oguchi et al., 2010).

Data quality varies by source, and sources are often inconsistent with each other. Product sales and stock data from past years are usually sporadic and incomplete (EEA, 2003). Product lifespan data are often roughly obtained without comprehensive consumer surveys and further validation. Furthermore, rapidly changing market conditions and the introduction of new product types demands dynamic modeling of actual flows. But existing studies often consider product weights and lifespan profiles to be constant over time, and complete time series data are rarely available (Babbitt et al., 2009). These issues regarding data quality create considerable difficulties for accurate estimation when applying the existing models.

To conclude, the common issue of data quality has to be addressed before applying any IOA model. In the following two sections, an advanced method is proposed to improve e-waste estimation with a multivariate analysis.

5.2.2 Structure of the "Multivariate Input-Output Analysis"

In many cases data is available for all variables in an IOA, and sometimes multiple sources are available for the same data point. All of these data can serve to construct more reliable datasets for e-waste estimation. It is possible to apply a multivariate IOA analysis, called the "Sales-Stock-Lifespan model."

Figure 5.1 illustrates the relationship between variables and data points in IOA. Basically, the mechanisms by which electronic products are consumed in society are portrayed as the inflows, stocks and outflows in the funnel image. Each variable from any historical year is regarded as a data point. Information can be extracted from each data point regarding sales, stock size, stock age composition, lifespan profile, quantity of e-waste generated and e-waste age composition. Relationships between these data points comply with the conservation of mass, IOA rules and algorithms provided following Figure 5.1. These mathematical and logical functions fill the data gaps and check data quality.
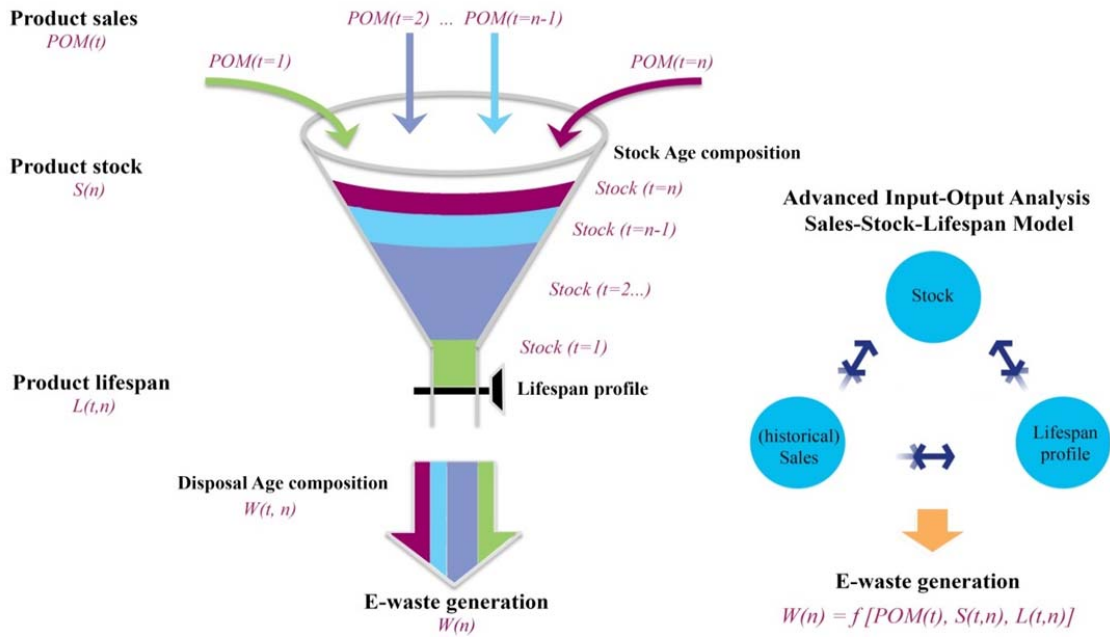
Figure 5.1 Multiple variables and data points applied in the Sales-Stock-Lifespan model enhance e-waste estimates

First, the change of stock within a period of time equals the difference between the total inflows of sales and outflows of e-waste in a system, and this follows the algorithm in Eq.(5.2) (Model A. Time Step model).

E-waste generation in evaluation year n can be calculated with Eq.(5.3) of Model B.

The disposal age composition of e-waste in evaluation year n can be calculated from historical sales and lifespan profiles:

$$W(t,n) = POM(t) \cdot L^{(p)}(t,n) \tag{5.7}$$

Total product stock size in the evaluation year n can be calculated by:

$$S(n) = \sum_{t=t_0}^{n} POM(t) \cdot [1 - L^{(c)}(t,n)] \tag{5.8}$$

Stock age composition in the evaluation year n can be calculated from historical sales and lifespan profiles:

$$S(t,n) = POM(t) \cdot \left[1 - L^{(c)}(t,n)\right] \tag{5.9}$$

Where $S(t,n)$ is the number of appliances measured in stock in evaluation year n, originally sold in year t, or has the stock age of $(n-t)$ years; $L^{(c)}(t,n)$ is the cumulative lifespan distribution for products sold in historical year t, which reflects the total number of products that become obsolete from year t to n.

100

The relationship between cumulative and probable lifespan distributions complies with the following formula:

$$L^{(c)}(t,n) = \sum_{t'=t_0}^{t} L^{(p)}(t',n) \qquad (5.10)$$

The lifespan of a product differs between individual owners and it takes the form of a probability distribution for a given population (Murakami et al., 2010). Due to social and technical developments, the lifespan of a product is time-dependent, so lifespan distributions have to be modeled for each historical sales year. In the present chapter, the Weibull distribution function is applied to model the lifespan profile, defined by a time-varying shape parameter $\alpha(t)$ and a scale parameter $\beta(t)$ (van Schaik and Reuter, 2004; Polák and Drápalová, 2012):

$$L^{(p)}(t,n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}} (n-t)^{\alpha(t)-1} e^{-[(n-t)/\beta(t)]^{\alpha(t)}} \qquad (5.11)$$

The probable rate of obsolescence $L^{(p)}(t,n)$ can be directly obtained from surveys or indirectly calculated from Eq.(5.3), Eq.(5.4), Eq.(5.5), Eq.(5.6) and Eq.(5.7), if corresponding data points for sales, stock and e-waste generation are available. Simulation of lifespan distributions can apply a non-linear regression analysis for curve fitting in order to determine best-fit data for these two parameters. For lifespan distributions in each historical year, at least two data points are required to calculate the parameters α and β. For instance, in order to determine $\alpha(1990)$ and $\beta(1990)$ for products sold in 1990, their probable rates of obsolescence in two years have to be obtained (such as $L^{(p)}(1990,2011)$ and $L^{(p)}(1990,2012)$). In addition, numeric and logical constraints can assist curve fitting from known data.

To summarize the analysis so far, each data point (as presented in Figure 5.1) not only carries information (the variable it represents), but also contains potential indications for other variables. By applying all the formulas presented in this section, additional or alternative data can be extracted from the known data. This ensures that the most information is captured from all available data to improve estimates without losing their potential implications. Therefore, multivariate IOA analysis involves all variables and multiple data points to estimate e-waste generation.

From the mathematical point of view, these three variables are equally important and functional. However, data from different sources in real-life calculations are rarely of equal quality. Some data points, like sales and stock size, may have an advantage over other data points because they are easier to measure or have a lower level of uncertainty. The following section will further explain the procedure of applying a multivariate IOA by taking data quality into consideration.

5.2.3 How to improve data quality with multivariate Input-Output Analysis

There is a variety of data sources for all three variables in IOA, and their qualities vary greatly. This section aims to explain the procedure of applying the Sales-Stock-Lifespan model, by constructing a dataset with the highest accuracy.

Constructing the most accurate dataset is necessary because data obtained from different sources and stakeholders might have distinct scopes and qualities. Effort needs to be spent identifying and cleansing unrealistic data and constructing continuous datasets by filling data gaps or mismatches. In many cases, the scope of EEE-related data is not uniform or clear. For instance, insufficiently specified data about computers might include both desktop and laptop computers. Sometimes such data also includes servers, work stations, netbooks, tablets and even peripherals. Sales figures from producers' registers are frequently incomplete or else they are based on assumed or outdated average product weights (this is a data issue). Non-reported extrapolations within input data need to be understood as well (this is a methodology error).

For these reasons, data need to be acquired via statistically robust sampling methods and pre-checked for structural and numeric errors. Input errors – such as incorrect units; unrealistic average product weights; confusing parts with products, household equipment with professional equipment and new products with second hand goods – must be corrected (Troschinetz and Mihelcic, 2009). As an important source for sales and lifespans, market survey data should be checked regarding geographical coverage, sampling size and demographic conditions in order to ensure that it is representative of a larger region (Murakami et al., 2010). Also, concerns about structural bias like the so-called "telescope effect" from respondents is relevant. The telescope effect causes people to perceive that recent events occurred longer ago than they really did and perceive that long-past events occurred more recently than they really did (Janssen et al., 2006). This could potentially bring uncertainty to the disposal-based lifespan distribution (Morwitz, 1997). For e-waste specifically, data obtained from sorting analysis requires careful examination. Due to the exclusion of data from other end-of-life streams such as informal recycling, illegal exports or landfills, the sampled return streams frequently consist of the least valuable and oldest equipment and are thus not representative of the entire stream.

Data quality considerations include the completeness, representativeness, accuracy and uncertainty of the collected data. During e-waste generation modeling, clear documentation of data quality is preferable. It can be evaluated qualitatively with the methods mentioned above such as data scope (consistent definition of referenced data, product types covered and target company/group/region), the acquisition method (statistical measurements, assumptions or unqualified sources) and time coverage (availability of historical data) (Weidema and Wesnæs, 1996). Data quality can be also assessed by its quantitative attributes, including population size, confidence interval, standard deviation, sample size and (the procedure for) removing erroneous data points.

A checklist for evaluating data quality for e-waste estimation is provided in Table 5.1. This table was developed from the experiences of mapping e-waste in the Netherlands, Italy and Belgium (Huisman et al., 2012; Magalini et al., 2012; Wielenga et al., 2013). More details about the e-

waste mapping study will be introduced in Section 5.3. Table 5.1 displays several factors that influence data quality: data definition and scope, data acquisition method, sample size, availability of time-series data and alternative data sources. Data quality for the same variables and different variables can be compared qualitatively with these criteria. As an advanced analysis, a weighting scheme or indicator system can be established to quantitatively evaluate data quality; all the aspects mentioned in the table are not equally important for estimating e-waste generation. The overall score can be used to create a hierarchy of quality for alternative data sources for the same data point or for different variables. When conducting e-waste modeling, data sources or variables with the best quality are given priority as model inputs when multiple data sources and variables are available.

Table 5.3 Checklist for evaluating data quality for e-waste estimates

	Criteria	**Variables**			
		Product sales	**Stock**	**Lifespan profile**	**Average weight**
1	Data definition	Unambiguous and consistent definition and specifications of the data (i.e. product types covered), clear scope, system boundary and counting units			
2	Data coverage	Referring to Business to Consumer (B2C), Business to Business (B2B), or both Household and professional use/possession			
3	Data acquisition method	- Fully or partially measured data using a statistically robust (sampling) method - Qualified or unqualified assumptions - Derived or interpolated data - Reference data			
4	Sample size	- All producers, retailers and importers included? - Only major producers included?	Statistically significant and representative for investigated households/business units/regions/countries, in terms of demographic and socioeconomic factors		Cover major brands and various product models
5	Level of detail	- Product level - Product group level - Shipment or company level	- Total stock size - Stock age distribution	- Lifespan distribution - Average lifespan	- Weight distribution - Average weight
6	Availability of time-series data	Availability and consistency of historical figures or records			
7	Availability of alternative data sources	Availability of multiple sources for the same data point			

After the data has been understood and assessed for quality, the Sales-Stock-Lifespan model can be used to carry out a multivariate analysis based on available data points. The main purpose is to construct reliable and continuous datasets for model calculations, either by filling the data gap or finding the most reliable data source. The approach applies the variable(s) with higher data quality to improve or compensate for the variable(s) with lower data quality. For example, if data for lifespan and stock figures are both available: after evaluating the data quality of both variables, if stock data are found out to be more reliable than lifespan distributions, then

available stock size and initial stock age composition can consolidate lifespan data. Calculations with multiple variables can be applied with the mathematical functions from Eq.(5.2) to Eq.(5.11). Through the process of cross-checking with other variables and data points, structural or data errors from less reliable variables become visible.

In addition to the formulas provided, empirical and logical constraints are also useful for compensating for weak data. A well-known example of a constraint is the saturation level of a product, such as one washing machine per household (the logical maximum). Another example is that people buy one washing machine to directly replace the old one, and there is hardly any dead storage time for washing machines; they are always removed from the house due to their large size. Constraints also take the form of external reference points like the number of cell phones in stock (in use) versus the number of subscriptions. Another important constraint comes from monitoring waste and export streams. For example, the total quantity of products identified in waste streams cannot exceed the outcomes modeled. For typical replacement products like washing machines, it is unlikely that more old products are discarded than new products are sold in a given year. These constraints, combined with measuring schemes for data quality, produce a Sales-Stock-Lifespan model that generates a more continuous dataset by closing the data gaps and prioritizing higher quality data when multiple sources are present.

After this step, Eq.(5.2) can be applied directly to calculate e-waste generation, if reliable sales and stock data are available. Eq.(5.3) can be applied if reliable sales and lifespan distributions can be retrieved from the analysis. There is a fundamental difference between directly applying these two-variable formulas (the Time Step model and the Market Supply model) and applying the advanced Sales-Stock-Lifespan model. The two-variable models usually do not verify the data and consolidate to improve the quality of data inputs. The advantage of the multivariate analysis is that it enhances the quality of data points for required variables before using formulas to calculate e-waste generation.

Through data consolidation and multivariate analysis, the accuracy of the model's output is significantly improved, compared with the other approaches. The following chapter will apply the Sales-Stock-Lifespan model to an empirical study in the Netherlands.

5.3 Case study: estimating e-waste generation in the Netherlands

5.3.1 Data collection

In 2011, a national study was conducted to determine the generation, collection, treatment and export of all types of e-waste in the Netherlands (Huisman et al., 2012). For most product categories, multiple data sources were obtained for EEE sales, stocks, lifespans and average weights. These included national statistics, consumer surveys and data from compliance schemes, producers, industrial associations, recyclers and exporters. The availability and quality of data compared to many other national e-waste studies was regarded as very high.

In order to capture all EEE present in Dutch society, the EEE classification method described in Chapter 4 was used to collect data at the product type level. Historical product sales were obtained from three data sources. Commodity registrations from Statistics Netherlands were

compiled, covering all 55 EEE categories between 1995 and 2010. Product sales were calculated from annual domestic production quantities (from Prodcom codes) plus imports (from CN codes) minus exports (from CN codes) at the national level. For each product category, underlying micro-data were scrutinized with detail and errors were resolved. Sales data for recent years were also obtained from the Wecycle producer foundation. Sales data from individually notifying companies were obtained from Agency Netherlands (a division of the Dutch Ministry of Economic Affairs that carries out policy and subsidy programs focusing on sustainability, innovation, international business and cooperation).

Lifespan distribution and stock levels of various EEE in the Netherlands were primarily derived from extensive market surveys. Lifespan profiles were calculated from two data sources: stock data including stock size and age distribution, and the age compositions of discarded household products. To obtain this data, a national survey of 5,200 representative Dutch households was conducted regarding the purchasing, possession and disposal of domestic appliances (63 types), consumer electronics (18 types) and IT products (5 types) during 2006 and 2007 (Hendriksen, 2007). In 2008, 3,000 representative Dutch households were interviewed about discharge lamps (Hendriksen, 2009). The stock levels of EEE in small and medium-sized enterprises were also surveyed (Hendriksen, 2010). In these surveys, face-to-face visits were conducted to validate or correct online responses. Additional data from complementary end-of-life streams and sorting analysis from Dutch e-waste recycling facilities in 2011 were referenced to validate the survey results. Data from various complementary streams were obtained from municipal waste sorting facilities, refurbishment stores, as well as interviews with metal trading companies and customs. Based on the Weibull distribution function, first year failure rates were incorporated when abrupt discarding behaviors were observed in the first year after product purchases (e.g. guarantee claims and consumer dislike of products). With the exception of lamps, it is assumed that lifespan profiles for business use are similar to those for consumer use.

Average weight per EEE category was acquired through sorting analysis and the Wecycle producer register. Data from the relevant literature was included for comparisons as well. The raw data obtained was processed by analyzing standard deviations and confidence intervals to reflect weight distribution over time.

5.3.2 Modeling process and results

Based on the formulas in Section 5.2.2 and fed with the data described in 5.3.1, the Sales-Stock-Lifespan model was developed. The main reason to apply this model as the calculation method for this case study is that no continuous historical stock and lifespan figures are available for the Netherlands. Due to the lack of sufficient data, it is not possible to directly apply the two-variable IOA models to estimate e-waste generation. Therefore, the multivariate model must be used to fill in the data gaps and to construct continuous historical datasets for model inputs.

The model is constructed in MS Excel to allow for flexible application of Microsoft Excel Solver (Frontline System Inc., 2012) for non-linear regression analysis per product category. Depending on the data quality of each pillar, the solver is applied to determine variable parameters, correct data errors and complete the missing data for model input. Data quality for all variables is qualitatively evaluated based on the criteria listed in Table 5.3, together with the accuracy of fit

(R-squared values) for the lifespan profiles. Then, variables with higher data quality are used to validate and consolidate the variables with lower data quality.

In this case study, the quality of time-series sales datasets was evaluated as high because the statistics records on the production and import/export were very detailed on both the company and shipment levels. Data points for lifespan profiles and stock data (for major products) in 2006 and 2007 were also regarded as reliable, mainly due to the large size of the detailed survey. In attempting to estimate e-waste generation for years past, stock data and lifespan profiles for years other than 2006 and 2007 were missing. Therefore, the Sales-Stock-Lifespan model was used to fill in the data gaps.

As a starting point, the Weibull parameters of lifespan profiles were directly obtained from the disposal age composition/distribution $W(t,n)$ for the surveyed years by fitting a curve (2006 and 2007). Then stock age compositions/distributions $S(t,n)$ in the surveyed years were used as a reliable source to determine dynamic lifespan parameters for other missing years. This was based on the assumption that the Weibull parameters change linearly over time in order to reduce the complexity of the computation. For products undergoing technological change (like CRT TVs after 2006), a different rate of lifespan change was applied within the relevant period. After time-series of lifespan profiles were obtained, data gaps in historical stocks were filled in with Eq.(5.5) and the known sales data. In addition, the consistency of this derived data was cross-checked with the known data points from sales and surveyed stock information.

From the steps described above, a continuous dataset of time-series sales, stocks and lifespan profiles was generated. As a result, the quantities of e-waste generated for all historical years were acquired by applying Eq.(5.2) or Eq.(5.3). This result confirms the ability of the multivariate model to fill in data gaps and consolidate existing data points. Table 5.4 provides the modeling results for selected years. By applying multivariate IOA methods, e-waste generation and product lifespans over time can be obtained. This exercise indicates that substantial efforts are needed to acquire more detailed and complete time-series datasets for all variables if more accurate e-waste generation results are expected. Applying data for e-waste categories at a more general level will introduce errors and lower the accuracy of estimates (for instance, applying the same average weight and lifespan data for all types of TV). Therefore, it is necessary to collect data (product sales, stocks, lifespans and average weights) for each e-waste category to reach reliable estimates of waste quantities.

Table 5.4 Sales, stocks, average weights and lifespan profiles of various EEE and e-waste generation in the Netherlands (for selected years)

EEE category		Average weight (kg/piece)		Lifespan distribution (Weibull)				EEE sales 2010 (kg/ca.)	EEE in stock 2010 (kg/ca.)	WEEE generated 2010 (kg/ca.)
Sub-key	Description	2000	2005	2000		2005				
				α	β	α	β			
1. Large household appliances(LHHA)										
1-01	Prof. heating and ventilation	83.7	83.7	1.8	16.0	1.8	15.8	0.44	5.24	0.37
1-02	Dishwashers	47.6	45.5	1.7	13.3	1.6	13.1	1.05	11.26	0.99
1-03	Kitchen (furnaces, ovens)	43.5	45.6	2.6	18.7	2.5	18.0	0.66	8.68	0.47
1-04	Washing machines	70.3	71.4	2.2	14.2	2.2	13.9	2.93	32.88	2.68
1-05	Washing dryers	40.5	43.2	2.6	16.7	2.6	16.5	0.89	11.36	0.69
1-06	Room heating and ventilation	9.6	9.9	2.0	13.5	2.0	13.5	0.35	3.68	0.30
1-07	Sun beds and tanning	70.3	71.4	1.5	11.3	1.5	11.2	0.02	1.06	0.14
1-08	Fridges (for food, wine, etc.)	35.6	38.2	2.2	16.7	2.2	16.5	1.39	16.28	1.01
1-09	Freezers (for food, ice, etc.)	43.7	43.9	2.6	23.6	2.6	23.2	0.67	12.94	0.62
1-10	Combi. fridges and freezers	59.4	64.4	2.2	16.7	2.2	16.5	1.11	12.81	0.78
1-11	Air conditioners	43.3	35.0	2.8	12.5	2.8	12.3	0.04	1.24	0.13
1-12	C&F Other (Cooling and Freezing)	9.8	9.8	2.4	13.8	2.4	13.6	0.08	0.85	0.08
1-13	Prof. C&F	128.0	137.9	2.5	20.8	2.5	20.6	0.82	10.88	0.40
1-14	Microwaves	16.8	17.5	0.9	16.3	0.8	14.7	0.63	5.56	0.48
2. Small household appliances (SHHA)										
2-01	SHA (iron, scale, etc.)	1.3	1.2	1.4	9.6	1.3	9.4	0.63	5.01	0.65
2-02	Food processing	3.5	3.1	1.5	13.5	1.3	12.3	1.33	11.63	1.10
2-03	Hot water (coffee, tea, etc.)	1.9	1.9	1.9	8.5	1.8	7.9	0.53	2.91	0.45
2-04	Vacuum cleaners	5.2	5.5	1.5	10.4	1.5	10.3	0.54	3.98	0.44
2-05	Personal care	0.6	0.6	1.3	11.2	1.3	10.8	0.13	1.15	0.13
3. IT and telecom equipment (IT)										
3-01	Small IT and accessories	0.5	0.5	1.3	6.0	1.3	5.9	0.47	2.46	0.51
3-02	Desktop PC (excl. monitor)	9.9	9.3	2.2	9.9	2.1	9.6	0.64	6.33	0.83
3-03	Laptop PC (incl. netbook, tablet)	4.1	3.7	1.6	5.4	1.5	5.2	0.43	1.36	0.31
3-04	Printing and imaging	7.9	7.3	1.9	11.0	1.7	10.1	0.86	5.86	0.67
3-05	Telephones and equipment	0.7	0.6	2.2	6.9	2.1	6.5	0.06	0.31	0.07
3-06	Mobile phones	0.11	0.10	0.8	7.8	0.7	7.6	0.02	0.13	0.02
3-07	Prof. IT (servers, routers, etc.)	36.0	36.0	1.5	7.9	1.5	7.8	0.76	4.17	0.63
3-08	CRT monitors (cathode ray tube)	16.7	19.4	2.3	9.0	2.2	8.5	N/A	4.32	1.28
3-09	FPD monitors (flat panel display)	5.0	6.5	2.6	7.7	2.5	7.5	0.76	4.75	0.57
4. Consumer equipment (CE)										
4-01	Small CE and accessories	0.4	0.4	1.6	11.9	1.4	10.2	0.15	0.93	0.11
4-02	Portable audio and video	0.4	0.3	0.8	8.1	0.8	8.0	0.07	0.57	0.07
4-03	Radio and HiFi components	3.7	2.6	2.1	15.7	2.1	15.6	0.63	7.21	0.51
4-04	Video and projection	4.1	3.3	1.7	10.6	1.7	10.5	0.33	4.37	0.56

4-05	Speakers	2.8	2.4	1.5	10.9	1.5	10.8	0.31	3.04	0.33
4-06	Camera	0.8	0.5	1.5	8.4	1.4	8.2	0.06	0.49	0.07
4-07	CRT TVs (cathode ray tube)	27.6	31.8	2.1	13.6	2.0	12.6	N/A	13.68	1.76
4-08	FPD TVs (flat panel display)	7.8	12.6	2.1	12.0	2.1	12.0	1.71	7.13	0.28
5. Lighting equipment										
5-01	Lamps (others)	0.09	0.09	2.0	11.7	2.0	11.6	0.27	2.33	0.23
5-02	Compact fluorescent lamps	0.08	0.08	2.1	9.2	2.1	9.4	0.08	0.44	0.04
5-03	Straight tube fluorescent lamps	0.11	0.11	1.6	5.9	1.6	5.8	0.11	0.59	0.12
5-04	Prof. special lamps	0.11	0.11	2.8	19.8	2.8	19.6	0.02	0.25	0.01
5-05	LED lamps	0.08	0.08	1.2	5.5	1.2	5.5	0.01	0.03	0.01
5-06	Household luminaries	0.08	0.08	N/A	N/A	N/A	N/A	0.02	0.02	N/A
6. Electrical and electronic tools										
6-01	Prof. tools (excl. dual use)	2.7	2.7	2.0	6.6	2.0	6.6	*0.40*	*1.93*	*0.31*
6-02	Small tools (household)	23.2	23.2	2.0	11.8	1.9	11.6	0.16	1.25	0.11
7. Toys, leisure and sports equipment										
7-01	Small toys	2.6	2.5	2.8	16.9	2.6	15.7	0.73	8.91	0.58
7-02	Game consoles	0.24	0.22	1.5	4.8	1.5	4.7	0.05	0.18	0.05
7-03	Large Music and Exercise	0.5	0.5	1.2	5.7	1.2	5.6	0.11	0.49	0.10
8. Medical devices										
8-01	Small medical (household)	14.5	14.5	2.5	11.8	2.4	11.6	0.06	0.44	0.03
8-02	Prof. medical	0.18	0.18	1.5	7.8	1.4	7.6	0.01	0.03	0.00
9. Monitoring and control instruments										
9-01	Small monitoring	67.0	67.0	2.7	19.6	2.6	19.2	0.32	3.11	0.13
9-02	Prof. monitoring	0.24	0.24	1.7	9.8	1.7	9.6	0.14	0.85	0.09
10. Automatic dispensers										
10-1	Prof. dispenser (non-cooled)	5.5	5.5	2.0	11.8	1.9	11.6	0.11	0.89	0.08
10-2	Prof. dispenser (cooled)	78.5	78.5	2.1	10.3	2.0	10.1	0.33	2.46	0.27
Total								**26.05**	**268.88**	**24.15**

5.3.3 Application of five types of IOA models in the Dutch case study

In order to understand the influence of model selection and data quality on e-waste estimation, a selection of representative EEE is used from the Dutch study for further examination. Four products are selected to illustrate different market types and discarding patterns: washing machines (saturated replacement market), laptop computers (steadily increasing market), Cathode Ray Tube (CRT) TVs (declining/phase-out market) and flat panel TVs (new market).

The four models listed in Table 5.3 are selected to review their performance, compared to the "Sales-Stock-Lifespan model" (Model E).

Model E. Sales-Stock-Lifespan Model: E-waste is calculated from a multivariate analysis, as has been described in Sections 5.2.2. and 5.2.3.

Sales, stock and lifespan profile data for four types of EEE are used as the inputs for these five IOA models. The e-waste generation modeling results from Models A through E are presented in Figure 5.2. In order to examine the discrepancies between the models, the results from Model E (the Sales-Stock-Lifespan Model) are referred to as the baseline (red lines in figure 2). Model E is intrinsically the most accurate as it links and validates existing data from multiple sources for all three independent variables based on their data quality and model algorithms. This figure generally demonstrates that these models lead to distinct results for all four appliances.

5.3.4 Comparison of results among five IOA models

The Time Step model (Model A, black lines) simply applies mass balances and the result contains "noise" from sales and stock fluctuations (washing machines in the first chart). Model E generates a smooth curve through these fluctuating points, and the noise is evened out by the dynamic lifespan profiles. Confined by unavailable historical stock data, the three other appliances used model-generated stock data for computation. Therefore, neither Model A nor Model E contains "noise" for laptop computers, CRT TVs and flat panel TVs. They totally overlap with each other due to the use of the same lifespan profiles and sales data. This case demonstrates that Model A can generate accurate and dynamic outcomes if the quality of the sales and stock data is high.

The Market Supply model (Model B) applies dynamic time-varying lifespan distributions (B-1, orange lines) and generates the closest results to the baseline. Using fixed lifespan distributions from a reference year (B-2, pink lines; B-3, yellow lines) leads to a deviation from the baseline for certain years. In the case of CRT TVs, applying a fixed-lifespan distribution from 1990 generates a result that is very similar to the baseline result during the years between 1990 and 2001, but it starts to deviate significantly after 2002, displaying an average relative difference of -6 percent compared to the baseline. This indicates that applying a fixed lifespan distribution is not the right modeling choice for phase-out market conditions.

The accuracy of the Stock and Lifespan model (Model C) calculation primarily relies on the representativeness of the lifespan distributions applied. The two scenarios with marginal lifespan distributions from 1990 (C-1, light green lines) and 2011 (C-2, deep green lines) show significant deviation from the baseline for the four products. For laptop computers, the scenario applying fixed-lifespan distribution from 1990 is very different from the baseline for 2001-2011; applying the 2011 lifespan distribution results in a similarly large deviation. Potential reasons for such a difference are decreasing sales prices per unit, desktop replacements and the subsequent shortening of lifespans over time.

The Leaching model (Model D) is the most different model. This model (D-1, light blue lines) has comparable results with the baseline for washing machines (2003-2011), laptop computers (1998-2011) and CRT TVs (1990-2002). In contrast, for unsaturated markets (i.e. flat panel TVs), all three scenarios from this model (D-1; D-2, deep blue lines; and D3, purple lines) are significantly different from the baseline, resulting in a faster growth rate. For declining markets (CRT TVs), the peaks of obsolete TVs in the three leaching models appear earlier than the baseline. Scenarios applying fixed average lifespans (D-2, D-3) have inferior results compared to

the dynamic ones (D-1). This model requires little data input and is therefore convenient when data is extremely scarce. However, the model is not suitable for all market types due to oversimplification and loss of dynamic elements compared to the actual situation. It is only valid when applying recent average lifespan data in saturated markets (van der Voet et al., 2002; Walk, 2009).

The four selected products represent four different types of markets, and the trends of sales, stocks, lifespans and e-waste generation vary greatly over time and among different market conditions. Regarding the results of the IOA models, the two-variable models demonstrate substantial deviations from the multivariable Sales-Stock-Lifespan reference model. The reference model is regarded as much more accurate because the input data have been checked and consolidated to improve quality. The two-variable models directly apply the available data without data processing, and errors can be introduced when it is not reliable or accurate. In stable or saturated markets (washing machines), the difference in results can vary by up to a factor of 1.5, as compared to the reference model. For stably increasing markets (laptop computers), results have varied by up to a factor of 2 in recent years. For decreasing markets (CRT TVs), the difference can reach a factor of 2. For steeply emerging markets (flat panel TVs), the gap between the leaching model and the reference model is extremely big due to low discarding rates of flat panel TVs in the early years of market development.
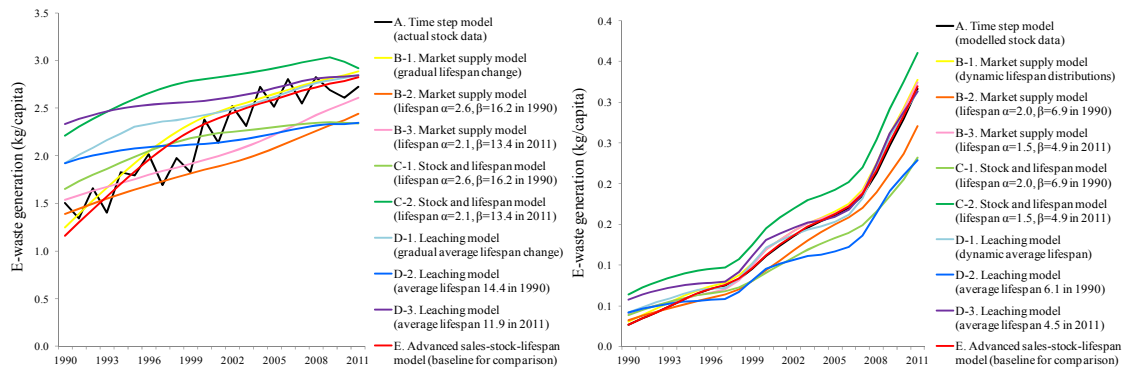
1. Annual generation of waste washing machines (Example of stable or saturated market)

2. Annual generation of waste laptop computers (Example of increasing market; In this graph, A overlaps with E)
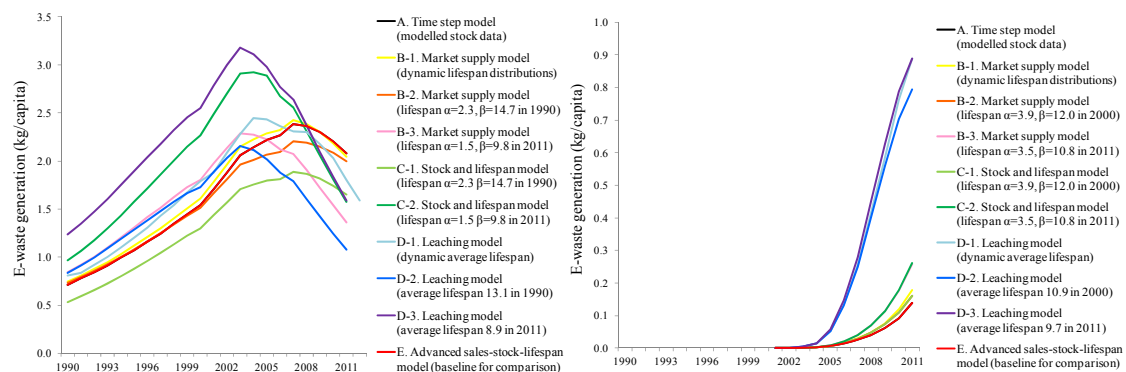
3. Annual generation of waste CRT TVs (Example of declining market; In this graph, A overlaps with E)

4. Annual generation of waste flat panel TVs (Example of steeply emerging market; In this graph, A overlaps with E, B2 overlaps with C2, B3 overlaps with C1)

Figure 5.2 Estimated annual waste generation of four representative EEE in the Netherlands (1990-2011) in ten appraisal scenarios with different IOA models and lifespan parameters

5.3.5 Discussion

From this case study, it can be concluded that the application of simple models that do not process data to improve its quality can lead to substantial e-waste estimate errors. Reliability in sales and stock data, together with the selection of lifespan profiles, determine the accuracy of the e-waste generation estimates. In contrast to sales and stock size, measurement of lifespan is much more complicated, entailing both extensive surveys and mathematical fitting of the distribution parameters. The Dutch study demonstrates that most products, except energy saving lamps, had declining average lifespans during the period from 1990 to 2010. This key variable should be monitored for changes, especially in non-saturated markets or for new technologies and subsequent replacements. The accuracy of time series modeling for lifespan profiles can be improved by better modeling techniques (more sophisticated mathematical

functions and complementary estimation methods) or more abundant data of higher quality (i.e. representative sampling and alternative data sources).

Advanced modelling of e-waste generation is instrumental to understand the volume of overall e-waste flows in society, but model sophistication should not go at the cost of efforts to collect more accurate data. Without reliable dataset as model input, even complex mathematical formulas and sophisticated modelling techniques cannot have accurate estimates alone.

The data used in e-waste related research is usually a compilation of information from a variety of sources. Data quality needs to be ensured for accurate modeling of e-waste generation. This study proposes an advanced IOA method involving all three variables (sales, stocks and lifespans), which uses the best available data points to prepare better datasets for modeling. The result from the Dutch case study demonstrates significant disparities between different estimation models arising from the use of data under distinct qualities. A multivariate analysis is recommended for improving data quality and creating more precise e-waste estimates.

5.4 Conclusions

Collection rate is an important indicator when evaluating the efficiency of established collection channels. This chapter mainly explores the modeling of collection rates based on the level of obsolete products, which requires data related to the e-waste collected in specific streams and the overall amount of e-waste generated. It is challenging is to accurately estimate e-waste generation due to low data quality related to complex market dynamics and consumer behaviors. Therefore, a multivariate input-out analysis is proposed, which applies multiple variables and data points to improve data quality. The result from the Dutch case study demonstrates the effectiveness of this consolidated data in improving the reliability of e-waste estimates. This more advanced model for estimating e-waste is one potential solution to low data quality. The model and method developed can greatly support the development of e-waste systems, help define effective collection targets and identify leaks in formal take-back schemes.

5.5 References

Araújo, M. G., et al. (2012). "A model for estimation of potential generation of waste electrical and electronic equipment in Brazil." Waste Management **32**(2): 335-342.

Babbitt, C. W., et al. (2009). "Evolution of Product Lifespan and Implications for Environmental Assessment and Management: A Case Study of Personal Computers in Higher Education." Environ Sci Technol **43**(13): 5106-5112.

Beigl, P., et al. (2008). "Modelling municipal solid waste generation: A review." Waste Management **28**(1): 200-214.

Brunner, P. H. and H. Rechberger (2004). Practical handbook of material flow analysis. Advanced methods in resource and waste management. Boca Raton, Florida CRC Press LLC.

Chung, S.-S. (2011). "Projection of waste quantities: the case of e-waste of the People's Republic of China." Waste Manag Res.

Chung, S.-S., et al. (2011). "Generation of and control measures for, e-waste in Hong Kong." Waste Management **31**(3): 544-554.

Dwivedy, M. and R. K. Mittal (2010). "Estimation of future outflows of e-waste in India." <u>Waste Management</u> **30**(3): 483-491.

EEA (2003). Waste from electrical and electronic equipement WEEE - quantities, dangerous substances and treatment methods. Copenhagen, Denmark, Environmental European Agency, European Topic Centre on Waste.

European Union (2003). Waste Electrical and Electronic Equipment Directive (2002/96/EC). Brussels, Belgium, Official Journal of the European Union L37.

European Union (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) (Recast), Official Journal of the European Union L 197. **Volume 55**.

Frontline System Inc. (2012). Solver tool in Microsoft Excel (2010 edition).

Hendriksen, T. (2007). Bezit, afdanking en verkrijging van witgoed, bruingoed en grijsgoed. Dongen, the Netherlands, GfK Panel Services Benelux.

Hendriksen, T. (2009). Possession, disposal and purchasing of discharge lamps in Dutch households. Dongen, the Netherlands, GfK Panel Services Benelux.

Hendriksen, T. (2010). Bezit van elektrische apparaten, energiezuinige lampen en batterijen binnen het Nederlandse MKB (in Dutch). Dongen, the Netherlands, GfK Panel Services Benelux.

Huisman, J. (2010). WEEE recast: from 4kg to 65%: the compliance consequences, UNU Expert opinion on the EU WEEE Directive. Bonn, Germany, United Nations University.

Huisman, J., et al. (2012). The Dutch WEEE Flows. Bonn, Germany, United Nations University, ISP-SCYCLE.

Huisman, J., et al. (2012). Dutch Ewaste Quantification 2012, final report (in development). Bonn, Germany, United Nations University.

Jain, A. and R. Sareen (2006). "E-waste assessment methodology and validation in India." <u>Journal of Material Cycles and Waste Management</u> **8**: 40-45.

Janssen, S. J., et al. (2006). "Memory for time: How people date events." <u>Memory & Cognition</u> **34**(1): 138-147.

Kang, H.-Y. and J. M. Schoenung (2006). "Estimation of future outflows and infrastructure needed to recycle personal computer systems in California." <u>Journal of Hazardous Materials</u> **137**(2): 1165-1174.

Magalini, F., et al. (2012). Household WEEE Arising in Italy. Bonn, Germany, United Nations University.

Melo, M. T. (1999). "Statistical analysis of metal scrap generation: the case of aluminum in Germany." <u>Resources, Conservation and Recycling</u> **26**: 91-113.

Morwitz, V. G. (1997). "It Seems Like Only Yesterday: The Nature and Consequences of Telescoping Errors in Marketing Research." <u>Journal of Consumer Psychology</u> **6**(1): 1-29.

Müller, E., et al. (2009). Assessment of e-waste flows: a probabilistic approach to quantify e-waste based on world ICT and development indicators. <u>R'09 World Congress</u>. Davos, Switzerland.

Murakami, S., et al. (2010). "Lifespan of Commodities, Part I." <u>Journal of Industrial Ecology</u> **14**(4): 598-612.

Oguchi, M., et al. (2008). "Product flow analysis of various consumer durables in Japan." <u>Resources, Conservation and Recycling</u> **52**(3): 463-480.

Oguchi, M., et al. (2010). "Lifespan of Commodities, Part II." <u>Journal of Industrial Ecology</u> **14**(4): 613-626.

Peralta, G. L. and P. M. Fontanos (2006). "E-waste issues and measures in the Philippines." <u>Journal of Material Cycles and Waste Management</u> **8**(1): 34-39.

Polák, M. and L. Drápalová (2012). "Estimation of end of life mobile phones generation: The case study of the Czech Republic." <u>Waste Management</u>(In Press).

Robinson, B. H. (2009). "E-waste: An assessment of global production and environmental impacts." <u>Science of The Total Environment</u> **408**(2): 183-191.

Steubing, B., et al. (2010). "Assessing computer waste generation in Chile using material flow analysis." <u>Waste Management</u> **30**(3): 473-482.

TemaNord (2009). Method to measure the amount of WEEE generated - Report to Nordic council's subgroup on EEE waste. Copenhagen, Denmark, Nordic Council of Ministers.

Troschinetz, A. M. and J. R. Mihelcic (2009). "Sustainable recycling of municipal solid waste in developing countries." <u>Waste Management</u> **29**(2): 915-923.

van der Voet, E., et al. (2002). "Predicting future emissions based on characteristics of stocks." <u>Ecological Economics</u> **41**(2): 223-234.

van Schaik, A. and M. A. Reuter (2004). "The time-varying factors influencing the recycling rate of products." <u>Resources, Conservation and Recycling</u> **40**(4): 301-328.

Walk, W. (2004). Appraoches to estimated future quantities of waste electrical and electronic equipment (WEEE). <u>Proceedings of the Eletronics Goes Green 2004</u>. Berlin, Germany**:** 263-268.

Walk, W. (2009). "Forecasting quantities of disused household CRT appliances – A regional case study approach and its application to Baden-Württemberg." <u>Waste Management</u> **29**(2): 945-951.

Weidema, B. P. and M. S. Wesnæs (1996). "Data quality management for life cycle inventories—an example of using data quality indicators." <u>Journal of Cleaner Production</u> **4**(3–4): 167-174.

Wielenga, K., et al. (2013). (W)EEE Mass balance and market structure in Belgium, study for Recupel, Brussels, Belgium, Recupel.

Yang, J., et al. (2008). "WEEE flow and mitigating measures in China." <u>Waste Management</u> **28**(9): 1589-1597.

Yu, J., et al. (2010). "Forecasting Global Generation of Obsolete Personal Computers." <u>Environ Sci Technol</u> **44**(9): 3232-3237.

Zhang, L., et al. (2011). "Predicting future quantities of obsolete household appliances in Nanjing by a stock-based model." <u>Resources, Conservation and Recycling</u> **55**(11): 1087-1094.

Chapter 6: Assessment of the effectiveness of e-waste treatment technologies

As introduced in Chapter 4, a great variety of e-waste appears in waste streams. Because there are numerous product types, it has been recommended that products with similar intrinsic properties should be collected and treated in the same stream for the best operational efficiency. Chapter 5 provided a method to evaluate e-waste quantities and collection efficiencies, and the next step is to recycle e-waste items according to collection categories. A treatment system has the objectives of controlling toxicity and material recovering materials in the pursuit of reducing environmental impacts and preserving resources. E-waste can end up in a great variety of destinations and facilities. The complex interactions between heterogeneous products and diverse treatment scenarios make it difficult for system managers and policymakers to make proper assessments. Treatment facilities and recyclers need to cooperate to fulfill the two objectives of a treatment system.

This chapter aims to analyze the basic structure and setup of the technical sub-system for treating e-waste. Sequential treatment stages with their requisite arrangements and alternative techniques are investigated in detail. The best approach for reaching high technical performance (for high material recovery rates and efficient toxic control) is discussed. This chapter will result in a better understanding of the formation and technical characteristics of different treatment scenarios.

6.1 Technical and societal aspects of e-waste treatment systems

E-waste contains both hazardous and valuable substances, which are assembled in a variety of configurations. These substances usually cannot be treated or refined by the same process. A cost-efficient treatment system that simultaneously liberates and refines target fractions in an environmentally sound way is needed. This complex task can be divided into two sub-systems: (1) the technical system that applies treatment technologies and innovations in industrial infrastructures; and (2) the societal system responsible for adopting innovations and managing the technical system in compliance with treatment standards and legal requirements (Wang *et al.*, 2012).

Treatment performance is mainly determined by the established recycling processes and techniques. A restricting condition, the selection of treatment technologies is predetermined by environmental, economic, social and legislative factors. The technical system is formed by a series of pre-processors, refiners and final disposers who recycle secondary materials and control toxic and hazardous substances (Castro *et al.*, 2007; Meskers *et al.*, 2009). The

efficiencies of material recovery and toxic control fundamentally depend on the chosen technologies, processing equipment and facilities. Establishment of the technical system relies on a series of external factors such as legislative requirements, the availability of investments and research and development (R&D). Meanwhile, the societal system influences the selection of technologies and performance of the technical system via the available quantity of e-waste, domestic take-back policies, economic capability, market dynamics and environmental standards.

Table 6.1 summarizes the main elements of both the technical and societal systems related to e-waste treatment, as well as their influences on performance. It shows how the technical system mainly influences the efficiency of material refining and emissions control by means of technological installations, machinery and equipment and health and safety protections. This is always determined at the facility level, which operates, maintains and manages the treatment techniques. One additional consideration is that performance may vary by treatment facility. Beyond the facility level, many other social factors influence the selection of technology and daily operations. A major consideration for recyclers is the profitability of treatment, which is determined by collection costs (the price to collect or purchase waste appliances), initial equipment investments, labor and managerial costs, material revenues, economies of scale (the quantity that is treated) and sometimes by subsidies. As they are also driven by legislation and social concerns, emissions standards require treatment facilities to prevent pollution. These standards influence the technical system, as well as overall treatment costs. Materials recycled from the treatment system can provide revenues according to market prices, acting as cost compensation. Additionally, research on material separation, chemistry, metallurgy and refining can lead to the development of technologies tailored for e-waste treatment in specific social contexts. Therefore, the installation of treatment technologies needs to be compatible with societal factors in order to achieve the best economic and environmental performance.

Table 6.1 Factors influencing the performance of e-waste treatment

System boundary	Influential factor	Influence on treatment performance
Technical system	Treatment methods	The outcome of material separation and refining, treatment of materials with toxic potential and emission controls
	Machinery and equipment	Actual performance of the designated technologies
	Emission control measures	The types and quantities of pollutants released into the environment
Societal system	Collection channels and quantities	Economies of scale and economic performance
	Material price	The order of priority for recycling materials Selection of recycling techniques and equipment Overall revenue
	Labor costs	Amount of manual work (such as dismantling and sorting) Overall economic performance
	Logistic costs	Cost of transportation from collection points to treatment facilities
	Investment, treatment subsidy or service charge	Selection of treatment equipment and facilities Overall profitability of treatment
	Environmental standards	The adoption of necessary emission control measures Environmental management system (like ISO, OSHA etc.)
	Availability of recycling facilities for secondary materials	Share of treatment facilities with other material streams Overall treatment cost
	Level of research and development	The adoption, maintenance and development of treatment technologies

Treatment performance can be examined from three perspectives: technology, the environment and the economy. They can be quantitatively evaluated by different indicators, either separately or altogether. Table 6.2 summarizes the existing indicators based these perspectives. The technical settings of a treatment system directly influence the quality and quantity of material output. At the same time, the quality and quantity of material input also influences the system performance. The same configuration of a treatment process may perform differently towards different material feed. For instance, a shredding line designed for IT equipment may not reach the optimal treatment efficiency for large household appliances or mixed categories of e-waste input.

A straightforward indicator for evaluating the technical performance of a system is recovery rate. This is expressed as a weight-based metric: the percentage of material that is eventually recycled versus total input materials. If the goal of the evaluation is to capture toxic material, the percentage of captured material can be used to evaluate efficiency. Data for calculating this can be taken from the input and output mass balances. The advantage of using this indicator is that it directly expresses the ability of a process to recover materials or capture toxics, and the

computation is rather easy and straightforward. This indicator is very useful for evaluating one specific type of material, but it has a limited ability to demonstrate the overall performance of all materials in one product. Critical materials (such as precious metals) are frequently present in very low concentrations. When these materials' recovery rates are multiplied by their low concentrations, there is hardly any effect on the overall recovery rate of the product. For instance, a treatment system with the recovery rate of 80 percent for all materials does not necessarily outperform a system with an overall recovery rate of 75 percent because of the differences in magnitude between materials' environmental and economic impacts (as shown in Chapter 4).

With regard to the limitations of weight-based indicators, economic indicators can account for market value disparities between different materials. This can facilitate the identification of recycling priorities for more highly valued materials, as well as the associated costs. The economic indicator is represented by the profit per input product (e.g. €/kg), calculated by subtracting operational costs from the revenues from recycled materials. The economic indicator is more dynamic than the technical indicator due to fluctuating market prices for materials and changeable operational costs. This indicator needs to be updated regularly to be in accordance with the latest market prices and costs.

As discussed in Chapter 4, economic analyses can only refer to materials that have market value. Not every material has a positive market value, especially materials with substantial potentials for toxicity. Low-value materials do not necessarily have low environmental impacts. Also, in many cases emissions from treatment processes are not fully reflected in monetary terms (they are known as external costs to the society). Given this, environmental indicators are a more useful tool to account for all the environmental impacts of treatment, including material use and gain, energy consumption and emissions. The calculation transfers the weights of different materials and emissions into a comparable indicator. An impact category indicator can be chosen from anywhere along the impact pathway, either at the midpoint (problem-oriented approach based on environmental mechanisms) or the endpoint level (damage to Areas of Protection) (Guinée *et al.*, 2002). The environmental analysis involves a detailed inventory with all material inputs and outputs of a system, as well as the respective characterization factors for the selected impact category for each material. The analysis demands extensive data and environmental modeling to assess pollutant diffusion mechanisms and conduct damage analysis.

In real-world decision making, choosing maximum profits (without working to prevent pollution) or minimal environmental impacts (without controlling costs) is not practical. Compromise or trade-offs are always needed between economic considerations (the price of goods and services) and environmental considerations (ecological impacts and resource intensity). A synthesized indicator incorporating both of these considerations can help provide a balanced view. A commonly applied indicator is eco-efficiency, which is the ratio between economic costs and environmental impacts. It seeks the optimal scenario with the most profits and fewest environmental impacts from e-waste treatment. Another indicator is "eco-cost," which transforms environmental effects into virtual pollution prevention costs. By applying eco-cost, LCA scores are monetized and presented as one-dimensional values. Compared to eco-efficiency, eco-cost is subjected to specific environmental and regional policies to define the

actual monetary value for the environment. Because of this, eco-cost data needs to be updated regularly according to the latest environmental offset costs. Its application in environmental analysis is still limited, and the method is not yet sophisticated enough to be applied here for evaluation of e-waste treatment.

Table 6.2 Overview of indicators for evaluating the performance of e-waste treatment

Indicator	Unit	Advantage	Disadvantage
Technical Recovery/capture rate (weight of recovered/captured material versus weight of input material)	%	- Direct indication of recovery or toxic control capability - Easy and straightforward computation	- The aggregated score for all materials does not always demonstrate actual performance - Influenced by both the quality of materials input and treatment process itself, more in-depth analysis is needed
Economic Profit per input product	€/kg	- Helps to identify the most cost-effective process or system	- Market price is dynamic and needs regular updating
Environmental Environmental impact indicator	environmental impact indicator/kg	- Indicates the environmental impact of treatment system	- High data demand of treatment processes - Complicated modeling and calculation of impact assessment
Synthesis Eco-efficiency Eco-value	€/kg €	- Incorporates both environmental and economic considerations - Provides a balanced view of systematic performance	High data demand for economic and environmental analyses of observed processes or systems

To summarize, an indicator is applied to suggest the level of "sophistication" of a treatment process or system. It can relate to a single criterion such as technical performance, environmental impact or the economy; composite indicators express more than one criterion. The following sections will apply these indicators to assess the technical, environmental and economic performances of various treatment scenarios for e-waste. A detailed analysis of a processing sequence and the stages of an e-waste treatment's technical system are introduced. This will help to explain the formation of various recycling scenarios, as well as their similarities and differences in the technical setting.

6.2 Structure of e-waste treatment chain

Electrical and electronic products contain various metals (as well as metal alloys and compounds), plastics, glass, many other materials and even composite materials. E-waste treatment has two objectives, material recycling and detoxification, so it requires connected steps to liberate target materials and separately refine and treat them. These interconnected processes construct an entire treatment chain, which can be divided into the following stages (Schluep *et al.*, 2009):

Stage 1, **Toxic removal** is an essential step, primarily for single components containing hazardous substances (i.e. batteries, mercury lamps, CRT glass and PWBs, as listed in Annex II

of EU WEEE Directive 2002/96/EC and also the last column of Table 4.5 in Chapter 4). Removal guarantees that these parts are segregated early in treatment, which eliminates dispersion, contamination and loss of target materials into undesirable streams (Salhofer and Tesar, 2011).

***Stage 2*, Pre-processing** applies physical techniques to liberate and upgrade desirable materials (from feedstock from stage 1) into relatively homogeneous streams, which are used as inputs for end-processing in stage 3. The most common automatic pre-processing method is mechanical size reduction and sequential sorting. Human labor is widely used for non-destructive disassembly. Manual dismantling achieves higher liberation rates than mechanical dismantling, and it does not break the original form of components and materials, which makes sorting easier and improves re-usability. Manual dismantling and mechanical separation can be combined to achieve the most cost-effective liberation results given economic conditions.

***Stage 3*, End-processing** is the final stage of refining and detoxifying various outputs liberated from stage 2 through chemical, thermal and metallurgical processes, which upgrade materials and reduce impurities as well as prepare them for final disposal. A wide spectrum of materials contained in e-waste demands diverse and separate treatment processes. Considerable investment is required in advanced technologies (especially metallurgical recovery technologies) to reach high recovery rates and low environmental impacts. For instance, a typical aluminum smelter in Europe requires a minimum input of 50,000 tons of aluminum scrap per year to run a plant, and the investment cost is approximately €25 million (Schluep *et al.*, 2009).Only a few companies in the world are equipped with technical know-how, sophisticated flow sheets and sufficient economies of scale which fulfill the technical and environmental requirements to refine precious metals. However, confined by limited investments and technology, the quality of end-processing in many developing countries is relatively low. "Backyard recycling" is common, characterized by primitive recycling techniques with low material recovery rates and significant emissions (Puckett *et al.*, 2002). Workplace protections and environmental, health and safety (EHS) measures are often lacking, which cause substantial damage to the health of local workers (Wong *et al.*, 2007).

In each stage of the treatment chain, alternative processes, equipment and materials are available. Various treatment scenarios can be configured by interlinking different pre-processing and end-processing options, which consequently produce distinct results. Figure 6.1 lists a selection of common treatment scenarios that result from the combination of different options in each treatment stage. Landfills and municipal incinerators are scenarios that do not include toxic removal, pre-processing or end-processing to separate toxic substances and recycle materials. They are not regarded as suitable treatment options for most products due to the absence of toxic control and material recovery. In many industrialized regions, mechanical separation is the dominant technique for e-waste pre-processing due to high labor costs; high-tech refineries for plastics and metals are available. In most emerging economies, manual dismantling for pre-processing is common due to low labor costs and good material outputs; low-tech means for recovering materials are used due to the lack of investments and technology. But this geographic distribution of treatment methods is not completely definitive, because e-waste and its fractions are highly mobile via international shipping and trading (Shinkuma and Nguyen Thi Minh, 2009; Lepawsky and McNabb, 2010). Shredded fractions from the industrial regions are sometimes

further sorted and treated in developing countries. Other times, disassemblies from developing countries are treated in global state-of-the-art refineries.
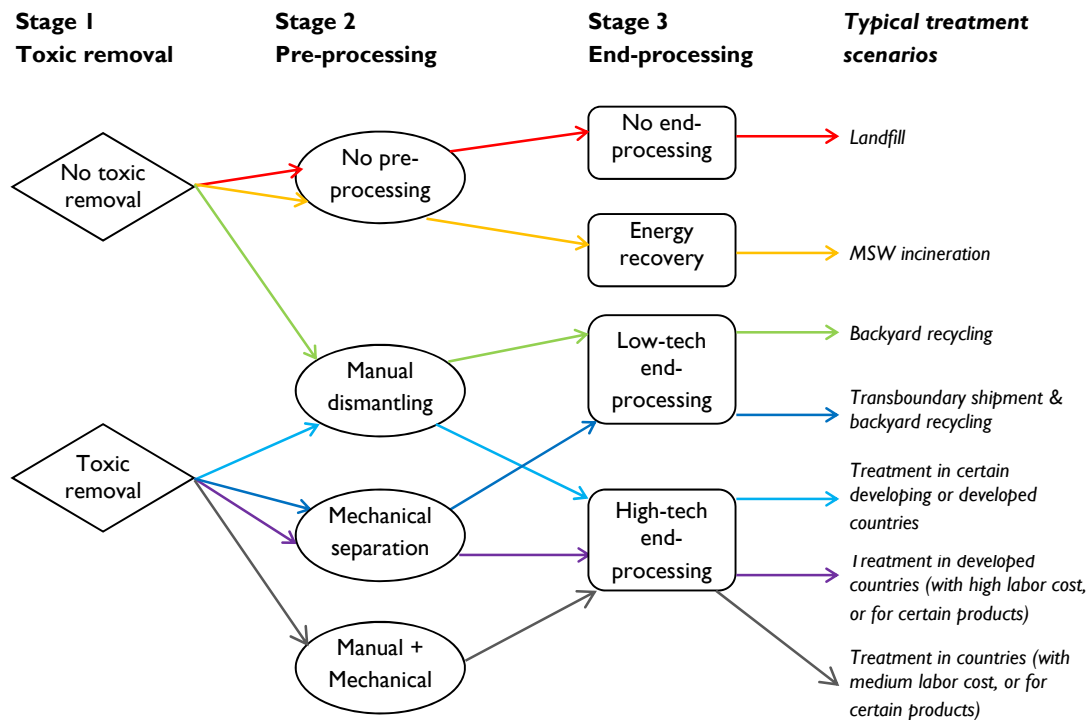

Figure 6.1 Typical treatment scenarios comprised from different options in each treatment stage

The figure shows how alternative techniques from each treatment stage are independently operated but interlinked. The outcome from each stage will influence the treatment outcome for the remaining stage(s). For instance, if components containing materials with toxic potential are not removed in the first stage, these toxic materials will further disperse in the following treatment stages. The introduced impurities demand extra refining or cleaning, and they are difficult to totally cleanse due to the limitations of thermodynamics or costs. A typical example is the mercury-containing lamps in LCD TVs or monitors. If these lamps are not safely removed in the first treatment stage, the embedded mercury will be directly released into the environment if the lamps are broken during the following treatment stages. Furthermore, if a product is shredded into a mixture of heterogeneous materials, effective treatment requires separation technologies to single out the target materials and refining to upgrade the secondary materials. Throughout this process, interrupting materials present in the mixture will compromise the refining process for the target materials (Castro, 2005). As a result, the efficiency of material recycling will be compromised.

The following sections will further explore the treatment techniques and evaluation methods in the pre-processing and end-processing stages. Overall performance of a treatment chain, which links options from each stage, is analyzed.

6.3 Effectiveness in the pre-processing stage

Materials in EEE are joined together to form electronic components, circuits and housings to fulfill certain product functions. The objective of pre-processing is to maximize the separation of mixed materials into homogeneous streams while minimizing the creation of unrecoverable impurities and residues. Recycling is primarily driven by the value of the recovered materials; economic incentives compel recyclers to separate materials into purer fractions. When materials in products are attached by temporary joiners such as screws and bolts, it is relatively easy to detach products into their constituent parts through manual dismantling or shredding. However, it is very difficult to reach perfect separation when materials are functionally assembled or fabricated with permanent joiners (such as adhesive materials, coatings, solders and welds). Examples of such complicated components and subassemblies are Cathode Ray Tube (CRT) glass, printed circuit boards, hard discs and batteries. These components are technically difficult or too costly to separate to release their original materials during pre-processing.

Manual dismantling and sorting is the simplest and most direct pre-processing technique. It only requires normal tools and working tables, and it is achievable without expensive investments and advanced technical know-how. Manual dismantling is very effective for separating components and materials attached with screws. Moreover, human disassembly sorting is very effective due to the unaltered size of materials and strong discerning abilities of workers. Dismantling small and medium-sized equipment is more convenient than dismantling large appliances due to the difficulty associated with moving and manipulating these items on normal working tables. Pre-processing large volumes of e-waste by dismantling involves intensive manual work and demands substantial labor. It is only justified if labor costs do not surpass revenues from the output materials. One negative effect is workers' direct contact with e-waste, which increases the chances of coming into contact with embedded materials with high potentials for toxicity. Environmental, health and safety measure are very important in preventing workplace accidents and reducing exposure to toxics. This issue will be further addressed in Chapter 7.

In addition to manual dismantling, mechanical size reduction and sequential sorting is a common method for pre-processing e-waste. With this method, waste products are usually broken (or shredded, cut or crushed) into small pieces in order to separate the materials. Then a series of sorting processes further separate these mixed materials into clean fractions (Froelich *et al.*, 2007). During this process, materials can be sorted according to their physical properties such as color, size, density, magnetism, electrical conductivity and transparency. Typical sorting techniques include: air or water sink-float separation (this separates plastics from metals), optical sensor separation (this separates different plastics), x-ray sensor separation (this separates glass from lead glass), magnetic separation (this separates iron from other metals) and eddy current separation (this separates different metals).

After mechanical separation, it is inevitable that a certain amount of impurities will remain due to imperfect liberation or separation. This may be caused by the randomness of particle distribution after size reduction (Reuter *et al.*, 2013). Furthermore, not all materials can be thoroughly detached from each other during shredding if they are attached with permanent joiners. For instance, after the size reduction of circuit boards, components might still contain lead solders due to the strong attachment of these connections. For maximum separation of materials, e-waste should be shredded into small and even fine particles, generally to sizes below 5-10 mm (Cui and Forssberg, 2003). Materials in the form of fine particles tend to mix more easily than materials in larger forms. Complete separation creates barriers for mechanical sorting processes. Two shredding tests of IT products have shown that purely mechanical pre-processing leads to major losses of precious metals in dust and ferrous fractions (Chancerel *et al.*, 2009; Meskers *et al.*, 2009). The degree of liberation of the target materials will influence their recyclability in the refining or upgrading phase, as determined by the amount of impurities.

Both dismantling and mechanical separation have advantages and limitations. Manual dismantling avoids reducing the size of materials during product disassembly, and it is therefore much easier to sort according to material types in their original size. Human workers are probably the most sophisticated sorters due to their learning capabilities, advanced visual sense and experience (Reuter *et al.*, 2013). Manual dismantling has the advantages of low investment costs, high yields of material liberation and creating job opportunities. However, its applicability is limited by high labor costs. Because of this, semi- or fully mechanical treatment of products and certain fractions has become the better option in most developed countries, both from an economic and an eco-efficiency standpoint (Gmünder, 2007). Although lower liberation efficiency is attained, the high labor costs of manual dismantling are offset by lower operational costs. Mechanical separation applies automatic technologies that can achieve faster separation for large amounts of e-waste. Gas emissions can be filtered to minimize the environmental impacts to workers and the environment. But mechanical separation has limited applicability in developing countries. It requires advanced technology and facilities, high energy consumption, high investment costs and it has lower material liberation yields than manual dismantling and sorting. In practice, manual dismantling and mechanical shredding can be combined to reach the optimal balance between liberation and economic costs. For instance, products can first be manually dismantled and then certain components can be shredded because further dismantling is difficult or time consuming.

Combining the classification results from Chapter 4 and features from different pre-processing methods, optimal treatment options for different types of e-waste are listed in Table 6.1. The table shows that manual dismantling is preferable for medium and high-value products (such as IT products) due to high returns from these materials. Manual dismantling is less effective for large household equipment due to the difficulty in manipulating them on normal working tables. But innovations in dismantling equipment and tools can help to improve dismantling efficiencies. Manual dismantling is also inefficient for small household appliances due to their small sizes and large quantities. For products containing materials with substantial potentials for toxicity, manual dismantling should be performed with very strict health and safety protections. Such measures

include strong ventilation, avoiding direct contact with sensitive materials or even dismantling in an enclosed environment.

For mechanical separation, it is faster to treat bulky products or large numbers of products within a short time. It also has the advantage of treating products containing materials with high toxic potentials by reducing the need for workers. Pre-processing such equipment usually requires enclosed shredding (for items such as cooling and freezing appliances, mercury-containing lamps and lead glass). To avoid the dispersion of target materials during mechanical separation, manual dismantling can still serve as a very effective approach for singling out relevant components and materials prior to shredding.

Table 6.3 Optimal pre-processing methods for different e-waste categories

Product category	Pros and cons of pre-processing techniques		Toxic control measures
	Manual	Mechanical	
Cooling and freezing equipment	Not preferred due to large size and easy leaking of refrigerants and coolants	Preferable for achieving high treatment efficiency	- Toxic removal of oil and compressors; degassing of circuits before pre-processing - Enclosed shredding with CFC capturing
Screens and monitors	Suitable for dismantling housings and sorting of non-hazardous materials	Suitable for sorting lead and non-lead glass by density, UV light or X-Ray	- Ventilation for dismantling activities - Enclosed shredding and sorting of mercury; Separate and capture mercury, phosphor powder and lead glass
Large household appliances	Time consuming due to large sizes and heavy weights	Efficient but energy intensive	-Toxic removal of ink cartridges, PCB-containing capacitors, mercury-containing switchers, circuit boards and batteries - Dust control in facilities with mechanical separation
Small household appliances	Time consuming due to small sizes and large numbers	Efficient but energy intensive	
Medium IT	Preferable due to fine output of high-grade materials	Efficient but critical materials may not be perfectly liberated	
Small IT	Preferable due to fine output of high-grade materials Time consuming due to small sizes and large numbers	Efficient but critical materials may not be perfectly liberated	
Mercury lamps	Not preferable due to workplace exposure to mercury	Preferable for achieving high treatment efficiency	Enclosed treatment with mercury capture
Non-mercury lamps	Not preferable due to difficulty in dismantling lamps	Preferable for achieving high treatment efficiency	

The performance of pre-processing is determined by product properties and the arrangements of pre-processing sequences. The efficiency of manual dismantling can be measured by total dismantling time and the quality of dismantled fractions. Overall, the market value from the dismantled fractions should exceed total labor costs; this ensures a profitable system. Evaluation of mechanical separation is more complicated and its results are less predictable. The performance of mechanical separation is influenced by multiple factors such as composition of input materials (mixed or homogeneous waste), moisture of feed materials, the size of shredding and the efficiency of specific sorting techniques (Hou *et al.*, 2010). Analysis of the influential technical factors in mechanical separation has been carried out in several studies (Veit *et al.*, 2006; van Schaik and Reuter, 2010; Guo *et al.*, 2011). Material Flow Analysis of the recycling process is an effective tool for mapping system inflows and outflows. It has the advantage of examining treatment quality without diving into the technical details. This helps non-experts understand the outcome of the mechanical process and make decisions.

For both pre-processing methods, technical performance can be measured by recovery rate per material, which is calculated by:

$$y_i = Out_i \, / \, In_i \qquad (6.1)$$

Where y_i is the recovery rate of material i during the pre-processing phase, In_i is the total weight of material i contained in input stream and Out_i is the weight of material i in the output stream that can feasibly be recovered or upgraded. For instance, after shredding circuit boards, gold losses in the dust cannot be counted as Out_{Au} if the dust is not collected and further refined for gold.

The overall recovery rate Y in a product is expressed by Eq.(6.2), where there are n types of recyclable materials in the product.

$$Y = \sum_{i=1}^{n} y_i \qquad (6.2)$$

As discussed before, recovery rate is only indicative for a specific material, and the overall recovery rate does not imply the priority of materials in pre-processing. Environmental and economic metrics can provide the extra information. As the major concern is the economic trade-offs between manual and mechanical work, the economic calculation provides the most direct answer. Additionally, the environmental impact of using human labor is not reflected in the current environmental assessment methods. Therefore, cost accounting is an effective and sufficient tool for evaluating pre-processing techniques. The overall economic performance of a pre-processing process is expressed by:

$$P = RV_{total} - C_{total} \qquad (6.3)$$

$$RV_{total} = \sum_{i=1}^{n} m_i \cdot p_i \qquad (6.4)$$

$$C_{total} = C_{fix} + C_{va.} = C_{overhead} + C_{facility} + C_{energy} + C_{labour} \qquad (6.5)$$

In these formulas, RV stands for the revenues from pre-processing; C is the cost related to the specific activity or item; m_i is the weight of liberated fraction i and p_i is the unit price of fraction i. The total cost can be broken down into fixed costs and variable costs. Fixed costs are the expenses that are not subject to the volume of e-waste that is treated, such as building and construction costs, machinery costs, etc. Variable cost is dependent on the quantity of treated e-waste, such as labor and energy costs. The formulas provided are simple representations of process-based cost accounting, and real-world calculations need to be associated with the actual process and facility.

To summarize, selecting an optimal pre-processing technique is mainly based on technical and economic efficiencies. Efficiency is driven by the market value of liberated materials and limited by labor and equipment costs. No matter which pre-processing method is selected, it is always necessary to balance manual and mechanical approaches to attain the highest efficiency. The following section will discuss refining and upgrading liberated fractions from the pre-processing stage.

6.4 Effectiveness in the end-processing stage

End-processing is the final step in the treatment chain, in which liberated material and component fractions are refined and upgraded into useful materials or products. Compared to product-oriented pre-processing technologies, end-processing is specified towards each recyclable material or component. Each target material has a characteristic set of technologies that can be used to reach critical efficiency and environmental performance during recovery. These technologies usually involve metallurgical, thermal and chemical processes to reduce impurities and refine materials. There is a high demand on both equipment and technologies in professional refinery facilities. Refineries require both investment and economies of scale to justify continuing operations, with consideration given to efficiency, safety and the environment. Most materials liberated from e-waste are not exclusive, and they are commonly seen in other waste streams. For instance, ferrous and non-ferrous metals, various plastics, glass and batteries often appear in other secondary material streams with household and industrial wastes. This implies that refineries do not have to be established to exclusively process these e-waste fractions. Combining with existing trading networks to process similar material streams can help identify proper outlets for liberated materials. This will result in a shared workload between refinery facilities and the relevant industries, and save substantial costs from the construction of new facilities. At the same time, some components or fractions from e-waste are unique, which distinguishes them from conventional waste streams (such as circuit boards, CRT glass, chips, capacitors, etc.).

Some components and materials are present exclusively in e-waste such as printed circuit boards and their components (such as capacitors, resistors, ICs, CPUs, etc.), CRT lead-glass, plastics with flame retardants, etc. Compared with known secondary waste streams, the liberated fractions in e-waste may be present in different forms or they may be highly integrated with other materials. This makes it difficult to treat them in existing facilities, due to the

complex nature of the feed material. Specialized technologies, or at least technical adaptations of available processes, are necessary to handle such emerging fractions and to reach the most efficient technical, environmental or economic practices. For instance, in order to recycle various metals in circuit boards, furnaces or smelters are needed to separate metals, as well as a sequence of hydrometallurgical and electrometallurgical processes, which further recover metals. Furthermore, extensive off-gas cleaning systems need to be installed to prevent the release of VOCs, dioxins and acidic gases into the environment (Schluep *et al.*, 2009). Such sophisticated processes rely greatly on substantial capital and intellectual input, as well as advanced technologies and experienced management. There are only a few companies in the world equipped with the technical know-how, advanced treatment processes and sufficient economies of scale (e.g. Aurubis AG in Germany, Boliden in Sweden, DOWA in Japan, Umicore in Belgium and Glencore Xstrata in Canada) to fulfill such technical and environmental requirements.

But in many developing countries it is far from realistic to construct and operate such high-tech facilities. Informal recycling of e-waste is prevalent in many of these countries, which operate outside of official institutional, regulatory and administrative structures. Informal recyclers generally use substandard processes and lack the appropriate facilities to safeguard human health and the environment. Typical practices include acid stripping of printed wiring boards, de-soldering of chips by heated stoves, using cupola furnaces for metal recovery and dumping unwanted residuals such as CRT glass, polychlorinated biphenyl (PCB) liquid and chlorofluorocarbon (CFC) liquid, among others, directly onto the soil or into the air and water sources. Shredding and low-temperature plastic melting are used to recover materials. As a result, backyard workers and nearby residents are exposed to high levels of dioxins, heavy metals, airborne ash and dust (Sepúlveda *et al.*, 2010). Through onsite investigations, toxicity and pathology analyses and other methods, these studies have clearly demonstrated the environmental and health damages caused by improper recycling of e-waste (Liu *et al.*, 2009; Gao *et al.*, 2011; Leung *et al.*, 2011; Luo *et al.*, 2011).

As the example in Figure 6.2 demonstrates, there is no correlation between the recovery rate of a material and its actual impact. A high recovery rate might come at the cost of high investments or even substantial emissions. Given this consideration, cost and environmental accounting are essential for evaluating the impacts of refining and recycling. Due to the complexities and various uses of distinct materials, cost and environmental accounting of end-processing treatment is less direct. For common materials, few alternatives are available, and the main interest lies in comparing alternative refinery processes for the same material type.

To conclude, refinery upgrades for treating liberated e-waste fractions have to be pragmatic. By beginning treatment work with technologies in existing facilities, refineries will avoid excessive investments in brand-new infrastructure. Furthermore, it is important to have a clear agenda for improving end-processing facilities step by step, with the input of proper investments and technological know-how. This can gradually develop emerging end-processing industries into a high-tech and mature state.

6.5 Overall effectiveness of a treatment chain

The previous sections demonstrate that pre-processing and end-processing are distinct from each other, both in treatment objective and in technical settings. Pre-processing separates and liberates materials from the compounds in e-waste. It produces secondary materials for end-processing, further refining and treatment. In this way, the grade and quality of the liberated materials from pre-processing directly influences refining efficiency. For instance, too much aluminum in copper fractions will greatly increase the burden of cleaning these fractions in the copper smelter. Losses of target materials in the pre-processing phase are non-recoverable; it is best to produce target materials with fewer impurities for the end-processing stage.

To calculate the overall recovery efficiency of a treatment system, all treatment stages should be considered collectively. Toxic removal and pre-processing are the preparation stages, which mainly serve to separate materials. Efficiency during these two stages will determine the percentage of material in e-waste that enters the final refining or treatment stage. By multiplying this liberation efficiency with the refinery efficiency from the end-processing, the overall recovery rate of a system can be computed as shown in the following formula:

$$Y_{Chain} = (y_{TR} + y_{PRE}) \cdot y_{END}$$

(6.6)

In this formula, Y_{Chain} is the overall recovery or yield rate of a treatment chain for a specific material; y_{TR} is the percentage of material that is removed during toxic removal, which is eventually treated in end-processing; y_{PRE} is the liberation or separation efficiency of materials, as achieved in pre-processing; and y_{END} is the recovery or refinery rate of materials during end-processing.

To further understand the treatment efficiencies from different scenarios, Figure 6.2 illustrates the loss of gold in six treatment scenarios for a computer. Gold is used to track the performances of liberation and refining because it exists in trace concentrations but can contribute 12 to 65 percent of the total value in some e-waste samples (Cui and Zhang, 2008). These scenarios are theoretically constructed based on the dismantling sessions, shredding sampling and investigation of refinery facilities in different studies (Keller, 2006; Gmünder, 2007; Huisman et al., 2008; Rochat et al., 2008; Meskers et al., 2009; Chancerel et al., 2009).

The first two scenarios represent two pre-processing options in Western Europe, in which the disassembly of motherboards and contacts yields 80 percent of the gold content, while further dismantling of the power supply and drives can yield 17 percent extra. Mechanical treatment can only yield a 70 percent recovery rate due to losses to dust and ferrous fractions. This implies that separation efficiency can improve as a function of dismantling depth and can be higher than mechanical methods. Scenario 3 investigates an optimized shredding configuration tailored to process homogeneous ICT equipment and maximize the capture of precious metal fractions (including the diluted mixture with other materials). Scenario 4 examines general shredding settings for mixed e-waste feeds. Reducing the complexity of material feeds fed into the shredding process may also increase the recovery rate of gold. These two scenarios show that different mechanical configurations can lead to liberation results varying from just 11 percent to

74 percent gold losses. This implies that there are differentiations between advanced pre-processing technologies and, logically, technical settings need to be adjusted to match the specific waste stream being processed. Another significant loss of gold appears in the informal sector in India (Scenario 6). Exactly half, 50 percent, or as much as 84 percent of the gold contained in circuit boards can be lost during pre-processing (Keller, 2006). The observation indicates that mistakes made while visually checking for gold-containing components will impact overall treatment efficiencies. Also, during the process of shredding, shearing and chiseling, dust containing gold is produced but not collected. All of this data suggests careful evaluation of the materials, gains and losses during pre-processing can help to explain the technical limits of each treatment alternative. Operational errors can be identified through this analytical process as well.

During the end-processing stage (scenarios 3, 5 and 6), gold recovery from an integrated smelter is more than 95 percent, surpassing the example of the copper smelter (50 percent) and informal cyanide leaching (36 percent). Generally speaking, informal cyanide leaching has a gold recovery rate between 36 percent and 60 percent, depending on the accuracy of sampling and measurements (Keller, 2006). Gold is mainly lost in the unrecovered components and waste liquid, due to imperfect leaching of surface gold. State-of-the-art refinery technologies are very difficult to establish in developing countries, as they are confined by their economic capabilities. For example, the integrated Umicore Precious Metal Refining smelter-refinery in Belgium has the capacity to produce 2,400 tons of silver, 100 tons of gold, 25 tons of palladium and 25 tons of platinum per year. But the overall investment cost for metallurgical processing was more than €500 million. Without such high-tech facilities available, easily operated leaching processes are likely to continue, which can operate on very small scales and are generally affordable. High recovery rates of gold and environmental quality are compromised by meager incomes in this process.

To draw a conclusion from the analysis so far, current treatment practices are very diverse, with many alternatives in the three stages of toxic removal, pre-processing and end-processing. When applying the gold data in Eq.(6.6), the scenario with the highest recovery rate for the whole chain is scenario 6. In this scenario, a 100 percent recovery rate is achieved in the first stage, wherein circuit boards are fully removed from computers, which avoids any gold losses in stage 2, pre-processing. Next the gold-containing circuit boards go directly to the integrated smelter for recovery. The most efficient pre-processing and end-processing methods only exist in separate worlds, which is a scenario that has proved difficult to align. This proves yet again that technical performance is determined by the configuration of processes but confined by economic rules and environmental standards.

The example of gold in this section demonstrates that there are a great variety of treatment options both for pre-processing and end-processing e-waste. The selection of treatment techniques will have a direct influence on the final recovery rate of materials, as well as environmental and economic performance. For pre-processing, there is a balance to be made between manual dismantling and mechanical separation, as determined by different countries' contexts and as described in Section 6.2.1. For end-processing, there is a balance to be made between high-tech metallurgical processes and low-tech acid-leaching, which is restricted by investment and available technologies (Section 6.2.2). But there are many materials contained in

e-waste besides gold, and there are also more treatment options than the examples show. It is important to note that the recovery rate of gold is not the only indicator for analyzing the treatment capabilities of a system. Both environmental and economic metrics should be introduced, while giving consideration to other materials.
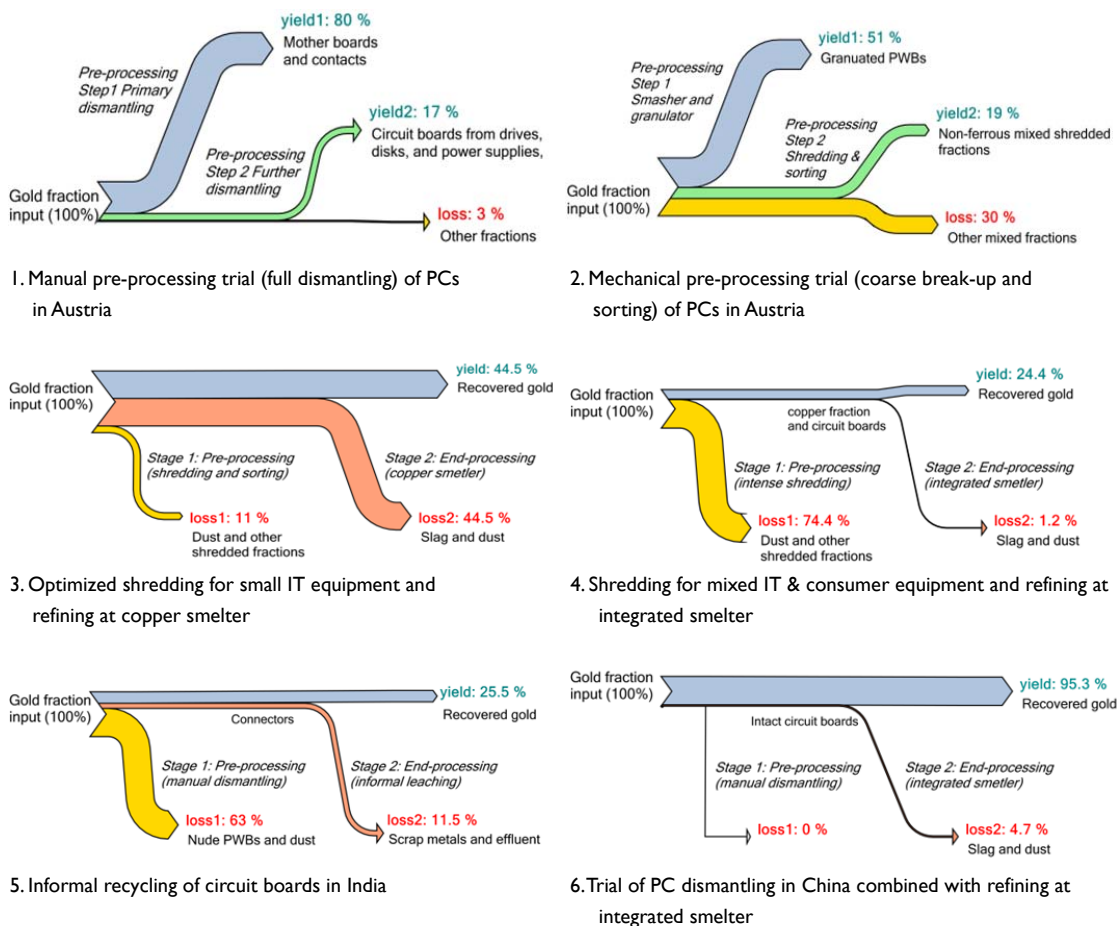

Figure 6.2 Gold losses and yields in six desktop computer recycling scenarios

6.6 Diversity of end-of-life scenarios: case study in the Netherlands

To further illustrate the diversity of various end-of-life scenarios, a case study in the Netherlands is discussed to show the destinations and quantities of e-waste flows. This case is a follow-up to the national study presented in Chapter 5, extending the analysis of national e-waste generation to encompass different collection and treatment channels.

By applying the classification method in Chapter 4 and estimation model in Chapter 5, product sales and quantity of e-waste generated can be calculated for all seven categories. The remaining questions are: how much of the generated e-waste is collected and treated on a national level via compliance schemes versus complementary recycling channels (reported by national

recyclers to local or provincial authorities), and how many other complementary streams are there, such as small door-to-door trade, secondhand shops, e-waste in household waste and exports (illegal).

In order to obtain the information for various end-of-life channels, extensive investigations, interviews and surveys were carried out in 2011. Various disposal channels such as municipal collection points (or container parks) and retail collection points were contacted and queried for collection figures. Data from take-back and treatment systems was obtained directly from the two national compliance schemes, including the quantities of EEE formally collected and treated by contracted collectors and recyclers. E-waste discarded in normal (household) waste bins goes to an incineration plant for treatment (together with other municipal solid wastes) in the Netherlands. Sampling data from incineration plants was collected for the content of e-waste in the overall stream of municipal solid waste.

Data on complementary recycling flows was obtained through an extended market survey of MRF (Dutch Metal Recycling Federation) and EERA (European Electronics Recyclers Association) members on national and regional levels. The recyclers interviewed included all national recyclers, the most relevant ones on a regional level and some foreign recyclers, to validate the data. National recyclers in the Netherlands receive sorted appliances, "mono-flows" and "pre-shredder" materials. Mono-flows are sorted materials that consist of one or two categories of e-waste (e.g. professional appliances, IT desktops and cooling and freezing appliances). The "pre-shredder" materials are bought from regional scrap metal processors and consist of metal scraps mixed with a certain percentage of e-waste (parts from professional and large household appliances, small household appliances, central heating units and IT appliances). National recyclers also import e-waste for recycling in the Netherlands. E-waste from compliance schemes is also processed by the national recyclers, but it is kept strictly separate from the analysis of complementary flows.

Figure 6.3 presents the mapping result of e-waste flows in the Netherlands. It is calculated that 26.5 kg per habitant (kg/inh.) or equivalently 440 kilo tons (kton) of new EEE was put on the market in 2010, and around 23.7 kg/inh. (392 kton) of used EEE and e-waste was generated by households and businesses. Within this amount of waste, export of used EEE (as whole appliances for re-use) was 2.7 kg/inh. (44kton). As a result, the amount of waste products ready for waste management in the country was 21.0 kg/inh. (349 kton).

After collection through various channels, around 7.6 kg/inh. of e-waste was reported on a national level as collected and treated by Wecycle and ICT~Milieu, the two main organizations that enforce producer e-waste responsibility in the Netherlands. The formally treated e-waste was 36 percent of the total e-waste generated in 2010, which means 64 percent of e-waste was still handled by other channels or recyclers. Parallel to the quantity treated by compliance schemes, the total complementary recycling stream was 6.6 kg/inh. (110 kton). From the complementary recycling stream, 60 percent was a so-called mono-flow and the remaining amount was present in a mixed stream with other metals and a small percentage of WEEE (derived parts).

A total 2.3 kg/inh., mainly small household appliances, ended up in household dust bins as municipal waste (38 kton). The remaining unidentified stream was 0.9 kg/inh., which can be regarded as the maximum potential amount for illegal export.
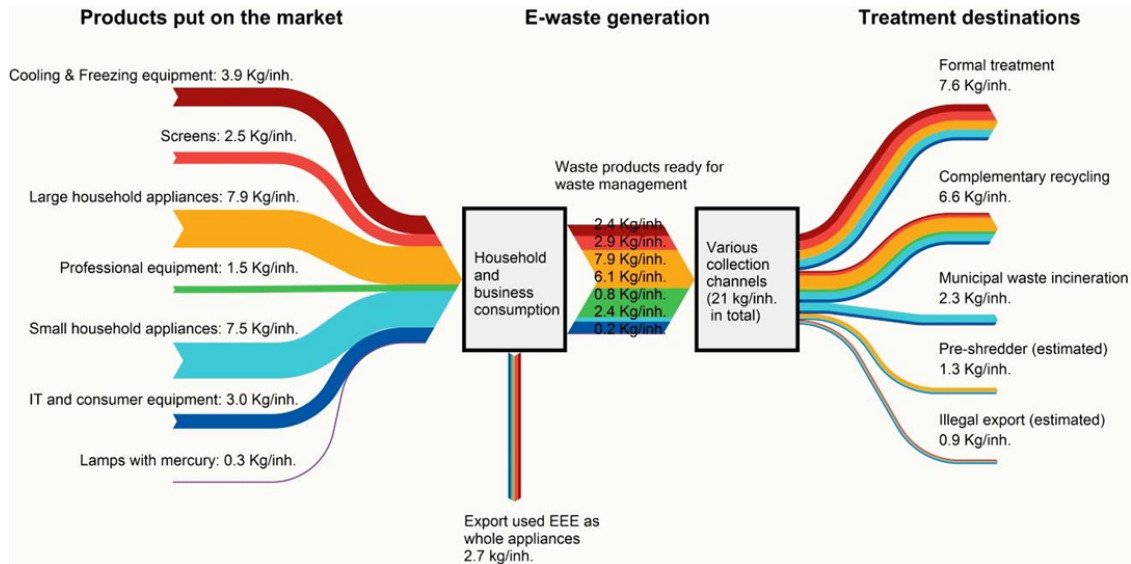

Figure 6.3 E-waste flows in the Netherlands (2010 level)

The case study demonstrates the diversity of treatment scenarios in Dutch society. Determined by the configurations of take-back systems and existing trading mechanisms, e-waste is collected and treated both by compliance schemes contractors and scrap dealers/metal recyclers. For equipment with a high potential to impact the environment and relatively low economic value (cooling and freezing equipment, screens and lamps with mercury), the collection rate between the two take-back systems has surpassed 50 percent (of the total generated quantities). Products with relatively high values (large household appliances, IT and consumer equipment) are popular categories for collection and they are traded by national scrap dealers who aim to get the best value for base metals and precious metals. There is still a substantial amount of e-waste that enters municipal incineration plants (around 30 percent of the total amount of small household appliances generated). This indicates that the collection rates for different product categories vary significantly among different stakeholders. This disparity is influenced by the properties of waste products (weight, material value and environmental impact) and the different goals of stakeholders.

As discussed in Section 6.5, the treatment efficiencies of different scenarios are distinct, as they are determined by the arrangement of technologies in each treatment stage. For instance, the CFCs in cooling and freezing equipment are captured and treated by compliances scheme contract recyclers (picture A in Figure 6.4). But such actions are not usually taken by scrap metal recyclers and exporters; picture B in Figure 6.4 shows a snapshot of imported

compressors in China, and CFCs are usually released directly into the environment during transport or subjected to substandard treatment in developing countries. Picture C in Figure 6.4 shows pre-shredder materials in which e-waste is mixed with other metal scrap. In picture D appliances are traded and treated by national metal recyclers. These treatment scenarios lead to different material recovery results, environmental impacts and economic gains. It is useful to apply such national studies to map the streams of different e-waste categories, their distribution among stakeholders and channels and the mechanisms behind them (such as trading, legal obligations and environmental awareness). Combined with the assessments of treatment quality in each scenario, flow mapping can help to estimate material yields and the associated impact, both for a specific waste stream and the overall e-waste stream.

The formation and status-quo of e-waste streams in the Netherlands proves again that socioeconomic factors shape the settings and configurations of take-back systems. Market value of various metals is the main incentive for scrap dealers and recyclers to collect and recycle products with high metal concentrations. Driven by European legislation, the two compliance schemes treat the product categories with high potentials for environmental impact. Due to the presence of global trading networks, pre-shredder materials and components from pre-processing facilities in the Netherlands can be sold to developing countries for further hand-sorting, dismantling and refining. Because of low labor costs and the demand for materials, deep-level dismantling of imported e-waste and its fractions is still profitable. As a result, the national flows of e-waste in the Netherlands are geographically extended to the global scale. The analysis of treatment effectiveness in one country needs to consider such a broad scope.

A. State-of-the-art refrigerator recycling in Coolrec in the Netherlands (Leegte, 2011)

B. Imported compressors from refrigerators found in a scrap yard in China

C. Pre-shredder materials in the Netherlands

D. Mono-flow products collected by metal recyclers in the Netherlands

Figure 6.4 Examples of various collection and treatment scenarios

6.7 Conclusions

This chapter introduces the technical system of e-waste treatment, as well as the external societal system that influences the implementation of technologies. Alternative techniques in three stages of a treatment chain are analyzed in detail: toxic removal, pre-processing and end-processing. Combining the theoretical analysis with project development, this analysis finds that realizing maximum recovery rates for all materials is very complicated in any country or context.

The assessment in this chapter shows that high liberation rates in pre-processing and high refinery efficiencies in end-processing are indispensable for achieving maximum resource efficiency. This is considered from a purely technical perspective of the treatment chain. Consequently, the best technical solution for e-waste treatment demands substantial support in the form of investments, machinery and infrastructure, technological know-how and innovation. But implementing the best technical solution is confined by the reality of socioeconomic conditions. A compromise needs to be reached between technology and the underlying societal factors when defining the optimal treatment technology for a specific region or country. The "matching" solution is not necessarily the best technical solution, although it will fit better and be more compatible with the local situation.

Analyzing the technical sub-system of e-waste treatment is a necessity, but it is not sufficient for determining optimal technology for a specific country or society. The next section will give a good idea of how a pragmatic and intelligent approach can result in an eco-efficient treatment scenario for take-back and treatment systems. It explores the possibility of implementing the best technical treatment solution in an extended geographical range.

6.8 References

Castro, B. (2005). Design for resource efficiency. PhD degree PhD thesis, TU Delft.

Castro, M. B. G., J. A. M. Remmerswaal, J. C. Brezet and M. A. Reuter (2007). "Exergy losses during recycling and the resource efficiency of product systems." Resources, Conservation and Recycling **52**(2): 219-233.

Chancerel, P., C. E. M. Meskers, C. Hagelüken and V. S. Rotter (2009). "Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment." Journal of Industrial Ecology **13**(5): 791-810.

Cui, J. and E. Forssberg (2003). "Mechanical recycling of waste electric and electronic equipment: a review." Journal of Hazardous Materials **99**(3): 243-263.

Cui, J. and L. Zhang (2008). "Metallurgical recovery of metals from electronic waste: a review." Journal of Hazardous Materials **158**: 228–256.

Froelich, D., E. Maris, N. Haoues, L. Chemineau, H. Renard, F. Abraham and R. Lassartesses (2007). "State of the art of plastic sorting and recycling: Feedback to vehicle design." Minerals Engineering **20**(9): 902-912.

Gao, S., J. Hong, Z. Yu, J. Wang, G. Yang, G. Sheng and J. Fu (2011). "Polybrominated diphenyl ethers in surface soils from e-waste recycling areas and industrial areas in South China: Concentration levels, congener profile, and inventory." Environ Toxicol Chem **30**(12): 2688-2696.

Gmünder, S. (2007). Recycling - from waste to resource: assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Master thesis, Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Testing and Research (EMPA).

Guinée, J. B., M. Gorrée and R. Heijungs (2002). Handbook on life cycle assessment. Operational guide to the ISO standards. Dordrecht, the Netherlands, Kluwer Academic Publishers.

Guo, C., H. Wang, W. Liang, J. Fu and X. Yi (2011). "Liberation characteristic and physical separation of printed circuit board (PCB)." Waste Management **31**(9–10): 2161-2166.

Hou, S., J. Wu, Y. Qin and Z. Xu (2010). "Electrostatic Separation for Recycling Waste Printed Circuit Board: A Study on External Factor and a Robust Design for Optimization." Environmental Science & Technology **44**(13): 5177-5181.

Huisman, J., F. Magalini, R. Kuehr, C. Maurer, S. Ogilvie, J. Poll, C. Delgado, E. Artim, J. Szlezak and A. Stevels (2008). Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Bonn, Germany, United Nations University.

Keller, M. (2006). Assessment of gold recovery processes in Bangalore, India and evaluation of an alternative recycling path for printed wiring boards, a case study, Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Testing and Research (EMPA), Master thesis.

Leegte, R. (2011). Werkbezoek Coolrec.

Lepawsky, J. and C. McNabb (2010). "Mapping international flows of electronic waste." The Canadian Geographer / Le Géographe canadien **54**(2): 177-195.

Leung, A. O., J. Zheng, C. K. Yu, W. K. Liu, C. K. Wong, Z. Cai and M. H. Wong (2011). "Polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans in surface dust at an E-waste processing site in Southeast China." Environ Sci Technol **45**(13): 5775-5782.

Liu, W. L., C. F. Shen, Z. Zhang and C. B. Zhang (2009). "Distribution of phthalate esters in soil of e-waste recycling sites from Taizhou city in China." Bull Environ Contam Toxicol **82**(6): 665-667.

Luo, C., C. Liu, Y. Wang, X. Liu, F. Li, G. Zhang and X. Li (2011). "Heavy metal contamination in soils and vegetables near an e-waste processing site, South China." J Hazard Mater **186**(1): 481-490.

Meskers, C. E. M., C. Hagelüken, S. Salhofer and M. Spitzbart (2009). Impact of pre-processing routes on precious metal recovery from PCs. Proceedings of European Metallurgical Conference EMC.

Puckett, J., L. Byster, S. Westervelt, R. Gutierrez, S. Davis, A. Hussain and M. Dutta (2002). Exporting harm, the high-tech trashing of Asia. Seattle, USA, The Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC).

Reuter, M. A., C. Hudson, A. van Schaik, K. Heiskanen, C. Meskers and C. Hagelüken (2013). Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Paris, France, United Nations Environment Programme.

Rochat, D., W. Rodrigues and A. Gantenbein (2008). India: Including the existing informal sector in a clean e-waste channel. . Proceedings of the Waste Management Conference 2008. Durban, South Africa.

Salhofer, S. and M. Tesar (2011). "Assessment of removal of components containing hazardous substances from small WEEE in Austria." Journal of Hazardous Materials **186** 1481–1488.

Schluep, M., C. Hagelüken, R. Kuehr, F. Magalini, C. Maurer, C. Meskers, E. Mueller and F. Wang (2009). Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling - from E-waste to resources. Bonn, Germany, United Nations Environment Programme & United Nations University.

Sepúlveda, A., M. Schluep, F. G. Renaud, M. Streicher, R. Kuehr, C. Hagelüken and A. C. Gerecke (2010). "A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India." Environmental Impact Assessment Review 30(1): 28-41.

Shinkuma, T. and H. Nguyen Thi Minh (2009). "The flow of E-waste material in the Asian region and a reconsideration of international trade policies on E-waste." Environmental Impact Assessment Review **29**(1): 25-31.

van Schaik, A. and M. A. Reuter (2010). "Dynamic modelling of E-waste recycling system performance based on product design." Minerals Engineering **23**(3): 192-210.

Veit, H. M., A. M. Bernardes, J. Z. Ferreira, J. A. S. Tenório and C. d. F. Malfatti (2006). "Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy." Journal of Hazardous Materials **137**(3): 1704-1709.

Wang, F., J. Huisman, C. Meskers, M. Schluep, A. Stevels and C. Hagelüken (2012). "The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies." Waste Management **32**: 2134-2146.

Wong, M. H., S. C. Wu, W. J. Deng, X. Z. Yu, Q. Luo, A. O. W. Leung, C. S. C. Wong, W. J. Luksemburg and A. S. Wong (2007). "Export of toxic chemicals – A review of the case of uncontrolled electronic-waste recycling." Environmental Pollution **149**(2): 131-140.

Chapter 7: Achieving a balance between technology and socioeconomic conditions for e-waste treatment

The previous chapter demonstrated that achieving high technical performance for e-waste treatment is difficult due to socioeconomic constraints. This dilemma applies to both developed and developing countries. The main barrier in industrialized countries is high labor cost, which "forced" the treatment industry to move towards mechanization and automation. Mechanical separation imperfectly liberates and separates materials during the pre-processing stage. Emerging economies often face challenges due to the lack of investment, technical know-how, legislation and managerial resources. It is hardly feasible to establish advanced, state-of-the-art refinery infrastructures for various dismantled fractions in these locations. Looking at the prevailing treatment arrangements in both regions, technical systems have adapted their process configurations to better fit with local economies, markets and environments.

The observation made above applies to a specific country or region, and the same local conditions are considered when selecting optimal technologies for all stages of e-waste treatment. This chapter further investigates the influences of socioeconomic conditions on the settings of technical e-waste treatment subsystems. An approach called the "Best-of-2-worlds" (Bo2W) is proposed as a treatment solution for developing countries, which demand easily implemented but economically and environmentally effective e-waste treatment solutions. The basic idea is to divide the best technical solution according to the treatment stages and find the location where the best technical solution matches well with local socio-economic conditions. This will create a potentially flexible and practical treatment solution for e-waste issues in developing countries.

7.1 The "Best-of-2-worlds" approach for e-waste treatment in developing countries

With the goal of integrating the best treatment options from geographically distributed sites, an innovative approach for e-waste treatment in developing countries is proposed. The Bo2W began as a StEP Initiative (Solving the E-waste Problem) and the United Nations University. It seeks a technical and logistical integration of suitable and available technologies in different treatment stages to form a complete recycling chain for all materials. Dividing e-waste treatment processes between developing and industrialized regions offers competitive advantages in terms of environmental impacts and resource recovery efficiency, posing a viable alternative to the current, regionally focused paradigm in developing countries (mostly with low-performing practices).

When applied in developing countries, the Bo2W concept retains manual dismantling because it generates adequate material outputs with low technical requirements. When the critical output fractions are forwarded to global state-of-the-art facilities, overall detoxification and recovery of valuable materials are optimal. Sharing the existing end-processing infrastructures globally among dismantling facilities in developing countries is attractive in terms of economies of scale and avoiding large investments. Several studies (e.g. Gmünder, 2007; Rochat *et al.*, 2008) indicate that this approach can create positive revenues with low environmental impacts. From a social point of view, such a configuration can improve treatment standards in developing countries and limit environmental impacts. The Bo2W concept is a labor-intensive approach that adheres to environmental health and safety standards, preserving abundant jobs for the informal sectors with improved working conditions.

7.2 Validation of Bo2W approach by dismantling trials

A series of dismantling trials between 2006 and 2009 were carried out in which prototypes of dismantling configurations and plants were developed. Various products were dismantled to track dismantling time and mass balances at different disassembly depths.

Disassembled fractions were sent to facilities for chemical analysis. Data was recorded for each treatment scenario, consisting of different pre- and end-processing options. Moreover, technical, environmental and economic performances were compared to identify the advantages and disadvantages of the Bo2W concept.

7.2.1 Comparison of scenarios and evaluation methods

To illustrate the outcomes, two metric tons of obsolete mixed brand desktop computers (excluding monitors) and other types of household equipment were collected and processed. The batch was dismantled by skilled workers in Taizhou, China; details about the settings of the dismantling sessions from this pilot plant can be retrieved from Gmünder (2007) and Wang *et al.* (2008).

A selection of treatment scenarios is shown in Figure 7.1. Component re-use is not considered in this trial. In scenarios 1 through 4, the depth of manual dismantling increases while the level of mechanical separation declines and all liberated fractions are sent to the same end-processing destinations. Scenarios 3 and 4 represent approaches according to the Bo2W concept, which involve manual dismantling and the treatment of PWBs and batteries in state-of-the-art end-processing facilities in another country. Scenario 5 shares the same dismantling depth as scenario 4 but PWBs are treated with a local low-tech leaching process. Scenario 6 is a landfill with leachate control and scenario 7 is municipal waste incineration with energy recovery.

			Waste computer 1000g										
MB 69.2g	Other PWBs 23.8g	Battery 0.5g	Speaker 2.2g	Screws 1.3g	Plastics 57.7g	Case 498.5	Switch 0.8g	Wires 14.6g	Connectors 7.4g	FDD 39.3g	CDD 95.8g	HDD 50.8g	PS 138.1g

Treatment stages / Scenario	1 Direct shredding	2 Toxic removal + Shredding	3 Bo2W: Partial dismantling	4 Bo2W: Complete dismantling	5 Informal recycling	6 Controlled landfill	7 Municipal incineration
Stage 1: Toxic removal	×	√	√	√	√	×	×
Stage 2: Pre-processing							
Manual dismantling	×	×	Main parts	All	All	×	×
Shredding	All	All	FDD, CDD HDD, PS	×	×	×	×
Stage 3: End-processing							
PWBs and batteries	Umicore integrated smelter & refineries				Informal Leaching	×	×
Aluminum, copper iron, steel fractions	Base metal refining, re-melting, recycling					×	×
Plastics	Plastic recycling					×	×

√ Applicable; × Not applicable
Mother board (MB), Floppy disc drive (FDD), Compact disc drive (CDD), Hard disc drive (HDD), Powder supply (PS)

Figure 7.1 Seven treatment scenarios for desktop computers combining different options in each treatment stage

Material Flow Analysis was applied to model and visualize the mass balances of flows and stocks in the sources, pathways and intermediate and final sinks of investigated processes within a defined space and amount of time (Brunner and Rechberger, 2004). Life Cycle Assessment (LCA) was used to evaluate the environmental impacts of the recycling processes (Guinée *et al.*, 2002). Treatment of 1 kg of desktop computer waste was used as the functional unit for comparing all scenarios. Eco-indicator'99 was used as a Life Cycle Impact Assessment (LCIA) indicator to transform the mass flows into the overall environmental impact (Goedkoop and Spriensma, 2001). Inventory data was converted into environmental effects by assigning mass loads of specific materials/energy/emissions to the corresponding impact categories and weighting factors. A single end-point damage score, milliPoints (mPts), was applied to integrate the results for damage to human health (HH), ecosystem quality (EQ) and resource damage (RD) with the 'Hierarchist' weighting method.

Process-based cost modeling (Gregory *et al.*, 2006; Wang, 2008) was applied to analyze the costs during treatment excluding the collection costs of obtaining obsolete computers. Revenue was calculated from the market prices of primary and secondary materials; costs include variable costs, which are subjected to the scale of processes and market dynamics (e.g. labor,

transportation, storage, material and energy use) and fixed costs (such as construction, machinery and overhead).

Eco-efficiency analysis was applied as a quantitative tool to measure the balance between the economic and ecological effects of the specific scenarios (Huisman, 2003). It was projected in diagrams with economic gains and losses vertically and environmental impacts incurred or avoided horizontally.

7.2.2 Data used in the evaluation

Material compositions of desktop computers and dismantling times were obtained during the trials, in which the equipment was ultimately separated into homogenous materials and components. Recycling efficiencies, material and energy consumption, emissions of shredding processes, plastic recycling, controlled landfill and municipal incineration were derived from empirical European studies (Huisman, 2003; Huisman *et al.*, 2008) and standard processes in the Eco-invent v2.2 database (Ecoinvent, 2010) due to unavailability of data from China. Information of base metal recycling was obtained from local copper, aluminum and steel smelters in China. Composition and recycling efficiencies of PWBs were acquired from a state-of-the-art integrated smelter in Belgium.

The environmental impacts of a single process were modeled with SimaPro software (PRé, 2011). Cost analysis was calculated for a pilot plant with an assumed annual treatment capacity of 1,000 tons of obsolete computers. Average material prices from 2010 were used in this study, with primary metal prices retrieved from the London Metal Exchange (LME, 2012). Primary and secondary plastics, secondary metals and circuit board trading data was retrieved from mixed internet sources (WorldScrap, 2010). Labor costs for Chinese dismantlers were set at €0.8/h, and the energy price in 2010 was €0.1/kWh (CNBS, 1996-2012). Fixed costs were estimated from the cost of building prototype plants and a mixed-metal scrap recycling yard in Taizhou, China.

7.2.3 Result

7.2.3.1 Desktop computer

The results (Figure 7.2) consistently show that the scenarios including state-of-the-art end-processing technologies (scenarios 1 through 4) generate more revenues as well as environmental gains, and they are therefore environmentally and economically preferable. The scenario with complete dismantling, following the Bo2W concept (scenario 4), has the best performance, but differs only slightly from scenario 3. Shifting from complete dismantling to partial dismantling combined with mechanical processing seems to produce an almost similar result. The informal scenario 5 generates medium revenues but creates significant negative impacts on the environment and is therefore not preferred, mainly due to the impacts of acid leaching. Controlled landfill and incineration (scenarios 6 and 7) have scores close to zero, as they do not have any environmental gains or substantial costs for disposal, but lead to a large loss of material value.
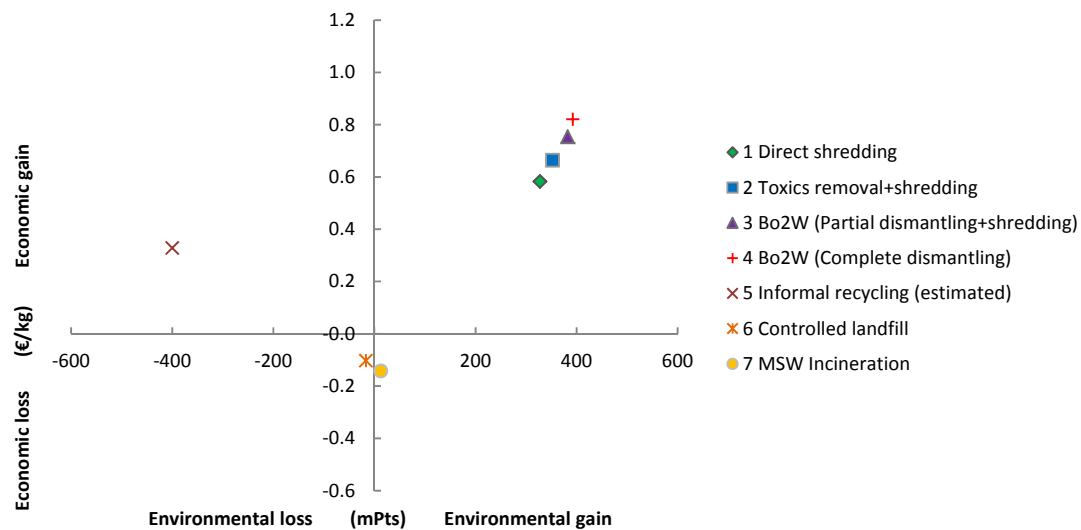
Figure 7.2 Eco-efficiency scores of seven recycling scenarios for desktop computers (based on 2010 price level)

As can be seen by comparing scenarios 1 and 2, removing the critical components (PWBs and batteries) before mechanical separation leads to an additional 8 percent environmental gain and 14 percent increase in revenue. This affirms the importance of removing hazardous fractions prior to mechanical separation, which avoids cross-contamination. Examining scenarios 2, 3 and 4, it can be concluded that eco-efficiency improves as a function of dismantling depth. Net revenue increases 14 percent when major plastic and metal fractions are dismantled instead of separated via mechanical separation. A further 9 percent value is added when disc drives and power supplies are manually disassembled. This demonstrates that in the pre-processing stage, full manual dismantling outpaces the eco-efficiency of mechanical separation under the trial settings and it is the optimal dismantling depth. The result of the "informal sector" scenario 5 was roughly estimated, without first-hand ecological damage and financial data from China. The basic settings from a similar study in India were applied, which indicated that gold yields in informal gold leaching processes are below 60 percent (Keller, 2006). Compared to a state-of-the-art integrated precious metal refinery in Europe, informal treatment results in 180 times higher metals emissions to water, three times higher CO_2, SO_X and NO_X emissions to air, but 1.5 to 4 times lower water and energy consumption. In total, scenario 5 causes substantial environmental damage and is less profitable due to loss of gold, silver and palladium. It confirms the finding that delivering PWBs to global state-of-the-art end-processing facilities prevents resource loss and ecological damage.

To examine the economic costs along the treatment chain, scenario 4 (the Bo2W approach with complete dismantling) is used to demonstrate the costs and revenues involved (Figure 7.3). Pre-processing profit was calculated by subtracting fixed and operational costs (mainly labor costs) from the revenues from selling liberated scraps (secondary materials in the trading markets). For end-processing, profits were calculated by subtracting the purchasing costs of secondary scraps,

fixed and operational costs from revenues from recycled materials (the market price of primary materials multiplied by the recycled mass).

The result suggests that the first step of removing circuit boards can create a profit of €0.31 per kg of desktop computer; deep level dismantling of all components can further yield a profit of €0.25 per kg. Eventually, when all the fractions are sent to the refinery, the overall profit from the various end-processing treatments can add up to €0.22 per kg. It is evident that dismantling desktop computers can generate 72 percent of all profits garnered through recycling, with 40 percent coming from the removal of the highly valuable circuit boards. This explains the benefit of intensive manual e-waste dismantling in countries with low labor costs.
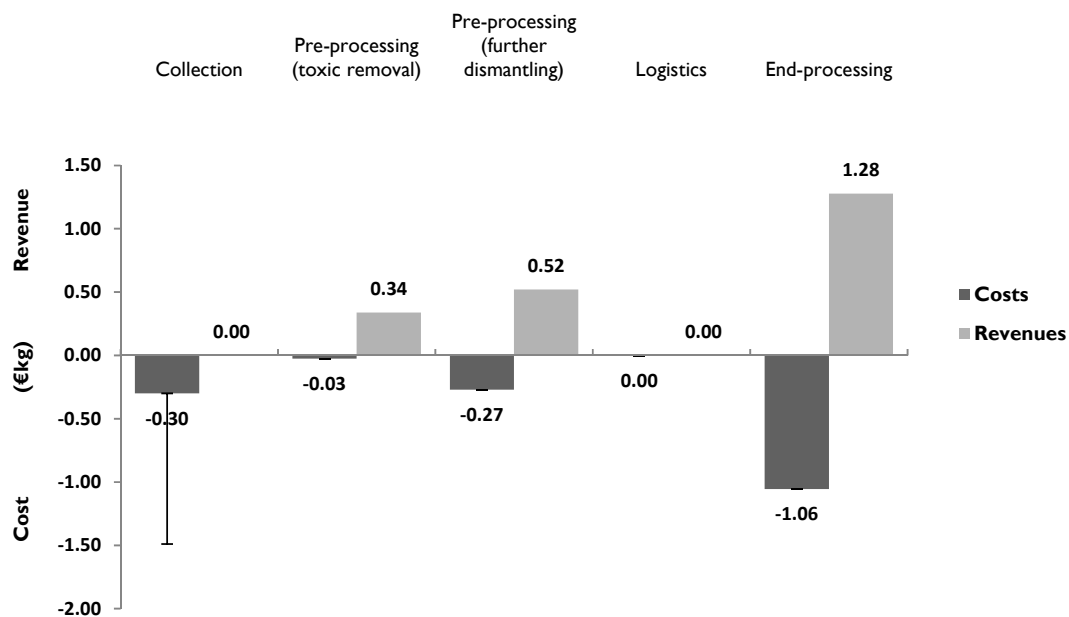
Figure 7.3 Revenues and costs of different treatment stages of desktop computers applying the Bo2W concept (complete dismantling)

Despite the relatively higher profits gained from pre-processing than those gained from end-processing, pre-processing collection costs (or costs from purchasing e-waste in the market) has not yet been included. According to a survey conducted by the Bo2W project team at local trading markets in Taizhou in 2010, an obsolete desktop computer can be valued between €3.3 and €16.7 per unit (€0.3 to €1.49 per kg), depending on the remaining re-use value from embedded components (e.g. mother boards, memory cards, power supplies/PSs, compact disc drives/CDDs, hard disk drives/HDDs, etc.). With the minimal collection price of €0.3 per kg, pre-processing can yield as much profit as €0.26 per kg, which is equivalent to the overall profits from the end-processing. If the collection price of a computer exceeds €6.28 per unit (€0.56 per kg), pre-processing will cease to be financially feasible. Separating the reusable components can definitely bring extra profits to dismantlers, but such a high collection price will make recycling scenarios without re-use less profitable (e.g. crushing memory cards and HDDs to destroy data, mechanical pre-processing, etc.). Therefore, integrating re-use into the general

recycling strategy will enable the formal sector's overall economic model to be more competitive in developing countries. Applying the Bo2W concept by sending circuit boards to Europe for better treatment is not expensive (€0.0012 per kg), so it is theoretically financially feasible.

7.2.3.2 Other types of equipment

Applying the same calculations, the eco-efficiency scores for other types of equipment following the Bo2W treatment concept are plotted in Figure 7.4. This figure shows that the material composition of products has direct influence on their profitability and environmental impact in treatment processes. Products containing substantial amounts of metals (especially precious metals) have higher eco-efficiency scores than products dominant in plastics or other low-value materials. Additionally, according to the treatment results of microwave ovens, vacuum cleaners and washing machines, complete dismantling (the Bo2W appraoch) is more eco-efficient than the combination of partial dismantling and shredding of complex components (such as transformers, motors, etc.) in China. However, the magnitude of difference between these two scenarios varies by product. Overall, the results suggest that the economic and environmental performances of the Bo2W concept are largely determined by products' intrinsic characteristics and recycling configurations should be adapted to different treatment categories for the best outcome.
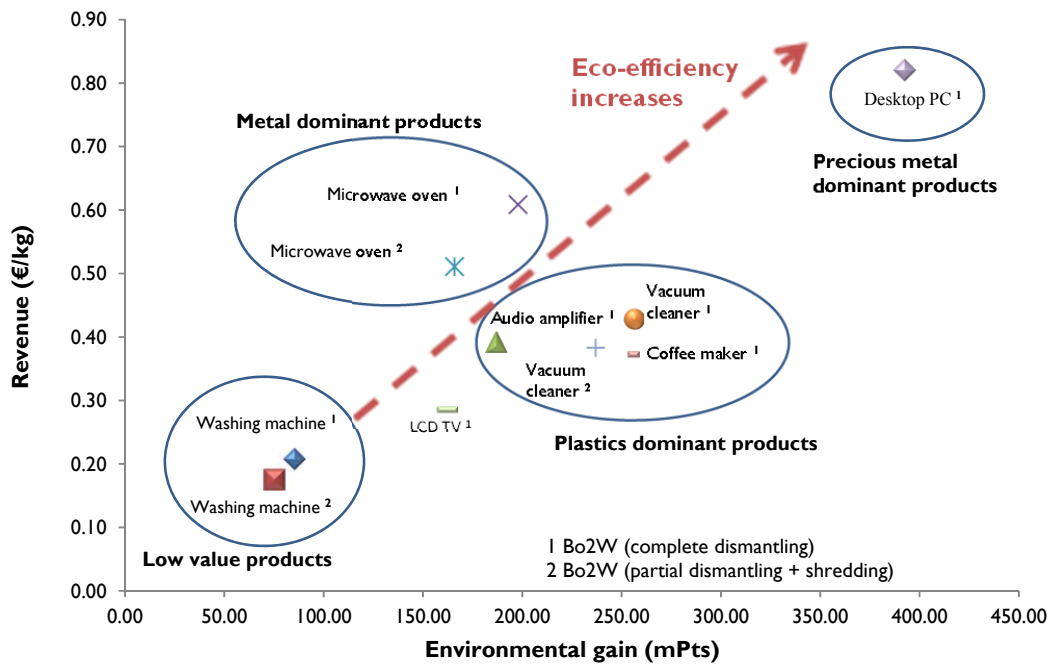
Figure 7.4 Eco-efficiency scores of seven electrical and electronic products under the Bo2W recycling approach

7.3 Sensitivity analysis of the results

As the dismantling trials are based on experimental data from China, it remains to be seen how eco-efficient the Bo2W concept is for other locales and market conditions. To investigate this,

this section analyses the sensitivity of the model to two dynamic economic conditions: market prices and labor costs. Environmental results are primarily determined by market preferences and are more treatment-configuration related. Additionally, the validity of the data collected in local plants in China and the restrictions of data availability are also discussed.

7.3.1 Market prices of resources

Material recovery of secondary resources is one of the key drivers for global e-waste trading and recycling, so the dynamics of material prices have a direct influence on the recycling industry. Figure 7.5 illustrates that from 2004 to 2010, the prices of copper and palladium roughly doubled and the price of gold increased by a factor 2.5 at an average annual growth rate of 14.5 percent (LME, 2012). When including the price dynamics of metals and plastics into the economic calculation in scenario 4 (complete dismantling of computers in state-of-the-art refineries), revenues from treatment obviously follow the same trend as the resource prices. There is a drastic drop in copper and palladium prices in 2009 due to the global economic recession, causing dismantling revenues to decrease by 28 percent, as compared to the 2008 peak. Despite these fluctuations, the same order of revenue yields as the scenarios investigated in Figure 7.2 is found in Figure 7.5.

Notwithstanding the downturn in 2009, resource prices have shown stable increases over the long term. External forces such as the depletion of oil reserves, resource scarcity and rising industrial demand for materials also contribute to the steady increase of resource prices. Rising resource prices will consequentially incentivize better recovery of e-waste materials. Processes that enable better liberation and end-processing of target materials continue to be encouraged by global markets.
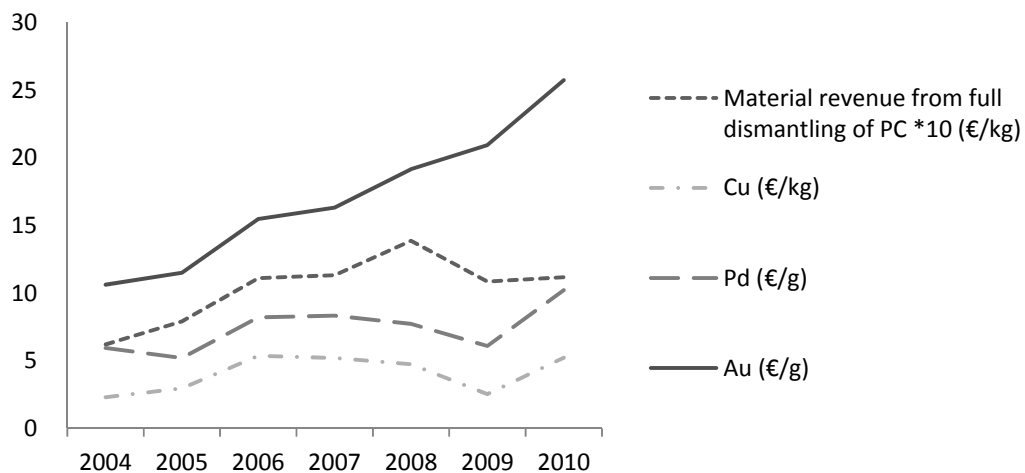
Figure 7.5 Dynamics of material prices and corresponding revenues from computer dismantling (2004-2010)

7.3.2 Labor costs

Rising labor costs will lower the profitability of manual dismantling and greatly influence the implementation of the Bo2W concept. In order to assess the impact of rising labor costs, net

144

profit is used to compare three pre-processing scenarios: A) complete manual dismantling, B) partial dismantling with partial mechanical separation and C) full mechanical separation. Net profit is calculated by subtracting labor costs for dismantling from material revenues (Eq.(7.1)). p_i is the market price for material i, m_i is the weight of recovered material from recycling, C_{labor} is the unit labor cost per hour and t_j is the duration for dismantling step j.

$$\text{Net profit = Material revenues - Labor costs} = \sum_{i=1}^{r} p_i m_i - C_{labour} * \sum_{j=1}^{s} t_i \qquad (7.1)$$

Figure 7.6 presents the change in profitability of pre-processing methods measured by net profits as a function of gradually rising labor costs from 2000 to 2035. The labor costs used in the analysis refer to Chinese manual workers' salary statistics (CNBS, 1996-2012), starting from €0.33/h in 2000 and growing annually at a rate of 13.6 percent until 2009. An estimated annual growth rate of 8 percent was used to extrapolate labor costs after 2009 to account for more modest economic growth in China than occurred in the last ten years. It was assumed that material prices, energy costs and consequently the revenues from dismantling and mechanical separation will stay constant at the 2010 level. The results of this analysis imply that complete dismantling will generate the highest profits until labor costs reach €1.26/h in 2015. As labor costs continue to grow, partial dismantling of higher value components becomes more profitable and mechanization is introduced to selectively replace manual work for complex components (e.g. transformers, power supplies and drives, etc.). After reaching €2.95/h in 2026, full mechanical separation becomes the most profitable pre-processing method, replacing all manual work.
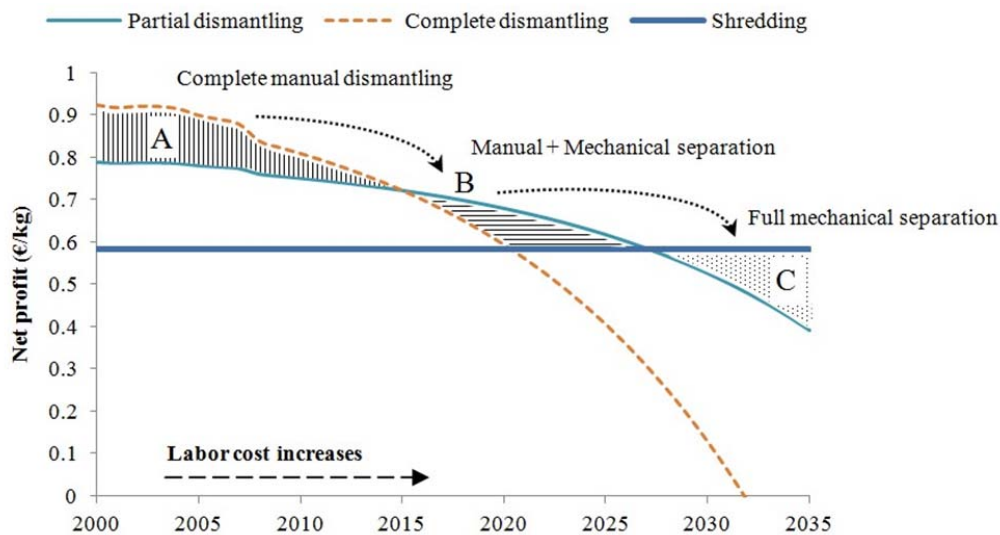
Figure 7.6 Transformation of pre-processing methods influenced by increasing labor costs in China (2000-2009, statistic data; 2010-2035, forecast).

As labor costs increase, mechanical separation gradually replaces manual dismantling as the most profitable method (displayed as a shift from zone A to B and finally C).

It is expected that based on strong economic growth and intense industrialization, processing in China will gradually transition away from labor-intensive work and become more mechanized and automated (Wang, 2008). As this development is also expected for other developing countries, albeit at a slower pace, it is suggested that this transitional change should be anticipated by fostering change in local industries to gradually transform them from manual processors into mechanical processors (Schluep *et al.*, 2009). By doing so, countries can ensure that they benefit from the efficiency of manual processes as long as socioeconomic parameters allow them to prevail over mechanical processes, and assuming that material and energy costs stay constant at the 2010 levels.

The analysis conducted so far in this section has been based on the recovery of valuable materials from IT, large and small household appliances. In most developing countries, informal recycling only focuses on equipment or components with positive market values. The treatment of environmentally critical fractions and emission controls are often ignored due to the additional costs of detoxification, which do not yield economic returns. This is especially the case for lead-containing CRT glass with quickly declining market value, mercury-containing lamps and coolants from cooling and freezing equipment. Due to the absence of mandatory legislation and financial incentives, removal and treatment of hazardous fractions is not common. Even when the toxic fractions are liberated and treated in responsible facilities abroad, following the Bo2W concept, the added environmental gains are not reflected in a concomitant economic gain. So for these fractions, the application of the Bo2W concept is only environmentally advantageous if it is simultaneously combined with the necessary political or economic interventions. Considering the great variety of e-waste categories and diverse interpretations of e-waste scopes in developing countries (Osibanjo and Nnorom, 2007), e-waste legislation and management should set priorities for the equipment and substances with the most environmental and resource impacts. In this way, the Bo2W concept can be better applied to reach an optimal eco-efficiency for most e-waste categories.

7.4 Experience from pilot project development

Results from the dismantling trials suggest that implementing the Bo2W concept in developing countries can be beneficial both environmentally and economically. However, the assessment as presented above is confined to a pre-defined technical system. This section presents case studies in which the Bo2W concept was implemented in pilot projects (China and India) to discuss the challenges and lessons learned from all relevant societal influences.

7.4.1 Pilot project in China: a comprehensive large-scale approach

In 2008 a project consortium was formed by the StEP Initiative that included two electronic multinational producers, one refurbisher, one European precious metal refiner, various research institutes and one mixed-metal scrap recycler. It aimed to set up a large-scale dismantling center in China while connecting to global state-of-the-art end-processing partners in order to demonstrate the value of implementing the Bo2W concept. Personnel (dismantling workers and managers) and 2000m² of industrial space were provided by a mixed-metal scrap recycler in the city of Taizhou. Despite substantial technical know-how accumulated after 1.5 years of

implementation, the original goal to set up a large-scale infrastructure network was not fully realized and it lacked commercial success.

The primary challenge was to collect sufficient e-waste at reasonable prices. Although free batches of waste (around 20 tons of ICT equipment) were provided by producers, such quantities were far from adequate to sustain the plant's daily operations. Given the absence of national legislation regulating e-waste treatment at that time, the informal sector dominated collection, trading, re-use and recycling. In many developing countries, collection prices do not solely reflect the material value of recyclables; they also reflect re-use value from the remaining equipment and components. The pilot project had to pay both material and re-use value prices to acquire e-waste, even though it did not specifically focus on refurbishment before recycling due to a lack of repair expertise (regarding hardware and software), official authorization from producers, standardization, quality control and guarantees. Together with the internalized cost for environmentally sound treatment, the pilot project was not economically competitive with its informal competitors.

Other challenges were found in business development and management issues, where responsibilities and expectations among the partners involved were not always clear. A pivotal role in leadership was lacking. This adversely affected the planning of the technical routes and material exchanging networks, evaluation of the financial feasibility and administrative tasks such as resolving export tax issues, custom notifications, transaction fees and overhead issues. Another challenge was communication across cultural and language barriers between the local dismantler and foreign end-processors and also with authorities regarding permitting and export licenses. Lack of transparency, in-depth communication, tracking mechanisms and safeguard measures limited cooperation between partners due to long distances and subsequent difficulties in continuously checking quality. Using the global market for the treatment of critical fractions increases the administrative complexities for authorities. The environmental bureaus in China were concerned that tracking multiple disassembly fractions overseas was very difficult and the chances of fraud or toxic transfers was regarded as significant. Combined with an increasing focus on strategic "urban minerals," treating precious metal-rich fractions overseas also created political resistance.

7.4.2 Pilot project in India: a pragmatic small-scale approach

A similar pilot project in India, where the Bo2W concept was also applied, resulted in more encouraging outcomes. Two batches of PWBs were shipped to a European end-processor. This pilot project was carried out by the Swiss e-Waste Programme through EMPA (Swiss Federal Laboratories for Materials Testing and Research) involving the informal sector in Bangalore, in partnership with local recyclers. The pilot project was based on alternative business models that target the informal sector in order to transform informal wet chemical processes into state-of-the-art recycling technologies (Schluep *et al.*, 2009). A win–win situation was created by encouraging the informal sector to concentrate on the preparation of optimal fractions as inputs for the integrated smelter. While creating a financial incentive to pay for their dismantling activities, the environmental impacts from improper recycling were minimized.

The alternative business model allowed the local recycling partners to establish themselves as innovation hubs and to act as the key players between the informal and the formal sectors. However, there was a major financing barrier in the form of a five-month delay between the shipment of disassembled fractions from India and payments from the refiner in the EU (after treatment). This posed a serious cash flow issue for the informal sector, which usually works on a day-to-day basis. One possible solution to this problem is the buffer model, in which a larger formal recycler (local or international) or another organization acts as an intermediate between smaller semi-informal recyclers and the integrated smelter. This model was found to be a feasible approach for the informal sector. Although they were only involved with pre-processing steps, their income was ensured, and the formal refinery gained access to higher e-waste volumes from emerging economies.

Although this project shows encouraging results for PWB recycling, it also creates a controversy because the alternative business model, unlike the Chinese attempt, only aimed to treat valuables and did not address hazardous materials such as CRT screens or other e-waste fractions with negative values. A partial implementation of the Bo2W concept that does not take care of all hazardous fractions can be regarded as "cherry picking" and it does not find a solution for other critical fractions. Even though the participating end-processors are not in the position to set up a fully monitored material delivery system for all e-waste fractions, the general challenge remains to carefully examine the environmental and social compliance of suppliers.

7.4.3 Conclusions from the pilot project
The implementation experience in China demonstrates that constructing a large-scale Bo2W recycling infrastructure can be successful when the necessary framework conditions are in place such as sufficient collection, fair access to waste material, legal clearance and financing. The Indian approach can be perfected if toxic control is installed and proper funding is secured to cover all fractions. Implementing the Bo2W concept, starting on a small scale and working towards profitable fractions, is more feasible than initiating ambitious plans with comprehensive solutions for all e-waste categories, specifically in cases without considerable governmental or financial support. Trust among the waste providers, dismantlers and end-processors can be established when there is stable flow of materials and payments. Informal sectors should be motivated with payments for their collection and disassembly work rather than being excluded or ignored. In the long run, the solution to non-profitable hazardous parts and equipment still has to be addressed. This should be enforced with a "systemic design" on the national level and local legislators who ensure that pre-processors are behaving responsibly with hazardous fractions.

7.5 Implications for wider implementation of the Bo2W approach

7.5.1 Support from policy and financing schemes
Establishing environmental policies and treatment standards can prevent improper recycling and encourage the environmentally friendly treatment of e-waste. According to the average costs of five long-running e-waste management systems in the EU (Huisman et al., 2008), there is an inevitable profit limit for some e-waste categories and derived fractions which prevents formal treatment from breaking even. Revenues from secondary materials are not sufficient to cover all

costs that occur throughout the entire treatment chain, including taking back discarded equipment from end users (which includes purchase, logistics and storage), toxic handling and material recovery. With respect to dynamic market prices and the size of markets for downstream fractions in developing countries, the risks for stakeholders who engage in improper recycling are still high without a financing system as a safety net to cover deficits.

In the societal system, environmental policies and recycling standards can facilitate movement of e-waste streams to the proper channels for safe treatment. Additionally, added environmental value from proper handling should be encouraged by policies to avoid cherry picking. Without these preconditions, practicing the Bo2W approach in developing countries will only have temporary success and lead to insufficient economic performance in a limited treatment scale in the long run.

7.5.2 Establishing mutual trust and transparency between partners involved

As experienced in the pilot projects, a significant challenge in setting up an eco-efficient treatment system is establishing trust between stakeholders, which takes time and effort. This is highly relevant for various end-processors and dismantlers, who are dominant in the recycling hierarchy and free to determine the destinations for their secondary streams. Alternative outlets in the informal market offer higher prices and inferior environmental performance at the same time. For dismantlers in developing countries, selling valuable fractions to the informal market can be rather attractive economically, and this could easily hinder the implementation of a Bo2W treatment network. Long-distance cooperation made it difficult to establish trust between pre-processors and end-processors through daily communication or field visits to track relevant fractions and destinations. A key to success for the implementation of the Bo2W approach is that dismantlers must deliver the critical fractions to designated facilities without "cherry picking," thus a global treatment network can be formed with the most eco-efficient performance. Lack of trust and acquiring authorizations in developing countries (e.g. from environmental bureaus and customs) regarding outgoing waste shipments also created difficulty. A direct way to strengthen cooperation is to file formal contracts between dismantlers and end-processors with explicit stipulations regarding material delivery and treatment quality and disallowing informal recipients from receiving the same fractions. Additionally, if critical materials are transferred abroad and become less traceable, a common international platform for sharing knowledge and assessing treatment quality and mass balances will help to monitor treatment and improve mutual trust.

7.5.3 Proper arrangement and transboundary shipments

Increasing globalization and production outsourcing are two significant trends in the modern economy. The majority of labor-intensive production activities have shifted to developing countries to lower manufacturing costs (Osibanjo and Nnorom, 2007). Along with this trend, a large percentage of the obsolete electronic equipment from the developed world is exported to developing countries for re-use, refurbishment and treatment. The high treatment costs in exporting countries, growing demand for cheap second-hand equipment and materials in developing countries, low labor costs and lax (or weakly enforced) environmental standards create strong economic incentives for this trade (Tsydenova and Bengtsson, 2011). However, such global transfer of e-waste has been called "digital dumping" because the environmental

quality and resource efficiency of such home-grown recycling activities are rather low (Puckett *et al.*, 2002; Brigden *et al.*, 2005). From this perspective, "outsourcing" treatment of e-waste in developing countries cannot generate an equivalent treatment quality in the immediate future compared to developed countries and should therefore be restricted.

In contrast to the prevailing activities which seek international destinations to reduce treatment costs, the Bo2W concept aims to create a net stream of hazardous or precious metal fractions to the best state-of-the-art end-processing facilities available in order to achieve the best treatment performances on a global scale. Transboundary shipment of such fractions has limited logistic and economic impacts due to relatively low volumes and a small portion of the fractions going to advanced end-processing. It is not against the principles of the Basel Convention, which explicitly restricts the shipment of e-waste from OECD (The Organization for Economic Co-operation and Development) to non-OECD countries. Taking into account the aforementioned social limitations, the Bo2W concept should not be misconstrued as supporting the export of e-waste from developed to developing countries. Industrial development and administration in the developing world is still far from mature enough to treat all critical fractions with sufficient environmental and economic performance. Bo2W is therefore to be regarded as a transitional and complementary solution for developing countries lacking refineries or treatment facilities for locally generated hazardous waste.

7.5.4 Roadmap for suitable implementing regions

Two major aspects determine the feasibility and approaches for implementing Bo2W: first, the level of labor costs allowing manual dismantling; second, the economic and technical conditions (e-waste market size, technical know-how and investment) determining whether advanced end-processes should be set up locally or critical fractions should be delivered to existing state-of-the-art end-processing facilities abroad. Among these factors, the most critical one is the market size of domestic e-waste, which is dependent on the total population and purchasing power (per capita) in the region (Huisman, 2010).

Given these two conditions, a group of countries that could potentially use the Bo2W approach are depicted in Figure 7.7, according to their labor costs and market sizes in 2012. On the right side of the figure, industrialized regions with high labor costs mainly apply mechanical separation. The other countries can fit into the scope of the Bo2W approach with different implementing models. Countries with low labor costs and limited market sizes are the best fits to apply full dismantling and share end-processing with global state-of-the-art facilities (like Uganda and Egypt). Countries with medium-level labor costs and large e-waste volumes (like China and India) can practice full dismantling to start and gradually mechanize processing and arrange for international treatment of critical disassembly fractions in the short term before constructing local end-processes in the long run. Countries with relatively high incomes but limited e-waste quantities (like Mexico and Turkey) can combine dismantling and mechanical processing intelligently and treat critical liberated fractions internationally. It is a first rough sketch of the possibilities for applying the Bo2W philosophy. More in-depth investigation of local and global refining and toxic handling industries is necessary when defining treatment solutions for specific countries.

The Bo2W philosophy approach is very relevant to social considerations, as the analysis demonstrates that optimizing e-waste processing configurations on an international scale could yield substantial environmental and economic improvements. It is a transitional method that enables developing countries to improve their informal sector treatment without making a large leap to high-tech investments and cutting jobs for the poor. Through the implementation process, skills and technology transfers can be used to facilitate the industrializing process. By its comprehensive nature, the Bo2W approach helps optimize global e-waste treatment and spurs faster development of highly desired sustainable take-back and recycling systems in a world of rapidly growing supply and demand for materials used in, and derived from, electronics.
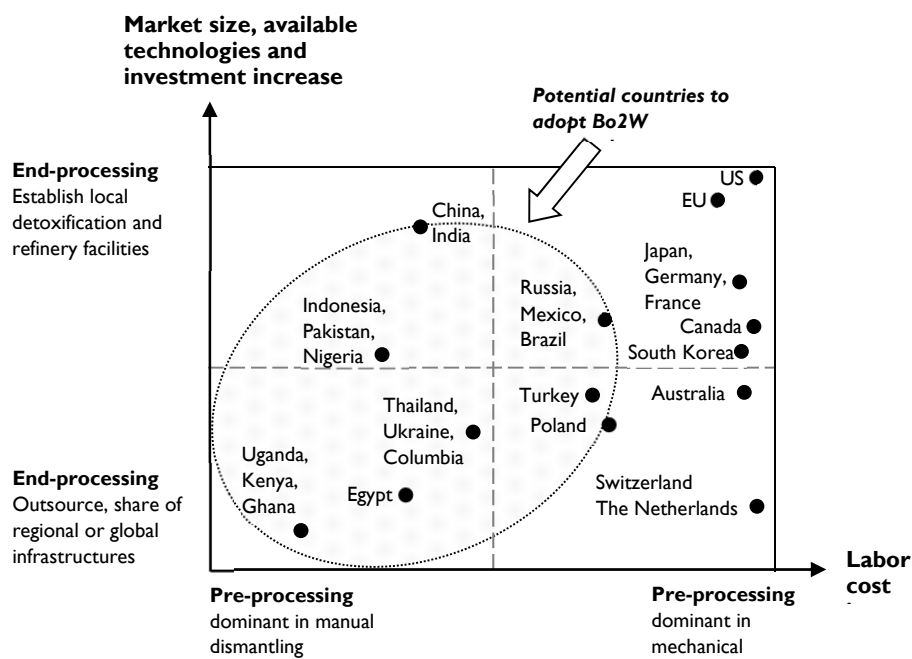
Figure 7.7 Countries that could potentially adopt the Bo2W philosophy for e-waste treatment (estimated at 2012 level)

7.6 Optimal treatment routes to match technical and societal subsystems

In Chapter 6, the theoretical analysis indicates that the treatment chain of e-waste is composed of three essential stages. Each stage has different functions which collectively influence the overall performance of the treatment scenario. The stage of toxic removal can significantly reduce the risk of dispersing materials with toxic potentials during subsequent treatment. The stage of pre-processing aims to separate various waste product materials into relatively pure streams. The stage of end-processing serves to refine and upgrade the liberated recyclable materials into usable materials, or treat the materials with toxic potentials. Each of these three

stages has different alternatives. Combining different options from each stage will construct scenarios with distinct performances.

Selection of proper treatment technologies does not only create the best technical route, but it should also comply with factors in the societal system. Two major considerations are the economic outcomes of applying certain treatment techniques and the associated environmental impacts. Assessment of treatment systems can help identify the technology that is most compatible with the local socioeconomic context. Technological appraisals should be combined with economic, environmental and social analyses.

The technical assessment of pre-processing techniques shows that liberation efficiency of materials generally improves as a function of the depth of manual dismantling. However, the economic assessment indicates that financial viability decreases when labor costs increase. As a solution, mechanical separation can work more efficiently if labor costs are high. Pre-processing method adjustments are dynamic in relation to the market prices of materials as well, because higher material revenues encourage better separation of target materials.

End-processing is oriented to each specific recyclable material or component, as well as materials with toxic potentials. Establishing such facilities usually demands substantial investments, technical know-how and proper emission control measures. Due to low concentrations in e-waste, certain materials will not be present in substantial volumes in the e-waste stream. These factors shape the reality that end-processing facilities will not be as widely available as pre-processing facilities. Seeking logistic arrangements with the available treatment facilities may be a better approach than constructing new refinery facilities. This will save initial investment costs and avoid maxing out the capacity of existing facilities.

Recovery rate is a fine indicator for evaluating the treatment efficiency of a certain type of material, both for pre-processing and end-processing facilities. Cost accounting can provide an extra indication of the balance between the value of material outputs and overall treatment costs. Environmental impact assessment is more suitable for specific treatment processes or technologies at the facility level. This is because each facility has different levels of material input/output and emissions, which may go through different environmental pathways leading to the final impacts.

The experiences in developing the Bo2W concept have shown that implementing technologies in developing countries is mainly influenced by the availability of investments, economic viability, e-waste-related policies (both domestic and trans-boundary), cooperation and trust between pre-processors and end-processors. All of these factors are affected by the societal system within which an e-waste treatment system operates. Establishment or development of e-waste related technologies should fully consider technical details, as well as such external factors.

7.7 Conclusions

Implementation of treatment technologies is always confined by economic and environmental factors. Making assessments not only based on technical performance, but also based on economic and environmental impacts, will provide a more realistic picture for selection, implementation and operation of treatment technologies. The information used for assessments

can include data such as: mass balances of products and materials, market prices of primary and secondary resources, various costs associated with treatment activities (especially for machinery and labor) and environmental impacts. In addition to assessments based on facts and data, pilot projects to test new techniques or treatment alternatives can provide fresh ideas and indicators for improving or upgrading current technologies. This will help to identify realistic opportunities as well as barriers that cannot be recognized by theoretical assessments.

7.8 References

Brigden, K., I. Labanska, D. Sanyillo and M. Allsopp (2005). Recycling of Electronic Waste in China and India: Workplace and Environmental Contamination, Greenpeace Report, Greenpeace International.

Brunner, P. H. and H. Rechberger (2004). Practical handbook of material flow analysis. Advanced methods in resource and waste management. Boca Raton, Florida CRC Press LLC.

CNBS (1996-2012). Statistical Yearbook of China (in Chinese). Beijing, China National Bureau of Statistics.

Ecoinvent (2010). Ecoinvent database version 2.2. Dübendorf, Switzerland, Swiss Centre of Life Cycle Inventories.

Gmünder, S. (2007). Recycling - from waste to resource: assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Master thesis, Swiss Federal Institute of Technology (ETH) and Swiss Federal Laboratories for Materials Testing and Research (EMPA).

Goedkoop, M. and R. Spriensma (2001). The Eco-indicator 99. A damage orientated method for life cycle impact assessment. Methodology Report. Amersfoort, the Netherlands, PRé Consultants B.V.

Gregory, J., J. Atlee and R. Kirchain (2006). Process-Based Cost Modeling: Understanding the economics of technical decisions. Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment. Scottsdale, AZ, USA: 138-143

Guinée, J. B., M. Gorrée and R. Heijungs (2002). Handbook on life cycle assessment. Operational guide to the ISO standards. Dordrecht, the Netherlands, Kluwer Academic Publishers.

Huisman, J. (2003). The QWERTY/EE Concept, quantifying recycability and eco-efficiency for end-of-life treatment of consumer electronic products. PhD thesis, Delft University of Technology.

Huisman, J. (2010). WEEE recast: from 4kg to 65%: the compliance consequences, UNU Expert opinion on the EU WEEE Directive. Bonn, Germany, United Nations University.

Huisman, J., F. Magalini, R. Kuehr, C. Maurer, S. Ogilvie, J. Poll, C. Delgado, E. Artim, J. Szlezak and A. Stevels (2008). Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Bonn, Germany, United Nations University.

LME (2012). Primary metal prices data 2004 - 2012 (non-ferrous metals, steel, precious metals), London Metal Exchange.

Osibanjo, O. and I. C. Nnorom (2007). "The challenge of electronic waste (e-waste) management in developing countries." Waste Management and Research 25 (6): 489–501.

PRé (2011). Simapro software. Amersfoort, the Netherlands, PRé Consultants b.v.

Puckett, J., L. Byster, S. Westervelt, R. Gutierrez, S. Davis, A. Hussain and M. Dutta (2002). Exporting harm, the high-tech trashing of Asia. Seattle, USA, The Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC).

Rochat, D., W. Rodrigues and A. Gantenbein (2008). India: Including the existing informal sector in a clean e-waste channel. . Proceedings of the Waste Management Conference 2008. Durban, South Africa.

Schluep, M., C. Hagelüken, R. Kuehr, F. Magalini, C. Maurer, C. Meskers, E. Mueller and F. Wang (2009). Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling - from E-waste to resources. Bonn, Germany, United Nations Environment Programme & United Nations University.

Tsydenova, O. and M. Bengtsson (2011). "Chemical hazards associated with treatment of waste electrical and electronic equipment." Waste Management 31(1): 45-58.

Wang, F. (2008). <u>Economic conditions for developing large scale WEEE recycling infrastructure based on manual dismantling in China: The learning experience from the setup of a pilot plant</u>. Master thesis, Leiden University and Delft University of Technology.

Wang, F., J. Huisman, T. Marinelli, Y. Zhang and S. v. Ooyen (2008). Economic conditions for formal and informal recycling of e-waste in China. <u>Electronics Goes Green</u>. Berlin, Germany.

WorldScrap. (2010). "The sales prices of waste plastics (PVC, ABS, PS, HIPS, PC) in various regions of China (In Chinese)."   Retrieved 16 March, 2012, from <u>http://china.worldscrap.com/modules/cn/plastic/</u>.

Chapter 8: Controlling human health impacts from e-waste treatment

As discussed in previous chapters, global environmental issues associated with e-waste are major concerns for the take-back and treatment system. From a geographic perspective, these have created substantial damage to the local and regional environment and ecology, especially in developing countries. Therefore, it is important to examine the environmental impact of e-waste treatment processes at both the local and global level. Regarding the environmental impact of e-waste, Chapter 4 has analyzed the product categories that possess the most potential for negative environmental impacts. In Chapter 6, the selection of best treatment technologies has been discussed based on the criteria of optional eco-efficiency performance. The present chapter will concentrate specifically on the health and safety dimension of environmental impact. A method of incorporating the occupational environment into the existing Life Cycle Assessment (LCA) framework is proposed. This can serve the objective of assessing the health impact and damage to workers associated with specific e-waste treatment process. A case study of mercury emission during several scenarios of LCD monitor treatment is applied to demonstrate the necessary steps and data needed for accomplishing the assessment.

8.1 Occupational and local human health effects

As analyzed in Chapter 2, emissions from e-waste treatment can arise from hazardous substances embedded in electronic devices, as well as auxiliary materials used or toxics formed during the treatment processes. Pollution is not only caused by substandard treatment techniques, but also due to lack of emission control measures in specific processes.

In environmental modeling, a schematic cause-response pathway needs to be developed that describes the environmental mechanism for each substance emitted. Along this environmental mechanism, an impact category indicator reflects the environmental effect in a specific area of the ecosystem. Environmental impacts in one category can be caused by many different emission substances, and one substance can contribute to several impact categories. In general, impact categories can be chosen either at the problem-oriented midpoint (e.g., global warming, ozone depletion, eutrophication, ecotoxicity and human toxicity) or damage-oriented endpoint level (e.g., resource damage, ecosystem damage and human health damage). A variety of impact categories can be associated with e-waste related emissions due to the diversity of embedded toxic substances and substandard treatment processes.

Among these impact categories, human toxicity is one that directly relates to the health of workers and local residents (close to the factories) under both short-term and long-term exposures. This category will be the focus in this chapter.

From a preliminary scanning of existing literature, damage to human health is identified as the major issue related to informal and substandard e-waste recycling compared to the damages to resources and ecosystems. (Sepúlveda et al., 2010; Tsydenova and Bengtsson, 2011). Emissions from substandard treatment are mainly heavy metals (Cd, Hg, Cr, Pb, etc.), dioxins and brominated substances. These substances have a heavier effect on human toxicity and consequently on health damages, as compared to other impact categories such as "damage to resource or ecosystem" (Shen et al., 2009; Lim and Schoenung, 2010; Lim and Schoenung, 2010). People can be exposed to pollutants through air inhalation, dietary intake, drinking water, dermal contact and other contact. Under the exposure of dioxins and health metals, human health impact from e-waste has much higher intensity at the local and regional levels (exposure to higher concentration of toxics), compared to the global scale. The impact to human health is especially critical as an occupational hazard faced by unprotected workers and local residents. Such pollution mostly takes place in developing countries where strict environmental regulations and appropriate monitoring are lacking. This has resulted in the serious pollution and ecological damages in intensive backyard recycling locations such as Guiyu, China; Agbogbloshie, Ghana and Bangalore, India. Therefore, evaluating the environmental impact of improper recycling is very significant for the process of upgrading of such primitive practice as well as subsequent improvements in the future.

In most technical studies related to treatment processes of e-waste, evaluation is mainly weight-based. This evaluation simply measures the mass balances of the released toxics and generated products. This type of research is functional to indicate the technical capability of a system, but insufficient to present a complete picture for all dimensions of environmental impact. This is because: 1) different substances have distinct magnitudes of environmental impact, and such disparities (especially in toxicity and other types of impacts) cannot be reflected by weight-based indicators; 2) weight-based analyses cannot indicate whether an emission is still acceptable for human beings and the environment in general (surpassing human intake limit or the environmental threshold). Without the impact analysis, the weight-based analysis will give a false impression that all discharges and chemicals are equally toxic through all environmental compartments and at all geographical levels. Therefore, environmental analysis can incorporate the mass balances data of the technical assessment into measurement, but it needs to consider the distribution and accumulation of pollutants in various compartments as well. These environmental models can also indicate potential exposure for workers and/or habitants during the e-waste recycling processes and hazard for human health (Suciu et al., 2013).

For existing environment-related studies, the chief focus has been on damage investigations in the informal recycling sites, but these studies have not particularly aimed at prevention. Numerous research projects have investigated the concentration of heavy metals and other pollutants in the water, soil and air of the informal recycling sites like Guiyu, China (Chan et al., 2007; Wong et al., 2007; Bi et al., 2011; Gao et al., 2011). These studies have provided valuable insight about the current environmental quality and ecological state of the investigated sites.

However, the results from such pollution investigations have not been linked to specific recycling processes, and the sampled data of pollution state is a collective result of many different activities. Therefore, the technical settings and mass balances of many specific processes have not yet been fully evaluated or reviewed. Furthermore, emissions data at the facility or process level are extremely scarce, especially for dismantling, shredding, metallurgical plants and most informal techniques. This has hampered the fundamental understanding and assessment of the performances and emissions from these processes.

According to the literature analysis in Chapter 2, there is a clear demand for investigating the actual environmental impact associated with specific recycling process. The result of such an investigation would provide valuable insight into identifying the critical parts of a process that generate the highest impacts, and it would help to propose further improvement. Due to the complex environmental mechanisms between the release of pollutants and the final effects faced by various subjects, it is very challenging to accurately portray the actual impact of simple method or indicator. At the same time, human toxicity is regarded as the most outstanding impact category associated with e-waste treatment. To narrow down the scope, this chapter will explicitly focus on the impact category of human toxicity and human health damage as a result of e-waste.

It is significant to develop methods and tools to quantify the environmental impact on human health for specific recycling process. The results can provide useful insights for:

- Understanding the magnitude of impact associated with a specific treatment process;
- Determining whether such environmental impacts or risks are acceptable or not;
- Comparing with alternative or similar recycling processes for technological selection; and
- Identifying improvement areas or options within the process to lower environmental impacts.

The following section will present a brief overview of the available methods that can measure the risk and impact on the environment and human health for specific treatment process.

8.2 Linking Risk Assessment and Life Cycle Assessment to address occupational hazards

Quantitative risk assessments (RAs) and life cycle assessments (LCAs) are two popular analytical tools that provide scientific information for decision making in environmental management (Ness et al., 2007). RA has a long history of use, and it mainly serves to resolve whether the risks arising from an activity, process or product are acceptable. Despite wide and long-time use, there is no internationally endorsed procedure to define and standardize the calculation steps (Cowell et al., 2002). The LCA tool assesses the environmental impacts associated with a functional unit defined in terms of the service delivered by a product. The procedural and analytical components of LCA have been agreed upon at the international level, especially under the system of the International Standards Organization.

This section will mainly compare these two methods for evaluating the environmental impacts of e-waste treatment. Respective advantages and shortcomings are summarized, and key areas for further methodological improvement are analyzed.

8.2.1 Chief characteristics of Risk Assessment

The aim of RA is to estimate the likelihood and severity of harm associated with a product, process, activity, agent or event (Cowell et al., 2002). The method is rooted in two analytical approaches: probability theory and methods for identifying causal links between adverse health effects and different types of hazardous activities. The outcome of the RA can be presented as a probability of a specific harm or decide whether the risk is acceptable by comparing with relevant criteria or standards.

According to the US-EPA's Citizen's Guide to Risk Assessment, RA estimates risk of health problems in people who are exposed to different amounts of toxic substances at various distances from the release location (US-EPA, 1991). Therefore, RA is often concerned with objects located at one or a limited number of defined geographic sites. Therefore, RA makes feasible site-specific impact modeling. Site-dependent impact modeling usually takes into account the spatial and temporal factors (such as volume and size of the target area, number of people under exposure, exposure time and dose of total intakes).

Despite of long history of use, there is no commonly accepted definition of risk, and there is no internationally standardized procedure to define the calculating steps for RA. Risk assessment guidelines are often developed within an individual nation to reflect its domestic policies and regulations (Bare, 2006). Furthermore, there is lack of widely accepted approach to interpret the technical estimation into clear implications for decision-making.

8.2.2 Chief characteristics of Life Cycle Assessment

LCA is the most widely applied method to quantify the environmental impact of a certain product through its life from raw material acquisition to final disposal. It is best known as a tool to calculate the life cycle impacts of physical products, but the methodology also analyzes services, systems and chemical processes (Björklund and Finnveden, 2005). A key feature of LCA is that all processes in a comparison must provide the same function delivered by a product or service system. In this way, an alternative product or system can be compared its environmental impact on equal grounds and same indicator.

The conventional procedure of conducting LCA is to measure the overall material and energy input and output from the life cycle inventory and assign the basic data to consequential environmental effect (midpoint) or/and final damage (endpoint). Environmental impact assessments of specific processes usually regard the process as a black box and only consider the overall quantity of emissions into the environment. Due to the demand of streamlined calculation and easy usability, most LCA studies have largely neglected the complexity of environmental mechanisms such as pathways and compartments of pollutant dispersion and target groups of contact of people in contact with the pollutant (Demou et al., 2009; Lim and Schoenung, 2010). Accurate estimation of the environmental impact requires temporal and

spatial information in order to associate sources with receiving environments of variable sensitivity.

In LCA, the characterization step assesses all the different substances contributing to an impact category for an overall measure of environmental damage in that category. This is fulfilled by using a reference substance or unit, through which the contribution of each measured emission is calculated by converting the amount of emission into the equivalent amount of the reference substance or unit. This conversion of specific material into selected impact category is done by using the parameter called "characterisation factors" (CF).

In order to evaluate the environmental impact, there are multiple intermediate and ultimate impact categories to choose from. The impact can be classified into midpoint impact categories (such as depletion of resources, global warming, human toxicity, marine ecotoxicity, etc.) and their endpoint damages (human health damage, resource depletion and ecosystem damage). The transport of toxics and chemicals determines different magnitudes of influences at the occupational, local, regional and global levels. Unlike global impact categories such as global warming, e-waste-related emissions usually affect the environment and people locally, as specific chemicals can induce an acute effect at high a concentration. Research has suggested that indoor emission intakes are up to several orders of magnitude higher than outdoor emission intakes (Jones-Otazo et al., 2005; Nazaroff, 2008). Therefore, an LCA methodology shall specifically look into the properties of the chemicals and identify the most vulnerable and influenced target groups for assessment.

However, spatial considerations and local environmental uniqueness (site-specific parameters such as population density and concentration of pollutants) are missing in existing LCA studies (Reap et al., 2008). In its current form, LCA is primarily a steady-state tool; it typically excludes temporal factors such as timing of emissions and release rates from time-dependent environmental processes (Udo de Haes, 2006). Temporal factors have a critical influence on human health at the occupational and local environment levels, and such system dynamics have been ignored in LCA (Demou et al., 2009; Lim and Schoenung, 2010).

The absolute magnitude of impact is generally regarded as irrelevant in applied LCA, because the system studied is assumed to exhibit linear behavior, and the objective is to identify improvement options (McClaren et al., 1998). For some impact categories such as human health, it is difficult to include the assessment of severity in LCA, and the result of the assessment can be difficult to understand (e.g. results may be expressed compared to a reference chemical).

To summarize, the main obstacle to applying LCA in evaluating the environmental impact of e-waste treatment is that the impact at the occupational and local levels has been lacking so far. The underlying problem is found in both methodological and data aspects. LCA is sophisticated in translating overall emissions to the environmental impact at a continent or global scale. In this way, specific local impacts are "diluted," or normalized, to the population of a whole continent. This leads to the conclusion that high intensity of toxic exposure in recycling sites cannot be properly reflected through the currently adopted LCA procedures. Lack of site-specific and process-related data has further limited the research in this area.

8.2.3 Comparison between RA and LCA

From the analysis in Section 8.2.2, the following table briefly summarizes and compares the key features of RA and LCA to evaluate the impact and risk on human health from e-waste treatment.

Table 8.1 Brief comparison between risk assessment and life cycle assessment

	Risk assessment	Life cycle assessment
Goal	Examine the magnitude of the risk arising from an activity and whether such risk is acceptable or not by comparing with standards or criteria	Assess the environmental impact through the whole life cycle of a product or service system
Modeling basis	Specific process	Functional unit
Spatial modeling	Site-specific	Site independent; Focus on regional and global impact
Scope	Single substance	Single or multiple substance(s)
Impact	Single risk category	Multiple impact categories
Time modeling	Focus on an endpoint defined in time; Require temporal information of pollutants in target location	Results are integrated over time and give no information about the timing of impact; Focus on long-term scale impact
Parameters	Usually single parameter or few parameters; Normally focuses on a specific and harmful end-point, and examine how endpoint might occurred in specific scenarios that are defined in time and space	Multiple and optional parameters; Include a large number of subsystems located in different geographic areas
Area of concern	Ecological health and human health	Human health, resource depletion and ecosystem
Result	In absolute magnitude of impact	Absolute magnitude of impact is irrelevant; Result is generally integrated over time and space

Assessing human health risk with RA can help protect the local population while not exceeding a certain level of acceptable risk. The role of LCA is to compare two or more alternative products or scenarios for their environmental impact under the same functional unit. RA is applied under the consideration that local populations are under higher doses of pollutants than people in broader scale, and their risk of being influenced is higher. In contrast, LCA represents the average impact on the whole geographical area (a country or globe). Without RA, LCA cannot assure that all locations of emission will be acceptable for local populations.

To the contrary, LCA is better at covering more comprehensive impact categories, stressors and locations than RA. However, the lack of modeling sophistication (especially for indoor and occupational environment) in LCA leads to the perception that it is a tool to characterize the potential for impacts, rather than to actually characterize the risks themselves (Bare, 2006). Furthermore, in order to come to a more meaningful interpretation of LCA results, the concept of acceptable risk or threshold has to be taken from RA into the framework of LCA. This will

improve the comprehension for the severity of the impact and facilitate better decision making concerning stakeholders.

RA and LCA are similar in many key aspects (such as translating emissions into impact assessment), even though their overall objectives are different. The major difference is that they use different time and spatial scales for assessment. Due to distinct methodological approaches used by these two established tools, it is difficult to directly integrate RA into the existing LCA framework. However, at least some spatial and time modeling could be incorporated into LCA for e-waste treatment from the assessment of indoor and occupational impacts. Combined with the existing impact analyses at the continental and global scales, such comprehensive analysis can be made when sufficient data are available for site-specific parameters. The procedure of conducting RA for local impact can be applied for life cycle impact assessment, which constructs a dose-response assessment for a target group under toxic exposure (US-EPA, 1991; Bare, 2006). In order to analyze the impact of human health, LCA needs the help of RA to go beyond the simplistic impact analysis from an inventory of environmental discharges (Matthews et al., 2002). Until then, risk analysis should check the dispersion of pollutants from local sites to continental and global scale. RA needs to seek LCA guidance in translating a risk analysis into policy conclusions.

Further research can focus on the evaluation of the impact caused by the emission during both its diffusion processes (short term) and final impact (long term). The existing LCA methodology has served for the relative comparison between alternative products or available options, but it is not a very effective tool for determining the intensity of the damage from a particular process and whether it is acceptable or not (from the perspective of maximal toxic limit for daily human intake, damage and even social/political acceptance). Therefore, health limits or threshold values for specific pollutant can be introduced as a baseline scenario to check the risk of such impacts. Another topic that could be adapted from the LCA analysis is to identify corresponding improvement options for better environmental performance, according to the analysis made.

8.3 Incorporating occupational environment into LCA by introducing the elements of RA

8.3.1 Enhancement of the methodology

Life cycle assessment is a widely accepted method to evaluate the environmental impact of a product through its entire life cycle stages. For measuring the impact of e-waste treatment, two additional improvements must be incorporated into the existing framework. The first addition is the assessment of indoor and occupational environment, and this plays an important part during the dispersion of pollutants. Secondly, the obtained results need to be translated into the level of severity in order to check whether such impact is acceptable or not.

Figure 8.1 illustrates the transmission of pollutants through different environmental compartments and geographic scales (Rosenbaum et al., 2008). For human toxicity, it can be seen that for specific occupations and local areas, the exposure to pollutants is high for workers and local residents. The consequence is that this group would encounter a relatively high dose of toxics, which results in serious damage. Meanwhile, the dose at the continental and global

level is much lower compared to the indoor impact group, but with a larger population. Indoor and local emission intakes can have up to several orders of magnitude higher than continental intakes (Hellweg et al., 2009). Therefore, if a substance is emitted in an indoor setting and is eventually transferred to outdoor air through ventilation, the major part of the impact is likely to occur in the indoor setting. This is illustrated through Figure 8.1 in which the size of the impacted area (Y-axis) is mapped against the concentration of pollutant (X-axis).
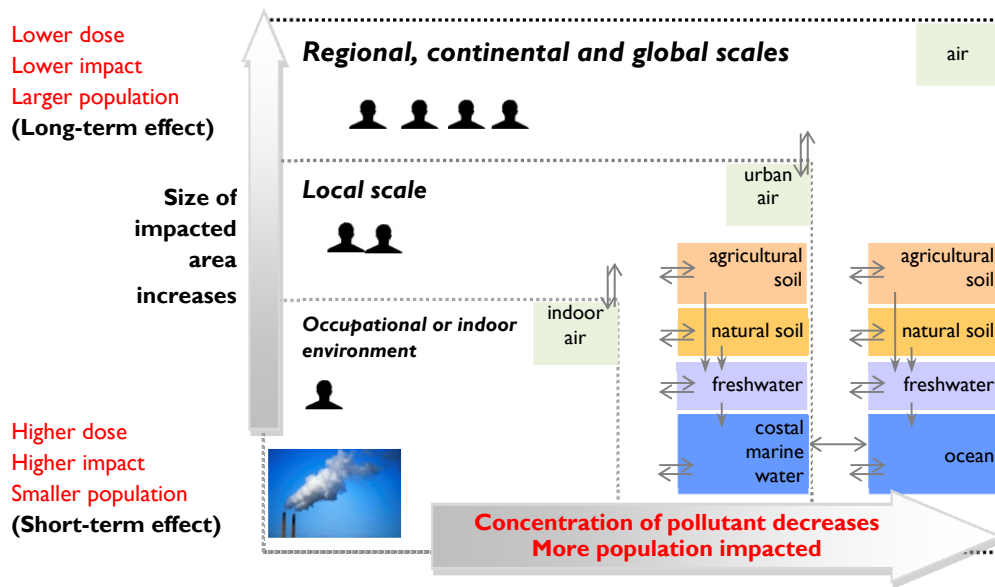
Figure 8.1 Transmission of a pollutant through different compartments and geographic scales

In LCA, Life Cycle Impact Assessment (LCIA) is a part of the assessment procedure aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (ISO, 2006). An important component of LCIA is characterization, in which characterization factors (CF) are used to quantitatively model the impact through a weighted summation of the releases of pollutants listed in life cycle inventory.

Globally, here are various methods for categorizing and characterizing the life cycle impact of materials and pollutants. Global scale models are generally used to derive generic characterization factors for life cycle studies where the exact location of the activities is unknown or not required. So far, most LCIA methods focus on the continental and global level. The effect on the occupational and local level has not been specifically addressed. For methodology, improvement is necessary for the evaluation at the occupational and local levels with specific diffusion models through various environmental compartments.

8.3.2 Applying USEtox model for assessing human health damage

In this chapter, the USEtox model is applied in the LCIA step to evaluate the occupational and continental impact of e-waste treatment. USEtox is the name of the UNEP–SETAC toxicity model, which was made by comparing and harmonizing existing characterization models

(Rosenbaum et al., 2008). There are other environmental models that can characterize the risks associated with certain chemicals. However, their coverage of compartment or chemicals is not as comprehensive as the USEtox model. For instance, the QWASI model can only simulate the fate of chemicals in aquatic systems, and the 2-FUN model is an integrated multimedia model, but it only contains five types of chemicals (Suciu et al., 2013).

USEtox is a stand-alone LCIA method specifically dedicated to the LCIA impact categories of human- and eco-toxicity. However, it is a multimedia model that can assess both the fate and the exposure for a number of chemicals emissions, providing characterization factors (CFs) specifically for LCIA. The CFs calculated via this model can then be potentially integrated in any other LCIA method for the human- and eco-toxicity impact categories. USEtox is used in this chapter because it is the UNEP-SETAC recommended model for human- and eco-toxicity LCIA. At the present time, it exists only as research model in Microsoft Excel (Hauschild et al., 2008; Pizzol et al., 2011). The basic equation for a toxicity impact score is used here:

$$IS = \sum_i \sum_x CF_{x,i} \cdot M_{x,i} \qquad (8.1)$$

In this equation, IS is the impact score for human toxicity (cases of illness); $CF_{x,i}$ is the characterization factor of substance x released to compartment i (case/kg) and $M_{x,i}$ the emission of x to compartment i (kg). The summation holds for all the substances and emission compartments addressed.

The USEtox model calculates characterization factors for carcinogenic impacts, non-carcinogenic impacts and total impacts (carcinogenic and non-carcinogenic) for organic and in-organic emissions to urban air, rural air, freshwater, seawater, agricultural soil and/or natural soil. The unit of the characterization factor for human toxicity is cases/kg$_{emitted}$, which is summarized as Comparative Toxic Unit (CTU) to stress the comparative nature of the characterization factors (Rosenbaum et al., 2008).

In USEtox, chemicals that have a potential to increase human disease have a characterization factor (CF) that can be calculated through the fate factor (FF), exposure factor (XF) and effect factor (EF). The calculating scheme of CF for each pollutant is present in Figure 8.2 and in the following formula.

$$CF = iF \cdot EF = FF \cdot XF \cdot EF \qquad (8.2)$$

In this equation, **iF** is the intake fraction (dimensionless, defined as kg$_{intaked}$ per kg$_{emitted}$); it expresses the fraction or percentage of a hazardous emission that is eventually taken in by the human population via various exposure pathways (the percentage of the total emission finally intake by human). It can be calculated by multiplying the fate factor (FF) by the exposure factor (XF).

FF is the fate factor (from pollutant to media), which links the substance release into the environment to the chemical mass increase in a given compartment (this is the main result of

the fate model) (e.g., how much of the emission is spread into the air or water body). In Figure 8.2, it is represented by the second model block on the left, which investigates the chemical fate of emission into various environmental compartments.

XF is the exposure factor (from media to human intake dose), which relates the chemical mass in a given emission compartment to the chemical intake by humans. It represents the equivalent rate of ingestion of the environmental medium by humans. (e.g., how much of the toxics in the air is eventually inhaled by humans). In Figure 8.2, it is represented by the third model block on the left, which investigates the amount of pollutant in various environmental compartments (as exposure routes), to which humans are exposed.

EF is the human health Effect Factor (from intake to disease), and it is expressed as the unit disease cases/kg_{intake} or CTU_h/ kg_{intake}. In Figure 8.2, it is represented by the fourth model block on the left, which reveals the linear dose-response relationship between intake quantity of pollutant and adverse effects (or potential risk) adopted by USEtox. It reflects the toxic characteristics of a specific substance, which is based on toxicity data for cancer and non-cancer effects derived from laboratory studies (Rosenbaum et al., 2008).
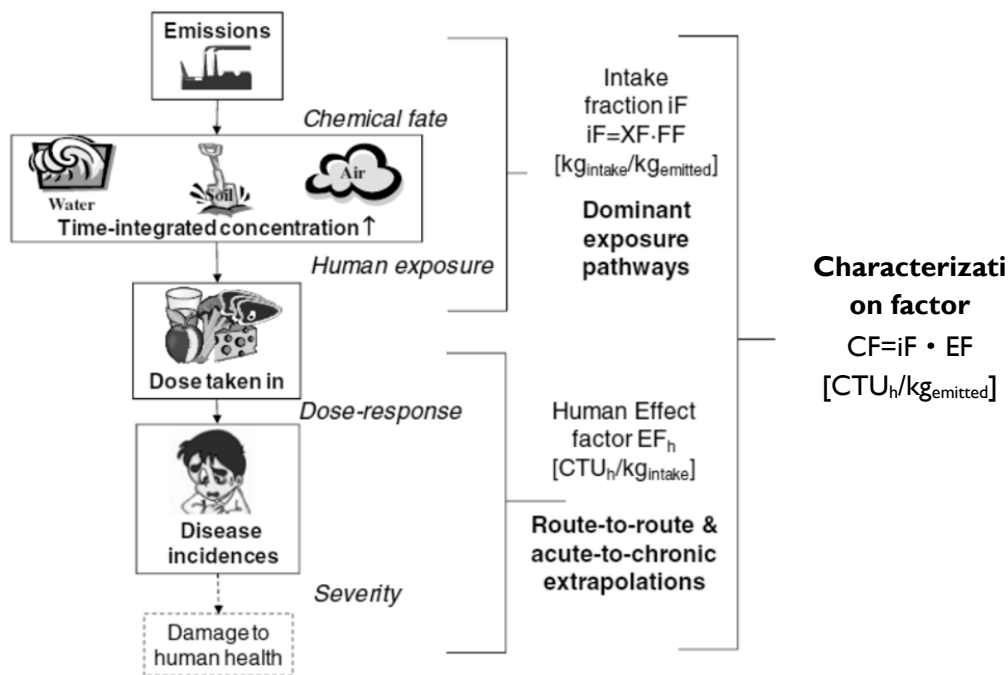
Figure 8.2 Calculation scheme of human toxicity potential in USEtox model (Huijbregts et al., 2010)

8.3.3 Incorporating indoor impacts into the USEtox model

In order to strengthen the model further, the global model for toxic assessment needs to be adapted to a local scale. In the database of USEtox, characterization factors (CF) of pollutants on continental and global scales are provided. USEtox includes all the transformation of toxics among different nature compartments, and it can be directly applied to the global scale.

However, there are no available CF data at the occupational and local levels. Therefore, the characterization factor has to be calculated manually according to Eq.(8.2), for indoor, occupational and local environment.

In further examination of CF construction in Eq. (8.2), both EF and iF are required for completing the calculation. The human effect factor EF is a constant parameter that is only determined by the toxicity of a specific pollutant; it is independent from the geographic scale and also irrelevant to the amounts of emissions or intake. Therefore, only the intake fraction (iF) has to be re-calculated for the indoor environment, in order to obtain the CF for local scale. For indoor environments, iF is determined by a several factors such as room size, inhalation rate, exposure time, ventilation rate, mixing factor and number of people exposed (Skaar and Jørgensen, 2013).

Thus, if the indoor and local impacts are included into the LCIA, the overall impact score through one compartment at full geographic scale can be calculated from the following formula:

$$IS = iF_{indoor} \cdot EF \cdot M_{indoor} + iF_{outdoor} \cdot EF \cdot M_{outdoor}$$
$$= iF_{indoor} \cdot EF \cdot M_{indoor} + (iF_{local} + iF_{continental/global}) \cdot EF \cdot M_{outdoor} \tag{8.3}$$

$$M_{total} = M_{indooe} + M_{outdoor} \tag{8.4}$$

In the current scheme of life cycle impact assessment (LCIA), the effects from the total emission have been well modeled at the continent and global scales under long-term influence. For temporal and site-specific impact, there is no general methodological framework to standardize the calculation process. However, several studies have made efforts to integrate human indoor pollutant exposure within LCIA, and the results have proven that such models are compatible with the existing environmental models used in LCIA (Hellweg et al., 2005; Meijer et al., 2005; 2005; Demou et al., 2009; Hellweg et al., 2009). The main method consists of applying exposure models from studies on occupational hygiene and indoor dispersion of chemicals. There is a great variety of models to assess exposure to indoor pollutants, which ranges from simple bulk mixing models to diffusion-based models (Hellweg et al., 2009). These models stimulate different diffusion scenarios by adopting various settings on emission rates, ventilation rates, mixing factors, room geometry and size, and arrangement of occupants. No matter which exposure model is selected, the goal is to calculate the intake fraction of an indoor pollutant through inhalation.

Intake fraction is a dimensionless indicator (kilogram$_{intaked}$ per kilogram$_{emitted}$). It expresses the fraction or percentage of an emission that is eventually taken in by the human population via various exposure pathways. The following equation represents intake fraction resulting from indoor pollutant inhalation:

$$iF = \frac{\partial I_x}{\partial G_x} N = \frac{\partial C_x IR}{\partial G_x} N = \frac{IR}{Q} * N = \frac{IR}{V \cdot K_{ex}} N \tag{8.5}$$

Where iF is the population intake fraction of a chemical (-); IR is the daily inhalation rate of air of an individual (m3/day); N is the number of people exposed; Q is the ventilation rate in the exposure area (m3/day); V is the volume of the exposure area (m3); and K_{ex} is the air exchange rate of the volume in the exposure area.

8.3.4 Additional steps to allow for indoor assessment

The following scheme (Figure 8.3) summarizes the necessary steps for improvement to incorporate occupational/indoor environment into the existing framework of LCA.

For the inventory step in LCA, extra data need to be collected for the emission rate and amount of pollutants in the working environment. This involves a detailed analysis of the recycling processes for its mass balances and technique settings. Through the establishment of emission modeling, the inventory will enable the calculation of total emissions from the treatment activities.

For the step of impact assessment, specific indoor exposure models are needed to calculate the intake fraction of pollutants by workers. This requires both the construction of environmental models of pollution dispersion and collection of site-specific data. Site-specific data include the size of working space, inhalation rate of workers, exposure time, ventilation rate, mixing factors, number and density of workers, etc. Sometimes, background data of toxic concentration, temperature and air pressures are also needed. Apart from the establishment of the toxic intake models, literature on pollutant toxicity is necessary to calculate the overall characterization factor.

In the step of interpretation, a baseline scenario can be set up based on the human exposure limit or threshold standard from county-specific legislations. This would enable an assessment of the severity and acceptance of each treatment process through comparisons with the baseline scenario.

Overall, these additional models and methods as shown on the left side of Figure 8.3 do not alter the basic procedure of conventional LCA. The added processes enrich the general framework of LCA by integrating the indoor assessment of e-waste treatment. Similar work can be done to further assess the local impact of e-waste treatment by incorporating chemical fate and human exposure models at the local scale.
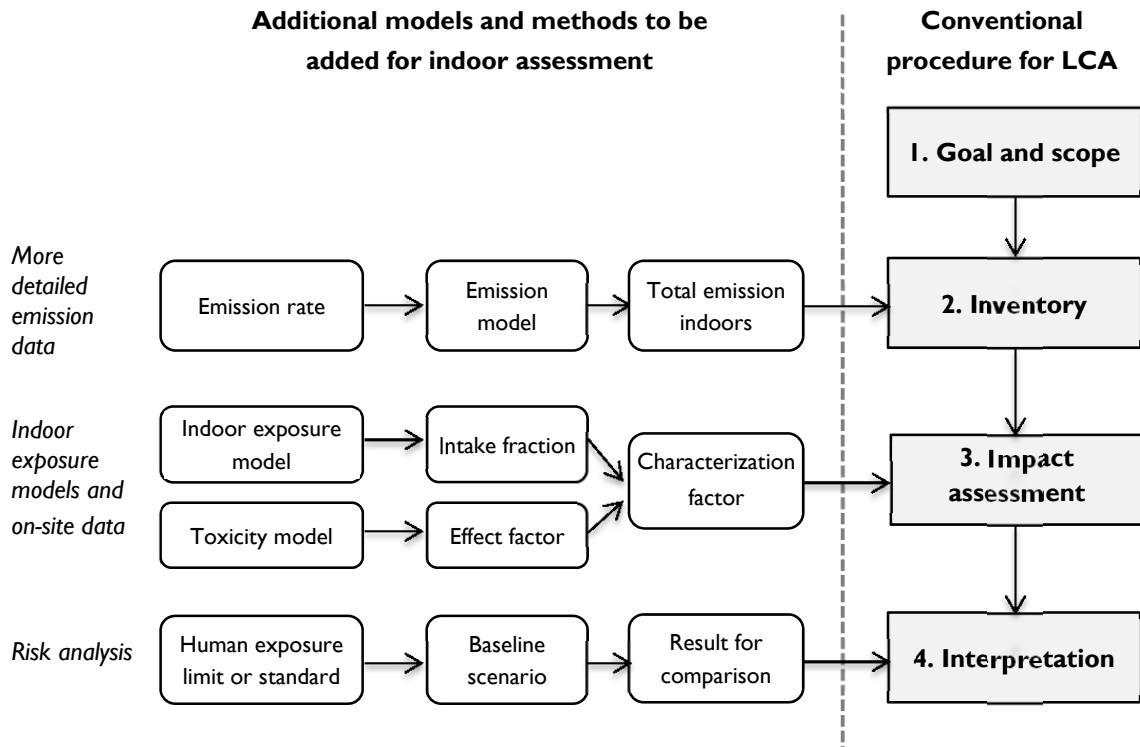
Figure 8.3 Integrating occupational/indoor environment into conventional LCA procedure

8.4 Case study: treatment of LCD monitors

Section 8.3, introduced the methodology aspect of incorporating occupational environment into the existing LCA framework and identified which kinds of data are needed to collect for completing the calculation. In this section, these general aspects are made explicit through a case study of treating LCD monitors to demonstrate the necessary adaptions and additions to the conventional LCA method.

8.4.1 Background and treatment scenarios

LCD (Liquid-crystal display) monitors contain mercury lamps; so improper handling will cause health damage to workers and residents. These monitors could be used as an indicative case to illustrate how LCA can more accurately evaluate the impact of such treatment process by incorporating occupational environmental into the existing framework.

A 17-inch LCD monitor weighs 4.3 kg per unit and contains 12 mg of mercury per unit, on average. For the functions unit of LCA, treating 1,000 metric tons of LCD monitors (annually) is applied to compare various treatment scenarios. Accordingly, 232,558 units of LCD monitors will be treated, and the total weight of mercury contained in these monitors is 2.79 kg (Böni and Widmer, 2011).

There is a great variety of treatment scenarios that relate to different pre-processing methods, including breakage rate of the mercury containing lamps, working space, ventilation situation and

mercury capture measures. Here, we categorize the treatment scenarios into the following main categories:

A1-A3   Dismantling without ventilation in a small room with lamp breakages of 100%, 50% and 5% (Informal recycling, working area for each worker is 4m*4m*3.5m = 56 m³)

B1-B3   Dismantling without ventilation in a larger room with lamp breakages of 100%, 50% and 5% (Informal recycling, working area for each worker is 150 m³)

C1-C3   Dismantling with natural ventilation with lamp breakages of 100%, 50% and 5%

D1-D2   Dismantling with ventilation hood with lamp breakages of 50% and 5%

E1   Open shredding (capturing the mercury)

E2   Encapsulated shredding (capturing the mercury)

8.4.2 Data inventory

For the life cycle inventory, it is necessary to determine how much mercury is released during the process, what percentage has been inhaled by the workers in the occupational environment and what percentage has been released into other compartments at continental and global levels.

Due to lack of on-site data, the following assumptions are used to simulate the actual treatment environment:

- Space settings and ventilation models (size of workshop, ventilation rate)
- Breakage rates for mercury contained lamp
- Placement of workers in the treatment place (number of workers, density)

The following data are retrieved from existing literature (Böni and Widmer, 2011):

- Dismantling efficiency (dismantling time or speed)
- Monitored concentration of mercury in the air during dismantling
- Shredding settings and monitored data for LCD modules

According to the basic scenario setting in the previous section, a data inventory is made specifically for each scenario.

Manual dismantling

Scenarios A–D represent dismantling LCA monitors, and human labor is applied for such work. It is presumed here that one worker works on one table (workplace) for dismantling. It is critical to have a realistic estimate about the dismantling efficiency in order to indirectly figure out the total number of workers needed. According to the mentioned literature, dismantling efficiency is set as 16.45 minutes per unit, per worker, per workplace. When working eight hours per day, one worker can dismantle a maximum of 29 units. Therefore, in order to fulfill the defined function, 8,019 workdays are required to dismantle 1,000 tons of LCD monitors. If there are 260 workdays per year, then 31 full-time workers are required to complete the dismantling work annually.

In a different dismantling scenario, the amount of mercury inhaled by workers is determined by several factors such as rate of mercury release or the ventilation rate of room. For a male worker, the inhalation rate of air is 2.5m³/h.

Scenarios A and B: No ventilation in the working place

When there is no ventilation installed during dismantling, a worst-case scenario occurs when workers inhale the highest concentration of mercury, as compared to other scenarios. If 100% of the mercury-containing tubes are broken during dismantling, then the total emission per dismantling table per day is 0.348 g. This operates under the additional assumption that all mercury is evaporated and is present in the gaseous state. Specifically, all the lamps of one monitor will be broken for every 16.45 minutes, so the release rate of mercury is sporadic under such a time interval. As the dismantling quantity increases, the mercury concentration in the dismantling room accumulates. Therefore, the total inhale amount of mercury for all workers per day can be calculated with the following formula:

$$m_{inhale} = \frac{IR \cdot N \cdot \alpha \cdot \beta}{V} \cdot \sum_{n=1}^{N} n \cdot M_{monitor} \tag{8.6}$$

Where m_{inhale} is the total weight of mercury inhaled per day by all workers; IR is the inhale rate of air for normal worker (2.5m³/hour); N is the total number of workers (31); V is the size of the room (m³); α is the breakage rate of mercury lamps when dismantling (%); β is the dismantling speed (0.27 hour/unit); N is the total number of units that can be dismantled by one worker per day (29); and $M_{monitor}$ is the mercury content per monitor (1.2E-5 kg/unit).

Suppose there is ventilation at the end of the working day, and all the mercury suspended in the working room is released into the urban air. In this case, the total inhaled mercury in a working year is can be obtained linearly by multiplying the calculated m_{inhale} with 260 working days per year.

Scenario C: Dismantling place with single-door ventilation

Under normal settings, working rooms are usually equipped with ventilation from either a window or door. By using the air exchange rate, the intake fraction can be presented by the following one-box model:

$$iF = \frac{IR}{Q} * N = \frac{IR}{VK_{ex}} N \tag{8.7}$$

iF is the population intake fraction of a chemical (-); IR is the daily inhalation rate of air of an individual (m³/day); N is the number of people exposed; Q is the ventilation rate in the exposure area (m³/day); V is the volume of the exposure area (m³); and K_{ex} is the air exchange rate of the volume in the exposure area.

When there is an incomplete mixing of pollutants in the room, the formula is:

$$iF = \frac{IR}{VmK_{ex}}N \qquad\qquad (8.8)$$

Therefore, in a room with a ventilation rate of 80m³/hour and incomplete mixing, the intake fraction of a chemical will be 0.065.

Scenario D: Dismantling with a ventilation hood

In order to capture the mercury vapor released during dismantling, installing a ventilation hood on top of the dismantling table is expected to lower workers' exposure. From real-time monitoring data of mercury concentration under ventilation hood, the measured stable concentration of mercury in the air at dismantling working place is 2 µg/m³ (Böni and Widmer, 2011). Therefore, the daily intake per worker is calculated at $4*10^{-8}$ kg.

Shredding

For the shredding process of LCD module, the EMPA study is used for reference (Böni and Widmer, 2011). It was found out in this study, in a worst-case scenario of open shredding (scenario E1), 76% of mercury is dispersed as a gaseous state and 24% is attached to solid matters. This means 76% of mercury will be released into the working environment. For a daily shredding capacity of nine tons, suppose there will eight workers in a shredding plant (1400 m³). In this case, the mercury inhaled by workers will be 0.24 kg per day.

For a best-case scenario (scenario E2), the LCD monitors will be shredded in an encapsulated environment, and the mercury fractions will be collected and separated, thus no impact will be caused. However, it is more relevant to look into less optimized shredding scenarios.

8.4.3 Result

Table 8.2 lists the calculation results for all the treatment scenarios under occupational and continental scales.

Table 8.2 Various treatment scenarios of LCD monitors and their human toxicity impacts at both occupational environment and continent scales

Scenario	Total Hg emission (kg)	Hg inhaled by workers (kg)	Hg released to the urban air (kg)	Hg released to soil (kg)	Impact from occupational environment (cases)	Occupational + continental impact (cases)
A1 Dismantling without ventilation (100% breakage) in a small room	2.79	0.52	2.28	0	13.97	15.84
A2 Dismantling without ventilation (50% breakage) in a small room	1.4	0.26	1.14	0	6.99	7.92
A3 Dismantling without ventilation (5% breakage) in a small room	0.14	0.03	0.114	0	0.7	0.79
B1 Dismantling without ventilation (100% breakage) in a larger room	2.79	0.19	2.6	0	5.22	7.35
B2 Dismantling without ventilation (50% breakage) in a larger room	1.4	0.1	1.3	0	2.61	3.68
B3 Dismantling without ventilation (5% breakage) in a larger room	0.14	0.01	0.13	0	0.26	0.37
C1 Dismantling with natural ventilation (100% breakage)	2.79	0.03	2.76	0	0.91	3.17
C2 Dismantling with natural ventilation (50% breakage)	1.4	0.02	1.38	0	0.45	1.59
C3 Dismantling with natural ventilation (5% breakage)	0.14	0.002	0.14	0	0.05	0.16
D1 Dismantling with a ventilation hood (50% breakage)	1.4	0.003	1.39	0	0.09	1.23
D2 Dismantling with a ventilation hood (5% breakage)	0.14	0	0.14	0	0.01	0.12
E1 Open shredding	2.79	0.24	1.88	0.67	6.57	8.12
E2 Protected shredding	0	0	0	0	0	0
F1 Direct landfill (in natural soil)	0	0	0	2.79	-	0.03
F2 Direct landfill (in agricultural soil)	0	0	0	2.79	-	6.66

Indoor assessment

The results of the human toxicity impacts from the occupational environment are examined separately in Figure 8.3. This examination indicates that the size of the dismantling hall/room has a linear influence on the human toxicity score, since space determines the concentration of mercury in the indoor air and the dose inhaled by workers. Dismantling LCD monitors in small rooms without ventilation leads to significantly higher impact than the scenarios with one-door ventilation (factor of 15) or with a ventilation hood at the working desk (factor of 75). The dismantling scenarios with a ventilation hood have the lowest impact among the dismantling category. This indicates that effective ventilation system can greatly lower damage to workers' health in the workplace.

The breakage rates of mercury lamps during dismantling also greatly influence the impact result, since it positively relates to the quantity of released mercury. Although only a 5% breakage rate is reported by the EMPA study, high breakage probability will occur if incorrect tools or

dismantling methods are used. The shredding setting with encapsulation has no health impact due to full capture of all the mercury. However, open shredding without off-gas control can lead to a noticeable impact result of 6.57 cases, which shall not be encouraged as a proper recycling practice.

After all, these scores are extremely sensitive to a great variety of variables such as room size, ventilation rates and means, mixing factor, number of workers, dismantling efficiency, and even room or ambient temperatures. All of these factors collectively determine the amount of toxic intake by workers. The scenarios presented in this section are a rough stimulation of actual situation under presumed or empirical values. For accurate estimation that reflects the actual risk and impact occurred through the process, on-site data must be collected.
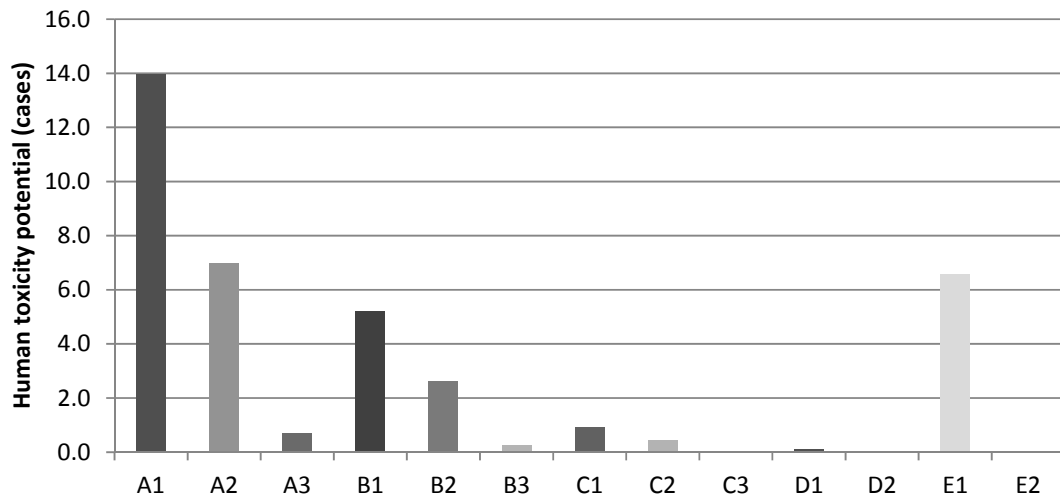
A1-A3 Dismantling without ventilation in a small room with lamp breakages of 100%, 50% and 5%
B1-B3 Dismantling without ventilation in a larger room with lamp breakages of 100%, 50% and 5%
C1-C3 Dismantling with natural ventilation with lamp breakages of 100%, 50% and 5%
D1-D2 Dismantling with a ventilation hood with lamp breakages of 50% and 5%
E1 Open shredding
E2 Protected shredding

Figure 8.4 Environmental impact of human toxicity for occupational environment under various treatment scenarios

Baseline of exposure limit

For indoor exposure, it is critical to understand whether the exposure level under each treatment scenario exceeds the health threshold. Due to the difficulty of measuring the air concentration in a continuous state for most working spaces, it is impossible to directly compare the concentration data with certain concentration threshold values. Therefore, it is instrumental to introduce a baseline scenario to compare the overall impact, instead of merely comparing transient concentrations of a pollutant.

In this chapter, the legal limit of chemical exposure according to the United States OSAH (Occupational Safety and Health Administration) is applied as a baseline to compare risk and severity. As regulated by the OSAH, the occupational exposure limit for mercury concentration is 100 µg/m³ (eight-hour, five-day average workweek). This permissible exposure limit is given as a time-weighted average. When transposing this baseline concentration into the same process of impact assessment, it is possible compare the impact scores of various treatment scenarios with this baseline. Therefore, the concentration baseline of OSAH is transferred into a Comparative Toxic Unit (CTU) under LCIA applying USEtox here.

Figure 8.5 shows the baseline level and impact scores from selected treatment scenarios. The figure demonstrates that Scenarios A1, A3 (dismantling without ventilation in a small room with breakage rates higher than 5%), B1 (dismantling without ventilation in a larger room with lamp breakage rates of 100%), C1 and C2 (dismantling with one-door ventilation in a small room with breakage rates higher than 50% of 100%) go above the baseline. Therefore, these scenarios are regarded as unacceptable, as they exceed the OSHA limits. Among these scenarios, A1 is 32 times higher than the threshold score, and it has the most significant risk and impact for the health of workers. Other scenarios either with lower breakage rate of lamps, in larger dismantling halls or with better ventilation have scored under the limit, which can be regarded environmentally acceptable for the occupational health of workers.

From this preliminary analysis, it can be concluded that proper ventilation, careful operation for low breakage rate of lamps and large working space can greatly lower the health risk. From the perspective of occupational protection and EHS, the most preferred scenario is encapsulated shredding, which causes the least impact on workers. The second best option is to install ventilation hood on each dismantling table while maintaining a low breakage rate of mercury lamps.
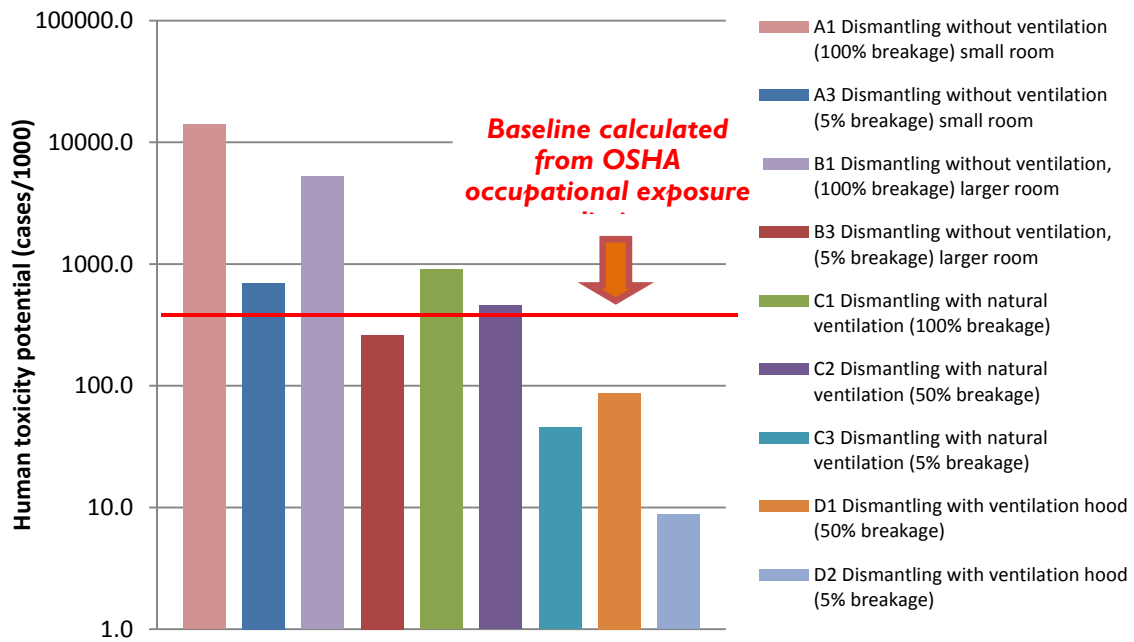
Figure 8.5 Assessment of human toxicity for the occupational environment under various treatment scenarios of LCD monitors, compared with the calculated baseline from OSAH occupational exposure limit

Indoor environment versus outdoor impact

Apart from assessing the occupational environment alone, it is also important to examine whether it is significant to incorporate it into the general LCA framework. The approach involves comparing the impact score from the indoor environment with the impact score from the outdoor environment. Figure 8.6 presents both the impact from the occupational environment and the impact from the outdoor environmental.

The result shows that for most dismantling scenarios, the impact mainly arises from the occupational environment, instead of the continental scale. For scenarios without proper ventilation, the impacts from the indoor environment take up more than 70 percent of the total impact. In extreme cases of dismantling monitors in small rooms without ventilation, the impact from the occupational environment is 6.5 times higher than the continental impact. This verifies the preliminary hypothesis that concentrations of mercury are higher in indoor environments, especially when the density of workers is high in a small room without proper ventilation.

However, as the ventilation rate improves, the contribution of the occupational impact decreases, because workers inhale less mercury due to a lower concentration in the working air. For the study of mercury in LCD monitor recycling, the impact from the occupational and indoor environment cannot be neglected in the LCA assessment.
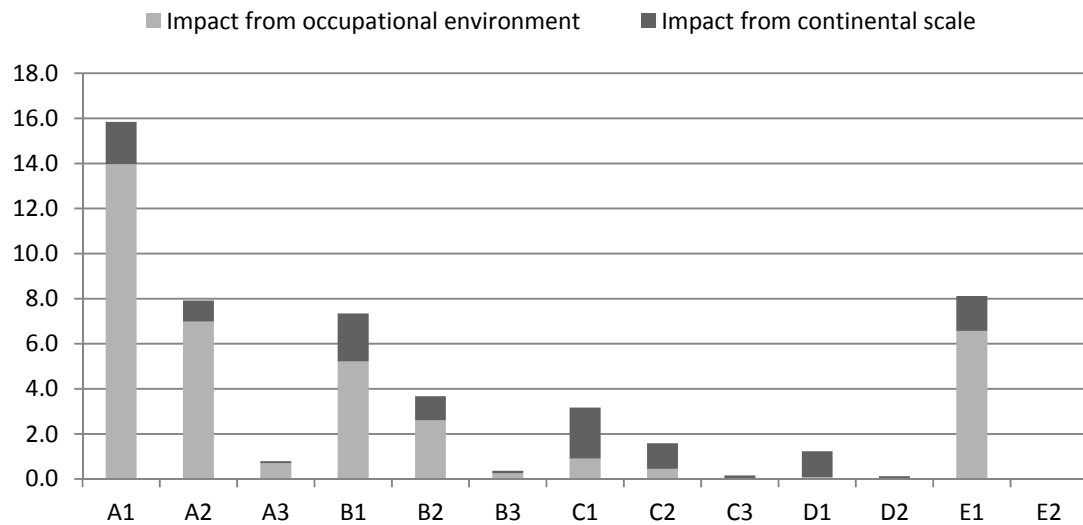
■ Impact from occupational environment   ■ Impact from continental scale

A1-A3   Dismantling without ventilation in a small room with lamp breakages of 100%, 50% and 5%
B1-B3   Dismantling without ventilation in a larger room with lamp breakages of 100%, 50% and 5%
C1-C3   Dismantling with natural ventilation with lamp breakages of 100%, 50% and 5%
D1-D2   Dismantling with a ventilation hood with lamp breakages of 50% and 5%
E1   Open shredding
E2   Protected shredding

Figure 8.6 Human toxicity impact from both global scale and occupational environment, under various treatment scenarios of LCD monitors

8.5 Discussion

Both the methodological development and case study demonstrate that assessment of occupational/indoor impact should be included in the general LCA assessment framework. Indoor dispersion models of pollution need to be combined with the outdoor models at the continental and global scales. This is especially essential for the scenarios or activities in which low ventilation rates and high pollutant concentrations are present in the working environment. Products possessing higher environmental impact as analyzed in Chapter 4 should be prioritized for such assessment, particularly when toxic control is the dominant objective of treatment. The case study of the LCD monitors has also showed that carrying out detailed LCA can help identify areas for further improvement in treatment processes, in order to achieve the acceptable levels. Therefore, it is necessary to include RA thinking into the existing LCA framework.

From a methodological point of view, there is no fundamental difference between modeling the health impact from indoor and outdoor environments. The shared goal is to estimate what percentage of the pollution released is eventually ingested and inhaled by people. This percentage is presented by the parameter of characterization factor. In order to retrieve this parameter, separate environmental models for pollution dispersion and human exposure are applied to simulate a distinct environmental compartment and settings.

When using relevant environmental models to characterize the human exposure to pollutant and assess the environmental impact from a specific recycling process, researchers can no longer treat the system as a black box (by simply accounting for the quantity of emission). Instead, more detailed examinations and measurements are required in great variety of relevant factors, such as the environmental pathways of pollutants, number of influenced people, facility size, ambient settings, emission control measures, placement of ventilation, etc. These settings greatly determine the result of impact assessments. As shown in the case study, many of these factors are unavailable, and assumptions must be applied in order to complete the calculation. This will lower the reliability of the modeled result, and on-site measured data should be given priority for proper computation in these specific models. Further, sensitivity analysis on the assumed parameters will demonstrate the margin of errors,

In conventional LCA, the result of human health impacts is usually presented in comparison to a reference substance (such as benzene equivalent). This result cannot actually indicate the severity or level of risk from such activities or processes. Therefore, it is useful to integrate RA thinking by introducing relevant threshold limits or standard into LCA. This can provide a baseline scenario, whether the actual impact is acceptable or not. Such standards (e.g., maximum human intake of a pollutant) for occupational safety and health practices may vary among nations, according to respective legislation, regulation and enforcement. Baseline selection should comply with the occupational standards or limits defined by local government.

The LCD monitors case study shows that reasonable assumptions for relevant parameters are necessary to simulate the actual treatment processes. Such parameters include spatial and ventilation settings of treatment facilities, arrangement of workers, dismantling efficiency and quantities, rate of emission, ambient and background data. Such assumptions are vital when on-site data are unavailable. This kind of preliminary assessment for different scenarios can provide useful guidance to design the optimal treatment process and proper environmental, health and safety measures. Therefore, incorporating RA with LCA will not only provide the status-quo analysis of existing processes, but it can also act as a design tool to predict potential impact prior to the construction of recycling facilities. This can provide suggestions for investment bringing substantial benefits for health and wellbeing of workers.

So far, this chapter only briefly analyzed the necessity of integrating occupational and indoor environments into LCA. As analyzed in the introduction, impact from improper e-waste recycling may significantly influence the indoor and local environments. It is also relevant to investigate the magnitude of local impacts by integrating local scales into the existing framework. Such work has substantial demand on both local exposure models and on-site data on air, water and soil. This type of impact study can be aligned with the prevailing studies of investigation on toxics in typical informal recycling, by associating the local parameters with specific treatment process.

Overall, environmental assessment of treatment scenarios can greatly facilitate the selection of the best treatment options, identify the potential improvement areas and check the environmental acceptance of specific processes. First of all, by simply comparing the calculated scores for different scenarios under uniform LCA approach, it is easy to rank performance to

facilitate technology selection. Secondly, due to multiple influential factors from both indoor and outdoor environments in human exposure models, it is possible to determine which settings should be adjusted within the process or facility in order to lower the overall impact. Finally, by establishing a baseline scenario for the exposure limit, it is possible to better understand or interpret the LCA result when incorporating risk analysis at a local level.

8.6 Conclusions

Toxic control is a major goal for the whole take-back and treatment system of e-waste besides material recycling. Environmental analyses show that substandard treatment results in severe health damage on workers and local residents. This chapter has proposed methods and approaches to incorporate the occupational and indoor environment into the existing framework of LCA. These solutions allow for proper assessment of environmental impact at all geographical scales and identification of a meaningful action agenda to reduce health risks for workers. This will comprehensively capture the environmental impact for people under significant exposure to pollutants and their influence. The case study of LCD monitor treatment demonstrates that the impact of occupational environmental is much higher than the impact in outdoor environment, when there is no proper ventilation or toxic control measures in the working environment. Comprehensive LCA studies covering all geographic and temporal scales will provide more accurate guidance for technological comparison, improvement and upgrades for e-waste treatment processes. It can also provide useful insights and precautions for designing an appropriate treatment process and EHS measures in order to minimize health risks for workers and residents.

8.7 References

Bare, J. C. (2006). "Risk assessment and life-cycle impact assessment (LCIA) for human health cancerous and noncancerous emissions: integrated and complementary with consistency within the USEPA." Human and Ecological Risk Assessment **12**(3): 493-509.

Bi, X., et al. (2011). "High levels of antimony in dust from e-waste recycling in southeastern China." Sci Total Environ **409**(23): 5126-5128.

Björklund, A. and G. Finnveden (2005). "Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies." Resources, Conservation and Recycling **44**(4): 309-317.

Böni, H. and R. Widmer (2011). Disposal of flat panel display monitors in Switzerland, final report. St. Gallen, Switzerland, EMPA, SWICO Recycling.

Chan, J. K., et al. (2007). "Body loadings and health risk assessment of polychlorinated dibenzo-p-dioxins and dibenzofurans at an intensive electronic waste recycling site in China." Environ Sci Technol **41**(22): 7668-7674.

Cowell, S. J., et al. (2002). "Use of risk assessment and life cycle assessment in decision making: a common policy research agenda." Risk Analysis **22**(5): 879-894.

Demou, E., et al. (2009). "Evaluating Indoor Exposure Modeling Alternatives for LCA: A Case Study in the Vehicle Repair Industry." Environ Sci Technol **43**(15): 5804-5810.

Gao, S., et al. (2011). "Polybrominated diphenyl ethers in surface soils from e-waste recycling areas and industrial areas in South China: Concentration levels, congener profile, and inventory." Environ Toxicol Chem **30**(12): 2688-2696.

Hauschild, M. Z., et al. (2008). "Building a Model Based on Scientific Consensus for Life Cycle Impact Assessment of Chemicals: The Search for Harmony and Parsimony." Environ Sci Technol **42**(19): 7032-7037.

Hellweg, S., et al. (2009). "Integrating Human Indoor Air Pollutant Exposure within Life Cycle Impact Assessment." Environ Sci Technol **43**(6): 1670-1679.

Hellweg, S., et al. (2005). "Confronting Workplace Exposure to Chemicals with LCA: Examples of Trichloroethylene and Perchloroethylene in Metal Degreasing and Dry Cleaning." Environmental Science & Technology **39**(19): 7741-7748.

Huijbregts, M., et al. (2010). USEtoxTM User manual.

ISO (2006). Environmental management -- Life cycle assessment -- Requirements and guidelines, International Organization for Standardization. **ISO 14044:2006**.

Jones-Otazo, H. A., et al. (2005). "Is House Dust the Missing Exposure Pathway for PBDEs? An Analysis of the Urban Fate and Human Exposure to PBDEs." Environmental Science & Technology **39**(14): 5121-5130.

Lim, R. and J. Schoenung, M. (2010). "Toxicity potentials from waste cellular phones, and a waste management policy integrating consumer, corporate, and government responsibilities." Waste Management **30**: 1653-1660.

Lim, S.-R. and J. M. Schoenung (2010). "Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays." Journal of Hazardous Materials **177**(1–3): 251-259.

McClaren, J., et al. (1998). Life Cycle modelling of consumer electronic products with convergent functionality. 6th LCA Case Studies Symposium. Brussels, Belgium, Society of Environmental Toxicology and Chemistry**:** pp: 61 -67.

Meijer, A., et al. (2005). "Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings - Part 1: Characterisation Factors (8 pp)." The International Journal of Life Cycle Assessment **10**(5): 309-316.

Meijer, A., et al. (2005). "Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings - Part 2: Damage Scores (10 pp)." The International Journal of Life Cycle Assessment **10**(6): 383-392.

Nazaroff, W. W. (2008). "Inhalation intake fraction of pollutants from episodic indoor emissions." Building and Environment **43**(3): 269-277.

Ness, B., et al. (2007). "Categorising tools for sustainability assessment." Ecological Economics **60**(3): 498-508.

Pizzol, M., et al. (2011). "Impacts of "metals" on human health: a comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA)." Journal of Cleaner Production **19**(6–7): 646-656.

Reap, J., et al. (2008). "A survey of unresolved problems in life cycle assessment." The International Journal of Life Cycle Assessment **13**(5): 374-388.

Rosenbaum, R., et al. (2008). "USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment." The International Journal of Life Cycle Assessment **13**(7): 532-546.

Sepúlveda, A., et al. (2010). "A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India." Environmental Impact Assessment Review **30**(1): 28-41.

Shen, C., et al. (2009). "Dioxin-like compounds in agricultural soils near e-waste recycling sites from Taizhou area, China: chemical and bioanalytical characterization." Environ Int **35**(1): 50-55.

Skaar, C. and R. Jørgensen (2013). "Integrating human health impact from indoor emissions into an LCA: a case study evaluating the significance of the use stage." The International Journal of Life Cycle Assessment **18**(3): 636-646.

Suciu, N., et al. (2013). Human and Environmental Impact Produced by E-Waste Releases at Guiyu Region (China). Global Risk-Based Management of Chemical Additives II. B. Bilitewski, R. M. Darbra and D. Barceló, Springer Berlin Heidelberg. **23:** 349-384.

Tsydenova, O. and M. Bengtsson (2011). "Chemical hazards associated with treatment of waste electrical and electronic equipment." Waste Management **31**(1): 45-58.

Udo de Haes, H. (2006). "How to approach land use in LCIA or, how to avoid the Cinderella effect?" The International Journal of Life Cycle Assessment **11**(4): 219-221.

US-EPA (1991). "Risk Assessment for Toxic Air Pollutants: A Citizen's Guide." <u>EPA 450/3-90-024</u>. Retrieved August 27, 2013, from <u>http://www.epa.gov/airquality/air_risc/3_90_024.html</u>.

Wong, C. S. C., et al. (2007). "Trace metal contamination of sediments in an e-waste processing village in China." <u>Environmental Pollution</u> **145**(2): 434-442.

Chapter 9: Future development of e-waste take-back and treatment systems

The previous chapters have summarized research related to the performance of e-waste take-back and treatment systems. These subjects include developing classification methods for EEE and e-waste (Chapter 4), modeling of e-waste quantities to improve accuracy (Chapter 5), evaluating treatment performance (Chapter 6), defining optimal treatment scenario under different socio-economic conditions (Chapter 7), and assessment of health damage in occupational environment (Chapter 8). The acquired information, data and results have been the outcomes of scientific modeling, data analysis and carrying out pilot projects. The gained knowledge and insights are very useful for the future development of e-waste take-back and treatment systems.

This chapter explores how the outcomes of the research conducted can contribute to the development and improvement of take-back and treatment systems in practice. The content is organized as recommendations to the following stakeholders: legislators (Section 9.1); recyclers (Section 9.2); operators and managers of take-back and treatment systems (Section 9.3); and producers (Section 9.4). Last but not least, potential research topics extended from this dissertation are listed for future development in Section 9.5. These topics are introduced in the categories of developing new methods, gathering new data and planning new applications to gain practical insights.

9.1 Recommendations for legislators

Over the last two decades, there has been a considerable increase in the number of environmental policies and legislation globally that focus on reducing the environmental impacts throughout the entire lifecycle of electrical and electronic products. In this dissertation, the target policies of concern are those that focus on the end-of-life management of electronics. These policies specify the guiding principles and implementing details related to the collection and treatment of e-waste within a national territory.

Legislation can be adjusted in a multitude of ways to improve the performance of take-back and treatment systems. Such legislation could contain a dimension related to defining guiding principles, such as who should be responsible for managing the "e-waste problems." Legislation could also include a technical dimension to determine product scope, relevant targets and standards for different activities. A financial dimension could regulate the fee-collecting scheme and issuing subsidies with allocation of responsibilities among stakeholders. An administrative dimension could cover registration and reporting obligations to allow system monitoring. Based

on the findings from previous chapters, additional areas for improving legislation include setting proper product scopes, targets and financing schemes.

9.1.1 Organize the product scope to allow for differentiation in e-waste management

Ideally, e-waste legislation would cover all types of electrical and electronic products for mandatory take-back and treatment. However, handling all categories of e-waste will not reach the most optimal eco-efficiency. For most developing countries, there is limited infrastructure and investment available to deal with all end-of-life products. Therefore, priority has to be given to products with the most environmental and economic impacts. Starting here, the key question is what products have more impacts than others in terms of end-of-life management. In countries where there is already legislation for mandatory take-back and treatment, the selected scope of e-waste mostly focuses on common large household appliances, screens and IT products. Defining applicable coverage of e-waste categories in legislation needs to be better supported by scientific analysis that explores both the intrinsic and extrinsic characteristics.

The classification of e-waste in Chapter 4 provides a thorough overview of the intrinsic characteristics of the nine e-waste categories. The grouping of e-waste was analyzed from the perspectives of product type, average weight, material composition, potential market value and toxic potential. In general, average weight can be used as a proxy for the size of a product. Because it takes up storage space in dwellings, heavy and bulky equipment requires more attention than smaller equipment, and they need to be removed immediately when new products are bought. However, not all large household equipment requires specialized collection and treatment. For instance, most heating system, dishwasher and furnace units are comprised of ferrous metals, and they can be handled efficiently by base metal scrap dealers and recyclers, and no substantial pollution will occur in this process due to low concentrations of hazardous substances. After classification according to weight and size, it is economically beneficial to take back and treat the obsolete products that possess significant material values for recycling. For instance, most computers, flat panel TVs and mobile phones contain high-grade circuit boards with high concentrations of precious metals, which have a high market value. Furthermore, recovery of secondary resources will lead to an environmental gain, because impact from primary material production can be avoided. Apart from market values and resource potential of secondary materials, the most important incentive for establishing take-back and treatment systems for e-waste is the environmental concern of potential toxicity. Embedded hazardous materials with toxic potential can directly cause health damage to workers and ecology, if not treated in an environmentally safe manner. As a result, categories such as CFCs containing large household appliances; CRT screens and TVs; and mercury-containing lamps and screens need to be given priority.

Apart from their intrinsic characteristics, the extrinsic properties of products need to be considered for scoping as well. This is because socio-economic conditions vary greatly from country to country. For instance, tropical countries are likely to have more cooling and freezing equipment than cold countries. The types and quantities of products purchased, stocked and disposed of are required to be investigated for a specific country. These quantities collectively

influence the scale of the e-waste stream, and determine the necessity of establishing specialized channels and new treatment facilities.

In regard to environmental concerns, Chapter 4 assesses the intrinsic toxic potential for embedded materials. However, materials contained in e-waste are not the only source of pollution and health damage. In many developing countries, substandard treatment techniques are commonly applied by the informal recyclers. This can result in a huge amount of hazardous emissions released from both uncontrolled reactants and products of (chemical and physical) reactions. Typical examples include the burning of cables, de-soldering of circuit boards on a heated stove and acid leaching of circuit boards. Therefore, equipment with a high possibility of causing pollution when entering the informal treatment channels, needs to be given priority for management.

The scoping of e-waste needs to be regularly updated according to changes in markets and social dynamics over time. For instance, CFCs were gradually phased out in the 1990s for use as refrigerants. After a society disposes and treats most CFC-containing refrigerators and freezers, the impact of newer models could be much lower. Similarly, lighting products and screens have seen a decrease in the application of mercury. On the contrary, emerging technologies and products may contain new hazardous materials with high toxic potential, or they may cause new problems for treatment. For instance, new tablets and mobile phones have embedded batteries that are difficult to dismantle and separate. The treatment methods need to be adjusted according to the latest technological development.

Defining the e-waste scope is based on scientific evidence and analysis, but it also involves input from stakeholders such as recyclers, collectors and producers. Any category defined will lead to financial and operational consequences for different stakeholders. This will complicate the decision making process and may even lead to unintended consequences that stray from the scientific analysis. However, comprehensive analysis about the multiple characteristics of e-waste from different perspectives and criteria can provide a good basis for such discussion and decision-making. The ultimate goals in defining the e-waste scope are to minimize the environmental impact, improve resource efficiency and reduce operational and financial burdens to the whole society.

9.1.2 Define effective collection and recycling targets

For legislation on mandating e-waste take-back and treatment, clear targets should be stipulated for both collection and treatment. This will give clear guidance to government, producers, PRO (producer responsibility organizations), recyclers and other responsible agencies for evaluating the actual performance compared to the defined targets. An effective policy target can stimulate the improvement of both the quantity and quality of e-waste treatment. E-waste related targets can include qualitative targets, such as the mandatory removal of hazardous materials prior to further treatment and other treatment standards. It can also include quantitative targets, such as specific collection rates, re-use levels or treatment efficiency for certain e-waste categories. For the convenience of management, these targets also need to be straightforward and easy to comprehend and measure.

Among these policy targets, the collection target is critical; it defines the quantity or level needed for formal take-back schemes. The collection target will guarantee the sufficient e-waste feedstock with economy of scale for the operation of certain pre-processing and even end-processing plants. It also predetermines the effort and investment required for establishing take-back schemes under the planned capacity. As the EU Directive and Recast implied, a uniform weight-based or absolute collection target is unsuitable for different Member States with significant differences in markets, economies and consumption patterns. A relative collection target based on product sales is easy to estimate, but it may not fully synchronize with the e-waste generation trend during a specific time period. A collection target based on discarded e-waste is more logical, but it demands accurate estimation and uniform methodology for the overall quantity of the e-waste being discarded. Each alternative target has pros and cons, and there is no "one size fits for all" target that meets all requirements for accuracy and easiness to conduct. The selection of a suitable target needs to fit with the data availability (registrations and statistics), market pattern, trend of e-waste generation and administrative preference. Also linked with the classification of e-waste, different collection targets may apply for each category due to distinct impacts on environment and resource efficiency, which has been discussed and improved by the analyses made in Chapters 4 and 5.

In terms of treatment, technical standards usually specify the treatment requirements for different categories of e-waste. Detailed articles provide requirements about controlling emissions and reducing occupational damage. Legislatively, it is useful to regulate the compulsory removal and disposal of hazardous components and materials prior to further treatment. The aggregation of such target materials from the beginning will minimize the contamination of hazardous materials in the follow-up treatment processes. For recyclable materials, regulations have defined the minimal recycling rate for certain product category, in some cases. Although in principle, the recycling target can motivate recyclers to improve the efficiency, it is difficult to actually measure and monitor the recycling rate in practice. First of all, clear definitions for recycling rates and a standardized calculation method are needed. Secondly, when a product is pre-processed in one factory, and the liberated fractions are sent to a variety of "external" facilities for refinery and treatment, it is difficult to apply the recycling target to track the overall performance of the entire treatment chain. Instead, the legislation shall enforce the proper treatment of all liberated fractions with state-of-the-art technology. Finally, the efficiency of material recycling can dynamically change with fluctuations in market prices of both secondary and primary materials, as well as other technical and social conditions. As an environmental policy, the ultimate emphasis should be placed on the safe handling of hazardous materials and the reduction of environmental impact throughout the recycling chain.

9.1.3 Systematic cost accounting for financing schemes

Another essential issue of e-waste-related policy is the financing scheme needed to cover the cost of establishing and operating take-back and treatment systems. According to the analysis in Chapters 4 and 6, the material value of most e-waste categories cannot fully cover the overall system cost needed to accomplish environmentally-sound treatment. Therefore, the deficit needs to be covered by a treatment fee or tax on stakeholders, in order to sustain the system.

Apart from the principle question of who should cover the cost, it is scientifically and technically more relevant calculate out the actual cost needed.

Systematic accounting for all costs and revenues from each stage of the recycling chain is needed. This includes collection, pre-processing and end-processing for each e-waste category. The assessment can include two cost types: technical costs and managerial costs. The technical cost involves the actual logistic and treatment costs (including labor, energy and start-up investment on land, machinery and facilities), as well as the revenues from material recycling or sales of liberated components. Managerial costs include overhead, administrative burden and even a justifiable margin (or profit) for collection and recycling companies.

For country at the early phase of setting up a take-back and treatment system, costs may be very high and unstable due to initial investment and lack of managerial experience. For countries with long-running systems, the overall cost per category is relatively more stable as a result of technical and administrative optimization. Furthermore, substantial cost disparities may exist between different operators and recyclers due to the respective selection of technologies, business models and margins. Applying the average cost of all contract operators and recyclers can stand in as a realistic result for the actual cost. It is also practical to estimate the maximum and minimum costs based on extreme scenarios.

Chapters 4 through 8 will greatly contribute to setting priorities in answering the key questions for take-back and treatment systems in regard to how much environmental gain can be obtained and at what cost. All items addressed in these chapters directly or indirectly relate to finance, regarding collection and treatment costs. There are multiple factors that influence the overall cost of handling e-waste. First of all, the size and material composition of equipment determine that the cost structures of end-of-life management systems vary according to the category of e-waste. The disparity in cost is a result of different collection arrangements, treatment technologies and outputs for each category. Secondly, the volume of the collected e-waste in each category plays a critical role in the overall cost due to the economy of scale. Thirdly, selection of different treatment technologies for the same category of e-waste will result in distinct costs (for instance, manual dismantling versus mechanical separation). Finally, prices of (primary and secondary) materials and the availability of markets for downstream materials and components on both the regional and global scales influence the system's revenues.

To summarize, cost accounting of e-waste take-back and treatment systems needs to consider the development trajectory for the whole system. Initial stages always incur more costs than mature stages, owing to high start-up cost and less optimized systems. Cost per e-waste category differs greatly due to distinct product characteristics, and therefore, it requires separate accounting. The overall cost is subject to the total volume of collected e-waste, the market dynamics of materials, the selection of technologies, as well as the development of new treatment technologies. Consequently, system cost is highly volatile, and it needs to be updated regularly to keep the influential factors and items on track. This will provide an accurate overview of the cost to cover the system deficit, which avoids underestimating and creating extra financial burdens for stakeholders.

9.1.4 Legislation and system development in emerging economies

There is an apparent difference in e-waste issues faced in developed and developing countries. Comparatively, developing countries face many more challenges due to illegal traffic, complex trading networks and limited infrastructure. The import of used electronics is regarded as an opportunity to provide the market with affordable products. Informal sector engagement commonly exists in importing, trading, refurbishing, collecting and recycling used electronics. In these regions, e-waste management is more than simply establishing new collection and treatment systems; effective management shall go beyond the work of technological development, and more attention shall be paid to socio-economic realities. Strict controls on illegal imports and integrating and upgrading the informal sector, together with appropriate financing schemes, are essential for the success of the formal system in developing countries.

In developing countries, e-waste is likely to be one of the many environmental issues on agenda. With limited administration and investment, priority must be given to the category with most environmental impact. This can specifically orient the work around limited categories of e-waste; e-waste categories that cause significant impact in informal recycling shall be given priority for proper management. Smart and convenient collection channels favored by consumers need to be set up. Early on in establishing collection channels, the collection rate maybe low due to market size, competition from the informal sector and consumers' awareness. In order to improve the collection rate of the formal channels, economic incentives are effective to encourage consumers to hand in their equipment. For treatment, dismantling is possibly the most economic and efficient technique to pre-process end-of-life equipment. Basic working protection and proper EHS measures can reduce the occupational hazards faced by dismantling workers. When the scale of downstream fractions is limited, it is cost-effect to send fractions to existing facilities with state-of-the-art treatment technologies. Constructing a large scale refinery facility for a specific material or component should be supported by sufficient feedstock, initial investment and technological knowledge. Most importantly, the entire deficit incurred through operating take-back and treatment schemes still needs to be covered by financing scheme in order to maintain the system.

Establishing formal system does not necessarily lead to the shrinkage of informal activities. Apart from setting up a take-back and treatment system, extra efforts are required to restrain the parallel substandard treatment. Heavy polluting activities such as open burning, acid leaching and dumping of waste into rivers and land must be prohibited with strong enforcement. Following the general rules of economics, the size of the informal sector will decrease along with economic and social development. This also provides a good opportunity for the development of local collection systems and treatment industries for e-waste in emerging economies.

9.2 Recommendations for recyclers

The e-waste recycling industry is tasked with recovering valuable materials, while minimizing the environmental impact from both the embedded hazardous materials and the treatment processes. There are key factors that can influence the overall performance, from the technological, environmental and managerial perspectives. The analysis and lessons learned from this dissertation can facilitate a better understanding of the structure of e-waste treatment

systems. Future improvement options can be identified for the most eco-efficient treatment technology, as well as measures to improve the environmental, health and safety conditions of treatment facilities.

9.2.1 Identify the most eco-efficient treatment technology

Treatment technology for e-waste varies largely by category. It is critical to determine a suitable treatment technology that matches the characteristics of specific e-waste category in order to promote optimal technical and environmental performance. For categories with a high potential for environmental impact, the measures to control emissions and pollutions need to be in place. This requirement makes the treatment process for these categories rather fixed. For instance, the treatment of refrigerators and mercury containing lamps needs to be conducted in an enclosed environment to prevent hazardous materials (CFCs and mercury) from leaking into the environment. The facilities for such categories require the installation of a complete set of equipment and machinery to separate the materials and capture the hazardous substances. This has been mainly discussed in Chapter 4 to differentiate the management for separate e-waste categories.

For some e-waste categories with a low potential for causing environmental impact, there are treatment alternatives available for separating recyclable materials. For instance, the pre-processing technologies and treatment priorities vary greatly among refrigerators, computers and small household appliances. At the same time, reaching the best technical result for material recycling and toxic content requires collective input of labor, investment of infrastructure and optimized process management. It has been demonstrated that reaching the highest recycling rate is not always cost-effective, due to a higher cost incurred than the extra margin gained from better treatment. From a purely economic perspective, a cost analysis can determine the optimal treatment technique under a specific set of market and social conditions. As a common example, the dismantling depth and level of mechanical separation can be flexibly combined and adjusted according to the local labor cost and material prices. Therefore, it is critical to assess the pre-processing treatment technologies according to the latest market prices of materials, labor and energy costs, the scale of the feedstock stream and requirements from downstream recyclers (for the grade and quality of a specific fraction). Options for adjustment can include depth of manual dismantling and mechanical separation, as well as change of refinery or disposal facilities for downstream fractions.

For end-processing, specialized facilities are required to treat various types of liberated fractions, such as base metals, batteries and circuit boards. End-processing or refinery facilities usually require much more technical familiarity and investment than pre-processing facilities. This is determined by the involvement of complex chemical and metallurgical processes, as well as off-gas control and pollution prevention measures. Compared to the weight of product, liberated downstream fractions constitute only part of the total weight. Therefore, it is important to collect and accumulate sufficient quantities to refine them efficiently. When there are alternative processes available for one fraction, the assessment of technology should not only include mass balances for input and output of the system, but it also needs to include the economic and environmental performances. A complete network including pre-processors and various end-processors is crucial to treat the product itself and all types of materials embedded. When

setting up new refinery facilities locally, the key concern is whether the volume of the target stream collected within the region has reached the critical amount. Chapter 7 has demonstrated that, when the collected volume is low, it is more economical to send it to existing facilities for treatment. By geographically sharing the end-processing, facilities can avoid excessive investment and overcapacity for downstream fractions. If treatment of certain fractions is "outsourced," it is crucial to track the performance and outcome of the contract refining factories. This will guarantee the responsible handling of these fractions, in order to avoid them ending up in substandard or inappropriate treatment.

9.2.2 Improve the environmental, health and safety conditions in treatment facilities

It is commonly understood that informal or backyard recycling adopts primitive and uncontrolled processes, which causes substantial impacts to the health of workers and the environment. Consequently, it is rather obvious that activities such as burning of plastics, open heating and acid leaching of circuit boards should be prohibited and these processes upgraded. On the other hand, less attention has been paid to the environmental, health and safety issues that stem from formal treatment plants. It is presumed that formally established plants are operating properly according to relevant standards. Nevertheless, the environmental, health and safety issues in the formal plants need to be treated as a priority, with regular environmental monitoring and checking.

In dismantling plants, workers could have significant exposure to hazardous materials. The case study in Chapter 8 has demonstrated that under poor ventilation, dismantling workers are exposed to mercury during disassembling LCD TV or monitors. The accumulated dose of mercury intake can surpass the health limits set by relevant occupational standards. Similar damage to the health of workers can take place in CRT dismantling plants, when there is a breakage of lead-containing glass. Moving or dismantling CRTs screens can cause implosion due to the vacuum inside the tubes, and the fluorescent phosphor (composed of cadmium, zinc and rare earth metals) coating on the inside of the CRT glass can be inhaled by workers. Dust is also a crucial issue, and dust attached on the enclosures of products can be liberated during dismantling. During dismantling of vacuum cleaners, there is a high potential of exposure to dust present when consumers have not removed the dust bag before disposal.

In shredding plants, products are broken down into small pieces, and other size-reduction processes (e.g., milling and grinding) further decrease the size of materials. Fine particles of substances have much higher mobility compared to when they are in their larger size. Without occupational protection, there is a high possibility for workers to inhale dusts containing ceramics, glass, heavy metals, brominated flame-retardants and other hazardous substances. The dust does not only pose hazard exposure to workers, but it also causes contamination to the local environment near the plant.

In pyrometallurgical processes, hazards can arise from fumes of metals, especially for ones with low melting points (e.g., copper, cadmium, lead, etc.). During the burning processes, it is also possible that brominated and chlorinated dibenzofurans and -dioxins are formed due to the

presence of halogens in plastic parts of the e-waste feedstock. In hydrometallurgical processes, hazards can occur due to exposure to acid fumes, liquid acid, and cleaning solvent.

These mentioned hazards in established facilities are not considerably visible and acute as the pollution caused by the informal recycling. The most important precaution is to install an enclosed system for treatment and apply an off-gas purification system for the volatile fume, dust and particles. This can reduce the overall emissions from the treatment processes, which prevents the dispersion of pollutants into the environment. Workers are the most vulnerable target group as they have the highest exposure to hazards, compared to other groups making up the whole population. If enclosed treatment is not feasible (such as dismantling or shredding of large household appliances), occupational protection for workers can greatly reduce respiratory, oral and dermal contact with toxics. Increasing the space of the working area and installing better ventilation systems can effectively reduce the concentration of toxics in the occupational environment. This will lower the total intake of toxics for workers under long exposure time.

E-waste treatment is an emerging, evolving and dynamic industry, and its hazards are not fully understood or regulated so far due to a great and growing number of substances and processes involved. Among all materials, heavy metals and halogenated compounds are of particular concern. Both the risk assessment and life cycle assessment can provide useful suggestions to lower the environmental risks, before and after the establishment of facilities. Furthermore, such theoretical assessments needs to be supported by first-hand, on-site data. The monitoring data on environmental quality in both the working and near-factory areas are useful to recognize the accumulation and dispersion of toxics. Monitoring priority and procedures need to be customized for specific categories of e-waste, considering the dominant hazardous materials involved. These monitoring data will provide fundamental information to establish and calibrate models for predicting the emission and dispersion of toxics under concrete settings of treatment facilities. Regular examination of workers' health (including sampling of blood and hair, etc.) can help to keep track the accumulation of toxics in human body over time. All of these measures will improve the environment, health and safety for e-waste treatment facilities.

9.3 Recommendations for operators and managers of take-back and treatment systems

Operators and managers of take-back and treatment systems are in charge of various daily managerial tasks. These tasks include: establishing collection points and channels; contracting with municipalities and recyclers; collecting and spending treatment fees; and monitoring and reporting on progress. Recommendations for better managing the take-back and treatment systems are provided based on the results in this dissertation.

1. It is critical to understand the magnitude of the e-waste stream being generated, stocked and disposed by consumers in society. These data can help determine the necessary amount for collection and identify potential loopholes to be closed. The multivariate Input-Output Analysis proposed in Chapter 5 can present a detailed and accurate estimation to product stocked in dwellings and e-waste generation.

2. The treatment performance between alternative recyclers and facilities may vary greatly due to different techniques, destinations for downstream fractions and business models. It is critical to track the environmental and economic performances of contract recyclers as well as other optional recyclers in order to have a realistic overview about the bandwidth of environmental impacts and cost involved.

3. Monitoring of treatment performance by contract recyclers should not be limited to pre-processing. It is critical to track down the destinations for all downstream fractions, whether or not they have been refined and processed properly. This has extended the monitoring work from the product level to component and material level. It will guarantee the environmental handling of e-waste in all stages of the entire treatment chain.

4. It is relevant to have a realistic assessment and overview that covers the emissions and occupational hazards in treatment facilities, instead of only checking mass balances. This work can involve the measurement of the actual environmental performance, as well as the presence of toxics in the working areas and neighborhood of the facilities.

5. Reducing the overall operational cost can occur by optimizing the end-of-life system for better eco-efficiency. Relevant strategies may include increasing the economy of scale by collecting more quantity, selecting the most cost-effective treatment techniques or solutions, exploring the downstream treatment networks for all fractions and comparing domestic systems with similar systems in other countries.

9.4 Recommendations for producers

Producers can make both incremental and radical changes to product design, which consequently will influence the settings and performances of take-back and treatment system. The following concrete recommendations are made for designers, producers and manufacturers of electrical and electronic equipment:

1. It will fundamentally change e-waste management the use of materials with considerable toxic potential in products can be reduced at the design phase. This will greatly reduce the hazard to the workers' health in treatment facilities, as well as the overall end-of-life impact.

2. Reduce the complexity of products, in terms of inner structure, joints, material mixing and apply less composite and metallurgically conflicting materials. This can improve the ease with which products can be dismantled and increase the dismantling efficiency in pre-processing. Less complex products can be treated better in size reduction and sorting processes, with less cross-contamination of mixed materials and better separation. Avoiding use of conflicting materials can partly save the efforts for separation and purification for both pre-processing and refinery.

3. At the phase of product design, predicting the product's end-of-life impact upfront can be based on a variety of treatment scenarios. In usual practice, designers or producers will estimate the disassembly time of a product based on its structure, components and material composition. Streamlined environmental benchmarking and assessment shall take consideration of more diversified treatment options. This is due to the reality that products have the possibility to end up in different destinations under both state-of-the-art and substandard treatment. Such

scenarios can include manual dismantling, mechanical size reduction, municipal landfill, municipal waste incineration, open burning, etc. Designing the products according to the best and worst scenarios can provide a bandwidth of environmental and economic impact scores. Most vitally, results from the worst-case scenario application could lead to significant reduction of end-of-life impact in developing countries.

4. End-of-life models can be established using the basic set-up of e-waste the treatment chain in Chapter 6 and empirical treatment configurations. This can provide support for designers and producers in understanding the environmental impacts of products in various end-of-life scenarios. In the meantime, costs involved with the collection and treatment of specific products can be calculated from such models as well.

9.5 Recommendations for researchers

There are several aspects and content of this dissertation can be further extended and explored. This section will point out key directions for future research as follow-ups to this dissertation. They are discussed separately in terms of developing new methods, gathering new data and apply the theoretical findings in practice.

9.5.1 Methods

1. In Chapter 4, the classification methods only limit to the intrinsic and generic characteristics of e-waste, which are not influenced by socio-economic conditions. For analysis in a specific country, the classification can further include external criteria such as quantity of product sales and e-waste generation, the potential re-use value of products, market price of products, etc. These external criteria vary greatly by country, but they will provide insight compatible to a local situation in order to prioritize the critical e-waste category for management.

2. Re-use is a very important and relevant topic in the end-of-life management of electrical and electronic products. It influences the lifespan of product, the amount of obsolete products, the collection and trading network and the economic performance of the whole treatment chain. However, the nature of the re-use topic is different from the take-back and treatment of e-waste; therefore, it has not been analyzed in this dissertation. Valuable learning and insights could be gained from research on the technical, economic and environmental impacts of product and component re-use for the whole treatment chain. Such a study could also be extended to the area of material re-use and make comparisons between different re-use scenarios as well.

3. Size reduction of e-waste and sequential sorting are rather complex, as they are comprised of different processes and machineries. From empirical data, the settings of these processes are rather flexible and able to process different materials' input and requirements of output. As a result, the result of mechanical separation becomes less predictable. Better understanding about the treatment efficiencies of mechanical separation will improve the optimization of pre-processing and determine the most efficient combination with manual dismantling.

4. The method of assessing the health damage in occupational environment (Chapter 8) is a basic approach. This approach should be developed further from methodological data and

case study perspectives. Further integration of Risk Assessment into the framework of Life Cycle Assessment can lead to standardized procedures for such analysis. In this dissertation, a very pragmatic approach of streamlined LCA has been taken to obtain results. More comprehensive environmental modeling and on-site data for the dispersion of pollutants in occupational environment can provide more reliable results. In the meantime, it is necessary to further develop the adapted LCA methodology to evaluate the impact for all geographical levels: indoor and occupational, local, regional, regional and continental. More impact categories may be included besides human health damage.

9.5.2 Data

Apart from the methodology, more accurate data are essential to justify, calibrate and improve the applied models in this dissertation. Data qualities in the following areas need to be improved.

1. The data for the material compositions of different product types are difficult to obtain and often not publicly accessible. Data from different sources are inconsistent, owing to a series of influential factors, including different sampling methods and sizes, age of products, brands and sources of materials. Sufficient scale of sampling for each representative type with an aligned sampling protocol is necessary to guarantee the quality of the data and reduce uncertainty. More chemical analysis is needed to track precise composition data at the substance level. For instance, the content of hazardous materials contained in various products is still lacking (e.g., brominated flame retardants, polyvinyl chloride/PVC, cadmium, chromium, and toner dust, etc.). In the meantime, product design changes both gradually and radically over time, and time series data to track such changes are essential to obtaining up-to-date information.

2. In order to estimate the quantity of e-waste generation, product lifespan is a critical parameter. There is very limited literature and research that attempt to develop uniform methodologies for calculating lifespan. There is also a lack of reliable lifespan data for typical products in most countries. It is also relevant to track the time-series of lifespan, which changes over time in different countries.

3. Both the data about pre-processing and end-processing are still incomplete. Performance of mechanical separation needs to be better understood by collecting more process-related data for each category of e-waste. Influences from different size reduction machineries, particle size, feedstock of material types, and arrangement of sorting sequences need to be investigated. Material efficiencies and emissions of various metallurgical processes are rarely available from refineries. Gathering more data in these areas will improve the technical assessment about different treatment options. This will result in better selection of optimal technologies for each category of e-waste.

4. The available data on environmental and occupational impacts of e-waste recycling in both developed and developing countries are fragmental. The data demands more studies on collecting workplace monitoring data and analyzing the effects of occupational exposure. This work will support risk assessment for mitigation measures and establish industry specific guidelines. For substandard treatment in development, the process related mass balances and emissions of chemicals of concern are rather limited.

9.5.3 Application

Apart from the theoretical analysis, additional knowledge can be generated if the proposed models, concepts and suggestions are applied in practice.

1. The classification methods in Chapter 4 need confirmation and improvement from daily management. It is useful to check the compatibility of the proposed categories with statistical routine, administrative preference and feedback from compliance schemes and recyclers.

2. Most estimations of e-waste quantity from management are rather simple and lack sophistication. Applying the multivariate analysis in Chapter 5 with support of sufficient data on e-waste flows will improve the reliability of e-waste estimation. This will provide more accurate guidance for defining the collection target, tracking e-waste streams and planning of the take-back and treatment systems.

3. The Best-of-2-worlds philosophy will add much more value and perspective if implemented in more developing countries (besides China and India). This will be especially functional for small-sized developing countries with urgent environmental issues on e-waste (like Ghana or Nigeria). Practical experience can enrich the concrete procedure to execute the philosophy, and improve the chance of success.

9.6 Conclusions

This chapter has provided a series of recommendations and improvement options for developing more eco-efficient take-back and treatment system of e-waste. The main implication is to apply scientific methods and tools to better understand the nature and scale e-waste streams in society to identify priorities and formulate clear targets for management. Scientific research can also help determine the most efficient treatment techniques and approaches, from economic and environmental perspectives. With more knowledge, data and results collected, the solutions to solve the e-waste problem will become more apparent and functional.

Chapter 10: Conclusions

This research has attempted to add onto existing methodologies to analyze the performance of e-waste take-back and treatment systems. The main subjects investigated include the collection schemes and treatment infrastructures of established take-back and treatment systems. A take-back system consists of two sub-systems: the technical sub-system (collection and treatment) and the societal sub-system (legislation, environment, society, economy and market). The results of this work and experience are expected to identify pertinent improvement options for better fulfillment of both the technical and societal subsystems. Following this structure, the performance assessment in this dissertation covers the technical aspect (collection quantity and efficiency, treatment efficiency), as well as the societal aspect (environmental and economic impacts). This will guarantee the validity of results in both theoretical analysis and applications in daily management.

Based on the evidence presented in different chapters, the following conclusions are made.

Classification of e-waste

Chapter 4 of this dissertation has demonstrated the complexity of the e-waste stream by qualitatively and quantitatively examining its heterogeneous characteristics. The analysis made was based on intrinsic properties of products, such as function, average weight and material composition. Due to the presence of numerous product types with distinct properties, it is instrumental to classify EEE and e-waste according to criteria based on respective characteristics. This work will greatly improve the operational and managerial efficiency for policymakers, operators of take-back system, collectors and recyclers.

A comprehensive classification of e-waste has been made possible by combining the individual classification results through separate criteria of product type, average weight, potential market value, environmental gain on recycling and potential toxicity in the end-of-life treatment. Based on these intrinsic characteristics, there are nine generic categories identified for existing EEE and e-waste. Each category has particular requirements for end-of-life management, such as collection methods, treatment technologies and toxic control measures. As a result, this combination can provide guidance for customized and differentiated management for separate e-waste categories.

The results of the classification also facilitate setting priorities for the most critical categories with high environmental and economic impacts. E-waste categories with (relatively) heavy weight, high toxic potential and high material values shall be given priority for take-back and treatment. These categories include large household appliances with CFCs, screen products (TV and monitors with CRT glass and mercury-containing lamps), professional IT equipment, medium and small IT and consumer equipment with high grade of circuit boards and mercury-containing lamps. The obtained result illustrates the relevance of waste management from its internal physical and chemical properties. Priority setting needs to be further assisted by the societal attributes of products, especially for the magnitude of the waste stream ready for waste management.

Evaluation of e-waste quantities and collection efficiency

Collection is the first stage in e-waste take-back and treatment systems, which engages in aggregating obsolete products from consumers distributed in various geographical locations. The collected volume of the take-back schemes directly influences the feedstock to the treatment facilities. The collection rate is an important indicator to evaluate the efficiency of established collection channels, and it also implies the magnitude of the uncontrolled "leakage" of e-waste not captured by the take-back schemes.

Chapter 5 of this dissertation mainly explores modeling the collection rate off of the level of obsolete products. This requires the collection quantity from the formal take-back schemes and the overall generated e-waste. As the most challenging task to accurately estimate is the quantity of e-waste generation, a multivariate input-out analysis has been developed to enhance the current methods to and approach of estimates. This proposed method applies multiple variables and available data points to improve data quality. It enables the improvement of estimate accuracy by maximizing the use of the best available data from product sales, stock and lifespan in both historical and present years. Each data point of variables contains indication for other interconnected variables, and such a method can extract useful information from the data point with higher quality to consolidate data with lower quality. The result from a Dutch case study has demonstrated the relevance and significance of applying consolidated data to improve the reliability of e-waste estimates.

Structure of the treatment chain and evaluation of its performance

After collection, the next step is to process e-waste in a network of facilities in order to fulfill both the tasks of material recycling and toxic control. A complete treatment chain is composed of three sequential stages: toxic removal, pre-processing and end-processing. The two treatment tasks are collectively accomplished by a cluster of recyclers focusing on different treatment stages, products and material fractions. Alternative approaches in three stages of a treatment chain are analyzed in detail in Chapter 7. That chapter demonstrated that it is possible to construct various end-of-life scenarios by connecting different treatment alternatives in

processing and end-processing. In the meantime, the treatment chain can be differentiated according to the characteristics of separate e-waste categories as introduced in Chapter 4. In order to reach the peak technical performance to recover all materials, high recovery rate in each treatment stage is required. Nevertheless, recycling is a very capital-intensive business with high fixed costs for initial investment in a facility, equipment and technology. High technical performance requires the installation of state-of-the-art technology under substantial investment support. However, implementation of advanced treatment technologies also needs to have a proper combination and balance with socio-economic factors such as economy and environment.

Chapter 7 further examines the external societal sub-system influencing the implementation of technologies in the technical sub-system. Combining the theoretical analysis and developing experience from pilot projects, it has been found out that realizing maximal recovery rates for all materials in a single product is very difficult. This applies to both industrialized countries and emerging economies as well. A series of material dismantling trials for various products has proven that socio-economic conditions greatly influence the feasibility and selection of alternative pre-processing (dismantling versus mechanical separation) and end-processing techniques (state-of-the-art treatment versus low-tech or substandard treatment). Therefore, making assessments not only based on technical performance, but also their economic and environmental impacts will provide a more realistic picture for selection, implementation and operation of optimal technologies under a given societal context. The elements for assessment can include data such as: mass balances of products and materials, market prices of primary and secondary resources, various costs associated with the treatment activities (especially for technological installation, machinery and labor) and associated environmental impact. Besides assessments based on fact and data, pilot projects testing innovative techniques or treatment alternatives can provide fresh ideas for improving or upgrading the current technology. It will help to identify realistic opportunities and barriers beyond the theoretical assessment.

Exclusively for developing countries, a philosophy named the "Best-of-2-worlds" (Bo2W) has been proposed as an intermediate treatment solution for these regions. In most emerging economies, there is a lack of comprehensive treatment infrastructure spanning all the steps from disposal of products until final processing due to limited infrastructure and access to technologies and investment. The Bo2W philosophy seeks technical and logistic integration of "best" pre-processing in developing countries to manually dismantle e-waste and "best" end-processing to treat hazardous and complex fractions in international state-of-the-art end-processing facilities. The Bo2W philosophy can serve as a pragmatic and environmentally responsible transition before the establishment of end-processing facilities in developing countries is made feasible. The executive models of Bo2W can be flexibly differentiated for various countries by adjusting to local conditions related to operational scale, level of centralized activities, dismantling depth, combination with mechanical processing and optimized logistics to international end-processors.

Occupational impact from e-waste treatment

Due to the presence of hazardous materials and substandard treatment, the environmental issues of e-waste recycling are a major concern. It has been recognized that most environment impact of substandard treatment can result in severe health damage on workers and local residents. Workers are regarded as the most vulnerable target group under long-term and high-concentration exposure to pollutants.

Chapter 8 has proposed methods to specifically incorporate the occupational and indoor environment into the existing framework of Life Cycle Assessment (LCA). The developed "extended LCA" allows for a more thorough assessment of environmental impact covering all spatial/geographical scales and coming to a meaningful action agenda to reduce health risks for workers. Furthermore, the fundamental consideration of Risk Assessment has also been integrated into LCA in order to understand the severity of the impact by comparing with baseline scenarios and relevant health standards. The case study of LCD monitor treatment demonstrates that the impact intensity in the occupational environmental is much higher than the impact in outdoor environments. Health damage to indoor workers will escalate when there is no continuous ventilation or toxic control measures installed in the occupational environment. To obtain credible assessment results, data for the actual settings of working space and processes need to be obtained, with support from environmental modeling of pollutant dispersions in various compartments.

Extended LCA studies covering comprehensive geographical and temporal scales can provide more accurate guidance for technological comparison, improvement and upgrading for e-waste treatment processes. It can also present useful insights and precautions for designing appropriate treatment processes and EHS measures at the planning phase in order to minimize the intake of pollutants and lower health risks for workers and residents.

Overall conclusions

Combining the chief findings of the research work, it can be concluded that establishing take-back and treatment system to manage e-waste is a challenging task due to the complexity of e-waste streams. An optimized system must achieve high technical performance for collection quantity and treatment efficiency, as well as societal performance in terms of the environment and cost. E-waste is an emerging and dynamic waste type, and the development of take-back and treatment system needs to take a progressive approach to improve steadily. It has been demonstrated that science and research can play a significant role in understanding the nature of problems and identify gaps for improvements during this development process.

Evaluating the performance of the present system can help to identify improvement options by comparing with expected targets, scenarios and visions. The classification of e-waste in this dissertation has improved the understanding about the heterogeneous characteristics of e-waste. It can reduce the complexity of e-waste management and facilitate priority setting by nine generic categories instead of using numerous product types. The multivariate method developed

to evaluate the e-waste quantities can enhance the accuracy of estimating collection efficiency for take-back schemes by consolidating available data and improving data quality. Assessment of the technical, environmental and economic performance of treatment systems can help to improve the eco-efficiency for the industry, while taking the local situation into consideration. The method proposed on evaluating the occupational impact of treatment can facilitate the implementation of essential environmental, health and safety measures in facilities. The multidisciplinary research conducted in this dissertation will assist the progress of upgrading take-back and treatment systems for more collection and better treatment in both developed and developing countries.

Appendix 1: Abbreviations

Bo2W	Best-of-2-Worlds
CDD	Compact Disc Drive
CE	Consumer Equipment
CF	Characterization Factor
CFC	Chlorofluorocarbon
CN	Combined Nomenclature Database for the external trade statistics of goods
CRT	Cathode Ray Tube
CTU	Comparative Toxic Unit
DVD	Digital Video Disc
EEE	Electrical and Electronic Equipment
EF	Effect Factor
EHS	Environment, Health and Safety
EMPA	Swiss Federal Laboratories for Materials Testing and Research
EoL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
FDD	Floppy Disc Drive
FF	Fate Factor
FR	Flame Retardant
HDD	Hard Disc Drive
HH	Household
ICT	Information and Communication Technology
IOA	Input-Output Analysis
IT	Information Technology
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCIA	Life Cycle Impact Assessment
LED	Light-emitting Diode
LHHA	Large Household Appliances
LME	London Metal Exchange
MB	Mother Board
MFA	Mass Flow Analysis
MSW	Municipal Solid Waste
NGO	Non-Governmental Organization
OECD	The Organization for Economic Co-operation and Development

OEM	Original Equipment Manufacturer
OSAH	Occupational Safety and Health Administration (United States)
PBB	Poly-Brominated Biphenyls
PBDE	Poly-Brominated Dimethyl Ethers
PCB	Polychlorinated Biphenyl
PRO	Producer Responsibility Organization
Prodcom	Production Statistics Database for the domestic statistics on the production of manufactured goods
PROF.	Professional (Equipment)
PS	Powder Supply
PVC	Polyvinyl Chloride
PWB	Printed Wiring Board
QWERTY	Quotes for environmentally WEighted RecyclabiliTY
RA	Risk Assessment
RoHS	Restriction on the use of Hazardous Substances (EU Directive)
SFA	Substance Flow Analysis
SHHA	Small Household Appliances
StEP	Solving the E-waste Problem Initiative
TBBA	Tetrabromo-bisphenol-A
TPO	Third Party Organization
UNEP	United Nations Environmental Programme
UNU	United Nations University
US EPA	Environmental Protection Agency (United States)
USEtox	The UNEP-SETAC Toxicity Model
WEEE	Waste Electrical and Electronic Equipment
XF	Exposure Factor

Appendix 2: List of Tables

Appendix 3: List of Figures

Samenvatting

Afval van elektrische en elektronische apparatuur, met een Engelse term ook wel e-waste genoemd, vormt een groeiende afvalstroom met complexe en heterogene eigenschappen. De afgelopen 20 jaar hebben beleidsmakers en producenten overal ter wereld speciale inzamelings- en verwerkingssystemen opgezet om e-waste van eindgebruikers te verzamelen en het te verwerken in recycling- en afvalverwerkingsbedrijven. Deze dissertatie is er in eerste instantie op gericht om methoden te ontwikkelen waarmee de prestaties van deze systemen voor het ophalen en verwerken van e-waste kunnen worden geëvalueerd. Met de uitkomsten van het onderzoek kunnen verbeterpunten en mogelijke systeemaanpassingen aangewezen worden, die de prestaties van een systeem qua eco-efficiëntie verbeteren.

Deze dissertatie onderzoekt met name de infrastructuren voor inzameling en verwerking op basis van een gedegen begrip van de eigenschappen van e-waste. De prestatiebeoordeling in deze dissertatie rust op twee pijlers: een beoordeling op technische aspecten, zoals de hoeveelheid ingezameld elektronisch afval en de efficiëntie van de verwerking, en een beoordeling op sociale aspecten, zoals de impact op economie en milieu. Hiermee zijn de resultaten niet alleen valide qua theoretische analyse, maar ook toepasbaar in de dagelijkse praktijk.

De algemene onderzoeksvraag is uitgesplitst in vier onderling samenhangende delen: 1) een complete analyse van de kenmerken van e-waste; 2) een methode om de hoeveelheid e-waste en de efficiëntie van een inzamelprogramma te bepalen 3) een methode om de technische, milieutechnische en economische resultaten van een verwerkingsinfrastructuur en systeemoptimalisatie onder specifieke sociaaleconomische omstandigheden in kaart te brengen; en 4) een evaluatie van de beroepsrisico's die de verwerking van elektronisch afval met zich meebrengt. Voor deze vier delen zijn overeenkomstige methoden en casestudy's ontwikkeld en toegepast. Deze worden besproken in de verschillende hoofdstukken.

In hoofdstuk 4 worden EEE (gangbare Engelse afkorting voor elektrische en elektronische apparatuur) en e-waste geclassificeerd op grond van een aantal representatieve criteria om de kenmerken van deze afvalsoort volledig te begrijpen. Er worden negen algemene categorieën vastgesteld door de individuele classificatie te combineren met vijf afzonderlijke criteria: producttype, gemiddeld gewicht, potentiële marktwaarde, milieuwinst door recycling en toxisch potentieel bij de verwerking aan het einde van de productlevenscyclus. Per categorie worden gedifferentieerde vereisten geanalyseerd voor de uiteindelijke verwerking. Denk hierbij aan inzamelingsmethoden, verwerkingstechnologieën en maatregelen voor het beheer van giftige stoffen. De uitkomsten maken het mogelijk de operationele en beheersefficiëntie van deze

systemen aanzienlijk te verbeteren en de kritieke categorieën met de meeste impact te prioriteren.

In hoofdstuk 5 wordt een input/outputanalyse met meerdere variabelen ontwikkeld om de huidige benadering voor het schatten van hoeveelheden e-waste te verbeteren. De voorgestelde methode past meerdere variabelen en beschikbare datasets toe om de gegevenskwaliteit te verbeteren. Hiervoor wordt maximaal gebruikgemaakt van beschikbare historische en actuele gegevens over verkochte producten, voorraden en levensduur. Het resultaat van een Nederlandse casestudy toont aan hoe belangrijk het is om geconsolideerde gegevens toe te passen om schattingen van e-waste betrouwbaarder te maken. Deze methode kan nauwkeuriger inschattingen opleveren van de efficiëntie van bestaande inzamelprogramma's. Ook kan zo worden nagegaan waar er nog e-waste ongecontroleerd door de mazen van het systeem glipt.

Hoofdstuk 6 analyseert de basisstructuur en opzet van de e-wasteverwerkingsketen. Er wordt op detailniveau ingegaan op drie opeenvolgende verwerkingsstadia en de bijbehorende regelingen en alternatieve technieken: verwijdering van giftige stoffen, voorbehandeling, en eindverwerking. Door diverse alternatieven aan deze drie verwerkingsstadia te koppelen kunnen verschillende scenario's worden opgesteld voor het einde van de productlevensduur. Voor een optimaal technisch resultaat om alle materialen te kunnen terugwinnen is in ieder stadium een hoge terugwinscore vereist.

Hoofdstuk 7 gaat dieper in op de sociaaleconomische omstandigheden die invloed hebben op de implementatie van verwerkingstechnologieën. Op basis van de theoretische analyse in combinatie met de ontwikkelde ervaring uit testprojecten kan worden geconcludeerd dat sociaaleconomische omstandigheden (personeelskosten, wetgeving, verwerkingsnormen, beschikbaarheid van investeringskapitaal, etc.) van grote invloed zijn op de haalbaarheid en selectie van methodes voor voorbehandeling (demontage versus mechanische scheiding), en eindverwerking (technisch hoogwaardig, of lowtech en kwalitatief inferieur). Exclusief voor ontwikkelingslanden wordt een filosofie voorgesteld onder de noemer "Best-of-2-worlds" (Bo2W). Bo2W integreert de technische en logistieke best practices van handmatige demontage tijdens de voorbehandeling in ontwikkelingslanden met de best practices voor eindverwerking van gevaarlijk en complex afval in internationale, technisch hoogwaardige installaties. Dit wordt gezien als een pragmatische en milieuverantwoorde oplossing, totdat het haalbaar is om ook in opkomende economieën technologisch hoogwaardige installaties voor eindverwerking te bouwen.

Hoofdstuk 8 ontwikkelt een methode om de impact van de verwerking van e-waste op de werknemers te meten. Het voegt de werkomgeving en de binnenomgeving toe aan het bestaande kader voor Life Cycle Assessment. Verder wordt ook de risicoanalyse als fundamenteel element toegevoegd aan de methode, om inzicht te krijgen in hoe groot de impact is als men kijkt naar de relevante gezondheidsstandaards. Een casestudy van de verwerking van lcd-schermen toont aan dat de mate van impact op de werkomgeving veel groter is voor werknemers dan de impact op de buitenomgeving, zoals die door het grote publiek wordt ervaren. Deze methode maakt het mogelijk om essentiële maatregelen op het gebied van milieu,

gezondheid en veiligheid te implementeren om de gezondheidsrisico's voor medewerkers in verwerkingsinstallaties terug te dringen.

In hoofdstuk 9 worden aanbevelingen gegeven voor specifieke stakeholders, zoals wetgevers, producenten, recyclers, operators en managers van terugwinning- en verwerkingssystemen. Ook worden potentiële onderzoeksvragen geformuleerd voor verdere ontwikkeling op basis van deze dissertatie.

Het onderzoek in deze dissertatie vertegenwoordigt de meest recente stand van zaken op zowel wetenschappelijk terrein, als ervaringen met implementatie op het gebied van e-wastemanagement op wereldwijd niveau. Het kan een significante rol spelen voor het begrip van e-wasteproblematiek en bij het in kaart brengen van kritieke verbetermogelijkheden. De onderzoeksresultaten kunnen de systemen voor het terugwinnen en verwerken van e-waste helpen verbeteren, om meer elektronisch afval op te halen en het ecologisch efficiënter te verwerken, zowel in ontwikkelingslanden als in rijkere landen.

Publications

Articles published in peer-reviewed journals

Wang, F., J. Huisman, C. Meskers, M. Schluep, A. Stevels and C. Hagelüken (2012). "The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies." Waste Management 32: 2134-2146.

Wang, F., J. Huisman, A. Stevels and C. P. Baldé (2013). "Enhancing e-waste estimates: Improving data quality by multivariate Input–Output Analysis." Waste Management 33(11): 2397–2407.

Bakker, C., F. Wang, J. Huisman and M. den Hollander "Products that go round: exploring product life extension through design." Journal of Cleaner Production. http://dx.doi.org/10.1016/j.jclepro.2014.01.028

Stevels, A., J. Huisman, F. Wang, J. Li, B. Li and H. Duan (2013). "Take back and treatment of discarded electronics: a scientific update." Frontiers of Environmental Science & Engineering: 1-8.

Conference papers

Wang, F. and J. Huisman (2010). Formalisation of e-waste collection and recycling in China. Proceedings of CARE Innovation conference. Vienna, Austria.

Wang, F., J. Huisman, K. Baldé and A. Stevels (2012). A systematic and compatible classification of WEEE. Electronics Goes Green. Berlin, Germany.

Huisman, J., C. Luepschen and F. Wang (2010). E-Waste – How to ADDRESS the Size of the Problem. Proceedings of CARE Innovation conference. Vienna, Austria.

Schluep, M., C. Hagelüken, C. Meskers, F. Magalini, F. Wang, E. Müller, R. Kuehr, C. Maurer and G. Sonnemann (2009). Market potential of innovative e-waste recycling technologies in developing countries. R'09 World Congress. Davos, Switzerland.

Reports

Wang, F., R. Kuehr, D. Ahlquist and J. Li (2013). E-waste in China: a country report. Bonn, Germany, United Nations University.

Huisman, J., M. van de Maesen, R. J. J. Eijsbouts, F. Wang, C. P. Baldé and C. A. Wielenga (2012). The Dutch WEEE Flows. Bonn, Germany, United Nations University, ISP-SCYCLE.

Magalini, F., J. Huisman, F. Wang, R. Mosconi, A. Gobbi, M. Manzoni, N. Pagnoncelli, G. Scarcella, A. Alemanno and I. Monti (2012). Household WEEE Generated in Italy, Analyis on volumes & Consumer Disposal Behavior for Waste Electric and Electronic Equipment. Bonn, Germany, United Nations University.

Schluep, M., C. Hagelüken, R. Kuehr, F. Magalini, C. Maurer, C. Meskers, E. Mueller and F. Wang (2009). Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling - from E-waste to resources. Bonn, Germany, United Nations Environment Programme & United Nations University.

About the author

Feng WANG, was born on 23 May 1983 in Daye, China. He obtained his BSc in Environmental Engineering from the Nanjing University of Science and Technology in 2004 and his MSc in Environmental Management from Nanjing University in 2007. In 2008, he received his second MSc in Industrial Ecology, a joint program organized by Leiden University, Delft University of Technology and Rotterdam Erasmus University. He started his PhD studies at Delft University of Technology in 2009, with the research topic in assessing the performance of e-waste take-back and treatment systems.

He has been also working in the United Nations University and the Solving the E-waste Problem (StEP) Initiative since 2007. He has participated in a variety of development projects under the United Nations platform, focusing on e-waste recycling, technology transfer, knowledge sharing, and capacity building for developing countries. He has also been involved in research projects seeking to quantify regional and global e-waste quantities and flows, to assess life cycle impacts of e-waste activities and to identify the best policy instruments and tools for dealing with e-waste.