Evaluation of Recyclability and Recycling Efficiency of Metals for Waste Printed Circuit Boards

Hoang-Long Le

Acknowledgment

This work would not have been possible to do without the support and guidance that I received from many people.

I would like to first say a very big thank to my supervisor Prof. Keiichi N. Ishihara for all the supervision and support as well as encouragement he gave me, during my PhD studies in his lab. Without his kind guidance this PhD would not have been achievable. Many thanks also to Assoc. Prof. Hideyuki Okumura and Assist. Prof. Eiji Yamasue who gave me many valuable suggestions and advices. I would also like to express my sincere gratitude to the members of the dissertation committee, Prof. Shinichi Sakai and Prof. Susumu Tohno for their helpful comments.

I gratefully acknowledge the financial support from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan for providing me PhD fellowship. I am also grateful to the funding received through the "Energy Science in the Age of Global Warming" of Global Center of Excellence (G-COE) program (J-051). I am indebted to all my friends for all their kind helps and shares in my life in Japan. I would also like to say a heartfelt thank to my Mom, Dad, older sister for always believing in me and encouraging me to follow my dreams. I owe a very important debt to my wife's family for their enormous tolerance and support during my stay abroad.

Last but not least, a very special thank to my wife, Mrs. Vu Viet Ha, my daughters Le Vu Phuc Hoa and Le Vu Phuc Linh whose patient love enabled me to complete this work.

Abstract

According to European Association of Metals, recycling efficiency is an indicator of the recycling performance of products as well as recovery processes. It provides the crucial information helpful for metal recycling industry to optimize the system, for policy makers to develop an easily understandable benchmark in order to encourage rather than hamper metals recycling in any upcoming legislation, for public make informed choices when selecting products and services. However, up to now, a consistent measure to quote the metal recycling efficiency has not been available for the metals recycling in both practical and scientific points of view. As a consequence, a variety of different methods for calculating metals recycling efficiency with different meanings and implications has resulted in some confusion and a lack of understanding of the efficiency with which metals are recycled.

The recovery of valuable metals from waste Printed Circuit Boards (PCBs) is an attractive business recently since PCBs typically contain about 40% of metals with a wide range of elements from precious metals (e.g. gold, silver, palladium, platinum), rare metals (e.g. beryllium, indium), base metals (e.g. copper, aluminum, nickel, tin, zinc, iron), and toxic heavy metals (e.g. lead, cadmium, arsenic, antimony). Each metal element contained in PCBs has its own specific properties according to different points

of view such as weight content, economic value, environmental impacts, natural resources depletion, etc. Hence, each of metal fractions will have different shares of the total metal recyclability of product. The relative share value of each metal fraction will fundamentally affects the recycling efficiency of metals from waste PCBs.

The main frame of this study is the analysis of the metal recyclability from waste PCBs with three material recycling quoting approaches: Material Recycling Efficiency (MRE) which is based on solely weight basis, Resource Recovery Efficiency (RRE) which is based on natural resource conservation aspect, and Quotes for Environmentally Weighted Recyclability (QWERTY) which is based on environmental impact aspect. The results indicate that MRE is likely inapplicable to quoting the metal recyclability of waste PCBs because it makes the recycling of any metal equal to each other (e.g. recycling of 1 kg of gold is as important as recycling of 1 kg of iron). It is obviously irrespective to the sense of nature. RRE and QWERTY can overcome the poor yardstick of MRE because they concern not only the weight of recycled materials but also the contribution of recycled materials to the natural resource conservation and the environmental impact reduction, respectively. These two approaches, however, report extremely different results from each other. If followed one of them, the metal recyclability would be over or underestimated. That makes the target stakeholders get

confused with which material recycled. On the other hand, metal recycling mainly contributes to sustainability issues (natural resource conservation and reduction of environmental impacts), and furthermore, the study also finds that the weight aspect, the resource conservation aspect, and the environmental impact aspect of metal recycling always exist together. Hence, they should be evaluated simultaneously. Base on this general idea, this study proposes the Model for Evaluating Metal Recycling Efficiency from Complex Scraps (MEMRECS) as a new composite approach to quotes the metal recycling performance for waste PCBs. MEMRECS actually is a compensatory aggregation of MRE, RRE and QWERTY, which solves the trade-offs between these three criteria. Thus, MEMRECS can provide the result that enhances the role of metal recycling as raising the sustainability of production by reducing the need for primary production, thus saving energy and extending the longevity of natural resources.

For the sensitivity analysis, MEMRECS for waste PCBs is calculated with four difference life cycle impact assessment (LCIA) methods: the Eco-indicator ’95, the Eco-indicator ’99, EDIP 2003, and Impact 2002+ in order to estimate the influence of the choice of the LCIA method on the result. The findings demonstrate the recycling efficiency of metals from waste PCBs is remarkably varied with different LCIA methods. Such variation is indeed derived from the substantial change in the relative

contribution of individual metal fraction to the total metal recyclability. Within a certain LCIA method, the efficiency of metal recycling is strongly dependent on the individual recovery rate of each metal fraction.

QWERTY and MEMRECS are used to quote the efficiency of metals recovery from waste printed circuit boards (PCBs) at two well-known facilities: Boliden's Rönnskär smelter in Sweden and Umicore's integrated metals smelter and refinery in Belgium, under the certain assumptions. According to QWERTY, these two facilities yield a high efficiency of metals recovery from waste PCBs (i.e., from 80% to 96% depending on type of waste PCBs). The efficiency of metals recovery from waste PCBs at these two facilities is slightly different (less than 5%). According to MEMRECS, it however becomes clearly significant (about 17-27%) except the case of waste PCBs from cell phone (about 3%). Tin is found one of the most important contributors of the metals recyclability of waste PCBs. Thus the recovery of tin should be appreciated obtain high recycling performance.

MEMRECS approach is also used to investigate the sensitivity of gold content in waste PCBs to the recycling efficiency of metals from waste PCBs. The findings indicate that gold content is identified as a key factor determining the efficiency of metals recovery from waste PCBs. Furthermore, it could be used as indicator for the

categorization of waste PCBs before feeding into recycling process. Base on that, an integrated process is proposed to optimize the efficiency of metals recovery from waste PCBs in developing countries.

As an example application, MEMRECS is used to evaluate the metal recycling efficiency according to the end-of-life scenarios for waste printed circuit boards (PCBs) from consumer electronic products in Vietnam. The results demonstrate that MEMRECS is applicable to the end-of-life scenario analysis of metal recovery from metals-bearing products. Regarding the solutions for waste PCBs in Vietnam, the current situation of exporting to informal sectors in China would be the worst way due to the huge loss in both natural resources and environmental benefit. Feeding into an existing primary copper smelter could be a good way but only for PCBs containing high gold content. Exporting to the state-of-the-art end-processing facility would yield the highest efficiency for all types of PCBs, which is in an agreement with the 'Best-of-2-Worlds' philosophy.

Contents

List of Tables

List of Figures

Acronyms

RRP: Resource recovery potential

RRE: Resource recovery efficiency

LCA: Life cycle assessment

QWERTY: Quotes for environmentally weighted recyclability

MEMRECS: Model for metal recycling efficiency for complex scraps

LCIA: Life cycle impact assessment

PCBs: Printed circuit boards

MCDA: Multi-criteria decision analysis

WSM: Weighted sum model

WPM: Weighted product model

AHP: Analytic hierarchy process

ELECTRE: Elimination and choice expressing reality

TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution

MAUT: Multi attribute utility theory

CRITIC: Criteria importance through inter-criteria correlation

MRQ: Material recycling quoting

ICP-MS: Inductively couple plasma mass spectrometry

CRT TV: Cathode-ray tube television

Desktop PC: Desktop personal computer

QWERTY/Eco-indicator'99: QWERTY expressed with Eco-indicator'99

IPU: Institute for product development

WEEE: Waste from electrical and electronic equipment

EOL: End-of-life

CHAPTER 1

Introduction

1.1 Research background

Metals are one category of a trio of geological materials on which our present industrial civilization is based. The other two categories are mineral fuels like coal, petroleum and natural gas, and nonmetallic like stone, sand and gravel, salt or clays. Since the Bronze Age, our evolving civilization has depended on metals and this will continue in the future, despite the increasing competition metals are now receiving from organic and organometalic synthetics (e.g. plastic, silicone, graphite) and composite materials [1].

For thousands of years the primary mining industry has supplied the world with raw materials the growing population needed for ever increasing consumption. Metals mining and ore processing for metals production directly impact the environment through deforestation, habitat destruction, and pollution. Common problems include acid mine drainage and the use of toxic chemicals, such as cyanide. The supply chain, from ore in the ground to finished product, also usually requires large amounts of energy and produces significant greenhouse gas emissions [2]. On the other hand, metals are a finite and nonrenewable resource, and whether or not we care about the impact of mining, extraction cannot continue indefinitely. In this situation, next to the

primary mining industry a secondary mining industry as known as metal recycling is growing drastically, and becoming a key factor for the sustainable civilization.

Unlike other materials, metals are not biodegradable and have virtually an unlimited lifespan and the potential for unlimited recyclability. Hence they are well suited for sustainable development goals [3]. If appropriately managed, recycling metal can provide numerous benefits for the environment in terms of energy savings, reduced volumes of waste, and reduced greenhouse gas emissions associated with energy savings. For example, the amount of energy saved using various recycled metals compared to virgin ore is up to 95 percent for aluminum [4], 85 percent for copper [5], 60 percent for steel [6], 75% for zinc [4], and 90% for nickel [7]. Metal recycling also conserves natural resources by reducing the amount of virgin ore needed to be mine, as well as other resources. For instance, recycling one ton of steel conserves 2,500 pounds of iron ore, 1,400 pounds of coal and 120 pounds of limestone. Recycling a ton of aluminum conserves up to 8 tons of bauxite ore [8].

In general, efficiency is a measurable concept, quantitatively determined by the ratio of output to input. As a consequence, metal recycling efficiency can be defined as the ratio of output to input of a metal recycling system. The term output and input can be stand for the performance associated with various approaches. In practice, metal

recycling efficiency of the recycling process is mostly calculated based on weight basis approach, which is represented by the ratio of the amount of metal actually recycled over the total amount of metal available for recycling. In the scientific point of view, some models have been developed to quote the material recyclability of product. For example, the widely applied quantification tools for calculating the efficiency of recycling process based on natural resources conservation aspect are the concept of resource recovery potential (RRP) and resource recovery efficiency (RRE), developed by Legarth et al., 1995 [9]. RRP was constructed based on two factors. The first one describes the consequences of the recycling action – the times of primary raw material production saved by the recycling action. The second one indicates the importance of the resources conservation. The RRE states the performance of the recycling system realizing the potential RRP, in that RRE divided by RRP can be interpreted as efficiency. Life cycle assessment (LCA) is a standard approach for environmental impact evaluation. Based on LCA data, Huisman et al., 2003 [10] developed QWERTY concept (Quotes for environmentally Weighted RecyclabiliTY) for calculating product recyclability on a real environmental basis. The QWERTY score is based on the net 'environmental value' recovered over the 'total environmental value' of a product.

In summary, metal recycling efficiency is an important indicator to evaluate the

metals recycling performance. It provides the crucial information helpful for metal recycling industry to optimize the system, for policy makers to develop an easily understandable benchmark in order to encourage rather than hamper metals recycling in any upcoming legislation, for public to make informed choices when selecting products and services. However, up to now, a consistent measure to quote the metal recycling efficiency has not been available for the metals recycling in both practical and scientific points of view. As a consequence, a variety of different methods for calculating metals recycling efficiency with different meanings and implications has resulted in some confusion and a lack of understanding of the efficiency with which metals are recycled [12].

1.2 Problem definitions and research objectives

Although the weight basis only approach is mostly used in practice, it is, however, only appropriate for calculating recycling efficiency of homogeneous metal scraps such as recycling aluminum and tin from aluminum and tin cans, recycling steel from steel scraps, recycling copper from copper wire scraps, where without the competition between the contributions of different metal fractions to total recyclability of products. For scraps containing various metal fractions such as spent printed circuit boards, this measure probably provides incorrect information to target audiences, and leads to

misleading conclusions because each type of metal has its own particular properties regarding to various evaluation aspects. For example, it makes the recovery of 1 kg of iron or even concrete as important as recovering 1 kg of gold [11]. Thus metal recycling efficiency calculated on weight basis only approach is obviously not a solution in itself without considering the associated aspects to which the metals recycling directly contributes.

The RRE model based on natural resources conservation approach and the QWERTY model based on environmental impacts approach to quote the metal recycling efficiency can overcome the inherent problem of weight basis only approach. However, the metal recycling efficiency for the same product and recycling system reported by these two models is sometimes extremely different from each other. It means that if followed natural resources conservation approach, the environmental benefits would be sacrificed and vice versa. On the other hand, the natural resources conservation and environmental benefit of metals recycling always exits together, hence these two aspects should be considered simultaneously in the calculation of metal recycling efficiency.

For the notions mentioned above, the main objective of the study is to propose a new model to calculate the metals recycling efficiency specified for products that contains various metal fractions. The model is named as Model for Evaluating Metal

Recycling Efficiency for Complex Scraps (MEMRECS), in which two practical issues that metal recycling mainly contributes to the sustainable development (natural resources conservation and environmental benefits) are taken into account concurrently. As a result, MEMRECS probably solves the trade-offs between criteria, namely a poor result in environmental benefit aspect can be negated by a good result in natural resources conservation view point and vice versa. Thus, it can provide the result in an environmentally sound and sustainable exploitation manner.

Another objective of this study is to present the sample calculations as well as the sample applications of MEMRECS for metals recycling from spent printed circuit boards.

1.3 Layout of the thesis

The thesis is structured with 8 chapters as followings:

Chapter 1 describes an overview of the background of the importance of metal recycling to the sustainable development and civilization. It also introduces the measures used to calculate material recycling efficiency in either practical or scientific points of view, and their problem in application to practical issues. Finally, it shows the objective of the study.

Chapter 2 introduces the major concepts and definitions used in the study. In this

chapter, the overview of waste PCBs recycling, life cycle assessment, multi-criteria decision making methods, and metal reserves are described in succession.

Chapter 3 proposes the MEMRECS as a new quantitative measure to calculate metals recycling efficiency. The sample calculation of MEMRECS for waste PCBs and the comparison with previous models are demonstrated and discussed.

Chapter 4 calculates MEMRECS for different types of PCBs with four different life cycle impact assessment (LCIA) models to investigate the sensitivity of MEMRECS with the choice of LCIA models.

Chapter 5 uses MEMRECS and QWERTY to assess the eco-efficiency of metals recovery from waste printed circuit boards (PCBs) at two well-known facilities: Boliden's Rönnskär smelter in Sweden and Umicore's Hoboken smelter in Belgium, under the certain assumptions.

Chapter 6 examines the role of every metal fraction to the recyclability of metal from waste PCBs by using MEMRECS. The examined results are then used to identify and select the most sustainable solutions for recovery of metals from waste PCBs under given constraints in developing countries.

Chapter 7 is about a sample application of MEMRECS, in which the metal recycling efficiency for waste PCBs in Vietnam is assessed with different End-of-Life

scenarios.

Finally, chapter 8 summarizes the overall results of the study

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CHAPTER 2

Literature Review

2.1 Metals recycling from waste printed circuit boards

Printed circuit board (PCB) is one of the most common components inside the Electrical and Electronic Equipment (EEE) at which without it, those EEE cannot function properly [1,2]. In general PCB represents about 8% by weight of waste from electric and electronic equipments (WEEE) collected from mall appliances and about 3% of the mass of global WEEE [3].

Typically PCBs contain 40% of metals, 30% of organics and 30% ceramics. However, there is a great variance in composition of PCB wastes coming from different appliances, from different manufacturer and of different age [3]. The type of plastics is predominantly C-H-O and halogenated polymers. Nylon and polyurethane are also used sometime in smaller amounts. Metals in PCBs consist of a large amount of base metals such as copper, iron, aluminum and tin; rare metals like tantalum, gallium (and other rare platinum groups metals); noble metals such as gold, silver and palladium. Hazardous metals such as chromium, lead, beryllium, mercury, cadmium, zinc, nickel are also present [4]. Ogunniyi et al, 2009 [5] has summarized representative material compositions of PCBs as shown in Table 1.1

Table 1.1 Representative material compositions of printed circuit boards (wt%) [5]

Materials	%[a]	%[b]	%[c]	%[d,*]	%[e]	%[f]	%[g]
Metals (Max. 40%)[a]							
Cu	20	26.8	10	15.6	22	17.85	23.47
Al	2	4.7	7	–	–	4.78	1.33
Pb	2	–	1.2	1.35	1.55	4.19	0.99
Zn	1	1.5	1.6	0.16	–	2.17	1.51
Ni	2	0.47	0.85	0.28	0.32	1.63	2.35
Fe	8	5.3	–	1.4	3.6	2.0	1.22
Sn	4	1.0	–	3.24	2.6	5.28	1.54
Sb	0.4	0.06	–	–	–	–	–
Au/ppm	1000	80	280	420	350	350	570
Pt/ppm	–	–	–	–	–	4.6	30
Ag/ppm	2000	3300	110	1240	–	1300	3301
Pd/ppm	50	–	–	10	–	250	294
Ceramic (Max 30%)[a]							
SiO_2	15	15		41.86	30	–	–
Al_2O_3	6	–	–	6.97	–		
Alkaline and Alkaline earth oxides	6	–	–	CaO 9.95 MgO 0.48	–		
Titanates, Mica, etc.	3	–	–	–	–	–	–
Plastics (Max 30%)[a]							
Polyethylene	9.9	–	–		16	–	–
Polypropylene	4.8						
Polyesters	4.8						
Epoxies	4.8						
Polyvinyl-chloride	2.4						
Polytetra-flouroethane	2.4						
Nylon	0.9						

[a] Shuey et al. (2006) from Sum (1991).
[b] Zhao et al. (2004).
[c] Zhang and Forssberg (1997).
[d] Kim et al. (2004).
[e] Iji and Yokoyama (1997).
[f] Kogan (2006).
[g] ICP–OES Analyses of cellphone printed circuit boards with hot aqua regia digestion.
[*] Incinerated printed circuit boards Product.

Toxic substances in PCBs such as brominated flame retardants (BFR), PVC plastic and various heavy metals can cause serious environmental problems if not properly disposal. If they are discarded randomly in the opening or landfilled simply, the leachate may infiltrate into groundwater and soil. Uncontrollable incineration of waste PCBs also produces potentially hazardous byproducts (including mainly dioxins, furans, polybrominated organic pollutants and polycyclic aromatic hydrocarbons) caused by burning BFR, epoxy resins and plastics [2]. However, most of the valuable metals of WEEE such as copper, tin, and especially gold and palladium are concentrated in the PCBs. Hence, recycling of waste PCBs is an important subject not only from the treatment for waste but also from the recovery of valuable materials.

In developing countries, where no specific law for e-waste recycling yet, the recycling of e-waste in general and PCBs in particular is motivated by economic gain only, with no regard towards social and environmental concerns, and is managed by a largely informal sector [6,7]. In order to recover valuable metals such as gold, silver, copper from PCBs, the informal units employ primitive techniques such as surface heat to remove gold rich components; open burning to recover copper; acid bath process to recover gold, and silver. etc [8]. Moreover, the non profitable and hazardous fractions are simply discarded to environment directly. It causes direct impacts to the workers' health and the local environment. The recycling operations and environmental damages happening in Guiyu, China [9] and Tila Byehta, India [10] are typical examples for informal recycling of PCBs.

In developed countries, where e-waste recycling practices are regulated with high consideration of environmental issues, PCBs are correctly treated by state-of-the-art technology, which can fulfill the technical and environmental requirements. The typical process is partial disassembly by hand to remove hazardous materials such as batteries and other large components; Shredding to reduce particle size; Physical separation including magnetic separation for ferrous metals, eddy current separation for non-ferrous metals, triboelectric or density based separation for plastics; Smelting to

refine out valuable metals such as gold, silver, palladium, copper and other base metals [11]. There are several highly efficient metal refinery processes in the world such as Boliden in Sweden, DOWA in Japan, Umicore in Belgium, or Xstrata in Canada.

2.2 Determining criteria weights in multi-criteria decision analysis

Multi-Criteria Decision Analysis (MCDA) is a transparent and explicit decision-making process in which criteria are identified; weights are given to each criterion to reflect the relative importance of each criterion from the decision-making body perspective; evidence and information for the criteria are gathered, considered, and scored; and weighted preference scores are derived based on the criteria weights and criteria score [12]. The main purpose in most MCDA is to measure the overall preference values of the alternatives on some permissible scales [13]. The widely used methods of MCDA has been described in Palos, 2010 [14] and Munier, 2011 [15] include weighted sum model (WSM), weighted product model (WPM), analytic hierarchy process (AHP), ELECTRE, TOPSIS, and multi attribute utility theory (MAUT).

In the field of MCDA, criteria scores which represent the performance of each alternative with respect to each of criteria and criteria weights which represent the relative importance of each criterion are two important values because they are then aggregated together to produce the final priority scores. Thus, the true meaning and the

validity of these values are crucial in order to avoid improper use of the MCDA models [13]. Criteria scores can be easily obtained by quantifying their intrinsic information of each evaluation criterion, whereas the determination of criteria weights is still in conflict since there are several methods to obtain criteria weights, and each of these methods would elicit a different set of weight from the same decision makers.

Assigning weights to the criteria is possibly the most valuable aspect of MCDA because it allows different views and their impact on the ranking of alternatives to be explicitly expressed, and, in addition, the weighting process increase problem understanding [16, 17, 18]. Many different methods have been proposed for determining criteria weights [19, 20, 21, 22, 23, 24, 25, 26, 27]. Criteria weighting methods can be separated into two classes including direct and indirect methods. Direct methods require an explicit statement of the relative importance of each criterion from the decision makers. Such statements can be recorded in qualitative or quantitative ways. Indirect methods estimate criteria weights based on simulated or real decision behaviors. They generally require the decision makers to rank or score a set of alternatives against a set of evaluative criteria. Using various techniques such as multiple linear regression analysis, it is possible to implicitly derive weights for criteria [16, 28]. Alternatively, criteria weighting methods also can be classified in to subjective and objective

approaches. Subjective approaches select criteria weights based on preference information of attributes given by decision makers which includes the eigenvector method proposed by Saaty, 1977 [29]. These methods entail subjectivity in assigning weights to criteria, and because of that, there is no guarantee that these weights will be replicated when another person or team estimates them within the same set of projects and under the same conditions and assumptions [15]. Furthermore, each of these methods would elicit a different set of weights from the same decision makers [27]. The objective approaches determine criteria weights based on intrinsic information of each evaluation criterion. Thus objective approaches can avoid the subjective influence of weight determination as much as possible. For example, the CRITIC method [27] determines criteria weights based on the quantification of two fundamental notions of MCDA: the contrast of intensity and the conflicting character of the evaluation criteria. Entropy method described in Hwang and Yoon, 1981 [30] elicits criteria weights based on the informatics theory that for a given criterion the more variance of alternatives scores the more information criterion can provide, and the more significant criterion is [15].

Since a variety of criteria weighting methods is available, the selection of an appropriate method is a difficult task, and there are many arguments and comments

about selecting criteria weighting method. Bottomley et al. (2000) [31] recognize that the selection of a criteria weighting method generally has been considered somewhat arbitrary. Hamalainen and Salo (1997) [18] stated that there are no obvious reasons given in the literature for selecting one method over another, and if researchers have not been able to make it clear which is the best method of assigning criteria weights, then they are likely to remain unclear to the actors as well. Simos (1990) [32] conclude that the method chosen to elicit criteria weights should be simple and comprehensible to all involved in the process. Rogers and Bruen (1998) [33] commented that a method that was easily understood would have more credibility than other more complex, less easily understood weighting techniques. Levy et al. (1998) [34] stated that the particular weighting method used depends on the nature of criteria, the amount of information available and the preference of the decision makers.

2.3 Life cycle impact assessment (LCIA)

Life cycle assessment (LCA) is a popular tool for evaluating environmental impacts associated with all the stages of a product and service from cradle to grave. LCIA is defined as the "phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system" (ISO 14044:2006). LCIA translates inventory data on input (resources and

materials) and output (emissions and waste) into information about the product system's impacts on the environment, human health and resources [35].

In general, LCIA transforms inventory data into information about the environmental impacts from the product system. At the same time, it reduces the inventory's numerous data items into a limited collection of impact scores. This involves modeling the potential impacts of the inventory results and expressing them as impact scores that can be added within each category. Current knowledge about the relationship between emissions and their effects on the environment is used to model the impacts to the areas of protection [35]. In more detail, LCIA consists of four key steps:

Selection of impact categories and classification. The former is to define the categories representing the product system's relevant environmental impacts. The latter one assigns the inventory's substance emissions to the relevant impact categories, according to their contribution to the environmental problems.

Characterization models the impact from each emission according to the impact pathway, and expresses an impact score in a common unit for all contributions within the category. A characterization factor is derived, which expresses each substance's specific impact. Characterization is performed by multiplying the emission with the

relevant characterization factor. The impacts from emissions of different substances can then be summed within each impact category; this translates the inventory data into a profile of environmental impact scores and resources consumptions.

Normalization puts the different impact scores onto a common scale and facilitates comparisons across impact categories. Normalization then expresses the product system's relative share of the total societal impact for each category and for each of resource consumption.

Valuation or weighing reflects the relative importance assigned to the various environmental impact and resources consumption. It applies factors to the impact scores to aggregate them into one figure.

According to ISO standard, the first two steps are mandatory and the normalization and valuation steps are optional [35].

There are two main schools of approach which have been developed to model the environmental impact:

Mid-point approach: The LCIA mid-point approach also known as problem-oriented approach or classical impact assessment method. The term mid-point refers to the category indicator for each impact category which is expressed in the mid pathway of impact between LCI results and end-point. Mid-point translates the category

impact into real phenomenon as such as climate change, acidification and aquatic toxicity [36]. Example of methodology that was developed using mid-point approach is CML 2001 [37], EDIP 2007, and TRACI [38].

End-point approach: The end-point LCIA methodology is also known as damage-oriented approach. The term end-point refers to the category indicator for each impact category located at the end of impact pathway. End-point indicator translates the category impact based on the area of protection such as human health, natural environmental quality, natural resources and human made environment [36, 39]. Examples for end-point methodology are Eco-indicator 95 and 99, EPS 92, 96 and 2000 and LIME 2003 [40].

End-point impact category is less comprehensive and poses higher level of uncertainty compared to mid-point impact category. Nevertheless mid-point impact category is difficult to be interpreted especially in the process of decision making because the mid-point impact category is not directly correlated with the area of protection [41]. The mid-point and end-point schools of approach, however, are not incompatible. As more and better environmental models become available, the optimal indicator point will move toward the areas of protection. And, as larger parts of the impact pathway are include in the characterization modeling, the mid-point approach

will become more like the end-point approach. Until they converge, the two approaches will complement each other [35, 42].

Following is brief overview of some available LCIA methods:

Eco-indicator 95 [43] considers nines impact categories as shown in Figure 2.1. Normalization in Eco-indicator 95 refers to the reference value defined as the average yearly contribution for a given impact category per person in Europe. This is calculated by the estimate of the overall emission level, divided by 1990 European levels of population. Weighting in Eco-indicator' 95 is based on a distance-to-target criterion, which means the method considers the distance between present value of the category indicator and the objective value which should be reached at European level. The larger distance from target, the higher is the weight for the category indicator [44].

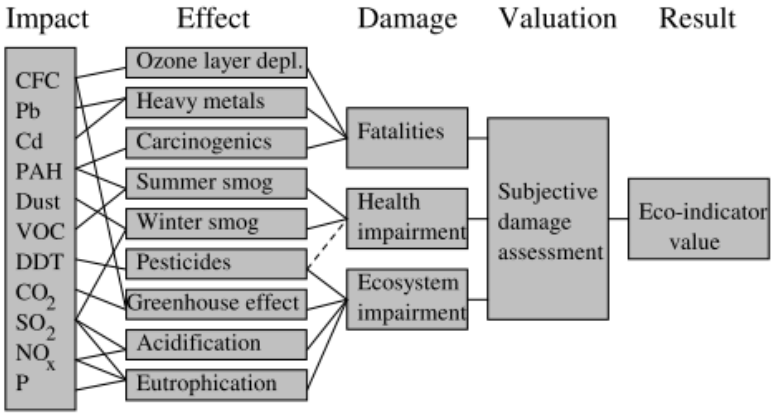

Figure 2.1 General representation of the Eco-indicator' 95 methodology [43]

Eco-indicator' 99 is the successor of Eco-indicator' 95 but it has some key changes. Instead of using the distance-to-target method, the weighting has been developed by an expert panel group. Eco-indicator' 99 is a damage-oriented method of LCA, thus all type of impact are reduced to three damage categories: damage to human health, damage to ecosystem quality and damage to resources. The indicators per damage category are expressed in a common unit: Damage to human health is expressed in Disability Adjusted Life Years (DALY); Damage to ecosystem quality is expressed as percentages of all species that have disappeared in a certain area due to the environmental load; Resource extraction is related to a parameter that indicates the quality of the remaining mineral and fossil resources. Figure 2.2 provides a graphical presentation of the Eco-indicator' 99.

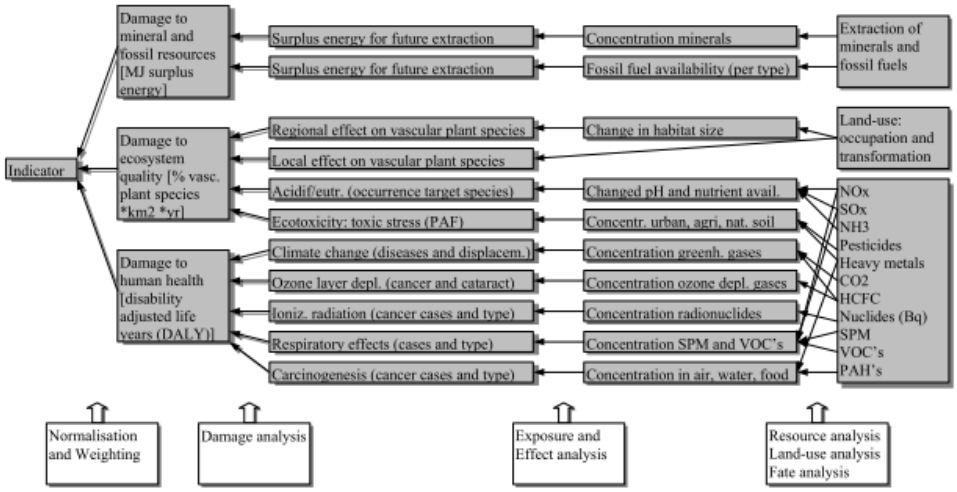

Figure 2.2 General representation of the Eco-indicator' 99 methodology [45]

IMPACT 2002+ proposes the implementation of a combined mid-point/damage-oriented approach. The IMPACT 2002+ links all types of life cycle inventory results from 14 mid-point categories to four damage categories (human health, ecosystem quality, climate changes and resources) [47]. The general structure of the IMPACT 2002+ is shown in Figure 2.3. For IMPACT 2002+, concepts and methods have been developed, especially for the comparative assessment of human toxicity and eco toxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. Both human toxicity and eco toxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from existing characterizing methods (Eco-Indicator 99 and CML 2001). All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be carried out either at midpoint or at damage level and the IMPACT 2002+ method presently provides characterization factors for different LCI-results [47].

CML 2001 is a mid-point LCA method. It is developed by the institute of environmental science (CML) of Leiden University. The general structure of the CML

2001 is presented in Figure 2.4. Each impact category is characterized by a mid-point indicator which uses a defined reference substance in order to quantify the impact of a classified emission in relation to the reference substance. CML 2001 includes normalization and weighting factors for mid-point indicators on a national (Netherland), regional (Western Europe) and global scale [48].

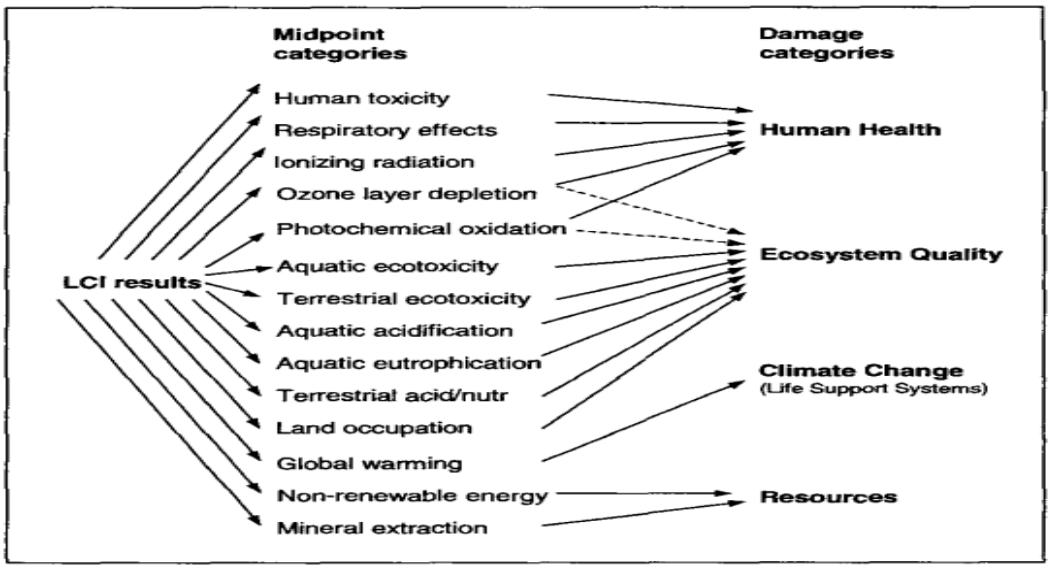

Figure 2.3 General representation of the IMPACT 2002+ methodology [47]

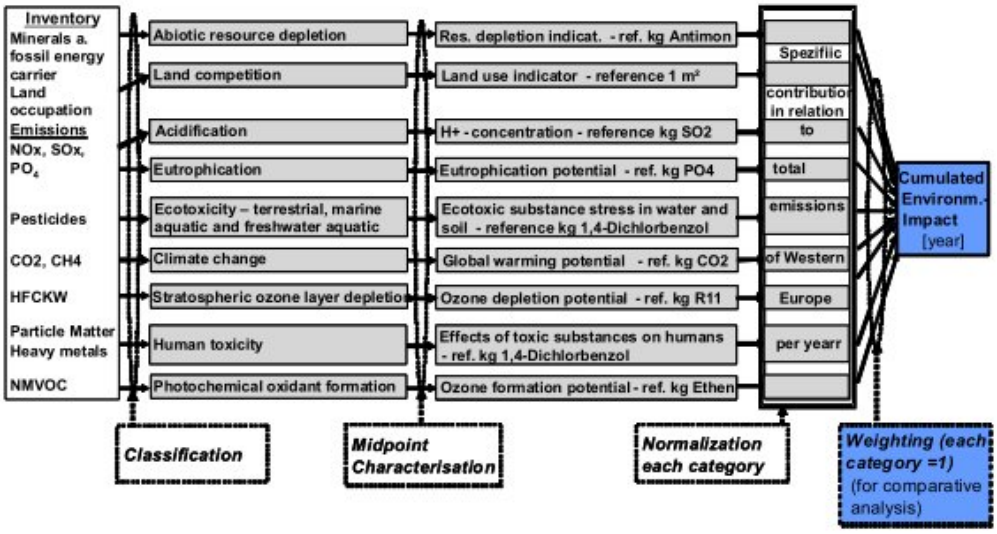

Figure 2.4 General representation of the CML 2001 methodology [48]

EDIP 2003 [49] is a Danish LCA methodology that represents 19 different impact categories. Some of them are updated versions of EDIP 97, whereas other are modeled totally different. Table 2.1 gives an overview of the EDIP 2003 impact categories. In the EDIP 2003, characterization factors for aquatic eutrophication are developed for two impact categories: aquatic eutrophication (N-eq) and aquatic eutrophication (P-eq). The emission to soil only takes into account the effects after plant uptake. Emissions to air are also included in the model. Characterization factors for human toxicity, exposure route via air, are enhanced. In EDIP 2003, due to lack of data, there is no normalization reference for ecotoxicity and resources is set at zero. The weighting for ecotoxicity and resource is also set at zero since it is already included in the characterization factor.

Table 2.1 Overview of the different impact categories in EDIP 2003 [50].

Impact categories:
Global warming
Ozone depletion
Acidification
Terrestrial eutrophication
Aquatic eutrophication (N-eq)
Aquatic eutrophication (P-eq)
Ozone formation (human)
Ozone formation (vegetation)
Human toxicity (exposure route via air)
Human toxicity (exposure route via water)
Human toxicity (exposure route via soil)
Ecotoxicity (water acute)
Ecotoxicity (water chronic)
Ecotoxicity (soil chronic)
Hazardous waste
Slags/ashes
Bulk waste
Radioactive waste
Resources

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CHAPTER 3

MEMRECS – A Sustainable View for Metal Recycling from Waste Printed Circuit Boards

3.1 Introduction

Metals are one category of a trio of geological materials on which our present industrial civilization is based. The other two categories are mineral fuels like coal, petroleum and natural gas, and nonmetallic like stone, sand and gravel, salt or clays [1]. Unlike other materials, metals are not biodegradable and have virtually an unlimited lifespan and the potential for unlimited recyclability. Hence they are well suited for sustainable development goals [2]. If appropriately managed, recycling metal can provide numerous benefits for the environment in terms of energy savings, reduced volumes of waste, and reduced greenhouse gas emissions associated with energy savings. For example, the amount of energy saved using various recycled metals compared to virgin ore is up to 95% for aluminum [3], 85% for copper [4], 60% for steel [5], 75% for zinc [3], and 90% for nickel [6]. Metal recycling also conserves natural resources by reducing the amount of virgin ore needed to be mined, as well as other resources. For instance, recycling one ton of steel conserves 1.13 tons of iron ore, 0.64 ton of coal and 0.05 ton of limestone. Recycling a ton of aluminum conserves up to 8 tons of bauxite ore [7].

As a matter of fact, the recovery of valuable metals from PCBs is an attractive business recently since PCBs typically contain about 40% of metals [8] with a wide range of elements from precious metals (e.g. gold, silver, palladium, platinum), rare metals (e.g. beryllium, indium), base metals (e.g. copper, aluminum, nickel, tin, zinc, iron), and toxic heavy metals (e.g. lead, cadmium, arsenic, antimony). Each metal element contained in PCBs has its own specific properties according to different points of view such as weight content, economic value, environmental impacts, natural resources depletion, etc. Hence, each of metal fractions will have different share of the total metal recyclability. Ideally, if all metal fractions of waste PCBs were recovered with 100% recovery rate, the metal recycling efficiency would always be full score (100%), irrespective of how much individual metal fractions contribute to total metal recyclability of product (further called "contribution score"). However, in reality it can never be achieved due to the limitations of technology, economy, thermodynamic, only several metal fractions are preferred to the task of recovery. Therefore, in order to optimize the recyclability of a product, it is necessary to understand the contribution score of every individual metal fraction contained in this product.

This study analyses the contribution score of metal fractions contained in 3 types of PCBs with three different material recycling quoting (MRQ) approaches: Material

Recycling Efficiency (MRE) [9], Resource Recovery Efficiency (RRE) [10], and Quotes for environmentally Weighted Recyclability (QWERTY) [11]. Furthermore, this study also proposes the so called Model for Evaluating Metal Recyclability from Complex Scraps (MEMRECS) as a new approach to quotes the metal recycling performance in sustainable sound manner. The contribution scores are then presented by MEMRECS approach and compared with previous approaches.

3.2 Contribution score for PCBs with different material recycling quoting approaches

Although the choice on the proper scientific method of measurement may be a subject to debate, the most common way of determining the recyclability of products is material recycling efficiency (MRE) – the amount of material per product that may be recycled, when the product reaches the end of its useful life [9]. In other words, it can be defined as Equation 3.1. E_i is specific recovery rate of material i, W_i is amount of material i contained in product.

$$MRE = \sum_i E_i \times W_i \tag{3.1}$$

When dealing with the resource conservation issue, Legarth et al. (1995) [10] proposed a quantitative measure which states resource recovery in terms of one number: The resource recovery efficiency (RRE) defined as Equation 3.2. F_i is the amount of

material i in one ton of product, P_i is annual production of of the resource i, C_i is annual consumption of the resource i, R_i is the world reserves of the resource i, and E_i is specific recovery rate of material i.

$$RRE = \sum_i E_i \times \frac{F_i}{P_i} \times \frac{C_i}{R_i} \approx \sum_i E_i \times \frac{F_i}{R_i} \tag{3.2}$$

Life cycle assessment (LCA) is a standard approach for environmental impact evaluation [12]. Based on LCA data, Huisman et al., 2003 [11] developed QWERTY concept (Quotes for environmentally Weighted RecyclabiliTY) for calculating product recyclability on a real environmental basis defined as Equation 3.3. $EVW_{actual,i}$ is the defined actual environmental impact for the weight of material i. $EVW_{max,i}$ is the defined maximum environmental impact for the weight of material i. EVW_{min} and EVW_{max} are total defined minimum and maximum environmental impact for the complete product, respectively. The minimum environmental impact is the best possible case and defined as all materials recovered completely without any environmental burden. The maximum environmental impact is the worst case scenario and is defined as every material ending up in the worst possible end-of-life route (e.g. all materials go to environment without any treatment)

$$QWERTY = \sum_i \frac{EVW_{actual,i} - EVW_{\max,i}}{EVW_{\min} - EVW_{\max}} \tag{3.3}$$

Data sources and assumptions for the calculation are presented as followings:

- In order to have samples for this study, PCBs separated from three types of consumer electronic products: CRT TV, Desktop PC, and cell phone are collected at a scrap village located in Vinh Phuc province of Vietnam. At laboratory, each PCBs sample is cut and ground to powder with particle size under 1000 µm by a laboratory cutting mill Retsch SM 2000. Powder product is then dissolved with aua regia in solid liquid ratio of 1:20 (1 g of sample to 20ml of aqua regia solution). The contact time between the fraction samples and aqua regia is about 24 hours at room temperature to ensure complete digestion of metals; followed by filtration with quantitative filter paper. The leached portion is then made up to 500 ml by adding deionized water before analyzing the metal content by inductively couple plasma mass spectrometry (ICP-MS). The metal compositions of 3 types of PCB samples are shown in Table 3.1.
- Environmental values are constructed by LCA software Simapro PhD version 7.2 using Eco-indicator'99 (H/A) as scoring indicator. Inventory database is referred from Eco-invent version 2.1 [13] specified for the Boliden Rönnskär copper smelter in Sweden, one of the world's most efficient copper smelters and a world-leader in the recycling of copper and precious metals from electronic scrap.
- System boundary: Environmental values are calculated for the recycling process

only. Which means the environmental burdens of previous steps such as collection, dismantling, and transportation are excluded from the calculations.

- The metal recovery rates (E_i) of the recycling process are assumed as: Cu: 95%, Ni: 90%, Pb: 90%, Ag: 97%, Au: 98%, Pd: 98%.
- The world reserves of metals referred from Mineral commodity summaries 2012 [14]

Table 3.1 Material compositions of PCBs from spent electronics

	CRT TV		Desktop PC		Cell phone	
	[a]	[b]	[a]	[b]	[a]	[c]
Weight (g/unit)	745.33	-	444.65	-	14.70	-
Al (wt%)	11.98	10	3.93	5	0.96	0.99
Fe (wt%)	11.41	28	7.68	7	10.79	6.53
Co (wt%)	0.002	-	0.001	-	0.17	-
Ni (wt%)	0.22	0.3	0.24	1	1.73	1.67
Cu (wt%)	11.79	10	25.50	20	38.87	38.33
Zn (wt%)	1.25	-	5.07	-	0.33	0.97
Pb (wt%)	2.68	1	1.77	1.5	1.67	1.26
Sn (wt%)	3.19	1.4	4.42	2.9	2.49	3.11
Sb (wt%)	0.016	-	0.10	-	0.04	-
Au/ppm	7	17	82	250	1645	1000
Pd/ppm	20	10	22	110	142	-
Ag/ppm	49	280	274	1000	3985	600
Non-metal	57.46	-	51.24	-	42.37	-

[a] This study
[b] Christian Hageluken, 2006 [15]
[c] Angela C. Kasper et al., 2011 [16]

Figures 3.1 – 3.3 present the contribution scores of three types of PCB according to

aforementioned material recycling quoting (MRQ) approaches. Obviously that MRE approach only focuses on the weight of recyclable parts. Metal fractions with high weight content such as copper, iron, aluminum therefore have high contribution score, without concerning about the other impacts of materials to environment, economic benefit, resource conservation, etc. The aim of MRE approach is clearly to reduce amount of waste in terms of quantitative terms rather than recovering really valuable materials, it is therefore only suitable to measure the metal recyclability of product that contains single metal fraction such as waste steel from demolition, cooper wires scrap, aluminum cans, where no competition between various metal fractions. RRE and QWERTY approaches can overcome the solely weight base problem of MRE since they are not only assessing the weight of metal fractions but the contribution of every metal fraction to specific evaluation aspect (natural resources conservation in RRE and environmental impact in QWERTY) is also taken into account. According to RRE approach, the weight dominant fractions such as copper, iron and aluminum have negligible contribution score to total metal recyclability of waste PCBs. Tin fraction makes up only less than 10% in weight base, but it becomes the highest contribution score in case of PCB from CRT TV and Desktop PC. It also considerably contributes to the total metal recyclability of PCB from Cell phone. Interestingly, the negligible weight

fractions like precious metals (gold, silver, palladium) become significant contributors

In terms of QWERTY approach, among the weight dominant fractions, iron and aluminum also have almost no contribution to the total metal recyclability of PCBs. On the other hands, copper fraction is found as the most dominant contribution score with respect to the PCBs from CRT TV and Desktop PC. Lead and zinc fractions also have considerable contribution scores. Despite of extremely low weight content, gold fraction still have remarkable contribution score for PCB from Desktop PC, and it has the highest value of contribution score for PCB from Cell phone.

In summary, the pie charts showing the relative contribution scores to the total recyclability of waste PCBs reported by MRE, RRE and QWERTY are substantially different from each other. The problem of MRE is that it concerns about weight only, thus it can make the recovery of 1 kg of iron or any different materials from a counterweight of product as important as recovering 1 kg of gold. It is irrational to the sense of nature. The aim of MRE approach is clearly to reduce amount of waste in terms of quantitative terms rather than recovering really valuable materials. RRE and QWERTY approaches can overcome the solely weight base problem of MRE since they are assessing not only the weight of metal fractions but also the contribution of every metal fraction to specific evaluation aspect (natural resources conservation in RRE or

environmental impact in QWERTY). However, they report an extremely different result, making the target stakeholders get confused with which material to be recycled.

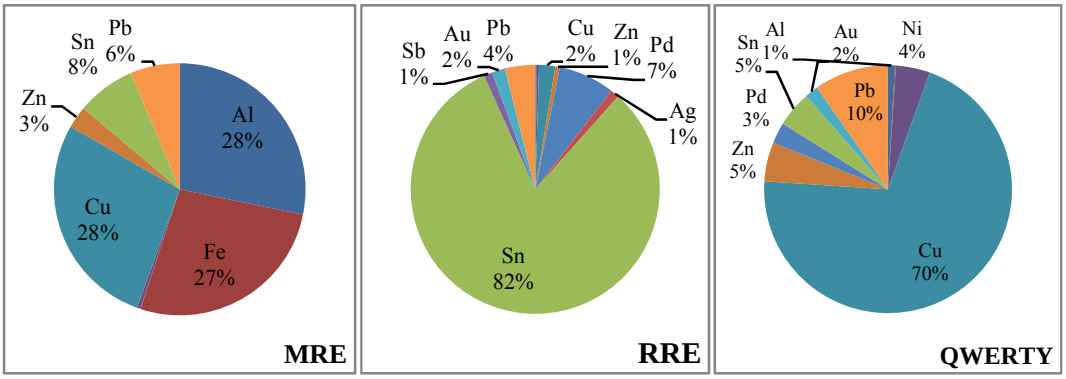

Figure 3.1 Contribution scores for CRT TV' PCB with different MRQ approaches

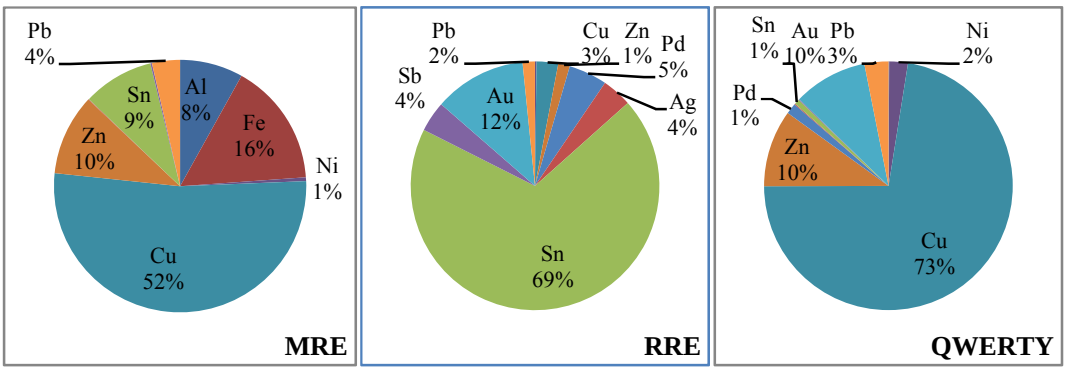

Figure 3.2 Contribution scores for Desktop PC' PCB with different MRQ approaches

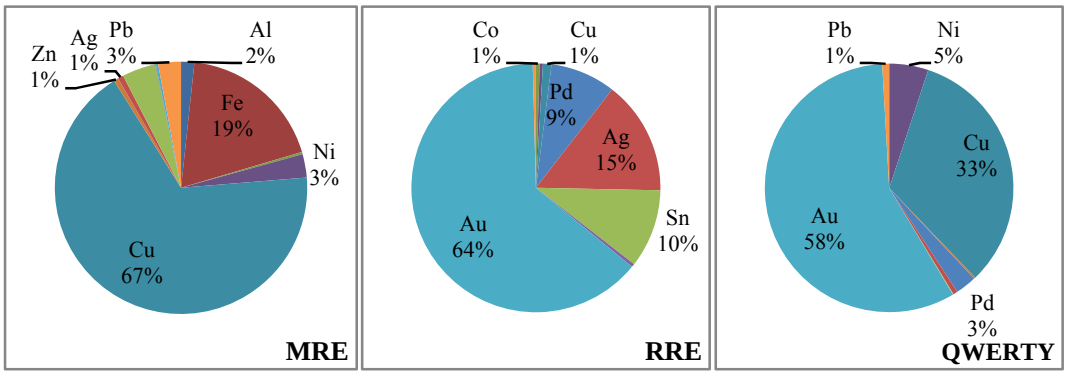

Figure 3.3 Contribution scores for Cell phone' PCB with different MRQ approaches

3.3 Proposing MEMRECS approach

As analyzed in section 3.2, the contribution score of several metal fractions contained in PCBs such as Cu, Sn, Fe, Al, Zn, Pb, Au, Ag, Pd is highly changed with different MRQ approaches. If followed one of these approaches to set the priority for the recovery of metal from waste PCBs, it might lead to over or underestimation with which metal fraction to be recovered. For example, in the case of CRT TV' PCB, if following MRE approach, copper, iron and aluminum are preferred for recovery. That will lead to the loss of benefit from natural resources conservation point of view which is embedded in tin fraction and the benefit from environmental impact which is hidden in lead fraction. If following RRE approach, tin fraction will be the main target to be recovered. In this case, the environmental benefit from copper fraction will be sacrificed. Conversely, if following QWERTY approach, benefit of natural resources conservation from tin fraction will be lost.

These notions have led to the development of the Model for Evaluating Metal Recycling Efficiency for Complex Scraps (MEMRECS) as a new approach to quote the metal recyclability of scraps containing various metal fractions in general and waste PCBs in particular. With the aim of evaluating metal recyclability in sustainable sound manner, MEMRECS not only include the weight of each metal fraction but also

comprise two critical aspects associated with sustainable issue: natural resources conservation and environmental impact reduction. In other worlds, MEMRECS is a combination of MRE, RRE and QWERTY.

Construction of MEMRECS

In general, given a complex scrap with *m* metal fractions, metal recyclability according to a certain aspect *j* can be expressed by equation 3.4. Whereas, E_i is the recovery rate of metal fraction *i*. M_i is the metric weight of metal faction *i*. w_{ij} is weighting factor of metal faction *i* according to evaluation aspect *j*.

$$MR_j = \sum_{i=1}^{m} E_i \frac{M_i w_{ij}}{\sum_{i=1}^{m} M_i w_{ij}}, i \in [1..m], j \in [1..n] \tag{3.4}$$

MEMRECS is the solution of a multicriteria problem, in which two fundamental viewpoints including natural resources conservation and environmental impacts are taken into account simultaneously. Hence, the task now is finding the way to combine the weighting factors representative for these two points of view into only one composite weighting factor $w_{i,comp}$ representative for composite viewpoint. Then, MEMRECS can be expressed by equation 3.5. Whereas, $w_{i,}$ is the weighting factor of metal fraction *i* according to composite viewpoint.

$$MEMRECS = \sum_{i=1}^{m} E_i \frac{M_i w_{i,comp}}{\sum_{i=1}^{m} M_i w_{i,comp}} \tag{3.5}$$

Combination of weighting factors using Entropy weighting method

In multicriteria problems, it is reasonable to assign a weight to each criterion in order to represent the relative importance of criterion against each others. There are many techniques to elicit the weights, such as the weighted evaluation technique, the eigenvector method, the analytic hierarchy process (AHP) method, the weighted least square method and so forth. However, most of them entail subjectivity in assigning weights to criteria due to using opinion of experts [17]. In order to guarantee the consistency, this study employs Entropy weighting method [18] to weight criteria, which will avoid the subjective influence of weight determination as much as possible. The calculation steps are as followings as in [17]:

A multicriteria decision making problem with *m* alternative and *n* criteria can be expressed in decision matrix as equation 3.6. Whereas, x_{ij} is alternative score of metal fraction *i* according to evaluation aspect *j*.

$$D = (x_{ij})_{mxn}, i \in [1..m], j \in [1..n] \tag{3.6}$$

A normalized decision matrix representing the relative performance of the alternatives is obtained as equation 3.7.

$$P = (p_{ij})_{mxn}, i \in [1..m], j \in [1..n] \tag{3.7}$$

where $p_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij}$

The amount of decision information contained in equation 3.7 and emitted from each criterion can be measured by entropy value as equation 3.8.

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} p_{ij} \ln(p_{ij}), i \in [1..m], j \in [1..n] \tag{3.8}$$

The degree of diversity of the information contained by each criterion can be calculated as equation 3.9.

$$d_j = 1 - e_j, \; j \in [1..n] \tag{3.9}$$

Then, the weight or relative importance for each criterion is given by equation 3.10.

$$I_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, j \in [1..n] \tag{3.10}$$

Finally, the composite weight representative for general viewpoint for metal fraction *i* is generated by equation 3.11.

$$w_{i,comp} = \sum_{j} I_j w_{ij}, \; j \in [1..n] \tag{3.11}$$

Calculation of MEMRECS

With the general idea and combination method described above, the four steps for calculating MEMRECS can be expressed as follows:

First step, compute the weighting factors of all metal fractions according to the natural resource conservation aspect *($w_{i,RC}$)*, and environmental impact aspect *($w_{i,EI}$)*. Based on the RRE concept and QWERTY concept, the $w_{i,RC}$, $w_{i,EI}$ are calculated by

Equation 3.12 and Equation 3.13, respectively.

$$w_{i,RC} = \frac{\frac{1}{R_i}}{\sum_i \frac{1}{R_i}} \tag{3.12}$$

Whereas, R_i is the world reserves estimated in the year of calculation of metal element i

$$w_{i,EI} = \frac{EV_{i,actual} - EV_{i,\max}}{\sum_i EV_{i,\min} - EV_{i,\max}} \tag{3.13}$$

Whereas, $EV_{i,min}$ is the minimum environmental impact value to recover metal element i in its initial grade without any environmental burden of treatment steps. In other words, it is the environmental substitution value for the extraction of raw material for metal element i. $EV_{i,max}$ is the maximum environmental impact value for metal element i in the worst end-of-life case. $EV_{i,actual}$ is the environmental impact value to recover metal element i in actual case.

Second step, compute the relative criteria importance using Entropy method with p_{ij} is substituted by w_{ij}.

Third step, compute composite weight for each metal fraction by Equation 3.11

Fourth step, compute MEMRECS score by equation 3.5

An important note: in some cases, the resource depletion impact has been also included in QWERTY through life cycle impact assessment (LCIA) models. For these cases, only score on environmental impacts is used in the calculation of $w_{i,EI}$, in order to avoid

overlapping the evaluation of resource conservation aspect.

3.4 Contribution score for PCBs with MEMRECS approach

In this section, the contribution score of metal fractions contained in waste PCBs is calculated with MEMRECS. Three types of PCBs separated from CRT TV, desktop PC, and cell phone with material composition given in Table 3.1 are used as samples. The recycling process in the evaluation model is Boliden Rönnskär copper smelter in Sweden, one of the world's most efficient copper smelters and a world-leader in the recycling of copper and precious metals from electronic scrap.

The calculation of $w_{i,EI}$ is based on life cycle inventory database referred from Ecoinvent version 2.1 [19]. Environmental values are constructed by LCA software Simapro PhD version 7.2 expressed with Eco-indicator'99 (H/A) [20]. However, instead of using whole score of Eco-indicator '99, only score on damage to ecosystems and damage to human health is put into the calculation in order to avoid overlapping evaluation since the damage to resources depletion is also integrated in eco-indicator'99. In addition, the calculation of $w_{i,EI}$ is based on an assumption that starting point for calculation is the moment PCBs scraps are fed into the process, which means environmental burden of previous steps such as collection, dismantling, transportation is excluded from the calculation. The calculation of $w_{i,RC}$ is only based on the data

regarding to the estimated world reserves of metals referred from [14].

Figure 3.4 indicates that the result of MEMRECS is a compromise between the results of RRE and QWERTY. It is a common sense because MEMRECS allows trade-offs between criteria. A poor score in RRE can be negated by a good score in QWERTY and reversely. According to MEMRECS, copper and tin fractions are the main contributors. They make up about 70 - 80% of the total metal recyclability of PCBs from CRT TV and Desktop PC. For PCB from Cell phone, gold is the most important contributor which share 60% total metal recyclability, irrespective of it's small weight content. Copper is also a significant contributor, which shares 22% total metal recyclability.

In general, in order to optimize the efficiency of metal recycling from PCBs in the context that not all of metal fractions can be recovered, a priority should be given to the metal fractions that have high contribution score. Table 3.2 is the summary of metal fractions that are preferred for the recovery from waste PCBs with respect to different MRQ approaches. It is easy to find that the preferred metal fractions according to MEMRECS mostly are the preferred metal fractions according to both RRE and QWERTY. If the target is simply qualitative determination of which metal fractions should be recovered to optimize the recycling efficiency of metal from waste PCBs in

the sustainable sound manner, selecting the preferred metal fractions according to both RRE and QWERTY is probably enough. However, the advantage of MEMRECS is that it is not only qualitatively identifying the preferred metal fractions but also quantitatively calculating the contribution score of every metal fraction.

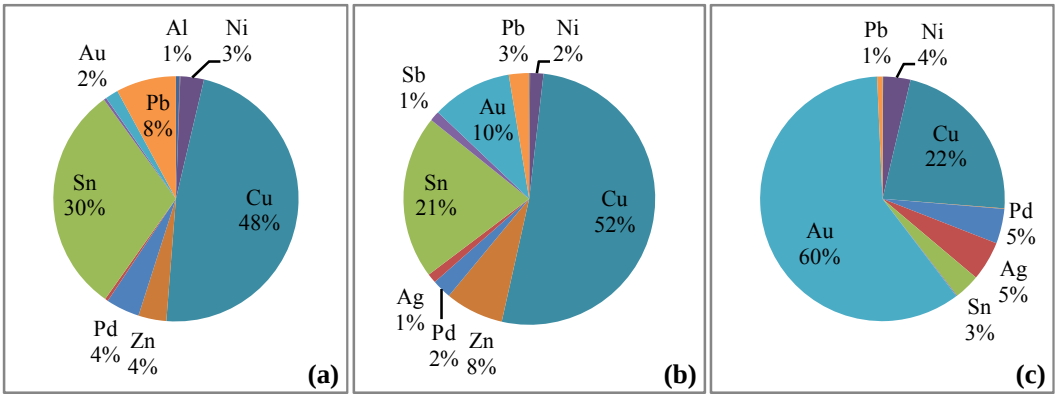

Figure 3.4 Contribution scores of different types of PCB according to MEMRECS approaches *(a: PCB from CRT TV, b: PCB from Desktop PC, c: PCB from Cell phone)*

Table 3.2 Metal recovery priority for PCBs according to different MRQ approaches

	CRT TV' PCB	**Desktop PC' PCB**	**Cell phone' PCB**
MRE	Cu, Al, Fe	Cu, Fe, Zn	Cu, Fe
RRE	Sn, Pd	Sn, Au	Au, Ag, Sn, Pd
QWERTY	Cu, Pb	Au, Cu	Au, Cu
MEMRECS	Cu, Sn, Pb	Cu, Sn, Au	Au, Cu, Ag, Pd

QWERTY is calculated with environmental values, those derived from any LCIA models. Depending on LCIA model, the environmental value expresses the environmental impacts only, or expresses both environmental impacts and resource depletion impact. The Eco-indicator '99 is a comprehensive method, in which resource depletion impact has been considered as one of environmental impact. Thus, the

QWERTY expressed with Eco-indicator'99 (QWERTY/Eco-indicator'99) seems to be similar to MEMRECS in terms of approaching ideal. It is notably valuable to discuss the difference between MEMERCS and QWERTY/Eco-indicator'99.

Table 3.3 The difference between QWERTY/Eco-indicator'99 and MEMRECS in terms of modeling the resource conservation aspect

	QWERTY/Eco-indicator'99	MEMRECS
Unit	"Surplus energy" in MJ per kg extracted material	The times natural resource can be saved by recycling
Weighting method	Expert panel group method	Entropy weighting method
Data source	Until 1990	Recent mining data

As shown in Table 3.3, the difference between two models occurs in three viewpoints. The first one is the unit or the way expressing the resource depletion impact. QWERTY/Eco-indicator'99 does not consider the quantity of resources, but rather the resource quality. The resource aspect is modeled via the term "surplus energy", which describes energy requirements for future mining will increase due to decreasing mineral ore concentration. The nature sense of surplus energy actually is energy consumption that finally reflects the environmental impacts rather than saving natural resources. In contrast, the resources depletion impact in MEMRECS is derived from RRE, which describes the times of natural resources can be saved by recycling based on the resource quality. By this way, the resource depletion impact is considered more clearly and closely to the resource depletion issue in the true sense of word. Thus, MEMRECS

enhances the role of resource conservation rather than that of QWERTY/Eco-indicator'99. It is demonstrated by the contribution score of tin fraction.

The second point is the weighting method to elicit the relative importance of criteria or criteria weights. In QWERTY/Eco-indicator'99, the criteria weights are determined by expert panel group method based on the opinion of group of experts or stakeholders. In this way, the relative importance of environmental damage and resources damage is subjectively fixed as 0.8 and 0.2, respectively [21]. In MEMRECS, the relative importance of environmental impact (0.53) and resources conservation (0.47) aspects are generated by Entropy method – an objective weighting method, which determines criteria weights based on intrinsic information of each evaluation criterion. Thus it can avoid the subjective influence of weight determination as much as possible. Obviously, the difference in weighting method also makes the resources conservation aspect in MEMRECS is appreciated rather than that in QWERTY/Eco-indicator'99.

The third point is the data sources that are used to model the resources conservation aspect. As mentioned, the resources damage in QWERTY/Eco-indicator'99 is modeled base on surplus energy. On the other hand, the estimated ore grade corresponding to a cumulative extraction value equal to five times the 1980 level is used to estimate the

surplus energy [22]. It is clear that the choice of five times is arbitrary and the data sources in 1980 are outdated, which probably makes the estimation contain considerable uncertainties. In MEMRECS, the data source for modeling the resources conservation aspect is derived from Mineral commodity summaries 2012 – a recent mining data, and such data source is annually updated. Thus the result of MEMRECS also can reflect actual issue to a higher degree than QWERTY/Eco-indicator' 99 does.

3.5 Conclusion

In this study, MEMRECS has been introduced as a new quantitative measure for quoting the metal recyclability of waste PCBs. MEMRECS can provide insights into the contribution of every metal fraction to the total metal recyclability of waste PCBs, on the condition that both environmental impact and natural resources conservation aspects are considered simultaneously. This information will be really helpful for setting the priority in metal recovery, according to both qualitative and quantitative forms.

The comparison between MEMRECS and QWERTY/Eco-indicator'99 is also implemented in this study. The analysis results indicate that natural resources conservation aspect in MEMRECS is considered more clearly and directly than that in QWERTY/Eco-indicator'99. Furthermore, MEMRECS enhances the role of resource conservation aspect other than QWERTY/Eco-indicator'99 does.

With its own properties, MEMRECS is probably applicable in setting the benchmark for metal recycling strategy. Furthermore, it is helpful in technological selection or technological improvement for metal recycling from waste PCBs in particular and scraps containing various metal fractions in general.

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CHAPTER 4

Sensitivity Analysis of MEMRECS with Different Life Cycle Impact Assessment Models

4.1 Introduction

As described in the Chapter 3, MEMRECS is a compensatory combination of RRE and QWERTY concepts. Data source for calculating RRE is the metal reserves of the world, which is derived from the mineral commodity summaries, annually published by the U.S. Geological survey. Whereas, QWERTY uses environmental values which is derived from one or more life cycle impact assessment (LCIA) models. The LCIA models are often developed by different expert groups with different approaching method to quantify the environmental impacts. They therefore results the different environmental values for the same process. The outcomes of QWERTY and MEMRECS are therefore dependent on the choice environmental impacts assessment model. The aim of this chapter is to investigate the sensitivity of MEMRECS approach in evaluating recycling efficiency of metals from waste PCBs with different LCIA models. Four different LCIA models: the Eco-indicator ’95 [1], the Eco-indicator ’99 [2], EDIP 2003 [3], and Impact 2002+ [4] are used in the MEMRECS calculation. The metal recycling of spent printed circuit boards (PCBs) by secondary copper smelter is

used to illustrate the results of analysis.

4.2 Life cycle impact assessment (LCIA) methods

In this study, four different LCIA methods are used in the calculations of MEMRECS. The four methods are chosen with following criteria: They are all multiple environmental assessment methods that describe the environmental impacts in comprehensive manner; they can provide simplified interpretation of the results as single scores, which are applicable for calculation of QWERTY; they are all adapted to the LCA software (Sima Pro 7.2) in common, and the same inventory database (ecoinvent 2.1).

The first model is the Eco-indicator ’95. It is an assessment method which is based on effect-oriented classification. It contains 100 indicators for important materials and processes. It uses a variety of effects such as greenhouse effect, acidification, eutrophication, carcinogenic, heavy metals, ozone layer depletion etc. to focus on three types of environmental damage: deterioration of ecosystems, deterioration of human health, and human deaths.

The second model is the Eco-indicator ’99, which is the successor of the Eco-indicator ’95. It is a damage-oriented Life Cycle Assessment method that is based on three types of environmental damages: human health, ecosystem quality and

resources. The results for these three damages can be combined into a single score using default weighting factors.

The third model is EDIP 2003. It is an evolution of the EDIP 97 that was developed by the Institute for Product Development (IPU) at the Technical University of Denmark. The EDIP 2003 represents 19 different impact categories. Some of them is traditional LCA categories like ozone depletion, acidification, global warming.

The final model is Impact 2002+, which is developed at the Swiss Federal Institute of Technology. This model proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results via 14 midpoint categories (human toxicity, respiratory effects, ..., non-renewable energy, mineral extraction) to 4 damage categories (human health, ecosystem quality, climate change, resources)

4.3 Data sources and assumptions

In this study, MEMRECS calculations are based on a number of data sources as follows:

- Environmental values are constructed by LCA software Simapro PhD version 7.2 using data derived from Ecoinvent version 2.1. A remarkable notification for the use of environmental values is that instead of using whole score, only score on damage to ecosystems and damage to human health is put into calculation in order to avoid

overlapping evaluation since the damage to resources depletion is also integrated in LCIA methods.

- Estimated world reserve of metals is referred from Mineral commodity summaries 2012.
- Material composition of example products used in this study is given in **Table 3.1**.

Besides data requirements, MEMRECS calculations in this study also rely on several assumptions:

- The recycling process is Boliden Rönnskär copper smelter in Sweden, one of the world's most efficient copper smelters and a world-leader in the recycling of copper and precious metals from electronic scrap. The outcome of process includes lead, copper, nickel, silver, gold, and palladium. The metal recovery rate of process is assumed as similar as average recoveries of metals at a copper smelter: Cu-95%, Ag-97%, Au-98%, Pd-98%, Ni-90%, Pb-90%.
- System boundary: Environmental values are calculated for the recycling process only. Which means the environmental burdens of previous steps such as collection, dismantling, and transportation are excluded from the calculations.
- The worst case for determining $EV_{i,max}$ is whole amount of metal contained in printed circuit boards is emitted to air, water and soil (each 33.33%).

4.4 Recycling efficiency of metals from waste PCBs with MEMRECS and different LICA models

Based on the database and assumptions mentioned above, a number of calculations have been executed with three types of printed circuit boards and four LCIA methods. The results given in Figure 4.1 indicate that in case of PCBs from CRT TV and desktop PC, there is a clear difference between the MEMRECS scores calculated by different LCIA models. The biggest difference occurs between EDIP 2003 and Impact 2002+. In case of PCBs from cell phone, however, MEMRECS scores are almost stable with different LCIA methods. One thing in common between these LCIA methods within MEMRECS concept is that they show somewhat the same tendency of scores corresponding to different types of PCBs although they are quite different from each other in terms of modeling the environmental impacts.

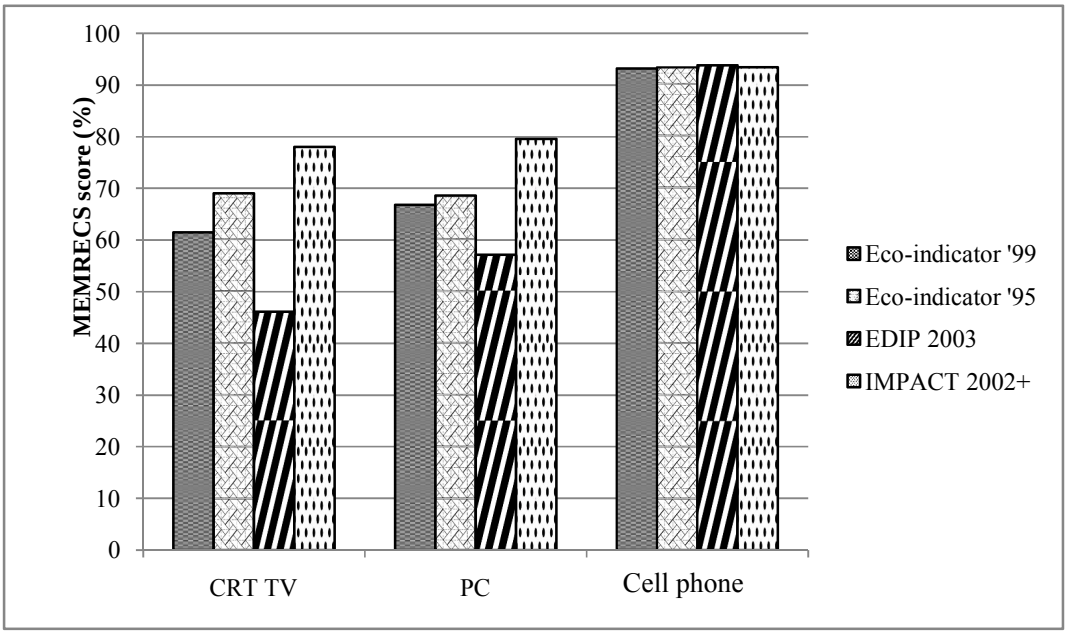

Figure 4.1 MEMRECS scores with different LCIA methods

In order to get more clear understanding of where the differences originated from, it is better to explore the relative contributions of the metal fractions to maximum score of MEMRECS (100%) according to each LCIA method. The case of PCBs from desktop PC is selected as an example. The results of example case are shown in Figure 4.2. Obviously, the contribution of an individual metal faction to 100% MEMRECS score is drastically changed with different LCIA methods, especially in the case of copper, lead, tin, zinc and gold fractions. Meanwhile, the intrinsic MEMRECS score or recycling efficiency is dependent on individual metal recovery rate (E_i) and contribution of each metal fraction to 100% MEMRECS score. Hence, such changes in contribution of metal fractions lead to the difference in the results of recycling efficiency with different LCIA

methods. In the case of tin fraction for instance, its contribution to 100% MEMRECS is 21%, 25%, and 35% with Eco-indicator ’99, Eco-indicator ’95, and EDIP 2003, respectively. With Impact 2002+, however, its contribution is only 3%. On the other hands, tin fraction is not recovered in the example recycling system (E_i for tin is zero). Thus there is a considerable loss in intrinsic MEMRECS score when it is calculated with Eco-indicator ’99, Eco-indicator ’95 and EDIP 2003 other than calculated with Impact 2002+. That is a reason why MEMRECS scores are reported as highest score in case of calculating with Impact 2002+ (79.6%), and the lowest score in case of calculating with EDIP 2003.

Same analyses are implemented with the cases of PCBs from CRT TV and PCBs from cell phone. A relatively similar change in contribution of metal fractions also occurs with PCBs from CRT TV. That explains why the tendency of PCBs from CTR TV case and desktop PC case are somewhat similar. In case of PCBs from cell phones, there are also the large disparities in contribution of metals fractions with different LCIA methods. However, all of main contributors according to all four LCIA methods are recovered by the recycling system. Thus, the intrinsic MEMRECS scores with respect to all four LCIA methods are reported as relatively similar results.

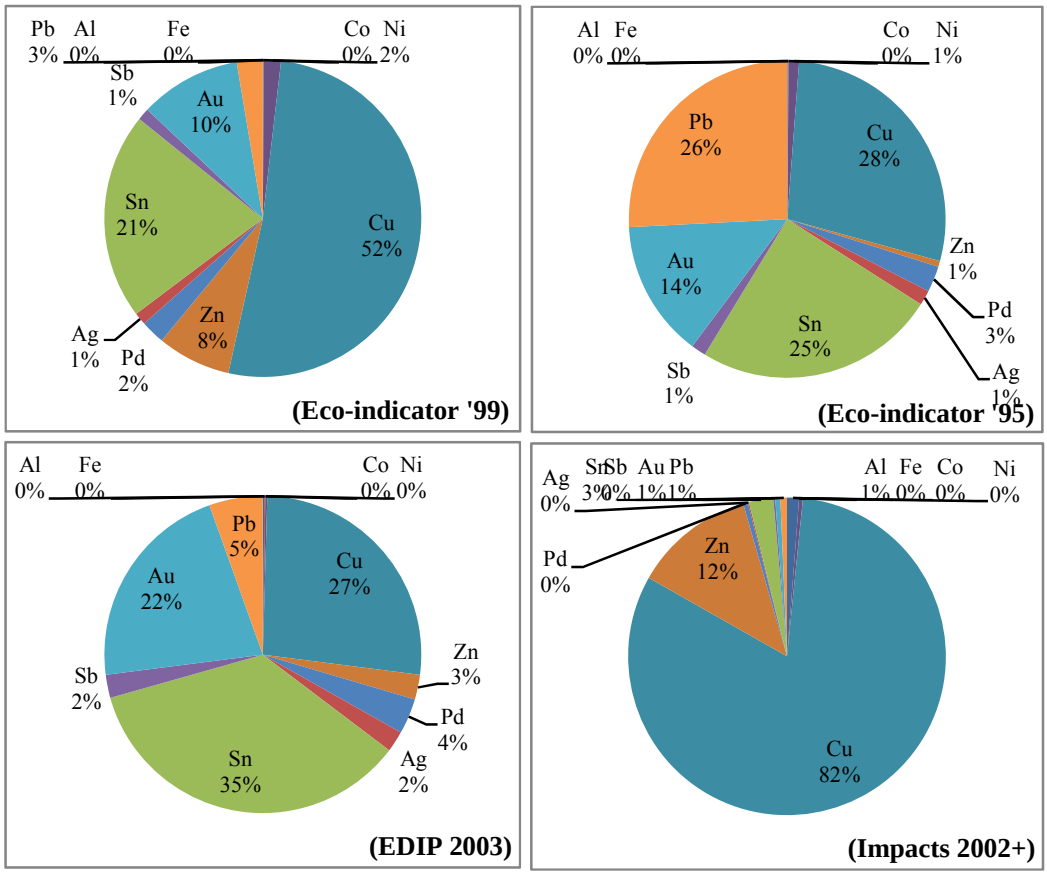

Figure 4.2 Relative contribution of metal fractions to 100% MEMRECS score of Desktop PC' PCB with different LCIA methods

4.5 Conclusion

The MEMRECS scores are remarkably varied with different LCIA methods. Such variation is indeed derived from the substantial change in relative contribution of individual metal fractions to 100% MEMRECS score according to different LCIA methods. This notion recommends that the accuracy and validity of LCIA method should be carefully concerned before putting into the model. Furthermore, it should be noted that in case of scenario analysis, all MEMRECS scores must be calculated using

the same LCIA method.

Within a certain LCIA method, the intrinsic MEMRECS score strongly dependent on the individual recovery rate of each metal fraction. This notion supports the priority setting for different metal-bearing products in term of technological selection and technological improvement.

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CHAPTER 5

Assessing eco-efficiency of metals recovery from waste PCBs at the state-of-the-art processes with QWERTY and MEMRECS

5.1 Introduction

Rapid changes in technology, changes in media, falling prices, and planned obsolescence have resulted in a fast-growing surplus of electronic waste around the globe [1]. Today the electronic waste recycling is an attractive business in not only the developed world but also emerging economies. One of the major challenges in recycling electronic waste is recycling PCBs, even though they only account for 3-5% by weight of the electronic waste. The reason is that PCBs are manufactured by sophisticated technologies, making an extremely heterogeneous structure, in which polymers, ceramics, and especially a variety of metals are complexly integrated. PCBs contain a wide range of metal elements, some of which are valuable (gold, silver, palladium, platinum), some of which are toxic (mercury, beryllium, indium, lead, cadmium, arsenic, antimony, etc) and some are both (copper, aluminum, nickel, tin, zinc, iron, etc). If such scrap is not treated in an environmental sound way, a high risk of environmental damage exists [2]. It is clearly demonstrated by the serious environmental problems in the Electronic Waste Dump of the World: Guiyu, China [1].

Achieving the environmentally friendly recycling of waste PCBs requires a stage-of-the-art facility equipped with technical know-how, sophisticated flow sheets and sufficient economy of scale, which can fulfil both technical and environmental requirements. Two typical examples for such kind of facility are Boliden's Rönnskär smelter in Sweden and Umicore's integrated metals smelter and refinery in Belgium.

The term 'eco-efficiency' was coined by the World Business Council for Sustainable Development (WBCSD) in its 1992 publication 'Changing Course'. It is based on the concept of creating more goods and services while using fewer resources and creating less waste and pollution [3]. In other words eco-efficiency means producing more value while reducing resources consumption and environmental impact. Therefore, in order to quote eco-efficiency of a recycling process, the two aspects of sustainability concept: resources conservation and environmental impact should be evaluated simultaneously. In this context, QWERTY concept [4], and recently published MEMRECS [5,6,7] are two approaches that can be used to quote the eco-efficiency of material recycling.

The aim of this study is quoting the eco-efficiency of metals recovery from waste PCBs at the Boliden's Rönnskär smelter and the Umicore's integrated metals smelter

and refinery. The comparison between the eco-efficiency of metals recovery of these two process according to both QWERTY and MEMRECS is also executed in this study.

5.2 Data sources and assumptions

- In order to obtain samples for this study, the PCBs separated from six types of consumer electronic products: CRT TV, CRT monitor, Desktop PC, DVD player, fixed wireless phone, and cell phone were collected at a scrap village located in Vinh Phuc province of Vietnam. At laboratory, each PCBs sample was cut and ground to powder with particle size under 1000 μm by a laboratory cutting mill Retsch SM 2000. Powder product was then dissolved with aqua regia in solid liquid ratio of 1:20 (1 g of sample to 20ml of aqua regia solution). The contact time between the fraction samples and aqua regia was about 24 hours at room temperature to ensure complete digestion of metals; followed by filtration with quantitative filter paper [11,12]. The leached portion was then made up to 500 ml by adding deionized water before analyzing the metal content by inductively couple plasma mass spectrometry (ICP-MS). The metal composition of 6 types of PCBs sample is shown in Table 5.1.

Table 5.1 Material compositions of waste PCBs from consumer electronic products

	CRT TV		CRT Monitor	Desktop PC		DVD player	Fixed wireless phone	Cell phone	
	[a]	[b]	[a]	[a]	[b]	[a]	[a]	[a]	[c]
Weight (g/unit)	745.33	-	320	444.65	-	47.37	95.30	14.70	-
Al (%)	11.98	10	12.28	3.93	5	8.48	2.10	0.96	0.99
Fe (%)	11.41	28	15.52	7.68	7	10.59	8.42	10.79	6.53
Co (%)	0.002	-	0.008	0.001	-	0.007	0.009	0.17	-
Ni (%)	0.22	0.3	0.10	0.24	1	0.25	0.40	1.73	1.67
Cu (%)	11.79	10	11.69	25.50	20	23.80	21.98	38.87	38.33
Zn (%)	1.25	-	1.98	5.07	-	0.91	14.38	0.33	0.97
Pb (%)	2.68	1	2.48	1.77	1.5	2.45	1.00	1.67	1.26
Sn (%)	3.19	1.4	3.02	4.42	2.9	3.79	1.39	2.49	3.11
Sb (%)	0.016	-	0.06	0.10	-	0.06	0.02	0.04	-
Au/ppm	7	17	3	82	250	134	96	1645	1000
Pd/ppm	20	10	4	22	110	13	14	142	-
Ag/ppm	49	280	81	274	1000	314	300	3985	600
Non-metal (%)	57.46	-	52.87	51.24	-	49.61	50.26	42.37	-

[a] Own analysis
[b] Christian Hageluken, 2006
[c] Angela C. Kasper et al., 2011

- Environmental values are constructed by life cycle assessment (LCA) software Simapro PhD version 7.2. The Eco-indicator'99 (H/A) is selected as scoring indicator because it is a comprehensive method comprising both environmental impacts and resource depletion impact, which is appropriate for quoting the eco-efficiency in this study. Furthermore, the Eco-indicator'99 is the default method used in the QWERTY calculations, and it is widely used in the LCA projects in Europe.
- Inventory database is derived from Eco-invent version 2.1 specified for the Boliden Rönnskär copper smelter in Sweden [8].
- System boundary: Environmental values are calculated for the recycling process

only. Which means the environmental burdens of previous steps such as collection, dismantling, and transportation are excluded from the calculations.

- The inventory database of Boliden's Rönnskär copper smelter is used as proxy to calculate the environmental value of the Umicore's integrated metals smelter and refinery because those data of the Umicore's processes are not reachable in this study.
- The world reserves of metals are referred from Mineral commodity summaries 2012 [9].
- It is also assumed that the metal recovery rate for each metal fraction is shown in Table 5.2, according to the average recoveries of metals at a copper smelter in [10]

Table 5.2 Average recoveries of metals at a copper smelter

Metal	Recovery rate	
	Boliden's Rönnskär	Umicore's Hoboken
Cu	95%	95%
Ag	97%	97%
Au	98%	98%
Pd	98%	98%
Ni	90%	90%
Pb	90%	90%
Sn	0%	90%

5.3 Eco-efficiency of metals recovery from waste PCBs at the state-of-the-art processes

Boliden's Rönnskär copper smelter in northern Sweden is the largest e-scrap recycling facility in the world with capacity about 120,000 metric tons a year, in which e-scrap accounts for 14 percent and recyclable materials as a whole contributing 31 percent [11]. The plant is a copper-lead smelter that treats complex ores and to a large extent electronic scraps and integrates the recovery of copper, gold, silver, palladium, lead and nickel into one facility [8]. Umicore's integrated metals smelter and refinery in Belgium is also one of the world's largest precious metals recycling facilities with a capacity of over 50 tons of platinum group metals (PGMs), over 100 tons of gold and 2400 tons of silver. Basically, the processes are based on complex lead-copper-nickel metallurgy with feed materials are various industrial waste and by-products from other non-ferrous industries, spent industrial catalyst, as well as printed circuit boards/electronic components. The outputs are a wide range of metals: gold, silver, and PGMs, special metals (selenium, tellurium, indium), secondary metals (antimony, tin, arsenic, bismuth) and base metals (copper, lead, nickel) [12]. In summary, these two facilities are well known for their high performance in terms of recycling waste PCBs. Therefore, this study examines and compares the eco-efficiency of metals recycling from waste PCBs

at these two facilities with two quoting methods: QWERTY and MEMRECS. Input materials are waste PCBs separated from five types of consumer electronic products: CRT TV, CRT monitor, desktop PC, DVD player, and cell phone. The results are shown in Figures 5.1 - 5.2. According to QWERTY concept, both two facilities yield high efficiency of metals recovery from waste PCBs, i.e., from 80% to 96% depending on type of waste PCBs. As expected, the Umicore's facility yields higher efficiency than Bolident's facility does because they have the same environmental value as assumed, but Umicore's facility can recover more types of metal element then Boliden's facility does. However, the result indicates that the eco-efficiency of metals recovery from waste PCBs at these two facilities is slightly different (about less than 5%), according to QWERTY concept. The picture is largely changed with MEMRECS concept. The difference of the eco-efficiency of metals recovery from waste PCBs between these two facilities is clearly significant (about 17-27%), except the case of waste PCBs from cell phone (about 3%).

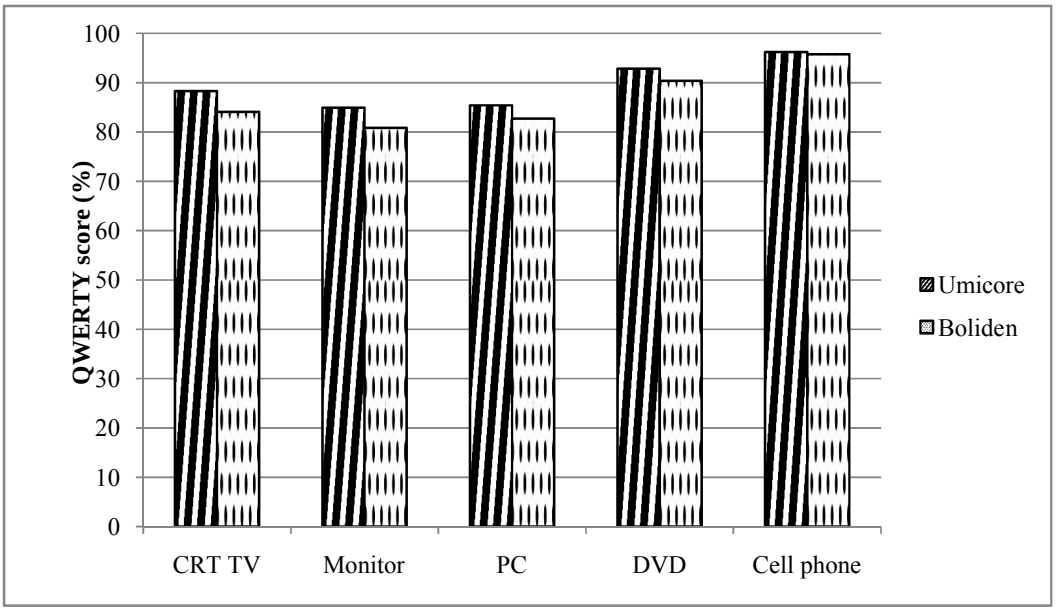

Figure 5.1 Eco-efficiency of metals recovery from waste PCBs according to QWERTY

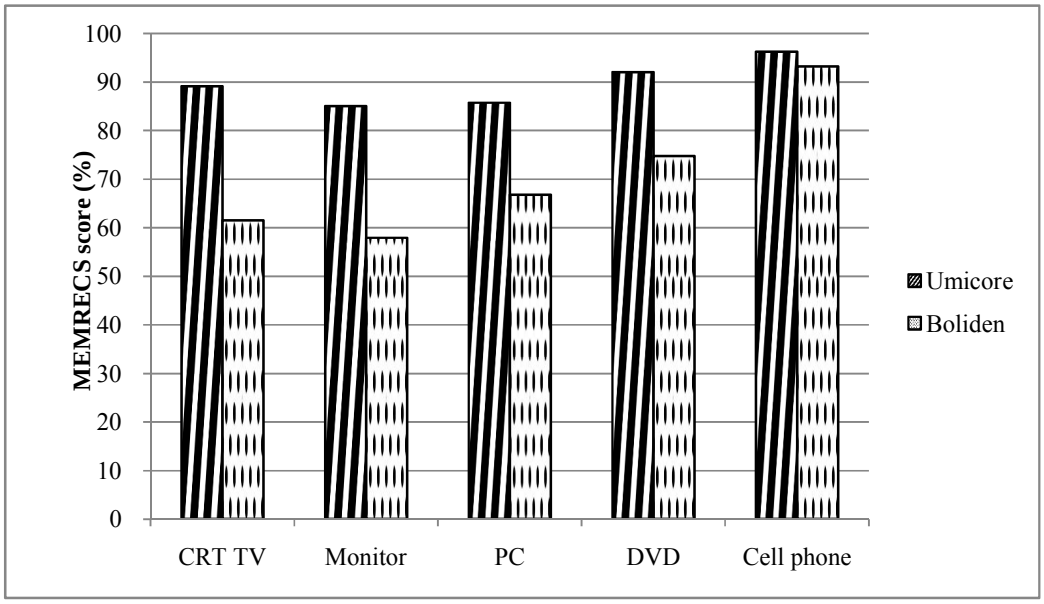

Figure 5.2 Eco-efficiency of metals recovery from waste PCBs according to MEMRECS

The composition of total recyclability of metals from waste PCBs shown in Figures 5.3 – 5.4 elucidates the results indicated in Figures 5.1 – 5.2. In case of waste PCBs from CRT TV (Figure 5.3) as well as PCBs from CRT monitor, PC, DVD player, tin fraction only contributes less than 5% to the total recyclability according do QWERTY. It, however, becomes one of the most dominant contributors of the total metals recyclability according to MEMRECS. It accounts for approximately 20-30% of the total metals recyclability. On the other hand, metals recycling efficiency is presented by how much of the total metals recyclability is realized by a recycling system. In other words, metals recycling efficiency is dependent on the types of metal and the recovery rate of those metals achieved by recycling process. Under the assumptions of this study, the point making these two facilities different from each other is that tin fraction is recovered at Umicore's facility while it is not recovered at Boliden's facility. In Boliden's facility, approximately all of the tin follows the process gases. It is then entrapped as filter dust, which is either sent to England, approximately 24%, for further refining or is temporarily stored, onsite [13]. According to QWERTY, tin fraction only accounts less than 5% of the total metals recyclability, thus the difference between the metal recovery efficiency of the two facilities is less than 5%. According to MEMRECS, on the contrary, the dominant contribution of tin fraction causes the

significant difference between the metals recovery efficiency of the two facilities. In the case of waste PCBs from cell phone (Figure 5.4), the contribution score of tin fraction according to both QWERTY and MEMRECS is dominated by other metals fractions, especially gold and copper. Hence, the metals recovery efficiency of the two facilities is slightly different from each other, according to both quoting approaches.

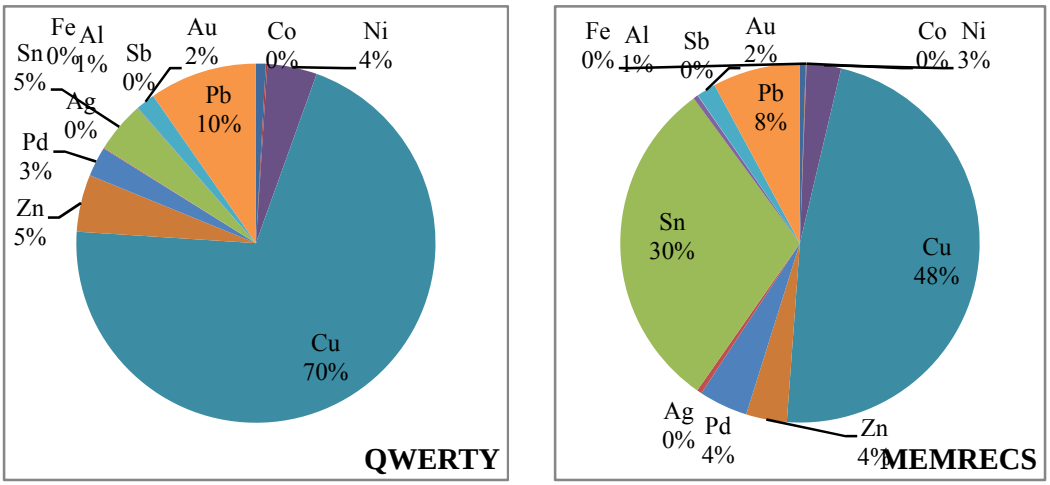

Figure 5.3 Breakdown of total metal recyclability of CRT TV's PCBs

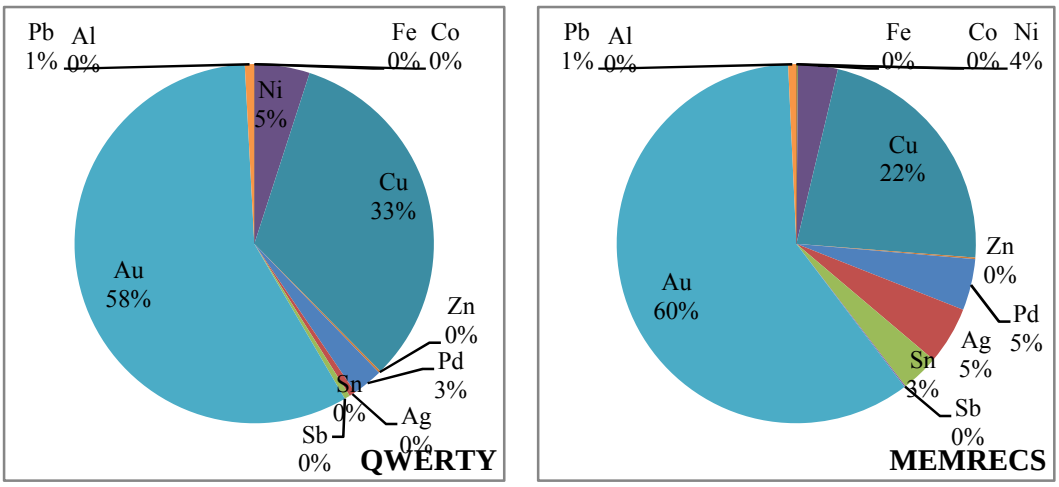

Figure 5.4 Breakdown of total metal recyclability of cell phone's PCBs

The question now is why the contribution score of tin fraction resulted by QWERTY is much less than that resulted by MEMRECS. The reason is tins as single atoms or molecules are not very toxic to any kind of organism [14], thus tin has low environmental impacts. Furthermore, it has a highly important role in terms of resource depletion impact according to RRE concept. However, the resource depletion impact in QWERTY is overwhelmed by environmental impacts because it is indirectly evaluated through a qualitative term (i.e surplus energy), and eventually translated into environmental impacts. In MEMRECS, by contrast, it is directly evaluated through quantitative value of the resource reserves. By this way, it clearly and closely expresses the resource depletion issue in the true sense of word. Thus the role of metal recovered in terms of resource conservation aspect is much more enhanced than that in QWERTY [7].

5.4 Conclusion

MEMRECS can clearly discriminate the eco-efficiency of metals recovery between these two facilities rather than QWERTY, because the role of metals recovered in terms of resource conservation aspect is much more enhanced than that in QWERTY.

According to MEMRECS, tin fraction is one of the most important contributors of the metals recyclability of waste PCBs containing low gold content such as waste PCBs

from CRT TV, CRT monitor, DVD player, PC etc. In order to obtain high eco-efficiency of metals recovery from such kind of waste PCBs, MEMRECS suggests the recovery of tin should be appreciated.

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CHAPTER 6

Improving Sustainable Recovery of Metals from Waste PCBs by Primary Copper Smelter

6.1 Introduction

End-of-life electrical electronic equipment (e-waste) is one of the fastest growing wastes all over the world because of the rapid increase in the usage of new products with latest technology. Printed circuit boards (PCBs) are one of the basic components of e-wastes comprising heterogeneous mixture of many valuable metals, ceramics, and plastics [1]. Most of hazardous but also most of the valuable materials are concentrated in the PCBs; hence the eco-efficient treatment of PCBs is a key of significance [2]. However, a big question is how to quote the eco-efficiency for metals recycling from PCBs in the context that most of recycling quotes in practice are solely weight based calculated, which makes the recovery of 1kg of iron as important as recovery of 1 kg of gold. It is very irrational to the sense of nature.

According to sustainability concepts, eco-efficiency is producing more value while reducing resources consumption and environmental impact. Thus material recycling in general and metal recycling in particular has therefore become a crucial integral component of sustainable development. In order to quote the metal recycling

performance from complex metals-bearing scraps like PCBs in sustainability approach, the MEMRECS (Model for Evaluating Metal Recycling Efficiency from Complex Scraps) has been developed. In which, sustainability factors that metal recycling mainly contributes to such as natural resources conservation and environmental impact reduction are identified and simultaneously modeled.

In view of the increasing concerns over eco-efficient treatment of waste PCBs, this paper will be focused on the development of sustainable solutions for PCBs recycling in developing countries where lack of proper management and treatment method. For this aim, existing primary copper smelter process is proposed as an alternative for backyard recycling process to recover metals from waste PCBs in developing countries. The study examines the role of every metal fraction to the recyclability of metal from waste PCBs by using MEMRECS. The examined results are then used to identify and select the most sustainable solutions for recovery of metals from waste PCBs under given constraints. In this study, PCBs of different consumer electronic products such as CRT TV, desktop PC, DVD player, and cell phone are selected as samples.

6.2 Primary copper smelter – an alternative for backyard recycling of PCBs in developing countries

In most developing countries, typically China and India, where no specific law

regulated to e-waste recycling yet, the recycling of e-waste in general and PCBs in particular is mainly managed by informal sectors, and motivated by economic purpose only without regard towards environmental concerns. There, PCBs are treated by very primitive techniques such as heating on hot plate, cyanide or acid dipping, open burning to recover mainly copper, silver and gold with comparatively low yields and discarding the rest. Such backyard operations are not only causing tremendous adverse effects on environment but also are making a huge and mostly irreversible waste of resources.

In developed countries, where recycling practices are regulated, metals contained in PCBs are recovered by the sate-of-the-arts refinery facilities. However there are only a few companies in the world equipped with technical know-how, sophisticated flow sheets and sufficient economy of scale like Aurubis AG in Germany, Boliden in Sweden, DOWA in Japan, Umicore in Belgium, Xstrata in Canada, which can fulfill the technical and environmental requirements. However, constructing such kind of facilities in developing countries for PCBs recycling is likely to be unfeasible in terms of economic aspect. In this context, feeding waste PCBs into existing primary copper smelter would be a promising option for waste PCBs issues in developing countries. The motivations for this are that an average copper smelter process is able to recover copper, silver and gold with relatively high yield (Cu: 95%, Ag: 97%, Au: 98%) [3]. Plastics or other

organic substances contained in PCBs can partially substitute the coke as reducing agent and fuel as energy source [4], and they are almost completely decomposed by very high temperature in the smelter. This further increases the utility of existing plants without the need to invest capital in new installations and at the same time, moves toward closing the materials loop [5].

6.3 Data sources and assumptions

- Material composition of PCBs is indicated in Table 6.1
- Environmental values are constructed by LCA software Simapro PhD version 7.2 using Eco-indicator'99 (H/A) [6] as scoring indicator. Inventory database is derived from Eco-invent version 2.1 specified for the Boliden Rönnskär copper smelter in Sweden [7], one of the world's most efficient copper smelters and a world-leader in the recycling of copper and precious metals from electronic scrap.
- System boundary: Environmental values are calculated for the recycling process only. Which means the environmental burdens of previous steps such as collection, dismantling, and transportation are excluded from the calculations.
- The natural resources data is referred from Mineral commodity summaries 2012 [8].
- The environmental data of Boliden Rönnskär copper smelter in Sweden is used as proxy because those data of existing copper smelter process in developing countries

are not available. However, it is assumed that the environmental burden caused by Boliden Rönnskär plan is ten times less than that of existing primary copper smelter, since the primary copper smelters in developing countries definitely have lower capacity and technical advantages.

- It is also assumed that the metal recovery rates of primary copper smelter are Cu: 95%, Ag: 97%, Au: 98%.

Table 6.1 Material compositions of waste PCBs

	CRT TV		Desktop PC		DVD player	Cell phone	
	[a]	[b]	[a]	[b]	[a]	[a]	[c]
Weight (g/unit)	745.33	-	444.65	-	47.37	14.70	-
Al (wt%)	11.98	10	3.93	5	8.48	0.96	0.99
Fe (wt%)	11.41	28	7.68	7	10.59	10.79	6.53
Co (wt%)	0.002	-	0.001	-	0.007	0.17	-
Ni (wt%)	0.22	0.3	0.24	1	0.25	1.73	1.67
Cu (wt%)	11.79	10	25.50	20	23.80	38.87	38.33
Zn (wt%)	1.25	-	5.07	-	0.91	0.33	0.97
Pb (wt%)	2.68	1	1.77	1.5	2.45	1.67	1.26
Sn (wt%)	3.19	1.4	4.42	2.9	3.79	2.49	3.11
Sb (wt%)	0.016	-	0.10	-	0.06	0.04	-
Au/ppm	7	17	82	250	134	1645	1000
Pd/ppm	20	10	22	110	13	142	-
Ag/ppm	49	280	274	1000	314	3985	600
Non-metal (wt%)	57.46	-	51.24	-	49.61	42.37	-

[a] This study
[b] Christian Hageluken, 2006 [9]
[c] Angela C. Kasper et al., 2011 10]

6.4 Efficiency of metal recycling from waste PCBs

Waste PCBs contain various metal fractions, thus there is a competition between every metal fraction in terms of their relative contribution to the total recyclability of metal from waste PCBs. The quantitative information of their relative contribution will be highly valuable for improving the recycling efficiency of metal from waste PCBs. In order to realize this situation, this study uses MEMRECS to quantify the metal recyclability of waste PCBs, and the results are presented in Table 6.2.

According to MEMRECS approach, iron and aluminium have almost no contribution to total recyclability of PCBs irrespective of their high content. Copper and tin are found to be very important contribution to sustainable recycling of PCBs, especially in the case of waste PCBs from CRT TV, desktop PC and DVD player. They make up approximately 70-80% of total metal recyclability. In case of PCBs from cell phone, they also still have significant contribution but their relative contribution is lessened because they are dominated by the contribution of gold fraction. Finally, the relative contribution of the other metal fractions such as cobalt, nickel, antimony, and zinc are relatively inconsiderable.

Table 6.2 Composition of the total metals recyclability of waste PCBs

Metals	Types of PCBs			
	CRT TV	**Desktop PC**	**DVD player**	**Cell phone**
Al	0.5%	0.1%	0.2%	0.0%
Fe	0.1%	0.0%	0.0%	0.0%
Co	0.0%	0.0%	0.0%	0.1%
Ni	3.1%	1.7%	1.9%	3.6%
Cu	47.5%	51.7%	51.4%	22.6%
Zn	3.7%	7.5%	1.4%	0.1%
Pd	4.4%	2.5%	1.6%	4.6%
Ag	0.4%	1.2%	1.5%	5.2%
Sn	30.2%	21.1%	19.2%	3.4%
Sb	0.4%	1.3%	0.8%	0.1%
Au	1.7%	10.3%	18.0%	59.4%
Pb	7.9%	2.6%	3.9%	0.7%
Sum	**100%**	**100%**	**100%**	**100%**

Table 6.2 theoretically shows the composition of total recyclability of metals from waste PCBs. Practically, metal recycling efficiency is presented by how much of the total metal recyclability is realized by a recycling system. In other words, metal recycling efficiency is dependent on the type of metal and the recovery rate of metal can be achieved by a recycling system. Figure 6.1 shows the efficiency of metal recycling from waste PCBs (MEMRECS score) in existing primary copper smelter, where 95% of copper, 97% of silver and 98% of gold are recovered as assumption.

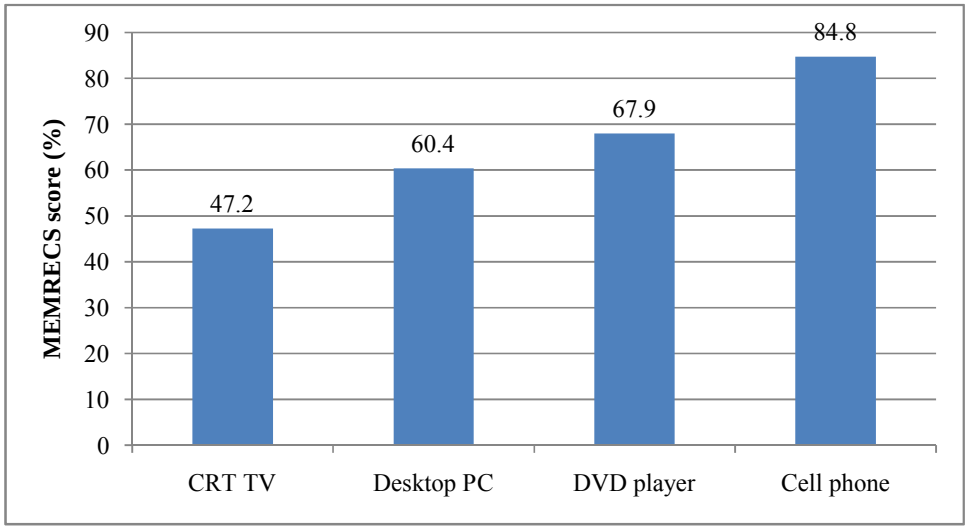

Figure 6.1 Metal recycling efficiency for different types of PCBs

Figure 6.1 indicates that there is a considerable difference between the metal recycling efficiency of different types of waste PCBs. Such difference is derived from two reasons. The first one is the loss of tin because tin is not recovered by the recycling system, which significantly lowers the metal recycling efficiency of PCBs. It is clearly demonstrated in Table 6.2 that 30% of total MEMRECS score of CRT TV' PCBs is lost from tin fraction, whereas only 3% loss occurs with PCBs from cell phone. The second reason is the increase of relative contribution of gold fraction. As indicated in Table 6.2, contribution score of gold drastically increases from 1.7% in the case of CRT TV to 59.4% in the case of Cell phone. That makes the relative contribution of copper, silver, and gold factions on the whole become dominance over the relative contribution of other metal factions.

6.5 Sensitivity of metal recycling efficiency from waste PCBs with gold content

It is found that the gold content of waste PCBs (Table 6.1) little increases but its contribution score to total recyclability of PCBs (Table 6.2) drastically increases. The metal recycling efficiency also increases from 47% in case of PCBs from CRT TV to 85% in case of PCBs from cell phone as shown in Figure 6.1. The reason is that according to MEMRECS calculation, $w_{i,comp}$ value of gold (0.512) and palladium (0.457) are extremely dominant over that of the other metals. Therefore, just a small change in their content can lead to the large change in their relative contribution score. However, only a trace amount of palladium is used in PCBs and thus its contribution score with different types of PCBs is still relatively small. These notions imply that according to MEMRECS, the efficiency of metals recycling from waste PCBs would be strongly influenced by gold content. In order to demonstrate how much sensitivity of metal recycling efficiency from waste PCBs to gold content, the metal recycling efficiency (MEMRECS score) as a function of gold content in PCBs is constructed in this study. In this work, four types of PCBs are selected as sample including PCBs from CRT TV, desktop PC, DVD player, and cell phone. Gold content in each type of PCBs is varied from 0 to 5000ppm. The MEMRECS score with primary copper smelter is calculated corresponding to each value of gold content with respect to each type of

PCBs. The corresponding values of different types of PCBs are then averaged in order to generalize the result about different types of PCBs. The calculation is made with three different life cycle impact assessment (LCIA) methods in order to take the influence of the choice of LCIA method into account.

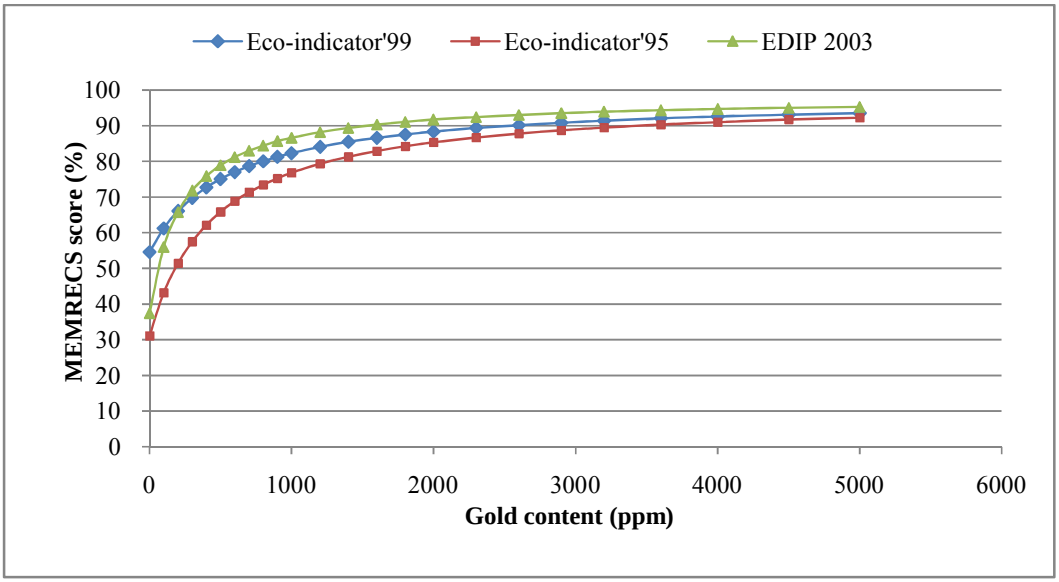

Figure 6.2 MEMRECS score vs gold content

The results shown in Figure 6.2 indicate that the choice of LCIA method makes a little difference in the intensity of MEMRECS scores. However all results have the same tendency that without gold or with very small amount of gold content, the metal recycling efficiency of waste PCBs with primary copper smelter is less than 60%. It is quickly getting to approximately 80% when the gold content in PCBs reaches to around 1000ppm. It is then slowly increasing with increasing gold content. Thus the metal recycling efficiency of PCBs is strongly affected by the gold content between 0 to

1000ppm. Within this range, gold content is the key factor determining the efficiency of metal recovery from waste PCBs by primary copper smelter process. It can be used as an indicator to categorize the waste PCBs for recovery of metal in primary copper smelter process as follows:

- Low grade: gold content lower than 50ppm, yielding MEMRECS score <50%, approximately.
- Medium grade: gold content is from 50 – 300ppm, yielding 50% < MEMRECS score < 70%, approximately.
- High grade: gold content is from 300 – 1000ppm, yielding 70% < MEMRECS score < 80%.
- Very high grade: gold content of minimum 1000ppm, yielding MEMRECS score > 80%.

6.6 Improving sustainable recovery of metals from waste PCBs

As described above, utilizing existing primary copper smelter could be a promising alternative for currently backyard recycling of waste PCBs in developing countries. However, the results from this study indicate that primary copper smelter process is really effective for only high grade PCBs. In order to improve the eco-efficiency of metal recycling from waste PCBs, this study proposes a strategic process for recovery

of metals from waste PCBs, which is represented in Figure 6.3.

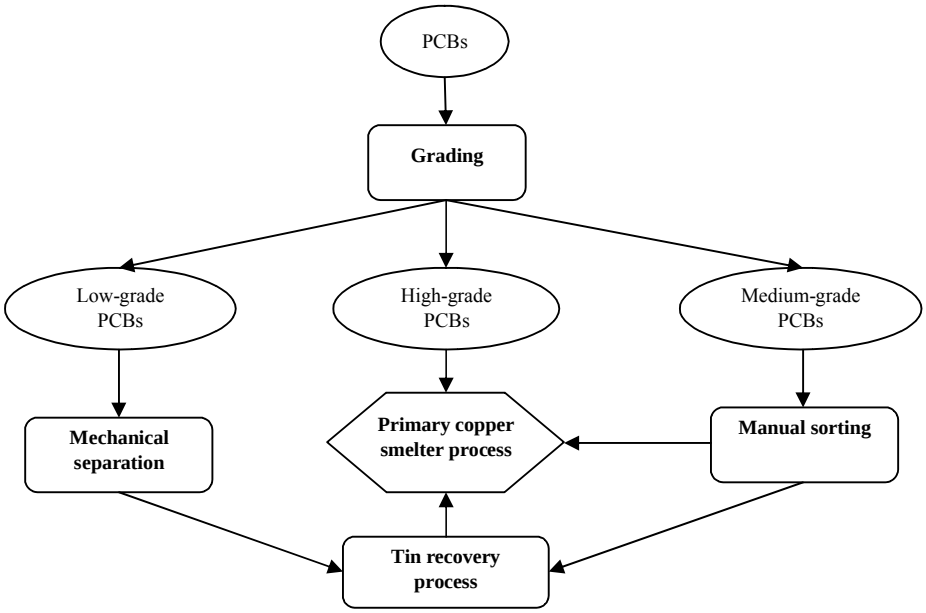

Figure 6.3 Schematic diagram of process for metal recovery from waste PCBs

Firstly, waste PCBs are categorized into three types based on their gold content mentioned above. The high-grade PCBs can be directly fed into copper smelter process to recover valuable metals (copper, gold, silver, palladium). Low-grade and medium-grade PCBs are subject to mechanical pre-treatment process to remove iron and aluminium in order to reduce the load of subsequent steps. Whereas, manual sorting is applied for medium-grade PCBs to remove iron and aluminium parts with care of losing precious metals (mainly gold, and silver, palladium). In order to improve the metal recovery efficiency by avoiding the loss of tin, low and medium grade PCBs are

treated in tin recovery process to recover tin. The tin recovery process can be a hydrometallurgical process, in which tin is dissolved by acid or alkaline solution, and then tin is recovered as metal form. The solid products from tin recovery process are then fed into primary copper smelter to recover copper, silver and gold.

6.7 Conclusion

MEMRECS could be a useful concept in assessment of the metal recyclability of metals-bearing products and the metal recovery efficiency of a recycling system, towards the sustainability approach. It further provides insight into the contribution of every individual metal fraction to the metal recyclability of whole product, which is very helpful for optimizing the eco-efficiency of recycling system.

In terms of metals recycling from waste PCBs using primary copper smelter process, gold content is found to be the deciding factor to the metals recycling efficiency. Thus gold can be used as an indicator to categorize PCBs before processing in order to improve the efficiency. With low gold content PCBs such as PCBs from CRT TV, tin becomes an important factor contributing to the efficiency. In this case, a tin recovery process should be used, in addition to the primary copper smelter.

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CHAPTER 7

Assessment of Metal Recovery Efficiency for Waste Printed Circuit Boards in Vietnam with MEMRECS and Different EOL Scenarios

7.1 Introduction

Electronic waste (e-waste), commonly known as waste from electrical and electronic equipment (WEEE) or end-of-life (EOL) electronics [1,2,3] is the fastest growing segment of the municipal solid waste stream because of increased affordability of new products and technological achievements that make it easy to purchase new electronics rather than repairing or upgrading old products [4]. Typically, about 95-97% of the e-waste contains, by weight, homogenous metals, plastics and glasses, which can easily be separated manually and recycled through the conventional recycling practices with less damage to environment. The rest 3-5% by weight consists of printed circuit boards (PCBs), and their recycling method is challenging due to their heterogeneity in composition. PCBs contain a wide range of elements, some of which are valuable (gold, silver, palladium, platinum), some of which are toxic (mercury, beryllium, indium, lead, cadmium, arsenic, antimony, etc) and some are both (copper, aluminum, nickel, tin, zinc, iron, etc). If such scrap is not treated in an environmental sound way, a high risk of environmental damage exists [5]. As a matter of fact, the recovery of valuable materials

from PCBs is an attractive business recently. However it requires a professional skill and high cost equipments. The lack of knowledge, affordable logistics and the greed for quick money motivates informal sector to employ unhygienic and non-scientific methods for recovery of valuable metals such as Cu, Ag, and Au [6].

Similar to other developing countries, Vietnam does not have any specific management system for e-waste as well as appropriate techniques for e-waste recycling. E-waste in Vietnam is spontaneously collected and recycled by a very active network of informal business sectors with economic benefit being the unique target. In this system, e-waste is collected from door to door. Once it is collected from its generators, usable or fixable items are resold to second hand markets whereas unfixable items are passed through several levels of scrap dealers, to dismantling scrap villages finally. E-waste is mostly manually dismantled to sort out valuable components. While valuable components such as metal frames and plastic cases are recycled domestically, PCBs are mostly sold to Chinese scrap dealers. They are then transported to e-waste recycling villages in China and treated by very primitive techniques like open burning and acid dipping to extract valuable metals such as gold, silver, copper.

Feeding scrap PCBs into existing primary copper smelters is one of the contemporary methods for PCBs recycling. The motivation for this is to replace a

portion of the primary copper bearing ore which is in decreasing supply, with secondary copper containing materials. This method further increases the utility of existing plants without the need to invest capital in new installations [7]. In developed countries, where e-waste recycling practices are regulated with high consideration of environmental issues, PCBs are correctly treated by state-of-the-art technology, which can fulfill the technical and environmental requirements. In this way, PCBs are designated to send to the highly efficient metal refinery process such as Boliden in Sweden, DOWA in Japan, Umicore in Belgium, or Xstrata in Canada.

With the aim of evaluating the metal recycling efficiency from spent PCBs in terms of two important aspects at global scale: environmental impacts and natural resources conservation, this study utilizes MEMRECS as an indicator for metal recycling performance. In this study, six types of PCBs from consumer electronic products are collected at scrap villages in Vietnam and analyzed the metal compositions. Three end-of-life (EOL) scenarios for recycling of PCBs are supposed and described with certain assumptions. The eco-indicator'99 (H/A v2.08) [8] is selected as the base line life cycle impact assessment (LCIA) method for calculation. For sensitivity analysis, two more LCIA methods: Eco-indicator '95 [9] and EDIP 2003 [10] are used in order to estimate the influence of the choice of LCIA method on the result.

7.2 End-of-life (EOL) scenarios for waste PCBs in Vietnam

Scenario 1: Selling to informal sectors in China

As a matter of fact, this scenario is currently in practice for PCBs issues in Vietnam. Once PCBs are separated from electronic products, they are sold to Chinese scrap dealers and transported to e-waste villages at Guiyu, Shantou, Guangdong, in China. The PCBs are treated there by the primitive techniques such as (i) heating on hot plate to separate the gold rich components (micro chips and connectors) from PCBs; (ii) cyanide or acid dipping to extract gold and silver from the components; (iii) open burning followed by acid leaching to recover copper; (iv) de-soldering by acid to recover lead. Since primitive techniques result in a large loss of valuable metals during the process, it is assumed that the overall recovery rate for gold, silver is 30%, and for copper, lead, it is 50%

Scenario 2: Feeding into existing primary copper smelter in Vietnam

There is a primary copper smelter in Vietnam with output capacity of ten million tons copper per a year. In this scenario, waste PCBs are proposed to be treated at the existing copper refinery plant. Here waste PCBs will be collected, transported and fed into smelter furnace, where plastics and other organic substances are completely burned out, copper and precious metals (Au, Ag, Pd) go into copper matte, most other metals (Pb,

Al, Fe, Sn, Ni, Zn, Etc.) go into slag which is then separated from the process stream. The copper matte is then undergone various refinery steps such as conversion, reduction, and electro-refining to produce commercial copper. Precious metals go into the anode slime, which is specially treated in the precious metal recovery process to recover gold and silver.

Scenario 3: Recycling at professional metal refinery plant in Japan

The third scenario would suppose that PCBs in Vietnam be collected and exported to a state-of-the-art metals-refining plant in Japan. The selected plant is the DOWA eco-system facility located in Akita prefecture, Japan. Using advanced metallurgy technologies, such a system is currently able to efficiently recycle as many as seventeen different metallic elements. The main processes of DOWA eco-system operation is also copper smelter and refinery processes to produce copper and precious metals such as gold, silver and palladium. In addition to copper smelting, base metals operations are also integrated in this system to recover most base metals contained in slag portion (Pb, Sn, Zn, Ni…)

7.3 Data sources and assumptions

In order to obtain samples for this study, the PCBs separated from six types of consumer electronic products: CRT TV, CRT monitor, Desktop PC, DVD player, fixed

wireless phone, and cell phone were collected at a scrap village located in Vinh Phuc province of Vietnam. At laboratory, each PCBs sample was cut and ground to powder with particle size under 1000 μm by a laboratory cutting mill Retsch SM 2000. Powder product was then dissolved with aqua regia in solid liquid ratio of 1:20 (1 g of sample to 20ml of aqua regia solution). The contact time between the fraction samples and aqua regia was about 24 hours at room temperature to ensure complete digestion of metals; followed by filtration with quantitative filter paper [11,12]. The leached portion was then made up to 500 ml by adding deionized water before analyzing the metal content by inductively couple plasma mass spectrometry (ICP-MS). The metal composition of 6 types of PCBs sample is shown in Table 7.1.

Table 7.1 Material compositions of waste PCBs from consumer electronic products

	CRT TV		CRT Monitor	Desktop PC		DVD player	Fixed wireless phone	Cell phone	
	[a]	[b]	[a]	[a]	[b]	[a]	[a]	[a]	[c]
Weight (g/unit)	745.33	-	320	444.65	-	47.37	95.30	14.70	-
Al (%)	11.98	10	12.28	3.93	5	8.48	2.10	0.96	0.99
Fe (%)	11.41	28	15.52	7.68	7	10.59	8.42	10.79	6.53
Co (%)	0.002	-	0.008	0.001	-	0.007	0.009	0.17	-
Ni (%)	0.22	0.3	0.10	0.24	1	0.25	0.40	1.73	1.67
Cu (%)	11.79	10	11.69	25.50	20	23.80	21.98	38.87	38.33
Zn (%)	1.25	-	1.98	5.07	-	0.91	14.38	0.33	0.97
Pb (%)	2.68	1	2.48	1.77	1.5	2.45	1.00	1.67	1.26
Sn (%)	3.19	1.4	3.02	4.42	2.9	3.79	1.39	2.49	3.11
Sb (%)	0.016	-	0.06	0.10	-	0.06	0.02	0.04	-
Au/ppm	7	17	3	82	250	134	96	1645	1000
Pd/ppm	20	10	4	22	110	13	14	142	-
Ag/ppm	49	280	81	274	1000	314	300	3985	600
Non-metal (%)	57.46	-	52.87	51.24	-	49.61	50.26	42.37	-

[a] Own analysis
[b] Christian Hageluken, 2006
[c] Angela C. Kasper et al., 2011

Since the inventory data of metal recovery process in all scenarios are not available, most environmental data for QWERTY calculations are referred from Ecoinvent v2.1 with certain assumptions. For example, the environmental data for processing of primary copper smelter in Vietnam are referred from those of the Boliden Rönnskär copper smelter in Sweden, one of the world's most efficient copper smelters and a world-leader in the recycling of copper and precious metals from electronic scrap. However, since the primary copper smelter in Vietnam has lower capacity as well as technical level, it is assumed that the environmental burden caused by copper smelter processing is ten times higher than that of Boliden Rönnskär. The choice of ten times is arbitrary assumption. However, because the environmental value to recycle metal is extremely less than the environmental value to produce metal from natural ore. Therefore, it just makes a slightly change in the composition of total metal recyclability of waste PCBs. Similarly, environmental data of Boliden Rönnskär are used as proxy for the environmental data of DOWA eco-system in Japan. Table 7.2 summarizes the data sources and assumptions for calculations of QWERTY.

Data regarding the estimated world reserve of metals for RRE calculations are referred from Mineral commodity summaries 2012 [13].

Table 7.2 Data sources and assumptions for the assessment of scrap PCBs recycling

Product stage	Data sources	Assumptions	Module name in Ecoinvent
Scenario 1			
Transportation on road	Ecoinvent v2.1	Lorry 3.5-7.5t, 200km	Transport, lorry 3.5-7.5t, EURO3
Transportation on sea	Ecoinvent v2.1	Freight ship, 503NM	Transport, transoceanic freight ship/OCE
Metal recovery processing at scrap village in China	Own assumptions	Environmental burden is only calculated with unrecovered metal fractions released to environment. They go to air, soil, and water (each 33%). Recovery rate for Au and Ag is 30%, for Cu and Pb is 50%	-
Scenario 2			
Transportation on road	Ecoinvent v2.1	Lorry 3.5-7.5t, 120km	Transport, lorry 3.5-7.5t, EURO3
Transportation on rail	Ecoinvent v2.1	Rail freight, 300km	Transport, freight, rail/RER
Metals recovery processing at primary copper smelter in Vietnam	Ecoinvent v2.1	Environmental burden of processing in Vietnam is 10 times higher than that of Rönnskär plant in Sweden. Recovery rate for Au, Ag is 98%, for Cu is 95%	Copper, secondary, from electronic and electric scrap recycling, at refinery/SE Gold/Silver, secondary, at precious metal refinery/SE
Scenario 3			
Transportation on road	Ecoinvent v2.1	Lorry 3.5-7.5t, 120km	Transport, lorry 3.5-7.5t, EURO3
Transportation on sea	Ecoinvent v2.1	Freight ship, 2168NM	Transport, transoceanic freight ship/OCE
Metals recovery processing at DOWA eco-system in Japan	Ecoinvent v2.1	Environmental burden of processing in Japan is similar to that of the Rönnskär plant in Sweden. Recovery rate for Au, Ag, Pd is 98%, for Cu is 95%, for Ni, Pb, Sn is 90%	Copper/Tin/Lead/Nickel, secondary, from electronic and electric scrap recycling, at refinery/SE Gold/Silver/Palladium, secondary, at precious metal refinery/SE

7.4 Efficiency of metal recycling from waste PCBs with different EOL Scenarios in Vietnam

Three different EOL scenarios for PCBs in Vietnam were evaluated with MEMRECS concept and three different LCIA methods. The results are presented in Figures 7.1 – 7.3. In general, there is a clear difference between MEMRECS scores with respect to different EOL scenarios. Scenario 1 (the current practice in Vietnam) results in very low metal recycling efficiency. In some cases, the MEMRECS scores show negative values since the environmental gain from recovered metals is unable to compensate the environmental loss from the recycling process. In this study, the environmental impacts of recovery processing in Scenario 1 is modeled based on only the emission of unrecovered metals to the environment, without considering an extra impact from additional chemical and energy consumption etc. Thus the environmental impacts of scenario 1 in reality would be higher, leading to the lower recycling efficiency. The MEMRECS scores of Scenario 2 showed the scenario indicative of being more advanced solutions for PCBs in Vietnam. However, the recycling efficiency is still relatively low (mostly less than 60%) except the case of cell phone PCBs. Even the environmental impact from long transportation is included in its calculation, the Scenario 3 results in the highest recycling efficiency for all types of PCBs. The reason is

that the environmental loss from transportation is very small in comparison with the environmental gain from recovered metals, and most of valuable metals that make main contribution to MEMRECS score with 100% in full are all recovered in this scenario. This result is appropriate for the 'Best-of-2-Worlds' philosophy [14], which provides a network and pragmatic solution for e-waste treatment in emerging economies like Vietnam. It seeks technical and logistic integration of best pre-processing in developing countries to manually dismantle e-waste and the best en-processing to treat hazardous and complex fractions in international state-of-the-art en-processing facilities.

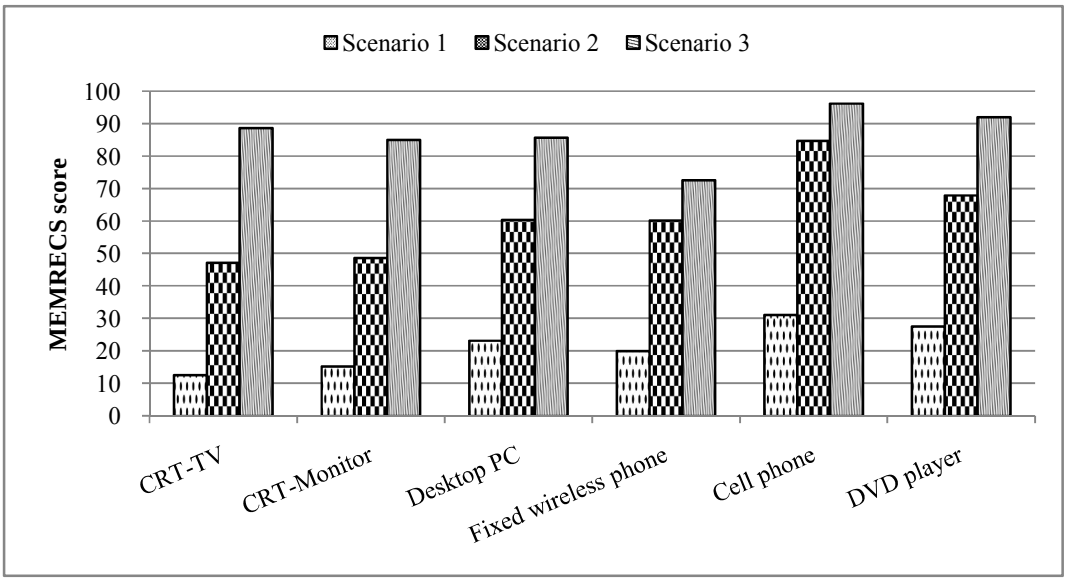

Figure 7.1 Metal recycling efficiency for each scenario with Eco Indicator'99

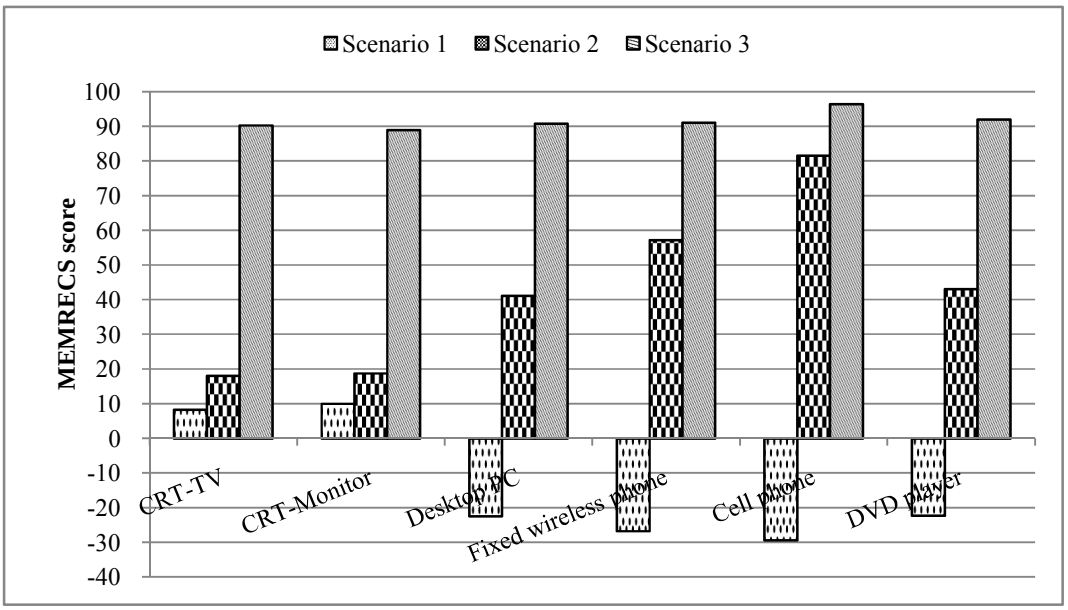

Figure 7.2 Metal recycling efficiency for each scenario with Eco Indicator‘95

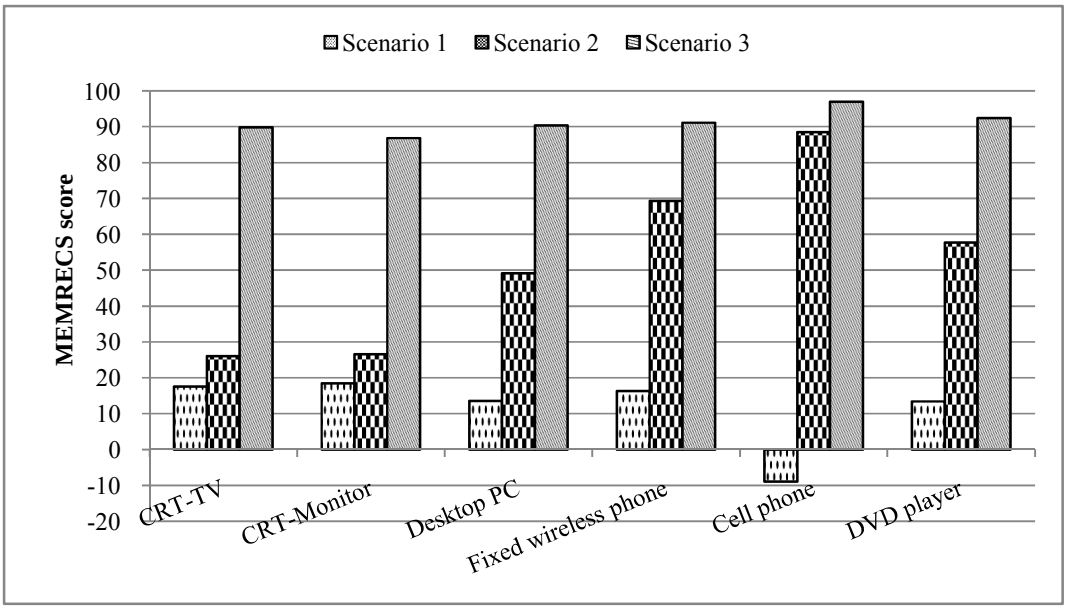

Figure 7.3 Metal recycling efficiency for each scenario with EDIP 2003

Within a certain scenario, the recycling efficiency results are strongly influenced by the choice of the LCIA method adopted, especially in the case of Scenario 1 where MEMRECS scores are highly different from each other not only in intensity but also in tendency depending on different PCBs types. The reason is that the environmental impact in this scenario is modeled based on only the effect of toxic metals going into the environment, whereas different LCIA methods model the environmental impact of toxic metals in completely different ways. This leads to the large disparity of the results. Unlike in Scenario 1, the environmental impact in Scenario 2 and Scenario 3 was calculated based on data referred from the same data sources. Hence, the tendency of MEMRECS scores corresponding to different PCBs types is somewhat similar despite the difference among MEMRECS scores with different LCIA methods.

In addition to the analysis with three scenarios mentioned above, this study also calculates the scenario 4 with assumption that PCBs are recycled by the primary copper smelter process proposed in Chapter 6. In which, not only Cu, Au, Ag, Pd by primary copper process, but also Sn is recovered by Tin recovery process with the recovery rate of 90%. The result in Fig. 7.4 indicates that the metal recycling efficiency for waste PCBs in Vietnam can be significantly improved if applying the recycling process proposed in Chapter 6.

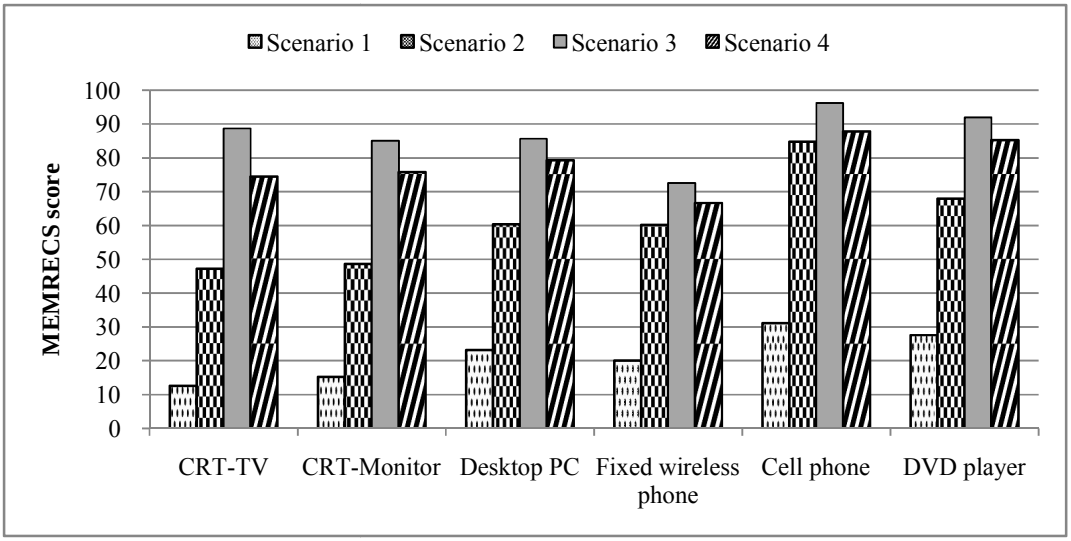

Figure 7.4 Metal recycling efficiency for four scenarios with Eco Indicator‘99

7.5 Conclusion

According to MEMRECS, the current situation of exporting to informal recycling sectors in China would yield the lowest metal recovery efficiency due to the huge loss of resources and environmental benefit. Feeding into the existing primary copper smelter could be a better alternative. However, in order to achieve high efficiency, the categorization of waste PCBs according to gold content and the recovery of tin are necessary. Exporting to the state-of-the-art metal refinery plan always ensures the highest efficiency because it can fulfill both technical and environmental requirements.

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CHAPTER 8

Conclusions and Recommendations

8.1 Conclusions

In this work, the relative contribution of every metal fraction to the total metal recyclability of waste PCBs according to different MRQ approaches has been investigated. Based on this, MEMRECS is proposed as a new quantitative approach to quote the metal recyclability as well as metal recycling efficiency for waste PCBs in particular and for scraps containing various metal fractions in general towards the sustainable sound manner. The results achieved in the thesis are summarized as followings.

1. In the chapter 3, the relative contribution scores of metal fractions to the total recyclability of waste PCBs reported by MRE, RRE and QWERTY are substantially different from each other. This probably results in some confusion of the recycling efficiency with which metals are recycled. Furthermore, if following one of these approaches to set the priority for the recovery of metal from waste PCBs, the outputs can only meet a single target while the other existing target may be lost. In this context, MEMRECS has been introduced as a new quantitative measure, which is able to compromise the contribution of metal recycling to practical issues in

multiple points of view. MEMRECS can provide insights into the contribution of every metal fraction to the total metal recyclability of waste PCBs, on the condition that both environmental impact and natural resources conservation aspects are considered simultaneously. This information will be really helpful for setting the priority in metal recovery, according to both qualitative and quantitative forms. In MEMRECS, the natural resource conservation aspect is modeled more clearly and directly than that in QWERTY/Eco-indicator'99. Moreover, it is much more appreciated in comparison to it is in QWERTY/Eco-indicator'99.

2. In the chapter 4, the sensitivity of MEMRECS with the choice of LCIA model has been examined. It is found that MEMRECS scores are remarkably varied with different LCIA model. Such variation is indeed derived from the substantial change in relative contribution of individual metal fraction with different LCIA methods. This notion recommends that the accuracy and validity of LCIA method should be carefully concerned before putting into the model. Furthermore, it should be noted that in case of scenario analysis, all MEMRECS scores must be calculated using the same LCIA method. Moreover, within a certain LCIA model, the recycling efficiency of metals from waste PCBs is strongly dependent on the individual recovery rate of each metal fraction. This notion supports the priority setting for

different metal-bearing products in terms of technological selection and technological improvement.

3. In the chapter 5, MEMRECS can clearly discriminate the eco-efficiency of metals recovery between these two facilities rather than QWERTY, because the role of metals recovered in terms of resource conservation aspect is much more enhanced than that in QWERTY. According to MEMRECS, tin fraction is one of the most important contributors of the metals recyclability of waste PCBs containing low gold content such as waste PCBs from CRT TV, CRT monitor, DVD player, PC etc. In order to obtain high eco-efficiency of metals recovery from such kind of waste PCBs, MEMRECS suggests the recovery of tin should be appreciated.
4. In the chapter 6, MEMRECS has been used to investigate the dependence of metals recycling efficiency with gold content in the hypothetic assumption that metals from waste PCBs are recovered by primary copper smelter process. In this case, the metals recycling efficiency is strongly sensitive to the gold content. Thus, gold content can be used as an indicator to categorize PCBs in order to improve the metal recycling efficiency. With low gold content PCBs such as PCBs from CRT TV, tin becomes an important factor contributing to the efficiency. In this case, a tin recovery process should be used, in addition to the primary copper smelter.

5. In the chapter 7, an application of MEMRECS has been applied to the evaluation of recycling efficiency of metals from waste PCBs according to different end-of-life scenarios in Vietnam. The scenario analysis results indicated that the current situation of exporting to informal recycling sectors in China would yield the lowest metal recovery efficiency due to the huge loss of resources and environmental benefit. Feeding into the existing primary copper smelter could be a better alternative. Exporting to the state-of-the-art metal refinery plant always ensures the highest efficiency because it can fulfill both technical and environmental requirements. These results is found to be appropriate for the 'Best-of-2-Worlds' philosophy, which provides a network and pragmatic solution for e-waste treatment in emerging economies like Vietnam. It seeks technical and logistic integration of best pre-processing in developing countries to manually dismantle e-waste and the best en-processing to treat hazardous and complex fractions in international state-of-the-art en-processing facilities.

7.2 Recommendations

The present work mainly focuses on the evaluation of metal recyclability and metal recycling efficiency for waste PCBs towards the sustainable development sound manner. In order to present the characterization of MEMRECS more clearly, and to expand the

application of MEMRECS, the following recommendations are proposed:

1. In present work, only the sensitivity analysis of MEMRECS with different LCIA models (representative for environmental impact aspect) is investigated. In the future work, the sensitivity analysis of MEMRECS with different annually updated data of the world metal reserves (representative for natural resources conservation) should be examined.
2. Entropy weighting method used in the present work is one of few objective weighting methods. In the future work, the other objective weighting methods such as the Critic method should be used in order to examine the influence of the choice of weighting method on the relative importance of the environmental impact aspect against the resource conservation aspect.
3. The present work has only calculated MEMRECS for waste PCBs - a type of highly complex metal-bearing products. In the future work, MEMRECS should be applied to evaluate the metal recycling from other types of complex metal-bearing product such as automotive shredder residues.

Appendix A

The World Reserves for Metals

(Source: Mineral Commodity Summary 2012)

Metal	World reserves (ton)
Aluminum	7,073,170,732
Iron	80,000,000,000
Cobalt	7,500,000
Nickel	80,000,000
Copper	690,000,000
Zinc	250,000,000
Palladium	33,000
Silver	530,000
Tin	4,800,000
Antimony	1,800,000
Gold	51,000
Lead	85,000,000

Appendix B

Metals Recycling at Boliden Rönnskär Plant

(Source: Eco-invent v2.1 report No.10)

The pyrometallurgical technique applied by Boliden (Rönnskär plant, Sweden) was used to represent the inventory for secondary metals production. The plant is a copper-lead smelter that treats complex ores and to a large extent electronic scraps and integrates the recovery of, among others, gold, silver, lead, palladium and other useful metals into one facility. The electronic scrap however passes only a part of the facility, which is indicated by the red circles in Figure I. The scrap enters the process at the Kaldo plant. The valuable metals distribute into the copper matte and which is further processed to copper. There again the precious metals go into the anode slime, which is specifically treated in the precious metal recovery plant.

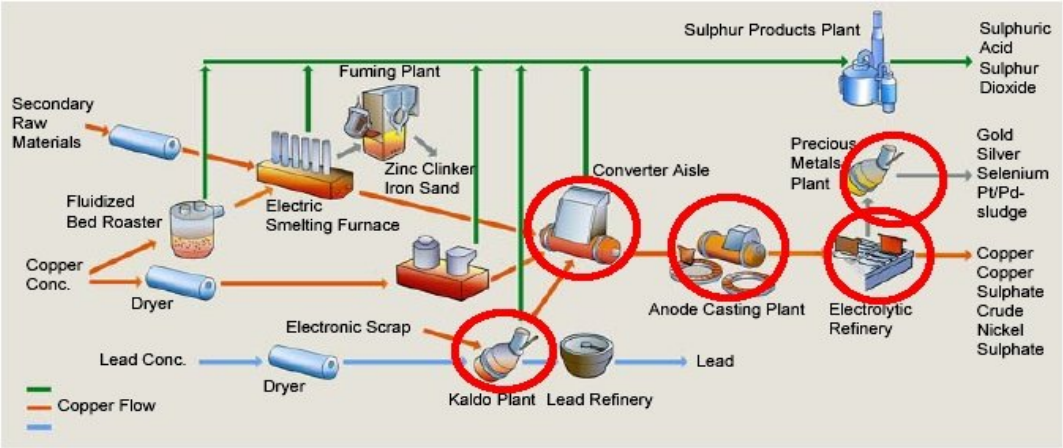

Figure I Concept of the Boliden Rönnskär process
(Source: Eco-invent v2.1 report No.10)

Pretreatment: Normally no pre-treatment (mechanical) is applied to the electronic scrap. Instead the plastics fraction of the gold containing scrap is used as energy carrier in the pyrometallurgical approach.

Converting: The actual recovery process begins with feeding the electronic scrap into the KALDO smelter unit. This in 1977 patented Boliden-own technology Peterson & Lundquist (1977) comprises in principle a brick-lined vessel made of stainless steel that has an effective volume of 2 m^3. This vessel is tiltable along its horizontal axis and can also be rotated during operation. For smelting, the vessel is fed with oxygen (via a lance), coke breeze and heat (oil). Key products of this treatment step are selenium-rich off-gas (which is then treated in the selenium plant) and black copper (74-80% Cu, 6-8% Sn, 5-6% Pb, 1-3% Zn, 1-3% Ni, 5-8% Fe). The latter is subsequently further processed in the Aisle converter unit.

In the Aisle converter unit the black copper is converted into blister copper. Secondary lead and slag are separated from the process stream. Technologically, the Aisle converter is a brick-lined (magnesite-chromium), horizontally aligned converter unit fed with hydrocarbon fuel, industrial oxygen and calcium oxide (Figure B)

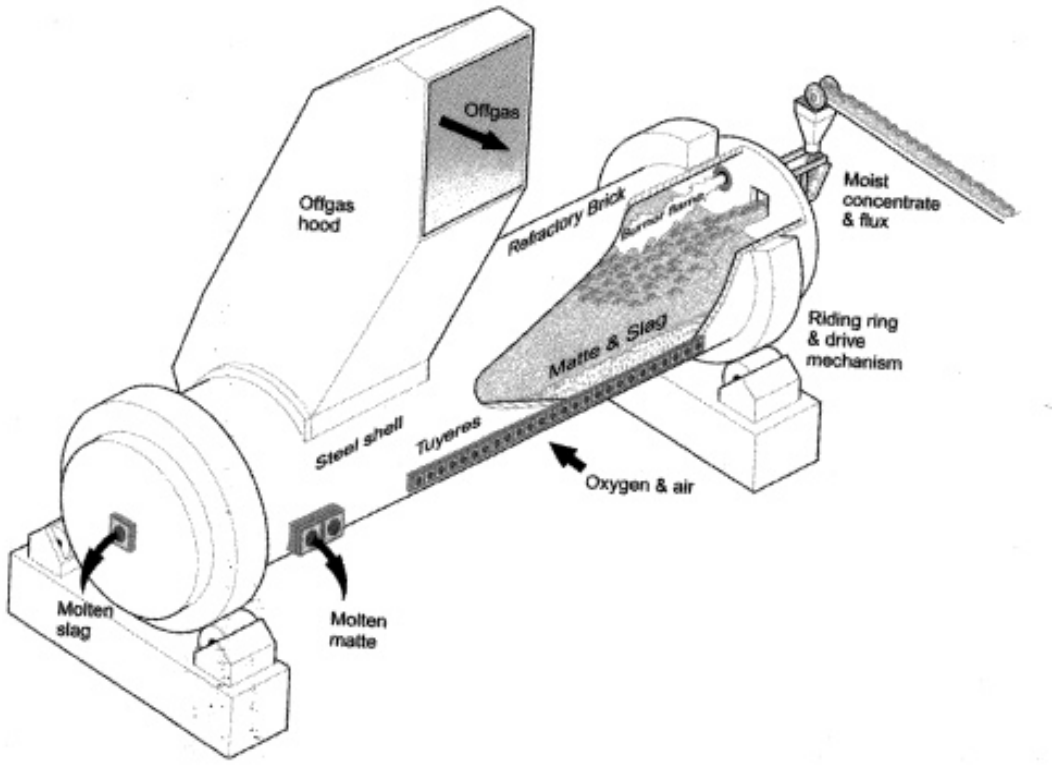

Figure II Detail of a converter unit
(Source: Eco-invent v2.1 report No.10)

Refining: The processing of the electronic scrap in the Aisle converter is followed by a further refinement in a) the anode casting plant and b) the electrolytic refinery. At BOLIDEN's Rönnskär facility a new Twin M-16 anode casting facility (Figure III) is deployed to cast the hot blister copper into anodes. The facility consists of an inlet through which the hot blister copper is transported to the loader. Increasing the processing efficiency, the loader alternately feeds the blister copper into two wheel caster.

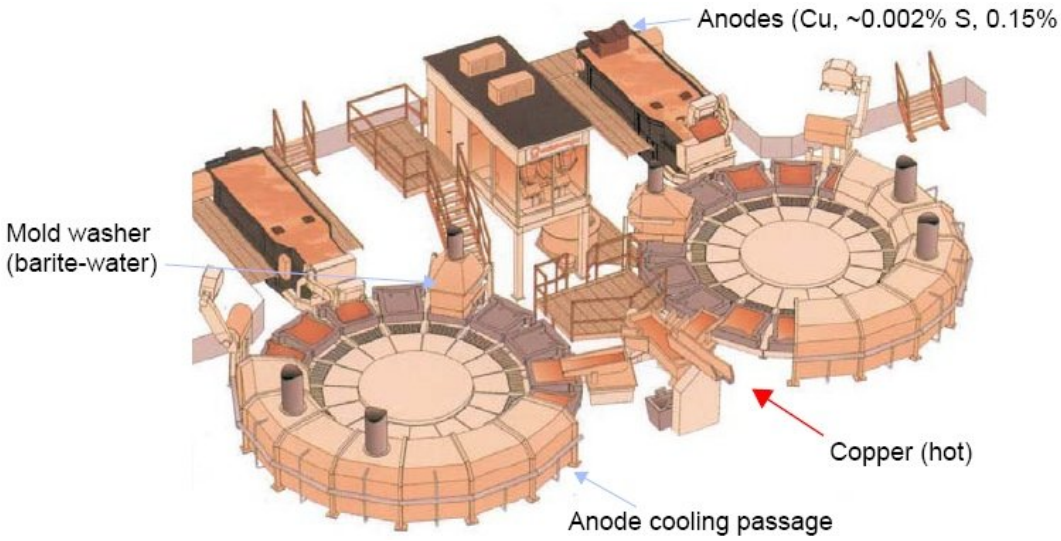

Figure III Sketch of a twin-wheel anode caster
(Source: Eco-invent v2.1 report No.10)

Once cast, the anodes are then finished and stored in the anode container. The anode sheets typically have a size of 1.00 m * 1.40 m (approximated based upon Outokumpu, 2004) and consist of 99.5% copper including, however, impurities of sulphur, oxygen and traces of precious metals (Davenport et al., 2002). In the next step the copper anode is processed in the electrolytic refinery plant. This facility is a large hall with a large number of cells.

In 1999, the Rönnskär plant was equipped with 644 electrorefining cells and with 2 circulation tanks (Boliden, 2006c; Corrosion Technology International, 2006). The cells are made of stainless steel and reinforcement of glass fibre. The volume of the cells can vary considerably depending upon the process it is intended to be applied. The cells are continuously circulated by water spiked with copper, sulphuric acid and chloride

(Davenport et al., 2002) Typically, the circulation time is about 0.02 m^3/min and the power consumption ranges from less than 300 kWh/t material to nearly 400 kWh/t material (Davenport et al., 2002). The final products of the electrolytic step are copper and nickel. As a residual, precious metal containing anode slime is generated, which is finally treated in the precious metals plant in order to recover secondary gold, silver, palladium, and platinum.

Anode slime treatment: In a first step the precious metals containing anode slime is decopperised. The remaining residues are dried and processed by pyrometallurgical means. There also exists a hydrometallurgical route. Whereas the pyrometallurgical route is apt to process large quantities of well defined anode slime from primary production, the hydrometallurgical route is more flexible to changes in feed composition as it occurs in the processing of slimes from secondary copper smelters. However, in Boliden the pyrometallurgical route is applied (Figure IV). After de-copperising and precipitation of copper telluride the residue is dried and pyrolytically refined to silver rich dorée metal, which is cast into anodes for a subsequent electrorefining of silver (Moebius electrolysis) and Gold (Wohlwill electrolysis). The remaining slime consists mainly of PGM (platinum group metal) that is recovered.

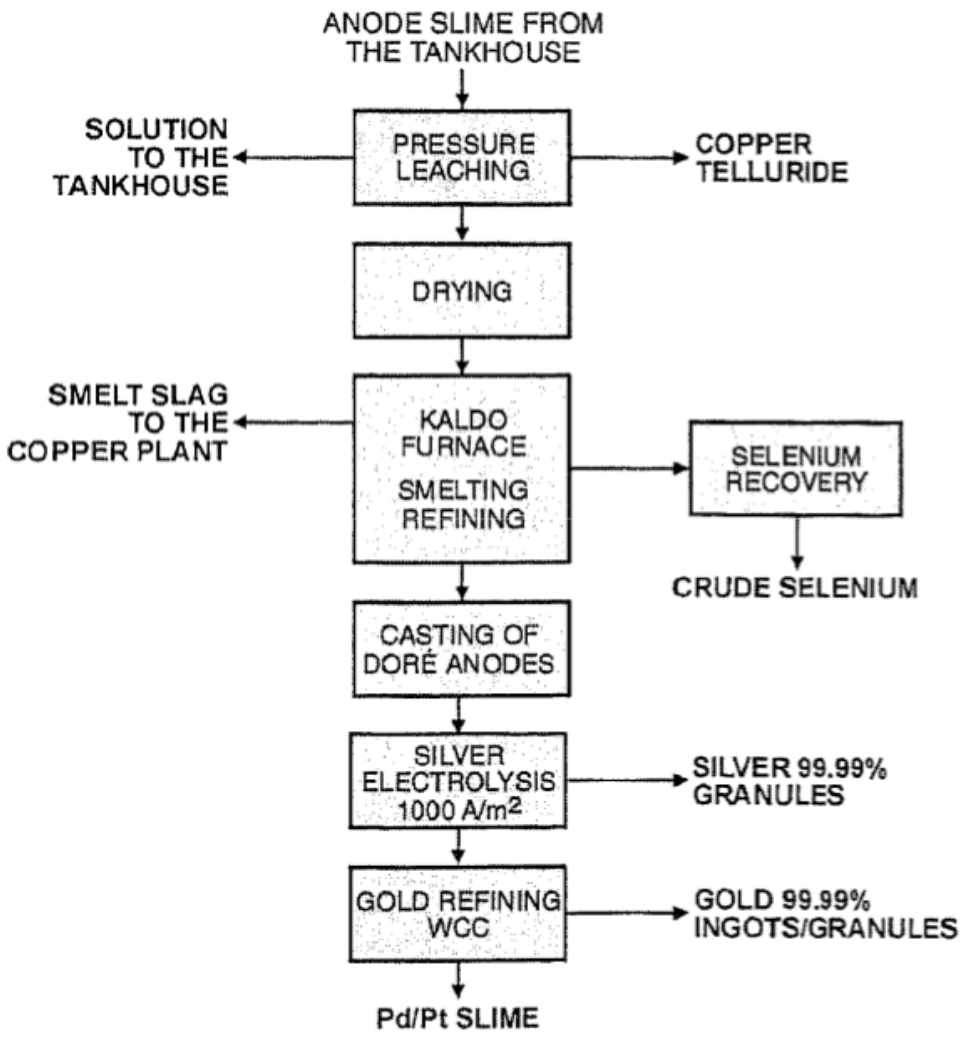

Figure IV Sketch of the anode slimes treatment and precious metal recovery (Source: Eco-invent v2.1 report No.10)

Waste: The recovery of precious metals, such as gold, is associated with the generation of a number of byproducts off-gases, sludge, slag, waste heat and dust. Most of the byproducts are captured by appropriate filters. From an environmental perspective, most important, is the treatment of the residuals of the cyanide-containing sludge generated

while concentrating gold from doré-grade gold. This sludge is treated applying sulphur-dioxide and air before it is dumped into tailing ponds. Concerning the other by-products and their treatment, no utilisable information could be compiled.

Emissions: Despite of the application of modern filter technologies, the precious metals recovery process is also associated with the generation of emissions to the environment (HELCOM, 2002). In particular the following emissions to air are considered problematic: dust, copper, lead, zinc, cadmium, arsenic, mercury, sulphur dioxide, nitrogen oxide, fluoride, chloride and PCDD/F. Emissions to water are include copper, lead, zinc, cadmium, arsenic, mercury.

Appendix C

Data Sources for Environmental Values

(Source: Eco-invent 2.1)

Metal	Module name in Ecoinvent 2.1	
	Primary Production	**Secondary Production**
Aluminum	Aluminium, primary, at plant/kg/RER	-
Iron	Cast iron, at plant/kg/RER	-
Cobalt	Cobalt, at plant/kg/GLO	-
Nickel	Nickel, 99.5%, at plant/kg/GLO	Nickel, secondary, from electronic and electric scrap recycling, at refinery/kg/
Copper	Copper, primary, at refinery/kg/GLO	Copper, secondary, from electronic and electric scrap recycling, at refinery/kg/
Zinc	Zinc, Special High Grade/kg/GLO	-
Palladium	Palladium, primary, at refinery/kg/RU	Palladium, secondary, at precious metal refinery/kg/SE
Silver	Silver, from copper production, at refinery/kg/GLO	Silver, secondary, at precious metal refinery/kg/SE
Tin	Tin, at regional storage/kg/RER	-
Antimony	Antimony, at refinery/kg/CN	-
Gold	Gold, primary, at refinery/kg/GLO	Gold, secondary, at precious metal refinery/kg/SE
Lead	Lead, primary, at plant/kg/GLO	Lead, secondary, from electronic and electric scrap recycling, at plant/kg/SE

List of Publications

Original Paper

1. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2013). *Analysis of Intentions to Recycle Electronic Waste (E-Waste) Using the Theory of Planned Behavior: A Case Study in Urban Areas of Vietnam*. Zero-Carbon Energy Kyoto 2012, Special Edition of the Joint Symposium "Energy Science in the Age of Global Warming" of the Kyoto University Global GCOE Program and the JGSEE/CEE-KMUTT, Springer, 2013, pp. 73-80.
2. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2013). *Model for Evaluating Metal Recycling Efficiency for Complex Scraps (MEMRECS) and Its Calculations with Different Life Cycle Impact Assessment Methods.* International Journal of Arts and Sciences 6(1), pp. 89-98
3. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2013). *MEMRECS – A Sustainable View for Metal Recycling from Waste Printed Circuit Boards.* Journal of Environmental Protection 4(8), pp. 803-810.
4. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (Forthcoming 2014). *Assessment of Metal Recovery Efficiency for Waste Printed Circuit Board in Vietnam with MEMRECS and Different End-of-Life Scenarios.*

Journal of Solid Waste Technology and Management (Accepted)

5. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara. *Improving Sustainable Recovery of Metals from Waste Printed Circuit Boards by Primary Copper Smelter Process.* Journal Material Cycles and Waste Management. DOI: 10.1007/s10163-013-0189-7

Abstracts and Proceedings of the International Conferences

1. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2013). *Analysis of Intentions to Recycle Electronic Waste (E-Waste) Using the Theory of Planned Behavior: A Case Study in Urban Areas of Vietnam.* Abstract of the 4th GCOE International Symposium on "Zero-Carbon Energy Kyoto 2012", Bangkok, Thailand, May 22-23, 2012.
2. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2012). *Model for Evaluating Metal Recycling Efficiency for Complex Scraps (MEMRECS) and Its Calculations with Different Life Cycle Impact Assessment Methods.* Abstract of the Academic Conference, Germany, December 2-6, 2012.
3. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2013). *Assessment of Metal Recovery Efficiency for Waste Printed Circuit Board in Vietnam with MEMRECS and Different End-of-Life Scenarios*. Proceeding of 28th

International Conference on Solid Waste Technology and Management, March 10-13, 2013, Philadelphia, PA USA, pp. 123-132.

4. Hoang-Long Le, Eiji Yamasue, Hideyuki Okumura, and Keiichi N. Ishihara (2012). *Application of the Theory of Planned Behavior to determine the drivers for e-waste recycling behavior in Vietnam*. Ajou-KIT-Kyoto University Joint International Symposium, January 31-February 1, 2012, Uji, Japan.