Economic & environmental assessment and optimization of recycling scenarios for IT equipment in developing countries

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Foreword

I would like to take this opportunity to express my gratitude to the following people:

- Jef Peeters and Paul Vanegas for their guidance, support and valuable recommendations throughout the project.
- Professor Joost Duflou for his appreciated guidance and kind financial contribution to support an internship in Kenya.
- Thomas Poelmans from WorldLoop for his advice, willingness to cooperate and the opportunity to do an internship in Kenya.
- Christel Heynickx for her revision of the text.

I sincerely hope that this text can contribute to a better understanding of the opportunities and challenges of recycling e-waste.

Frank Plessers

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Abstract

Once IT equipment reaches end-of-life, it poses challenges to society as recycling is of both socio-economic and environmental significance. The recycling of e-waste in industrialised countries typically consists of mechanical pre-processing and best available technologies for end-processing. In developing countries most is dismantled by informal recyclers who use harmful end-processes. The best-of-2-worlds (Bo2W) philosophy integrates manual dismantling in developing countries with proper end-processes in industrialised countries.

The first objective is to make an economic and environmental assessment of the mechanical treatment (MT) scenario in industrial countries and both the informal sector (IS) and the Bo2W scenario in developing countries. The second objective is to investigate whether recycling IT equipment from industrialised countries could be improved by exporting it to developing countries and applying the Bo2W philosophy. The third objective is to investigate opportunities to improve the Bo2W scenario in developing countries. The environmental impact is quantified with a Life Cycle Assessment and the economic assessment is based on the material revenue and all processing costs, except collection. The scope is limited to recycling CPUs and CRT monitors because they currently are the most common obsolete devices.

The environmental assessment shows that the Bo2W scenario is 44 % more eco-friendly compared to the MT scenario for CPUs, but is similar for CRT monitors. Informal recyclers have low recovery rates for gold and severely pollute the environment. The economic assessment shows that the Bo2W scenario is most profitable for CPUs, but the IS scenario is most profitable for CRT monitors.

If CPUs and CRT monitors would be exported from Belgium to developing countries who consequently apply the Bo2W philosophy, the environmental impact would improve with 35 % and 2 % respectively. High shipping costs make it most profitable to ship to Hungary and not to China or Kenya. European legislation based on the Basel Convention prohibits the export of WEEE to developing countries but permits internal transport. Shipping CPUs to Hungary could improve profitability with 27 %, but treating CRT monitors in Belgium is most profitable. Evolving products and fluctuating gold prices challenge the economic robustness of international cooperation. A more robust solution would consist of design changes that allow for efficient disassembly and recycling in developed countries.

Regarding opportunities to improve the Bo2W scenario in developing countries, the following conclusions are made:

- In Kenya, it is economically optimal to completely dismantle CRT monitors, but CPUs only partially. Completely dismantling CPUs could double employment opportunities at similar profits.
- Additional revenue could be earned if Neodymium magnets are liberated from HDDs.
- Recycling plastics after identification will likely improve current solutions from an economic and environmental perspective, but requires further research.
- To ensure sound treatment of all IT equipment in developing countries, different strategies for collaboration with the IS are investigated. It is recommended to buy environmentally significant fractions from informal pre-processors as it ensures environmental sound treatment, keeps job opportunities and is practically feasible. While its economic viability remains unclear, it can serve as a transient solution to gain trust with informal pre-processors in order to ultimately pay them on a wage basis for dismantling safe IT equipment.

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List of abbreviations and symbols

ABS	Acrylonitrile Butadiene Styrene
BAN	Basel Action Network
BAT	Best available technologies
Bo2W	Best-of-2-Worlds
CDD	Compact Disk Drive
CRT	Cathode Ray Tube
CPU	Central Processing Unit
EEE	Electrical and Electronic Equipment
EU	European Union
FDD	Floppy Disk Drive
HDD	Hard Disk Drive
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
IS	Informal sector
MT	Mechanical treatment
OECD	Organization for economic co-operation and development
PS	Power Supply
PVC	Polyvinylchloride
PWB	Printed Wiring Board
REE	Rare Earth Elements
StEP initiative	Solving the e-waste problem initiative
TCLP	Toxicity Characteristic Leaching Procedure
UEEE	Used Electrical and Electronic Equipment
Umicore PMR	Umicore Precious Metal Refining
UEEE	Used Electrical and Electronic Equipment
WEEE	Waste of Electrical and Electronic Equipment

1. Introduction

The purpose of this chapter is to supply the reader with sufficient background information to properly comprehend the research objectives. Firstly, the significance of WEEE management is illustrated. Subsequently, the WEEE recycling chain gives a brief overview of all actors in their respective phase in the process. The most commonly applied recycling chains in both developing and developed countries are introduced.

1.1. Significance of WEEE management

1.1.1. Characteristics of WEEE

Electrical and Electronic Equipment (EEE) refers to a broad range of devices such as computers, cell phones, televisions and refrigerators. There is no doubt that these products transformed our society by creating new modes of communication and by raising our living standards. Regardless how wonderful their effects are, once they reach the end of their life they pose significant challenges to society.

When EEE is disposed of by consumers it turns into Used EEE (UEEE) when it remains functional or Waste of EEE (WEEE) when it is no longer. Even though it may not serve ones needs anymore, it still holds value as its materials can be recovered by recycling or the device might be refurbished for reuse. WEEE is composed of a heterogeneous stream of products which contain both very valuable and extremely hazardous substances. Hence sound WEEE management can significantly contribute to the economy and the environment, but unsound practices can be environmentally harmful.

1.1.2. Origin and flows of WEEE

In Europe around 10 million tonnes of WEEE are generated per annum (Commission 2012). In Nigeria and Ghana around 1,3 million tonnes of WEEE are generated yearly (Schluep, Manhart et al. 2011). The latest years there has been a significant rise in the amount of WEEE generated and this is expected to even increase in the future (Schluep, Hagelüken et al. 2009). EEE can become obsolete when it is no longer functional, but more often it is disposed because it no longer fulfils the needs of consumers in industrialised countries..

While obsolete electronics might be of little use in developed nations, the value for refurbished equipment remains relatively high in developing countries. This economic incentive is the main driver for the export of UEEE and WEEE to developing countries (Espejo, Deubzer et al. 2010), as is illustrated in Figure 1. While the export of UEEE is permitted, the exports of WEEE are classified as illegal by the Basel Action Network (BAN) as it is categorized as hazardous waste (BAN n.d.). Nevertheless, the legislation has not entered into force everywhere and even when it has, exporters use creative methods to undermine control and misleadingly ship WEEE as functional UEEE. For example, of all the e-waste generated in Ghana only 25 % originates from new equipment. 75 % originates from imported devices, 60 % after a second life as refurbished equipment and 15 % is already useless after the import (Schluep, Manhart et al. 2011).

Figure 1 – Known and suspected routes of e-waste dumping (University_of_Northampton n.d.)

The main issue is that even while management practices in developed countries are not optimal, in developing countries the situation tends to be far worse. Informal recycling processes are dominant and show little respect for human safety and the environment.

1.1.3. Socio-economic significance

The recycling industry has a major economic impact by putting secondary materials on the market. By preventing primary production of materials and slowing down resource depletion the price for materials can be kept lower and geopolitical conflicts can be prevented (Schluep, Hagelüken et al. 2009). Furthermore the recycling of materials creates many job opportunities.

Also in developing and emerging economies the socio-economic impact of WEEE recycling is significant. In Ghana alone, it is estimated that up to 200.000 people are sustained by the income from collecting and recycling e-waste in the informal sector. The recyclers and collectors are low skilled workforces of who most migrated from rural areas to find jobs in the cities. Even though their work exposes them to tough and insecure working conditions with severe health hazards, most of these low skilled workforces are bound to these activities because they need the rapid cash or lack the means or experience for other jobs (Prakash, Manhart et al. 2010; Manhart, Osibanjo et al. 2011). Similarly, it is estimated that in China 700.000 people earn their income by collecting and recycling e-waste of which 98% work in the informal sector (Manhart 2007). It can be concluded that recycling of WEEE generates jobs for the ones who need it the most.

1.1.4. Environmental significance

The environmental impact of recycling can be broken down into two parts. On one hand there is the avoided impact by recycling materials rather than mining them. On the other hand there is the environmental impact caused by the recycling process itself.

In terms of avoided impact, recovering materials from e-waste can be very significant because it prevents the pollution of primary production and lowers the rate of resource depletion. For instance precious metals are typically found in ores in very low concentrations of below 10 gram/tonne (Hageluken, Buchert et al. 2009). Hence mining them results in relative high emissions of greenhouse gases, carcinogens and loss of land and biodiversity, not to mention the rough social conditions of mining. In IT equipment precious metal concentrations are relatively high, for example the average gold concentration of the main board of a computer is 225 gram/tonne (Gmünder 2007). Hence recycling similar parts with appropriate technology has a significant lower impact (Bigum, Brogaard et al. 2012). A similar reasoning holds for other materials in WEEE such as copper, aluminium, iron and plastics.

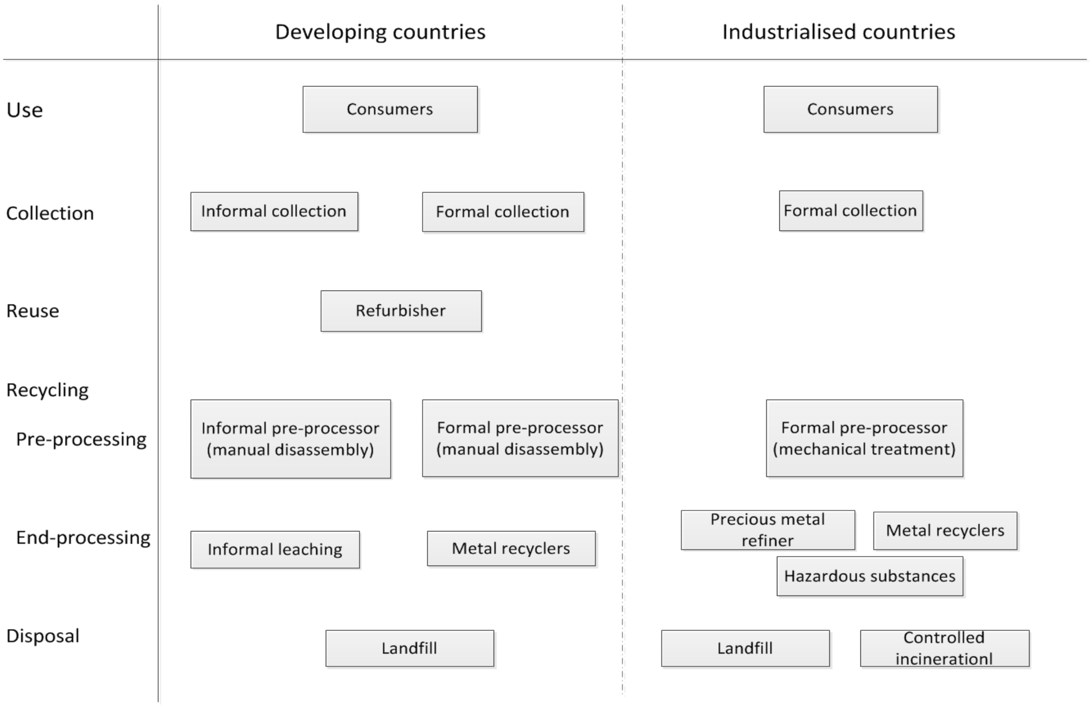
Next to these economic and environmental valuable materials, WEEE also contains many hazardous substances. For example, a Cathode Ray Tube (CRT) monitor has a high lead content and contains hazardous phosphors. In normal use the hazardous substances pose no or little risk to consumers, but when recycled they can become reasons for concern. The lead of the glass of CRT monitors can easily leach into the soil or groundwater if it is not treated properly (Musson, Jang et al. 2000). Lead is a heavy metal that is known to be carcinogenic and a neurotoxin that prevents the intellectual development of children. The plastic shell also can leach Brominated Flame Retardants (BFRs) of which some are known to be carcinogenic and endogenic disruptors. Furthermore, informal recycling processes, as is illustrated in Figure 2, burn parts in open air to recover copper but release hazardous substances, such as dioxins. In Ghana and in China unsound practices by the informal sector have resulted in contamination levels of heavy metals that exceed the regulatory limits with several orders of magnitude (Brigden, Labunska et al. 2005; Bridgen, Labunska et al. 2008; Sepúlveda, Schluep et al. 2010).

Figure 2 – Photograph of informal recyclers in Ghana (Hugo 2010)

1.2. WEEE recycling chain

1.2.1. Breakdown of the recycling chain

Figure 3 shows a schematic overview of all actors involved in the end-of-life management of WEEE in industrialised as well as in developing countries. The recycling chain of WEEE can be broken down into different phases: use, collection, reuse, recycling and disposal. The recycling step is subsequently broken down into pre- and end-processing. Each phase of the chain along with the differences between both worlds will be briefly discussed in this section. Only later in this chapter the relationships between the actors will be made clear when the recycling scenarios are discussed.



	Developing countries	Industrialised countries
Use	Consumers	Consumers
Collection	Informal collection Formal collection	Formal collection
Reuse	Refurbisher	
Recycling		
Pre-processing	Informal pre-processor (manual disassembly) Formal pre-processor (manual disassembly)	Formal pre-processor (mechanical treatment)
End-processing	Informal leaching Metal recyclers	Precious metal refiner Metal recyclers Hazardous substances
Disposal	Landfill	Landfill Controlled incinerationl

Figure 3 – Schematic overview of the WEEE recycling chain

1.2.2. Collection

The first step of WEEE management is collecting the input which is more challenging than it might appear. In Belgium many formal collection mechanisms are present and are funded by the extended producer responsibility. Despite this aid, current collection rates are only 50 % (Recupel 2012). The main losses have their roots in the fact that WEEE gets lost in municipal solid waste or is exported illegally. Nevertheless the recast of the EU WEEE directive aims at collections rates of 85 % by 2020 (Commission 2012).

In contrast, collection rates in Nigeria and Ghana are estimated to be 95 %. The success is due to informal collectors who go from home to home and pay a small fee for obsolete WEEE (Schluep, Manhart et al. 2011).

1.2.3. Reuse

Whereas recycling can prevent the primary production of materials, reuse also avoids the impact of manufacturing and is, therefore, to be promoted from an environmental and economic point of view. But due to quick technologic developments and changing consumer needs, IT equipment quickly becomes obsolete in developed countries. Consequently refurbishing activities in developed countries are rather rare.

This is in contrast with developing countries where the demand for used equipment is high, because new equipment is either too expensive or not available. Refurbishing can create a lot of added value by making obsolete WEEE functional again. The equipment can then be sold for a fairly high price compared to the material worth (Blaser, Schluep et al. 2012).

1.2.4. Pre-processing

After collection, the recycling chain can be further broken down to pre-processing and end-processing. Each step of the chain is important and needs to be adapted to the others as the overall yield is determined by a multiplicative relationship between collection, pre- and end-processing.

The pre-processing phase has the goal of separating and sorting the input material into different fractions for proper end-processing. Common fractions of WEEE are ferrous metals, non-ferrous metals, copper rich materials, precious metals, rare earth elements and plastics. Table 1 shows common fractions resulting from different components of IT equipment.

Table 1 – Common fractions resulting from different components of IT equipment

Fraction	Components
Precious metals	Printed Wiring Board (PWB) Connectors Small electronic devices, e.g. cell phones
Copper rich	Cables Copper coils
Ferrous metals	Housing Screws
Aluminium	Housing Heat sinks
Mixed metals	Motors
Plastics	Housing Various

The pre-processing of IT equipment has two dominant practices: mechanical treatment and manual dismantling. Due to high labour costs the mechanical treatment is preferred in most industrialized countries, although that manual dismantling lends itself to better recovery rates and purities.

1.2.5. End-processing

If the pre-processing has been successful, the fractions are treated by the proper end-process to recover materials or safely dispose them. In industrialised countries the end-treatment processes are typically Best Available Technologies (BAT). BAT refer to payable solutions that respect the environment to the extent that is economically viable. End-processes such as metal recyclers, sanitary landfills, incineration with energy recovery are available in most developed countries. Integrated smelter-refiners, which are important for effective precious metal recovery, are only available in a select number of countries(Schluep, Hagelüken et al. 2009). Furthermore, hazardous substances can be treated or safely disposed.

In developing economies most metal recycling technologies are also available with the only difference that they have to comply with weaker legislation. Other facilities such as integrated smelter-refiners, sanitary landfills and incineration with energy recovery are not readily available.

1.3. Recycling scenarios

In this section the commonly applied recycling chains are introduced. As will be elaborated upon in the research questions, the comparison and improvement of these scenarios will be part of the goal of this master thesis.

1.3.1. Mechanical treatment scenario

Due to the high labour costs in industrialised countries, mechanical treatment is the method of choice because of the higher productivity. Figure 4 shows a schematic overview of the mechanical treatment scenario. Mechanical pre-processing consists out of a series of steps in which machines liberate components and shred the input while manual and automatic sorting techniques are used for the separation. Despite this entropy increasing approach, the process achieves fair recovery rates of most metals and sends them to BAT for recycling. However, when treating IT equipment and consumer electronics, mechanical treatment causes high losses of valuable precious metals (Chancerel, Meskers et al. 2009).

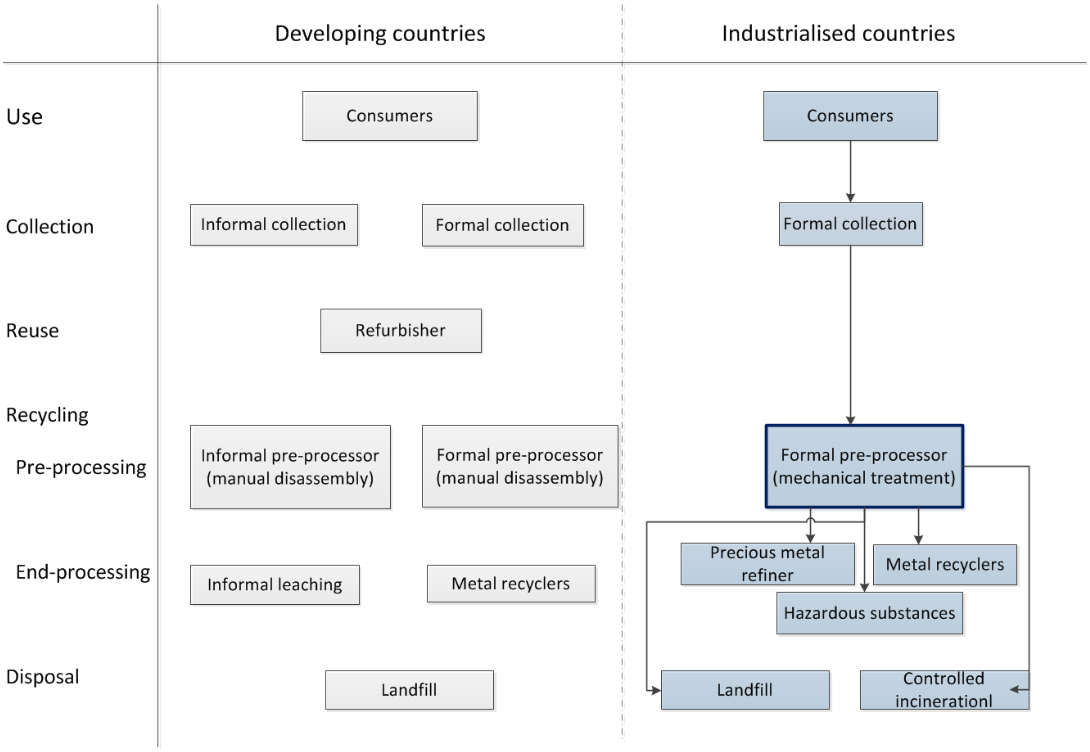


Figure 4 – Schematic overview of the mechanical treatment scenario

1.3.2. Informal recycling scenario

In most developing and transition countries the recycling of WEEE is dominated by recyclers active in an informal sector (Manhart 2007; Prakash, Manhart et al. 2010). They achieve very high collection rates and manually dismantle WEEE, but their end-processing techniques severely harm themselves and their surroundings. Figure 5 shows a schematic overview of the informal recycling scenario.

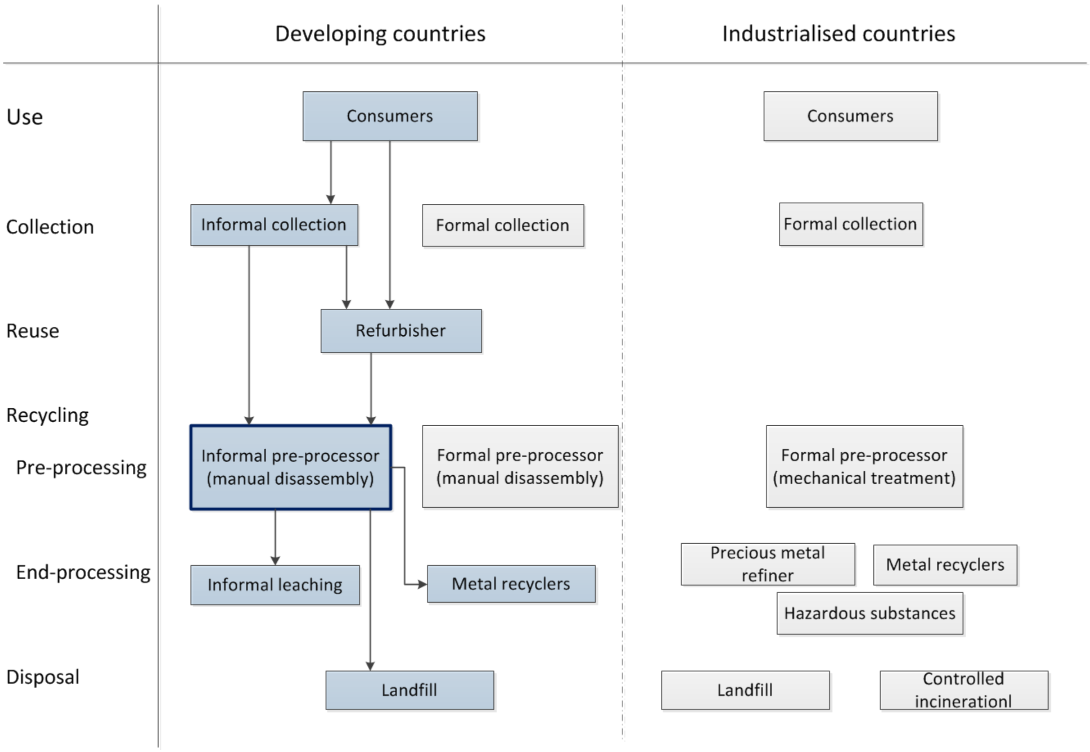


Figure 5 – Schematic overview of the informal recycling scenario

The complete disassembly results in high liberation of common metals as iron, copper and aluminium. However, it is common to burn copper rich materials in open air in order to clear the copper from its isolation for melting. The precious metals fraction are treated by crude leaching processes which have low recovery rates of gold, are dangerous to perform and pollute the environment. Furthermore, components that have no economic value are just disposed and left for what they are.

The manual dismantling lends itself for high recovery rates of metals. But due to a lack of knowledge and because no BAT end-processing techniques are readily available, the performance seems economically inferior to formal recycling processes. Integrating their processes with the formal recycling industry could create opportunities to improve their economic, environmental and social performance.

1.3.3. Best of two worlds philosophy

As a reaction towards the environmentally crude recycling processes in developing countries, the StEP initiative (solving the e-waste problem initiative) and United Nations University launched the best-of-2-worlds (Bo2W) project. The project is based on a philosophy that seeks a technical and logistic integration of suitable and available technologies in different treatment stages in order to be able to form a complete recycling chain for all materials.

When the Bo2W philosophy is applied in developing countries, manual dismantling can be retained locally because it generates fine material output with low technical requirements. When critical output fractions are then forwarded to global facilities with BAT, this should result in detoxification and recovery of valuable materials. The Bo2W philosophy adopts a labour-intensive approach under environment, health and safety standards, which preserve abundant jobs for the informal sectors in relation with improved working conditions (Wang, Huisman et al. 2012). Figure 6 shows a schematic overview of the Bo2W recycling scenario.

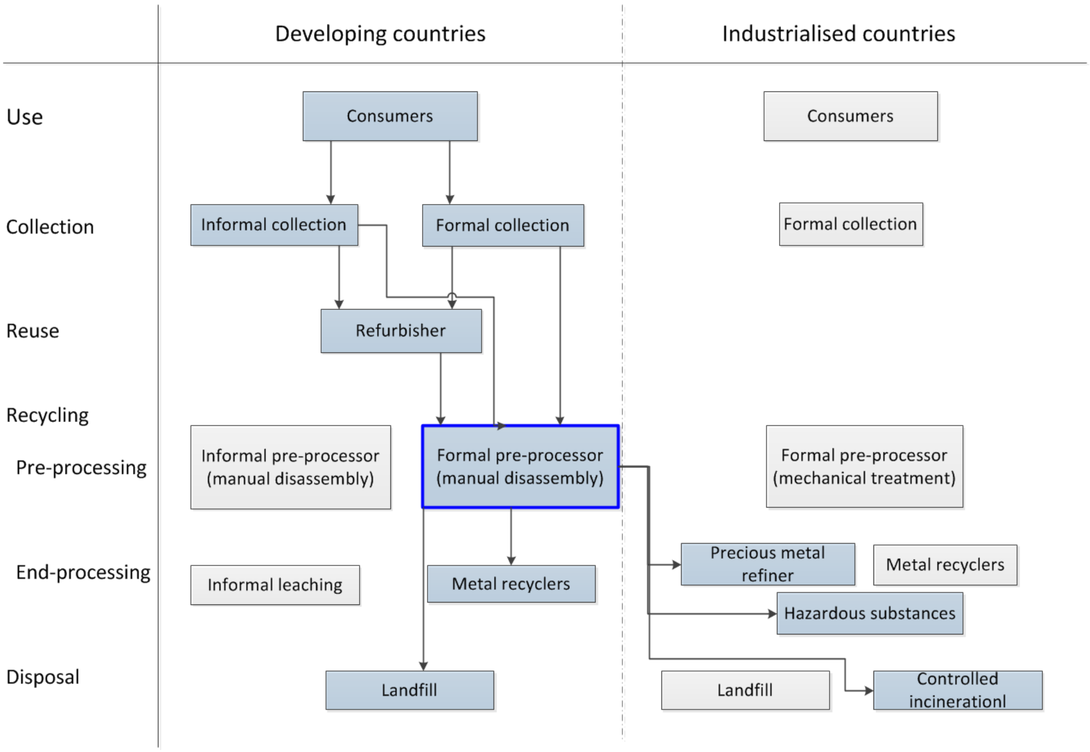


Figure 6 – Schematic overview of the Bo2W recycling scenario

The Bo2W philosophy has been proven to be more eco-efficient than mechanical treatment and informal recycling of desktop computers. The main contribution lies in the higher recovery rates of the economic and environmental valuable precious metals. Hence the value of the philosophy is the most pronounced for precious metal dominant products (Wang, Huisman et al. 2012).

1.3.4. Bo2W export scenario

The success of the Bo2W philosophy raises questions whether it also can serve as an improvement for WEEE generated in industrialised countries. Figure 7 shows a schematic overview of the *Bo2W export* scenario that is based on international cooperation that combines effective pre-processing techniques with proper end-processes.

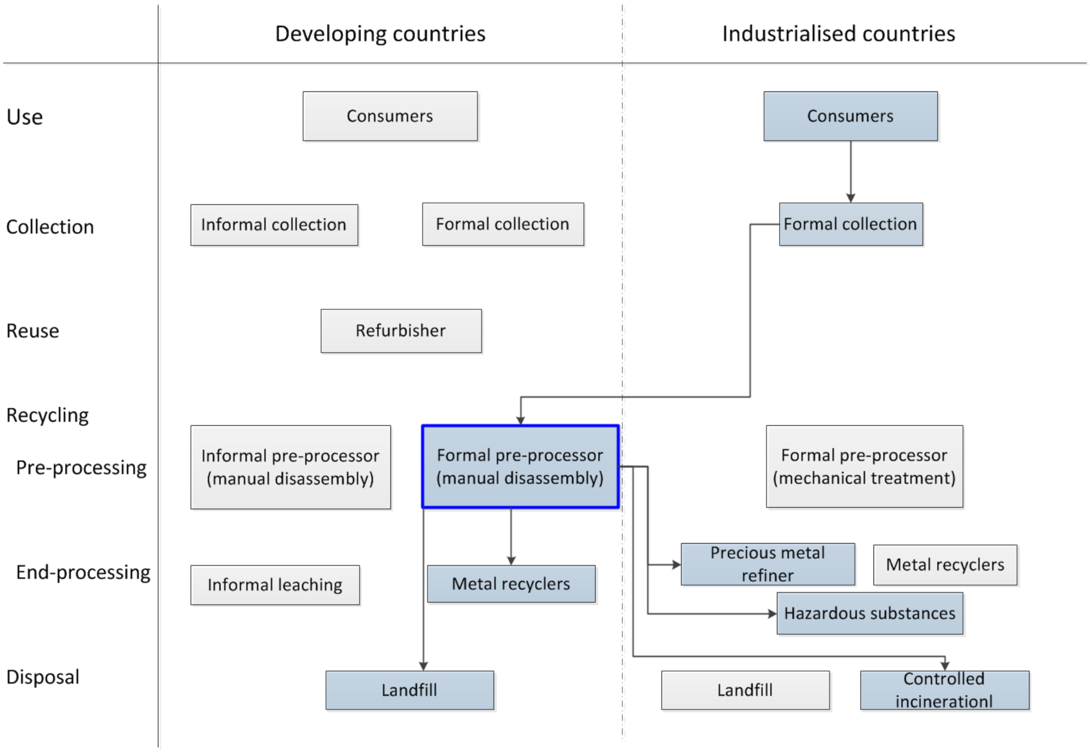


Figure 7 – Schematic overview of the Bo2W export scenario

2. Research objectives

The following chapter first explains the goal of this master thesis. Considering the scope of the research, the goals are subsequently translated into research objectives.

2.1. Goal

The goal of this master thesis is to make an economic and environmental assessment of the different recycling scenarios for IT equipment and investigate opportunities to improve the current situation. The main point of interest is to investigate whether the Bo2W export scenario can improve the economic and environmental performance when compared with mechanical treatment in developed countries. Additionally, the scope of the thesis has been expanded to investigate topics to improve the pre-processing in developing countries.

2.2. Scope of the research

The scope of the research is limited to the following IT and consumer equipment:

- Desktop computers without additional equipment such as a mouse, keyboard or screen. This product is as from here on referred to as the Central Processing Unit (CPU). Despite the confusion with the processor, this is a common term used to describe a desktop computer in literature.
- CRT Monitors. This is currently the dominating display technology that reaches end of life.

The calculations are based on data available from literature and provided by the non-profit organization WorldLoop. The main objective of WorldLoop is to facilitate an operational and economically viable network of collection points, dismantling and recycling facilities in developing countries with the goal to process e-waste in a safe and environmentally sound way. Currently WorldLoop is bringing the Bo2W philosophy into practice in East-Africa and can by consequence provide relevant information and advice.

The thesis takes Kenya as a reference for the scenarios in developing countries and Belgium as a reference for developed countries. The methodology section in chapter

3 elaborates more on the scope of the economic and environmental assessment. In the remains of this chapter the goals are pinned down into concrete research objectives.

2.3. Research objectives

2.3.1. Economic and environmental assessment of the recycling scenarios

The first research objective is to make an economic and environmental assessment of the recycling of CPUs and CRT monitors for the commonly applied scenarios. The scenarios of concern are the mechanical treatment in industrialised countries and both informal recycling and the Bo2W philosophy in developing countries. The calculations are required for a thorough understanding and are a prerequisite for the following research objective.

2.3.2. Evaluation of the Bo2W export scenario

Concerning IT equipment generated by developed countries, assess whether the export to developing countries and subsequently applying the Bo2W scenario can improve the economic and environmental performance compared with the mechanical treatment scenario. Additionally, investigate whether there are other qualitative arguments that concern the export of WEEE in the Bo2W export scenario.

2.3.3. Improvement of the Bo2W scenario in developing countries

Investigate the opportunities to improve the current pre-processing activities in developing countries. This objective can be divided as follows:

- Identify the economically optimal dismantling depth for CPUs and CRT monitors.
- Investigate opportunities regarding the competition and/or collaboration with the informal sector.
- Evaluate alternative end-processes for subcomponents and fractions.

3. Methodology

The following chapter explains the methodology that is used for the environmental and the economic assessment with their respective goals and system boundaries.

3.1. Environmental assessment methodology

3.1.1. Life Cycle Assessment methodology

The environmental impact of the recycling scenarios is quantified in a Life Cycle Assessment (LCA). An LCA characterises the environmental impact of the whole life cycle of a product or process. The LCA framework is given in Figure 8 and shows the consecutive steps of the assessment (Duflou and Dewulf 2013):

- Goal and scope definition
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation

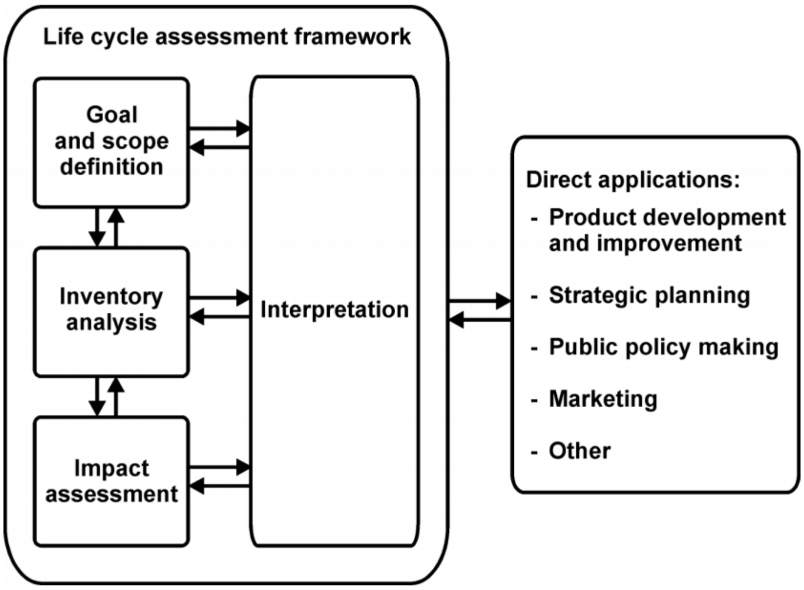


Figure 8 – The life cycle assessment framework

The goal and scope definition determines the purpose of the study. The system boundaries and the functional unit should allow for a fair comparison between the scenarios. In the LCI an inventory is built of all the material and energy flows through the system. The inventory then is classified to the environmental impact categories it contributes to, ultimately in terms of the end-indicators *human health*, *ecosystem quality* and *resource damage*. The environmental impact of the inventory is subsequently characterised and normalised to quantify the importance in the LCIA phase. In a final step the three different end-indicators are weighted to each other and translated in a single score expressed in *Points [Pts].* 1.000 Pts represent the impact caused by the actions and consumption of one average person on earth per year.

3.1.2. Goal, functional unit and system boundaries

As explained in chapter 2, the goal of the LCA is to allow for a comparison between the different recycling scenarios. Subsequently the resulting information will be used to base micro-level decisions. Hence, the modelling will be attributional with static and average data. Rebound effects will not be taken into account.

The functional units defined for the recycling of CPUs and CRT monitors that allow for a fair comparison are defined as 'the recycling of one CPU unit' and 'the recycling of one CRT monitor unit'. The system boundaries are illustrated as the coloured boxes in Figure 9. Despite that the scenarios focus on pre-processing, the impact of the chosen end-process, including the transport, is their responsibility and taken into account to allow for a fair comparison.

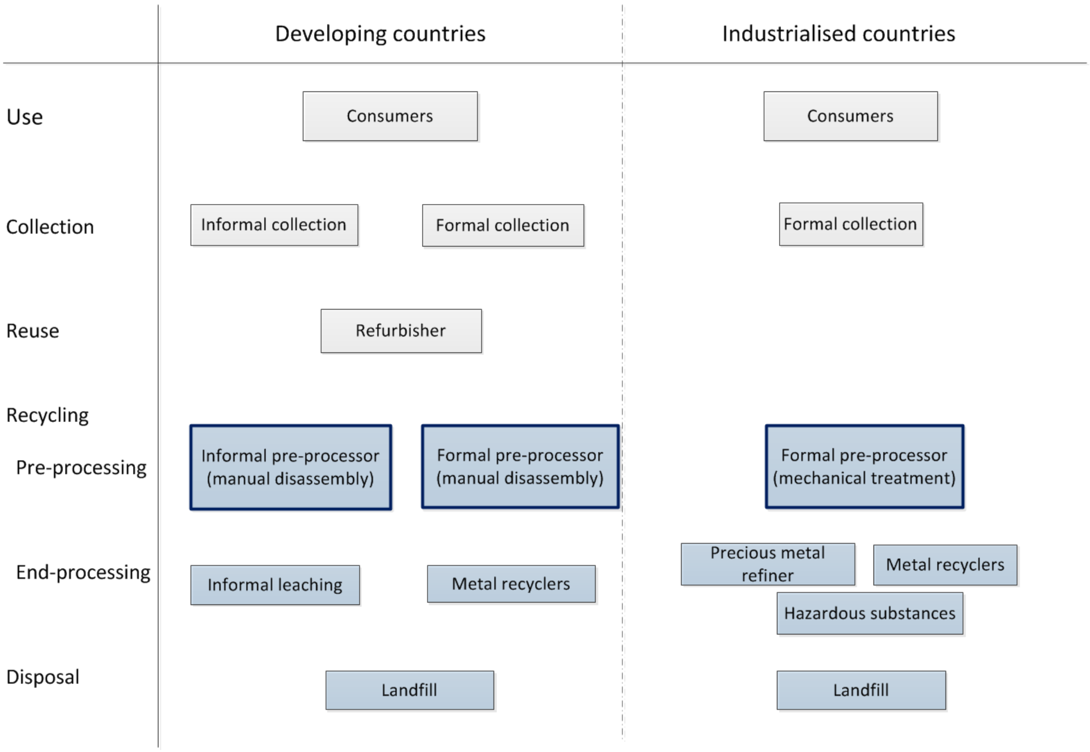


Figure 9 – System boundaries of the LCA

The collection of the IT equipment is not included in the system boundaries because the goal is to compare the different pre-processing scenarios and not the overall recycling chain.

The refurbishment of the equipment for reuse is not included due to several reasons. Firstly, similar to the collection, it is not the purpose to compare the overall recycling chain of developing countries versus industrialised countries. Second, when products are reused both the impact of the material extraction and the manufacturing phase tend to be extended. But in this study the LCI of CPUs and CRT monitors only contains the processes associated with the primary production of the material composition because the impact of the manufacturing phase is not readily available. Furthermore, if in the Bo2W export scenario some parts would be reused, the exporter currently cannot guarantee that there are no leaks to informal recyclers and sound treatment would not be ensured. Finally, too little is known about the processes and reuse rate of the refurbishing sector.

3.1.3. LCI & LCIA

The inventories of the CPU and CRT monitor composition as well as the recycling processes are mainly based on data from literature. Emissions to air, soil and water are modelled in a way that comes closest to the observed reality. The model of each recycling scenario is further elaborated on in chapter 4.

The model is implemented in the SimaPro software of the pré-consultants and is linked to the ecoInvent v2.2 database. The weighting of the end-indicators is done with the World ReCiPE H/H method which uses normalisation values of the world with the weighting set belonging to the hierarchist perspective.

3.1.4. Interpretation

The results of the LCA and the economic analysis are disclosed and interpreted in chapter 5.1. Because the environmental model is subject to many assumptions, results should be interpreted with care and within the restrictions of the model.

3.2. Economic assessment methodology

3.2.1. Goal and system boundaries

The economic assessment has the goal to allow for a fair comparison between the different recycling processes and to obtain insight into the revenues and costs. The scope of the economic analysis is limited to the pre-processor's perspective. It does not include the collection cost, gate fees or trade with the refurbishing industry.

The profitability of the pre-processors is estimated by calculating their revenues and costs. All calculations are based on a *per unit of equipment* basis and not on a weight basis. But as will be made clear in the following chapter those are based on data that approximately represent the average material composition. All data can be transformed to a per weight basis by dividing by the weight of the units.

3.2.2. Material revenue

The income that a pre-processor can generate from recycling IT equipment is fully determined by the material revenue. The material revenue mainly depends on how effective the materials can be sorted from others and differs strongly between the scenarios. Additionally, it also depends on the location as it is either sold on the local market at a prevailing price or sold elsewhere with the accompanying transport costs.

3.2.3. Cost estimates

The costs are broken down in the following components:

- Operating costs
    - Labour costs
    - Processing costs
- Transport costs
- Shipping costs
- Overhead costs
    - Infrastructure
    - Administration

The operating costs taken into account are the labour and the processing costs. The labour costs are mainly due to the dismantling that is needed for the separation of the components. The processing costs additionally account for electricity use and maintenance. To distinguish the costs due to transport required for ensuring sound treatment in the Bo2W scenario and transport required for shipping IT equipment from industrialised to developing countries in the Bo2W export scenario, the term 'transport costs' and 'shipping costs' are used respectively. Finally, infrastructure and administration represent the overhead costs of which the allocation is discussed in the next chapter.

4. Economic and environmental model

This chapter thoroughly describes the economic and environmental model used for the assessment of the recycling scenarios. Firstly, the composition of CPUs and CRT monitors is characterised as the material determines the economic and environmental potential of recycling. Secondly, the economic and environmental model of each recycling scenario is discussed in depth. The scenarios are explained in more detail and consequently an inventory is made of the efficiencies of the pre- and end-processes, the associated costs and their emissions to the environment.

4.1. Product characterisation

4.1.1. Composition of CPUs

The composition of the CPU is based on the analysis by (Gmünder 2007). Gmünder dismantled several hundred kilograms of CPUs in order to get a representative average material composition. Based on an average lifetime of 7 years, it is estimated that the dismantled computers were put on the market around 2001. In most likelihood, the data still is representative for today's CPUs.

The major subcomponents that one encounters after dismantling the 9,9 kg weighing CPU to the first level are shown in Figure 10. The metallic housing and casing make up for half of the weight of the device. Followed by the Power Supply (PS) and the Compact Disk Drive (CDD). The motherboard weighs almost 1 kg and contains the processor, memory, graphics card, sound card, etc.; but not the PWBs from the subcomponents. The plastic part of the housing weighs only half a kilogram. The Hard Disk Drive (HDD) and Floppy Disk Drive (FDD) are rather light. Despite that they are included in the model, there are still small components that are not presented here such as the battery, connectors, speakers, etc. . The reader is referred to Appendix A for the complete bill of materials.

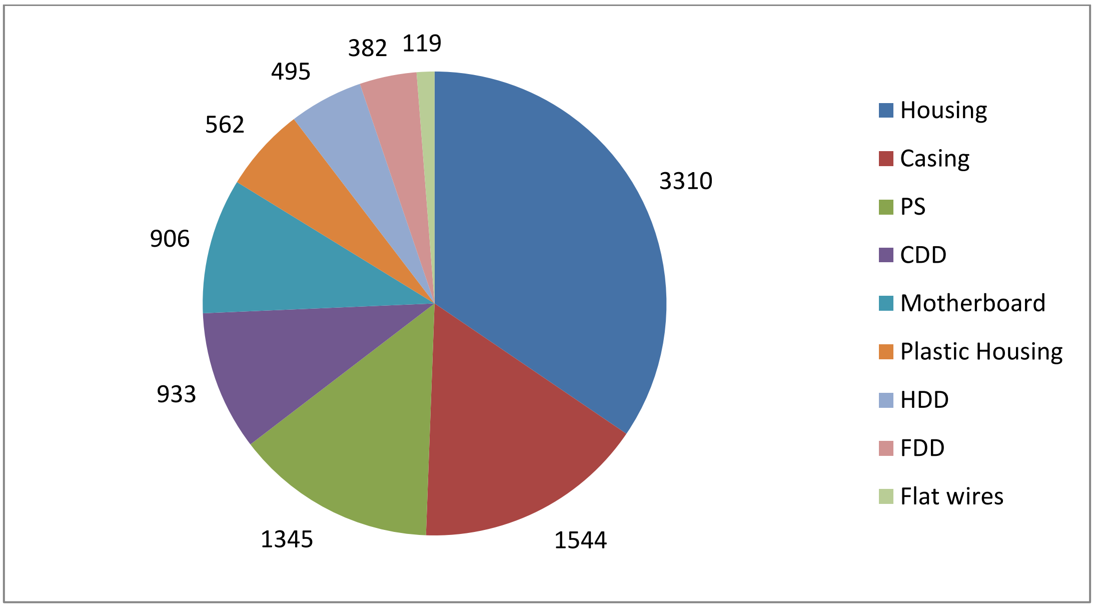


Figure 10 – Weight of the main subcomponents of a CPU [g]

If one would completely dismantle a CPU to the deepest level that is physically possible, the weight of the different materials would relate as in Figure 11. Steel is by far the most abundant material as it is used for the casing of the CPU and almost every subcomponent. Second are the PWBs which contain the valuable precious metals. Notice that by deep dismantling another 0,3 kg of PWBs can be liberated aside from the motherboard. However the precious metal content can differ greatly between components as is shown in Table 2. Consequently, the material revenue will be dependent on the dismantling depth of each component.

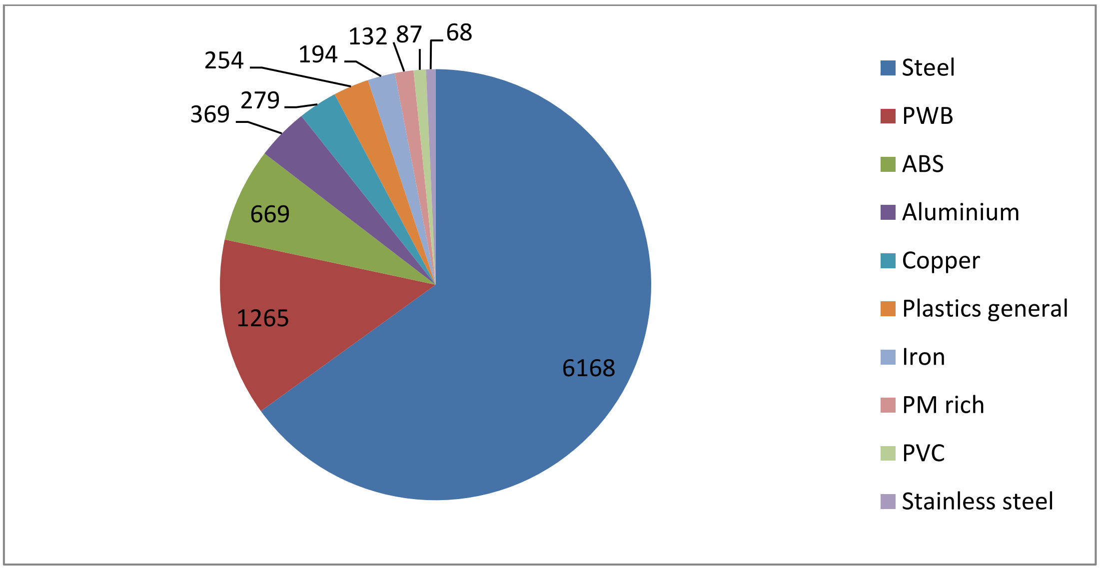


Figure 11 – Material composition of a CPU [g]

The plastic casing represents another big part of the weight and are assumed to be Acrylonitrile Butadiene Styrene (ABS). The aluminium is the sum of some rather small parts from subcomponents such as heat sinks and the HDD casing. The copper is mainly found in the wires, but is also present in complex parts such as motors and copper coils. Other precious metal bearing materials are connectors and readers, but they are a rather small weight fraction. Additionally, there are other materials that are not shown here such as the battery, capacitors, unknown ceramic parts and unidentified plastic parts.

Table 2 – Precious metal content of subcomponents from CPUs and CRT monitors

Component	Weight [g/unit]	Ag [ppm]	Au [ppm]	Pd [ppm]	Cu [%]	Source
PWB HDD	41,4	2630	415	286	21,9	(Gmünder 2007)
HDD Disk	35,1	860	21	14	0,2	(Gmünder 2007)
HDD Connectors	3,36	569	369	146	16,9	(Gmünder 2007)
CDD reader	18,6	295	42	45	3,8	(Gmünder 2007)
PWB CDD	98,2	4290	157	98	16,4	(Gmünder 2007)
PWB CDD small	5	116	18	6	4,1	(Gmünder 2007)
FDD Reader	10,9	116	18	6	19,5	(Gmünder 2007)
PWB FDD	44	1500	112	203	9,1	(Gmünder 2007)
PS PWB		177	5	8	20,6	(Gmünder 2007)
PS PWB upgraded	167	568	15	26	6,6	(Gmünder 2007)
PS Connectors	15	100	29	8	37,4	(Gmünder 2007)
PS Transistors	20,7	600	35	12	68,5	(Gmünder 2007)
PWB main boards	905,6	1000	225	90	18	(Gmünder 2007)
PC Connector Pins	1	80	370	18	75	(Gmünder 2007)
PC Connectors flatcable	67,2	16	74	4	15	(Gmünder 2007)
PWB CRT		280	17	10	14	(Hagelüken 2006)
PWB CRT (upgraded)	1350	400	35		16	WorldLoop

In addition to the provided model the following assumptions are made. Batteries are assumed to be Lithium-ion, while it's possible that some are still Nickel-Cadmium. The ABS shell is assumed to be free of cadmium colour pigments, but enriched with BFRs for fire safety. The HDD magnets are modelled as NdFeB magnets, as is investigated later in chapter 7.4.

4.1.2. Composition of CRT monitors

The composition of a 14" CRT monitor is characterised by (Lee and Hsi 2002) and is the average size that is collected in Kenya. However, the average composition of CRT monitors likely differs from the composition of the average screen size. Because the data provided by WorldLoop is rough and does not consider components, the composition of the 14" monitor of Lee is taken as the best available data to represent the average CRT monitor composition.

Figure 12 shows the weight of the various components one finds after dismantling CRT monitors. The heaviest component remains the CRT unit that needs to be properly treated for environmental and safety reasons. The plastic casing or shell is the second biggest and weighs 2 kg. The PWB weighs 1,6 kg but due to its low grade, shown in Table 2, it needs to be upgraded by removing large capacitors and heat sinks before it is profitable to recover the precious metals. Next are the copper wiring and the yoke, also called the deflection coil. Additionally, there are small unidentified plastic parts and a rather light metal explosion protection unit. The bill of materials can be viewed in Appendix B.

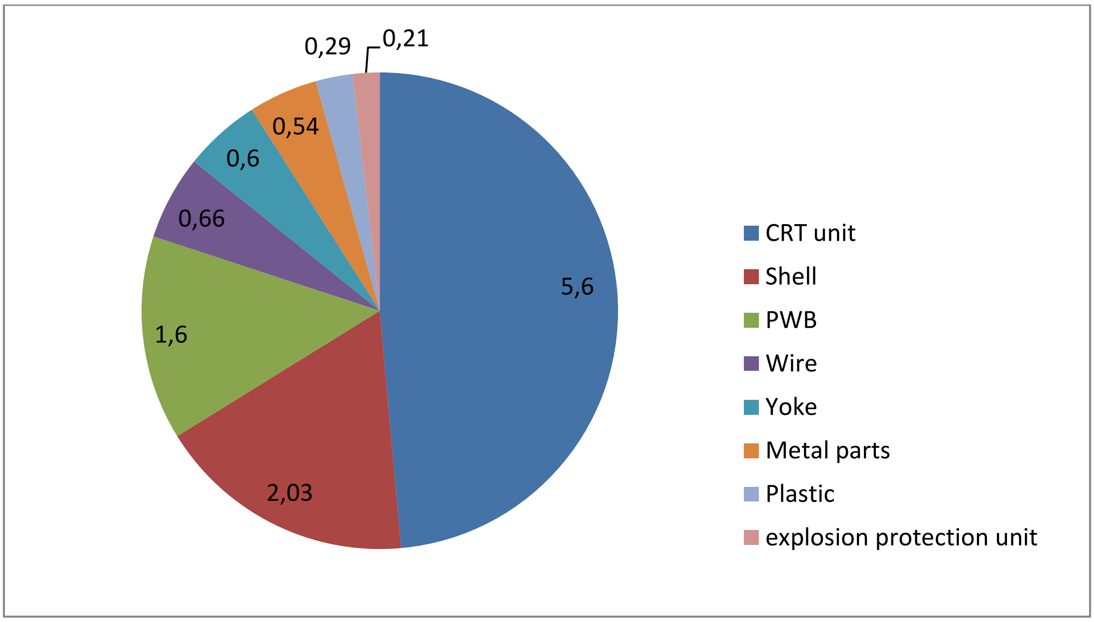


Figure 12 – Weight of the components of a CRT monitor [kg]

An overview of a CRT unit is shown in Figure 13. If a unit is further dismantled one will become the subcomponents which are shown in Figure 14. The CRT unit mainly exists out of different kinds of glass, namely

- Panel glass: glass composed of Strontium/Barium oxides in front of the monitor.
- Funnel glass: leaded glass that covers the CRT unit.
- Neck glass: highly leaded glass that covers the electron gun.
- Frit glass: highly leaded glass that results from welding the funnel glass to the panel glass.

The lead content of the different types of glass is shown in Table 3 and is relevant for selecting the proper end-process (ICER 2004).

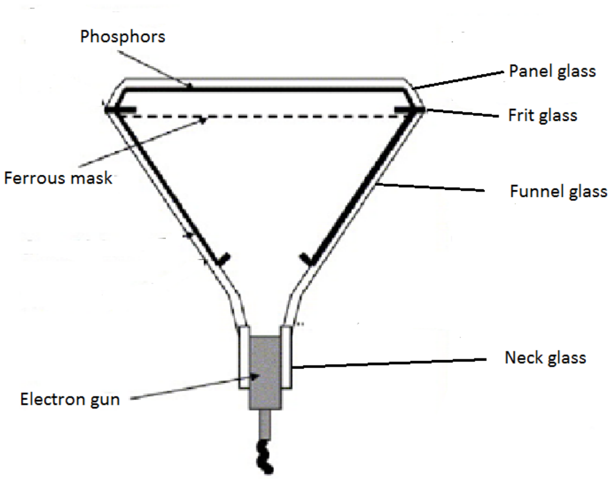


Figure 13 – Structure of a CRT unit

Table 3 – Lead content of CRT glass

CRT glass	Lead content [% PbO]
Funnel glass	13
Panel glass	0 … 3
Frit glass	70
Neck glass	21

Aside from the glass, the CRT unit contains a ferrous shadow mask and an electron gun. The phosphors account for only 3 gram of the weight but, due to their heavy metal content might pose an environmental concern. The composition of the phosphors is based on the analysis of (Resende and Morais 2010) and can be found in Appendix B. Despite likely variations in the use of phosphors among manufacturers and throughout the years, this evolution has not been taken into account.

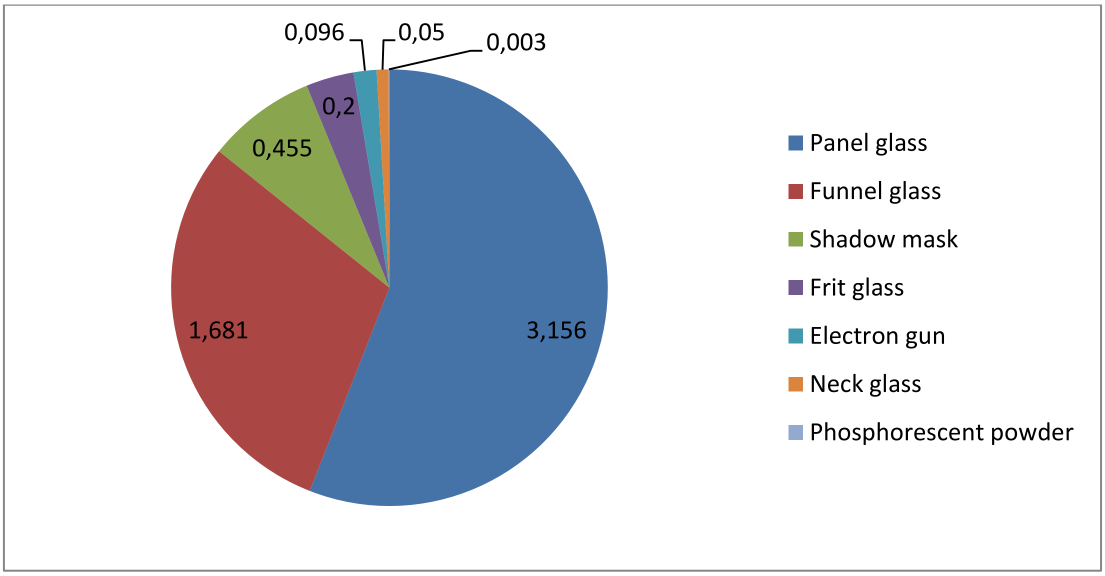


Figure 14 – Weight of the components of a CRT unit [kg]

If the CRT monitor is completely dismantled one would retrieve the materials shown in Figure 15. The panel glass accounts for the barium/strontium glass. The plastic shell is assumed to be BFR containing ABS, though this might be some other engineering plastic with other types of flame retardants too. The steel originates from the ferrous mask and various metal parts. After the PWB is upgraded it weighs less and delivers an extra aluminium heat sink of an estimated 250 grams. The precious metal content of the PWB is rather low, even after the upgrading. Due to the wiring and the yoke, a CRT monitor contains around 650 grams of copper. Furthermore, there remains the PVC from the cables, the unknown plastics and the phosphorescent dust.

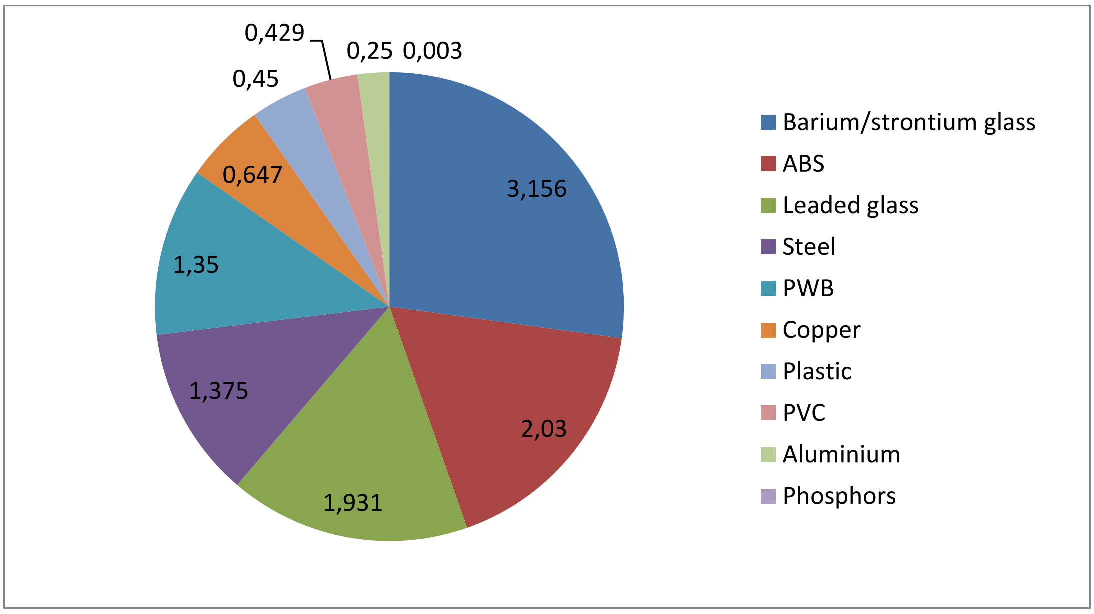


Figure 15 – Bill of materials of a CRT monitor [kg]

4.2. Mechanical treatment scenario

The remaining part of this chapter elaborates on the three most common recycling scenarios: mechanical treatment in developed countries, recycling by the informal sector and applying the Bo2W philosophy in developing countries. The scenarios are broken down into the pre-processing of both products and the available end-processing for resulting fractions. Each subchapter consists out of a description of the process and explanation of the economic and environmental model.

The Mechanical Treatment (MT) scenario is the dominant process in industrialised countries. WEEE is pre-processed with mechanical techniques to improve productivity and resulting fractions are sold to recyclers with BAT. Despite that there are many variations among mechanical pre-processing techniques and hence their economic and environmental performance, only one process is modelled per kind of device due to practical reasons.

4.2.1. Pre-processing of CPUs in the MT scenario

The pre-processing model of CPUs in the MT scenario assumes that CPUs are not separated from consumer electronics and IT equipment, and are treated mechanically with many other electrical devices. The process exists out of the consecutive steps that are illustrated in Figure 16 and is described below. Note that this process which consists out of both manual and automated sorting techniques likely has higher recovery efficiencies than can be obtained with merely automated sorting techniques that also are used for pre-processing WEEE.

- Pre-sorting. Manually removing copper and PM rich fractions such as cell phones.
- Smashing & manual sorting. A machine smashes the products until the components lose their connections. The loose components then pass a hand picking station in which labourers remove the precious metals rich material, copper rich material and hazardous components from a conveyor.
- Pre-shredding and manual sorting. Because the smasher cannot dismantle all the components, the remaining input first is pre-shredded and sorted to remove more copper rich material and parts of PWBs.
- Shredding and automated sorting. The remaining material is shredded to fine material and automated sorting techniques distinguish between ferrous metals, copper rich fraction, aluminium, other non-ferrous metals, plastics and PWBs. In this setting the automated sorting techniques are composed of a magnetic separator, an eddy current separator and density separators.

Figure 16 – Overview of the steps of mechanical pre-processing

In the specific case of a CPU the mechanical treatment would go as follows. The pre-sorting step is not relevant for CPUs. The smashing liberates the main subcomponents from the casing. Cables, the main PWBs and batteries are handpicked from a conveyor by labourers and sent to the proper end-process. All the remaining material, most importantly the HDD, PS, CDD and FDD; are shredded and sorted both by hand and with automated processes.

The flow of precious metals during mechanical treatment of WEEE in general with this process is assessed by (Chancerel, Meskers et al. 2009). They found that the overall gold recovery of the process is 24 % for WEEE in general. The main losses seem to occur during the deep shredding of the material in the last step. The reason behind this effect is that the gold is mainly used for plating, small contacts, integrated circuits and in layers of PWBs. Hence the impact of shredding could break of contacts and damage gold coatings and consequently dilute the gold to other fractions (Meskers, Hagelüken et al. 2009).

Nevertheless, it would be bold to apply this low recovery rate of precious metals of WEEE in general to CPUs. This would be an invalid assumption mainly due to the fact that the motherboard, which contains 80 % of the precious metals, can be handpicked after the smashing. Therefore the yield of 24 % would significantly underestimate the mechanical treatment process for CPUs. In order to adjust for this issue, the calculations of (Chancerel, Meskers et al. 2009) are broken down in two main parts:

- The first part in the process where the CPU is smashed and main boards and copper rich fractions can be handpicked (Smashing & manual sorting).
- The second part consisting of the steps where the remaining material is pre-shredded, manually sorted, shredded again into smaller pieces and then automatically sorted.

Appendix C shows the data and the calculations to retrieve the recovery efficiency of the different precious metals for the second part of the process. The calculations are based on the assumption that the amount of precious metals that are diluted due to the smashing is negligible, which is reasonable since the smasher doesn't break the PWBs. The mass balance of the second part results in the recovery rates that are shown in Table 4. The data highlights the poor recovery rates of precious metals due to the shredding as only 14 % of the gold and palladium; and 7 % of the silver gets to proper end-processing. The main share of the gold ends up with ferrous metals and plastics.

Table 4 also shows the recovery rates of the other metals that are based on the same calculations as shown in Appendix C. For ferrous metals this is 91 % and for both copper and aluminium it is 67 %. While only 55 % of the aluminium and 18 % of the copper directly is sent to the proper end-process, the ones that end up in the plastics fraction will be sorted again with a shaking table. It is assumed that 80 % of both metals can be freed and sent to the proper smelter. The recovery rate of aluminium consequently is 67 %. Similarly the recovery rate of copper is 67 %, if in addition it is taken into account that copper ending up with precious metals is recovered too.

Engineering plastics such as ABS, ABS/PC and HIPS are present in the casing of both the CRT monitor and CPU and make up for a big part of the weight. Effective gravitational sorting technologies are available to separate engineering plastics from each other and other plastics (Gent, Menendez et al. 2009; Malcolm Richard, Mario et al. 2011). Furthermore, it has been shown that the recycling of some engineering plastics, such as ABS/PC with phosphor flame retardants, is technically and economically feasible (Vanegas, Peeters et al. 2012). Even if the recycled plastics would meet required technical specifications, their BFR content needs to comply with European law. Together with the assumption that the casing of CPUs and CRT monitors contain BFRs, it is assumed that plastics are incinerated in installations with energy recovery and proper flue gas systems. Furthermore, it has been assumed that the minor plastics, of which the composition is unknown and are almost insignificant on weight basis, will also be incinerated.

Table 4 – Recovery rate of pre-processing CPUs in the MT scenario

Material	Pre-processing efficiency [%]	End-processing	Location
Flat cables	100	Copper refinery	Belgium
Main PWBs	80	Umicore PMR	Belgium
Gold from remaining material	14	Umicore PMR	Belgium
Silver from remaining material	7	Umicore PMR	Belgium
Palladium from remaining material	14	Umicore PMR	Belgium
Ferrous metal	91	Ferrous recycling	Belgium
Copper	67	Copper smelter	Belgium
Aluminium	67	Aluminium smelter	Belgium
Plastics	100	Incineration with energy recovery	Belgium

Table 4 summarizes the pre-processing efficiency of every subcomponent and the appropriate end-treatment. It is assumed that the smashing and manually sorting separates the flat cables, the main PWBs and batteries from the CPU. Because the manual picking is likely not perfectly effective, it is assumed that only 80% of the main boards can be handpicked and the other 20 % is treated together with the remaining material. The remaining material, also consisting of the casing and all subcomponents, is shredded in the second part of the mechanical process. As discussed above, shredding results in massive losses of precious metals from the HDD, CDD, FDD, PS and remains of the main board. Taking into account the precious metal content of the different parts, the overall gold recovery rate is 70 %. The gold yield under the assumptions stated above is consistent with the findings of researchers whom assessed similar mechanical pre-processing techniques for CPUs and also found a recovery rate of 70 % for gold from CPUs (Meskers, Hagelüken et al. 2009).

Economic model

The material revenue is calculated by linking the subcomponents of the CPU to the pre-processing efficiency and the material worth. Chapter 5.2 elaborates more on the material revenue and the differences among the scenarios.

The treatment costs for mechanical pre-processing is based on the assessment of (Cryan, Freegard et al. 2010). They estimated the costs of mechanical treatment for flat panel displays in the United Kingdom, but the data has been adapted to represent the treatment of WEEE in general. The facility consists out of a smasher, shredder and other equipment needed for automatic sorting such as a magnet, an eddy current separator and an air ballistic. The processing equipment with its investment cost and sources are shown in Table 5.

Table 5 – Processing equipment costs for mechanical pre-processing

Process equipment costs (k€)	809	
Smasher	200	Author's estimate
Shredder	500	(Cryan 2007)
Magnet	22	(Cryan 2007)
Eddy Current Separator	53	(Cryan 2007)
Air Ballistic	33	(Cryan 2007)

Table 6 shows the other investments needed for the facility. In order to be able to allocate the costs to the weight of the input material, the data has been expanded with an estimate for the life of the equipment and with the Weighted Average Cost of Capital of a hypothetical pre-processor. The life of the facility is estimated to be 10 years and the WACC 10 %. The resulting annual capital cost is 473.000 €.

Table 6 – Capital cost of a mechanical pre-processing facility

Capital cost	[k€]	Source
Civils and buildings	840	(Cryan 2007)
Conveyors and structures	320	(Cryan 2007)
Process equipment	809	Table 5
Pneumatic equipment	111	(Cryan 2007)
Electrical Installation	236	(Cryan 2007)
Health safety & environment	31	(Cryan 2007)
Mobile plant	43	(Cryan 2007)
Power supply	32	(Cryan 2007)
Sub Total	2422	
Project management (10%)	242	(Cryan 2007)
Contingency (10%)	242	(Cryan 2007)
Total	2906	
Life estimate	10	Author's estimate
WACC	0,10	Author's estimate
Capital cost (k€/year)	**473**	

The operating costs for the pre-processing are assumed to be similar as for the flat screen recycling in the UK setting and are shown in Table 7.

Table 7 – Operating costs of the pre-processing facility

Operating costs (k€/year)	1694
Electricity	230
Man power	521
Maintenance	472
Waste disposal	471

The facility has a capacity of 5 ton per hour and works 4.000 hours in one year. By allocating the costs to the treated weight, the processing costs are estimated at 0,11 € per kilogram treated. Hereof 0,85 € is due to operating costs and 0,24 € due to the overhead.

Table 8 – Treatment cost per kilogram of WEEE processed

Treatment cost	
Ton equivalent / hour	5
Hours of shredding/year	4000
Ton / year	20000
Infrastructure cost (€/ton)	24
Operating cost (€/ton)	85
Treatment cost (€/kg)	**0,11**

Environmental model

The pre-processing is modelled by linking the subcomponents to their destined end-process with the appropriate efficiency. The environmental impact of each fraction is discussed together with its end-processing later in this chapter. The environmental impact of the pre-processing also includes the shredding process, namely its consumed energy, emitted dust and an allocation of the used infrastructure. The inventory of the process is readily available by the ecoinvent data as *Shredding, electrical and electronic scrap/GLO.*

4.2.2. Pre-processing of CRT monitors in the MT scenario

The mechanical treatment of CRT monitors in developed countries differs from the treatment of WEEE. Though that there are variations in the way CRT monitors, and especially CRT units, are pre-processed, the process that will be considered here is based on the manual dismantling of a CRT monitor followed by the mechanical treatment of its CRT unit. Despite possible confusion because it is partly dismantled, the terminology of 'Mechanical Treatment' will be used to refer to this process in industrialised countries.

The CRT monitor first is dismantled to separate the CRT unit, the PWBs, the cables, the plastic shell, the yoke and the metals. Table 9 shows the end-processing of each fraction and the pre-processing efficiency. Because of the manual dismantling the efficiencies are assumed to be 100 %. The PWBs need to be upgraded before they can be economically treated by Umicore. The plastic shell will be incinerated due to the fact that it is assumed to contain BFRs. The cables are treated in a copper smelter with proper flue gas system. The yoke and the electron gun are more complicated fraction and are assumed to be mechanically pre-processed with other WEEE.

Table 9 – Pre-processing of a CRT monitor in the mechanical treatment scenario

Component	Pre-processing efficiency [%]	End-processing	Location
PWB (upgraded)	100	Umicore PMR	Belgium
Cables	100	Copper smelter	Belgium
Yoke & electron gun	100	Mechanical treatment	Belgium
Aluminium heat sink	100	Aluminium smelter	Belgium
Plastics	100	Plastics incineration	Belgium
Ferrous metals	100	Ferrous smelter	Belgium
Leaded glass	95	Non-ferrous smelter	Belgium
Glass	100	Landfill	Belgium
Phosphors	100	Landfill	Belgium

The mechanical processing of the CRT unit is a mechanical process consisting of shredding and automated sorting techniques. The ferrous metal of the shadow mask is removed by the magnet and the phosphors are washed from the glass. Additional density separation techniques sort the leaded glass from the panel glass. But due to changes in the lead composition of CRT glass over time and the rather small difference in density between funnel and panel glass, the separation is 95 % at best (ICER 2004). Hence the other glass cannot be used for zero lead tolerant applications and is assumed to be landfilled, despite that in some countries it might be legal to use it as construction material. The leaded glass itself is assumed to be used as a fluxing agent by non-ferrous smelters who can recover the lead.

Economic model

The material revenue of the MT scenario for a CRT monitor is based on the processing efficiencies of above and the material worth.

The operating costs are determined by the labour cost of the dismantling and the processing cost of CRT units. The processing costs of a CRT unit with the appropriate equipment is estimated by an expert opinion in (Zumbuehl 2006) as 0,22 €/kg treated for a Swiss plant.

Environmental model

The environmental model follows a similar reasoning as the mechanical treatment of CPUs. The product is linked to the pre-processing efficiencies and the designated end-processing. Additionally, it has been assumed that the inventory of the shredding of WEEE that is used for the shredding of CPUs is representative for the emissions caused by the shredding of CRT units.

4.2.3. Precious metal recovery in an integrated smelter refinery

Recovering precious metals requires technologies that can effectively recover most of the metals and deal with toxic and hazardous substances simultaneously in an environmental friendly way. Integrated smelter refineries are BAT for recovering precious metals, but due to the complex nature sufficient economies of scale are crucial. Currently such facilities only exist in five countries, in Belgium, Canada, Germany, Japan and Sweden. Precious metals recovery rates of over 95 % have been reported in the precious metal refiner of Umicore in Belgium (Schluep, Hagelüken et al. 2009). The Umicore Precious Metal Refining facility is modelled here for precious metal recovery in industrialised countries.

The Umicore Precious Metal Refining process is an integrated metals smelter and refinery which recovers and sells a wide range of metals. The processes are based on complex lead/copper/nickel metallurgy by combining precious metal and base metal operations. Figure 17 illustrates the input-output streams of the process. The base metals are used as collectors for precious metals and special metals. The precious metals that can be recovered are gold, silver and the platinum group, of which palladium is the most relevant for e-waste. The special metals that can be recovered are Sb, Bi, Sn, Se, Te, In. Furthermore the installations are equipped with BAT to limit emissions to air, water and soil (Hagelüken and Umicore 2005).

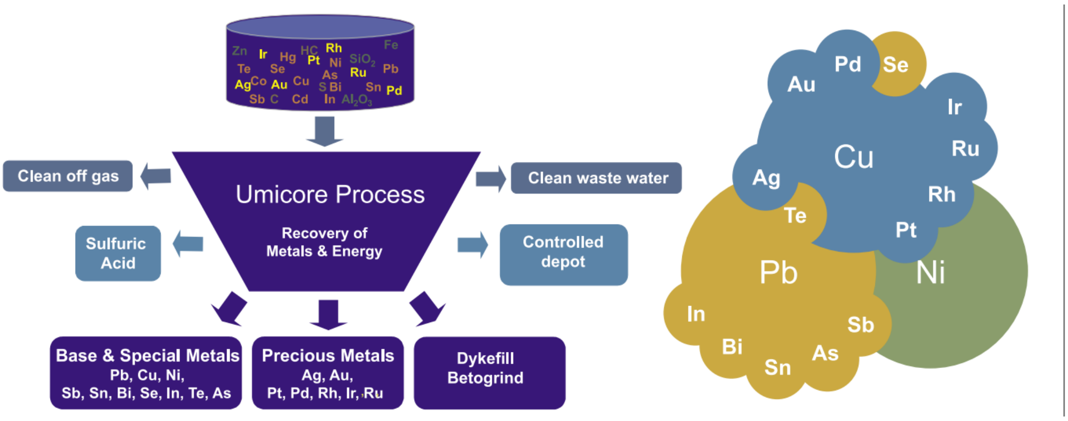


Figure 17 – Input-output streams for Umicore's integrated metals smelter and refinery

Economic model

The end-processing of precious metals by Umicore is charged as a service. Umicore samples the input material, refines the metals and charges for the service depending on the process conditions. The pre-processor then gets paid for the metals according the value on the London Metal Exchange minus the expenses. Hence the economic value of precious metals bearing material is estimated on the material value minus the treatment cost by Umicore. Despite that the treatment costs slightly depends on the input material the service is approximated with a fixed cost of 1,24 €/kg for the treatment of a 8 ton container. This calculation is made for all precious metals rich parts to estimate the material revenue.

Environmental model

The environmental model of the Umicore process is modelled as in Table 10. The recovered metals avoid materials at regional storage as recycling will avoid both the primary and secondary production. The ecoinvent inventory '*X, at regional storage'* resembles the mix of both. The required impact of the Umicore process is approximated with the ecoinvent data of refining precious metals and copper. The recovery efficiencies are estimated to be 95 % for gold, silver, palladium and copper.

Table 10 – Environmental model of the Umicore Precious Metal Refining

Material	Avoided product	Recycling process	Efficiency [%]
Gold	Gold, at regional storage/RER	Gold, secondary, at precious metal refinery/SE	95
Silver	Silver, at regional storage/RER	Silver, secondary, at precious metal refinery/SE	95
Palladium	Palladium, at regional storage/RER	Palladium, secondary, at precious metal refinery/SE	95
Copper	Copper, at regional storage/RER	Copper, secondary, at refinery/RER	95

4.2.4. Metal recycling in industrialised countries

The recycling of ferrous metals, copper and aluminium occurs in the respective metal smelter. In industrialised countries they typically are equipped with installation to restrict emissions such as flue gas systems.

Economic model

The economic value of the metals is provided by WorldLoop and shown in Table 11. Pure metals directly end up with the designated smelter. Mixed and non-ferrous metals are first mechanically pre-processed. Cables can be sold to copper smelters because burning the isolation poses no harm with the flue gas systems.

Table 11 – Economic value of metals in Belgium

Fraction	Value [€/kg]	Source	Location
Aluminium		WorldLoop	Belgium
Ferrous metal		WorldLoop	Belgium
Copper		WorldLoop	Belgium
Mixed metals		WorldLoop	Belgium
Cables, mixed		WorldLoop	Belgium

Environmental model

The environmental model of recycling metals in industrialised countries is modelled as in Table 12. The required input takes into account the transport for collection and the refining operation. Ferrous metals are assumed to be recycled in electric refineries and prevent the mixed production of steel. After refining secondary copper or cables, it prevents the mix of primary and secondary material. Smelting aluminium from scrap, prevents the production mix of aluminium. All data are coming from the ecoinvent database.

Table 12 – Environmental model of metal recycling

Material	Avoided product	Required input
Ferrous metal	Steel, low-alloyed, at plant/RER	Steel, electric, un- and low-alloyed, at plant/RER
Copper	Copper, at regional storage/RER	Copper, secondary, at refinery/RER
Aluminium	Aluminium, production mix, at plant/RER	Aluminium, secondary, from old scrap, at plant/RER

4.2.5. Plastics incineration in industrialised countries

As discussed in the pre-processing of the CPU, the model assumes that all plastics end up in an incineration facility with energy recovery and flue gas treatment. The cost for incineration of plastics is 0,12 €/kg (Duflou and Dewulf 2013). The environmental inventory uses the available ecoinvent data called *Disposal, plastic, consumer electronics, 15,3% water, to municipal incineration/CH*.

4.2.6. End-processing of leaded glass by a non-ferrous smelter

After leaded glass has been separated from CRT units, it can be both reused and recycled, but due to lead leaching it may not be landfilled (Musson, Jang et al. 2000). It used to be reused in the manufacturing of CRT monitors, but due to the success of flat screens there is little demand nowadays. Depending on the legislation regarding leaching behaviour, leaded glass is used as a construction material in some countries. The lead can also be recovered by non-ferrous recyclers such as Metallo Chimique in Belgium who use the glass as a fluxing agent (ICER 2004). The latter is assumed to be the end-processing for leaded glass in the MT scenario.

Economic model

The cost for restoring lead from the leaded glass is based on the treatment cost of NuLife in the UK who charge 0,08 € per kilogramme glass treated.

Environmental model

The avoided impact of the process is *Lead, at regional storage/RER* and the required processing impact is *Lead, secondary, at plant/RER*, allocated according the weight ratio of the lead in the glass. Actually, the impact of recycling is based on a process of restoring lead by melting plates from lead acid batteries. This seems a fair approximation of the input required as the rest of the glass is used as a fluxing agent.

4.2.7. Landfill in developed countries

The main fraction that is destined for landfill is barium/strontium glass. The cost for landfilling material in Belgium is 0,12 €/kg (Duflou and Dewulf 2013). In SimaPro this is included as *Disposal, glass, 0% water, to inert material landfill/CH*. The ecoinvent data takes the land and the energy use into account.

4.3. Informal sector scenario

The following subchapter describes the recycling of CPUs and CRT monitors by the informal sector which currently seems to be the dominant practice in developing countries. This recycling chain is from here on referred to as the Informal Sector scenario (IS scenario). First the pre-processing of CPUs and CRT monitors is discussed and subsequently the end-processing techniques that they use.

4.3.1. Pre-processing of CPUs in the IS scenario

Due to the limited employment opportunities, CPUs are completely dismantled to recover most of its value. Informal recyclers dismantle the main unit, its subcomponents such as the HDD, CDD, FDD and PS and even complex parts such as motors and copper coils. Table 13 shows the pre-processing efficiencies of the informal recycling of a CPU. In lack of better data, it is assumed that manual dismantling achieves perfect pre-processing efficiencies.

Table 13 – Pre-processing of CPUs by the informal sector

Component	Pre-processing efficiency [%]	End-processing	Location
PWBs & connectors	100	Cyanide leaching	China
Cables	100	Open air burning	Kenya
Ferrous metals	100	Ferrous smelter	Kenya
Aluminium	100	Aluminium smelter	Kenya
Copper	100	Copper smelter	Kenya
Plastics	100	Urban landfill	Kenya

Because no end-processing for precious metals is available in Kenya, the PWBs and connectors are sold to Chinese traders whom presumably use cyanide leaching processes to recover some of the gold (Prakash, Manhart et al. 2010). Most metals will be recovered as they are sold on local markets and will be treated in smelters. But to recover copper the recyclers refer to open burning processes to aid them in removing the isolation. It is assumed that plastics are disposed in an urban landfill, despite that it is unclear what actually happens to them.

Economic model

Because it is difficult to estimate how informal recyclers value their working time, the costs have been omitted. Hence, the economic model only focuses on the material revenue that the recyclers can retrieve. This approach can act as an upper boundary of the revenue and could be used to aid in the cooperation with the informal sector, as will be discussed in chapter 7.3.

Environmental model

Analogous to other scenarios, the model in SimaPro models the dismantling and sends the fractions to the relevant end-process.

4.3.2. Pre-processing of CRT monitors in the IS scenario

Once CRT monitors are collected the informal recyclers recover all the materials that have an economic value. In the case of CRT monitors this means that all of the subcomponents are completely dismantled, except for the CRT unit. Table 14 gives an overview of the pre-processing of a CRT monitor by the informal sector.

Table 14 – Pre-processing of CRT monitors by the informal sector

Component	Pre-processing efficiency	End-treatment	Location
PWBs	100	Open air burning	China
Cables & yoke	100	Open air burning	Kenya
Copper	100	Copper smelter	Kenya
Aluminium	100	Aluminium smelter	Kenya
Ferrous metal	100	Ferrous smelter	Kenya
Leaded glass	100	Urban landfill	Kenya
Plastics	100	Urban landfill	Kenya
Phosphors	100	Urban landfill	Kenya

The pre-processing is completely analogous to the treatment of CPUs. The recyclers recover the ferrous and aluminium metal by complete dismantling. It is assumed that the PWBs also are sold to Chinese traders who likely incinerate the boards to recover some copper. The cables and the yoke are burned in open air to remove the plastics and only then are melted to recover the copper. The non-valuable fractions such as the plastics and most of the CRT unit are just left for what they are on the recycling grounds. Prior to the disposal, recyclers will smash the CRT unit to recover the electron gun and the ferrous mask, but this leaves the glass to leach lead to groundwater and the phosphors to contaminate the soil.

Economic & environmental model

The reasoning and structure behind the models are the same as for CPUs.

4.3.3. Precious metal recovery by cyanide leaching

Although there are many different processes available for gold recovery, cyanide leaching is cheap and effective despite the high environmental cost and safety risks (Cui and Zhang 2008). This explains why the method is so popular among informal recyclers. Figure 18 shows a Chinese woman desoldering PWBs and putting components in buckets for leaching. The following section is based on the thesis of Keller who assessed the recovery efficiency, the process inputs and the emissions to waste water of cyanide leaching by the informal sector in India (Keller 2006).

The cyanide leaching process can be divided in two steps: further dismantling of PWBs and the chemical leaching. Recyclers first further dismantle the PWBs to liberate the components of which they know that they can recover gold from. Because cyanide leaching is only a chemical method, only the gold on the surface of components can be recovered. This preliminary step results in massive gold losses as only 17 % of the gold from the initial PWBs reaches the leaching process. The material that is separated from the 'gold containing' parts, which makes up for 60 % of the initial weight of the PWBs, will be burned for copper recovery. Table 15 summarizes the further dismantling of PWBs by the informal sector.

Table 15 – Further dismantling of PWBs by informal recyclers

Material	Comment	Weight [%]	Gold content [%]
PWBs		100	100
"Gold containing" parts	To: Cyanide leaching	40 %	17 %
Nude PWBs, copper parts, plastic parts, "non gold" parts	To: Open air burning	60 %	83 %

Subsequently, the gold from the connectors is recovered by putting them in a cyanide bath. As Figure 18 illustrates, the process poses concerns to health and safety as recyclers are exposed to nitrous oxide fumes. Additionally, when waste solutions are disposed this results in emissions of heavy metals and acids to surface water. The gold recovery rate of the chemical process is 60 %. 27 % still remains in the body components and 13 % is lost in the waste water.

Figure 18 – A Chinese woman extracting gold from PWBs

Table 16 – Environmental model of the cyanide leaching process

Material	Avoided product	Process input	Efficiency [%]
Gold	Gold, at regional storage/RER	See Appendix …	60
Silver	/	/	0
Palladium	/	/	0

The overall gold recovery of this process can be estimated at a mere 10 %, but the correct interpretation requires some additional considerations. First it should be noted that the assessment of Keller is merely a momentary record and no statistic test. Second, the leaching process showed some indications that the process refrains from optimal conditions for cyanide leaching. Finally, it is likely that there are big variations in professionalism among informal end-processors. However, because the observed recyclers' experience spans over several decades, it seems that the study is a good indication for what can be recovered by hydrometallurgical processes.

Economic model

To estimate the value of PWBs for the informal sector, the economic model only considers the material revenue and neglects their costs. The costs were not possible to assess due to a lack of data on prices of acids and infrastructure. The material revenue is estimated by calculating the precious metal value and multiplying with the recovery efficiency.

Environmental model

Table 17 and Table 18 show the input and the output material of the cyanide leaching process of the parts of the PWB that are further treated. The column on the left and the right differ because the numbers on the left are calculated per gram gold recovered. The numbers on the right are per gram gold contained in the qualified parts of the PWBs. The recyclers use silver in the process to help solute the gold. But this is actually superfluous as the same results could be achieved by adding more aluminium.

Table 17 – Required input for the cyanide leaching

Input material	[kg/ g gold recovered]	[kg/ g gold processed]
Qualified parts of the PWB	20,700	12,420
Water	53,600	32,160
Substance 1 (assumed NaCN)	0,185	0,111
Aluminium	0,047	0,028
Nitric acid	0,677	0,406
Lime	0,047	0,028
Silver	0,027	0,016
Sodium Chloride	0,393	0,236
Caustic soda	0,245	0,147
Unknown salt	0,135	0,081
Unknown substance (2,3)	0,020	0,012
Iron	0,050	0,030
Sodium Chloride	0,230	0,138

Table 18 – Output of the cyanide leaching process

Output	[kg/ g gold recovered]	[kg/ g gold processed]
Body components	20,700	12,420
Water vapour	8,410	5,046
Waste solution, cyanide leaching	30,200	18,120
Waste solution, silver recovery	23,833	14,300
NO2	0,080	0,048
Silver	0,000	0,000
Gold	0,001	0,001
Melting residues	0,030	0,018

The emissions from the waste solution to the drain are modelled as emissions to surface water in SimaPro. The spectral composition of the waste solution of the process is included in Appendix D in Table 43. The metals that were below the range of the measurement systems are neglected.

4.3.4. Open air burning of cables and PWBs

The informal recyclers refer to burning processes to separate copper from cables and PWBs because it is easier to burn isolation or plastics than separating them by hand. This section discusses how the environmental inventory of the open air burning of these components is modelled in SimaPro.

The emissions of open air burning of PWBs and cables are analysed by (Gullett, Linak et al. 2007). In conditions resembling the open air burning, emissions to soil and air are measured. The spectral composition of the PWBs that are burned are similar to that of the PWBs that don't end up in the cyanide bath in Keller's analysis. Table 44 in appendix D shows the spectral composition of the fly ash during the burning. When burning the PVC isolation of the wiring, the copper works as a catalyst to form a relative large amount of dioxins. Additionally, the emissions of metals as lead, arsenic and copper to air are also of concern for human health. The emissions to air are modelled in SimaPro as emissions in highly populated areas. Despite that this does not fully account for the way recyclers are standing in the smoke, this is the best possible approximation.

The spectral composition of the residual ash is shown in Table 45 in Appendix D. The emissions data first are corrected to represent the emissions of residual ash per mass input, and not per mass ash. Because after burning and removing copper parts, the residual ash makes up for 70 and 60 % of the original mass for PWBs and cables respectively, the data is corrected with this factor. The emissions are modelled in SimaPro as emissions to soil in urban areas. Based on the losses to the soil and air, the recovery rate for copper of burning cables and PWBs is 92 and 93 % respectively. The losses of copper from PWBs are likely somewhat higher as not all copper containing parts can be refined and 93 % is hence an optimistic figure.

4.3.5. Metal recycling in developing countries

Aluminium, copper and ferrous metals typically end up at regional smelters. However, these installations typically have no flue gas treatment. Hence paints and other organic material can cause undesired emissions (Schluep, Hagelüken et al. 2009). Despite this difference, this could not be accounted for in the environmental model due to a lack of data. Therefore the environmental impact of metal recycling in developing countries is assumed to be the same as it is in industrialised countries, as is shown in Table 12.

The economic value does differ slightly between industrialised and developing countries. Table 19 shows the value of commodity metals in Kenya.

Table 19 – Economic value of metals in Kenya

Fraction	Value [€/kg]	Source
Aluminium	[redacted]	WorldLoop
Copper	[redacted]	WorldLoop
Ferrous metal	[redacted]	WorldLoop

4.3.6. Disposal of leaded glass on urban grounds

Because there are no profitable solutions for CRT glass or plastics, informal recyclers tend to dispose them on the recycling grounds. In time, urban grounds are transformed and resemble landfills as is the case in Ghana, see Figure 19. This section investigates the importance of lead emissions to groundwater from landfilling CRT units.

Figure 19 – Recycling grounds in Accra, Ghana

The Toxicity Characteristic Leaching Procedure (TCLP) is a test that estimates leaching behaviour of samples in a municipal waste landfill. The procedure requires a sample of the product to be exposed to a leachate in an environment that simulates a landfill over time. The average leachable lead concentration of computer monitors is 19,3 mg/L and is a weighted average of the leaching from the panel-, neck-, frit- and funnel glass(Musson, Jang et al. 2000). Conform with the TCLP method, this is similar as leaching around 2 gram of lead per test and per CRT unit. The regulatory limits on disposing products on a landfill require a maximum lead leaching concentration of 5 mg/L.

This illustrates that lead leaching from CRT units is of concern and is therefore avoided in industrialised countries. Landfills in industrialised countries are located in stable clay grounds that leach very little to groundwater and moreover are managed to avoid these emissions. In contrast, the urban grounds where CRT units are dumped in developing countries do easily leach in ground water. But because little is known on the leaching behaviour over time, the lead emissions to groundwater cannot be estimated. The impact of dumping leaded glass is not quantified in the environmental model, but the contrast with industrialised countries indicates that it certainly is of concern.

4.3.7. Disposal of plastics on landfill

The disposal of plastics on landfill takes into account the land use and the energy required. It is modelled with ecoinvent data of *process-specific burdens, sanitary landfill/CH S*. The model does not take into account the leaching of hazardous substances as for example could be a threat in the case of BFR plastics and the generated impact are underestimated in this model.

4.4. Bo2W scenario

The Bo2W philosophy aims to solve the e-waste problem in developing countries by integrating local manual dismantling with BAT for end-processing in industrialised countries. The following subchapter describes the manual dismantling of CPUs and CRT monitors, the subsequent integration with proper end-processing and the importance of transport.

4.4.1. Pre-processing of CPUs in the Bo2W scenario

The level of manual dismantling of CPUs in the Bo2W scenario is dependent on the country setting as different wages change the economically optimal dismantling depth. For reasons of continuance with the research objectives, the results are shown in chapter 7.1. Based on the assumptions regarding the dismantling time that are stated there, it is argued that it is beneficial to completely dismantle CPUs in the Kenyan setting.

Table 20 gives an overview of the material streams of the Bo2W scenario for CPUs. The manual dismantling has the potential to liberate all PWBs and connectors as long as recyclers are aware of them. All precious metals bearing material is shipped to Belgium and sold to Umicore. A labourer first dismantles the mother boards and cuts connectors from the cables. The HDD, CDD, FDD and PS are subsequently further dismantled to recover their PWBs, readers and connectors. Complex parts such as motors and transformers are also dismantled by hand in the Kenyan setting. All liberated metal parts are sold to local smelters.

Table 20 – Pre-processing of CPUs in the Bo2W scenario

Component	Pre-processing efficiency [%]	End-treatment	Location
PWBs & connectors	100	Umicore PMR	Belgium
Flat cables	100	Copper smelter	Belgium
Ferrous casing	100	Ferrous smelter	Kenya
Aluminium	100	Aluminium smelter	Kenya
Copper	100	Copper smelter	Kenya
Plastics	100	Plastics incineration	Belgium

In most developing countries there currently are little restrictions on the reuse of BFR plastics and they can be recycled for local applications. However, to allow for a fair comparison between the MT scenario and the Bo2W export scenario that is discussed in chapter 6, it is assumed that plastics are incinerated in an incinerator with flue gas treatment and energy recovery in Belgium.

Economic model

The material revenue is based on the local market value of the liberated components and the value in Belgium. The costs are broken down to the labour cost due to the dismantling, the transport costs to ensure sound end-processing and the overhead costs due to the infrastructure.

The complete dismantling of a CPU is estimated to take 60 minute in the Kenyan setting. The transport costs are discussed later in this chapter.

The calculations behind the allocation of the overhead costs are shown in Table 21. The infrastructure and administration costs are allocated to both products in order to allow for a fair comparison between the Bo2W and the MT scenario. The allocation of the infrastructure cost is based on Time Driven Activity Based Costing (Kaplan and Anderson 2003). In this method, first it is calculated how often a certain asset is used to identify the unit cost per time amount. In the recycling facility this is done by estimating the amount of CPUs and CRT monitors that are processed per year and multiplying it with the dismantling time. The estimated amount of IT devices that are processed is an optimistic figure that estimates the capacity of the facility. In reality, collection levels remain a lot lower and many recycling facilities struggle with their overhead costs. But in the case of the Bo2W export scenario sufficient input could be provided to meet the facility's capacity. The infrastructure costs per CPU are X € and per CRT monitor X €. The cost due to administration is allocated per product and accounts for X € per product. In total, the overhead costs are 1,29 and 0, 83 € per CPU and CRT monitor respectively.

Table 21 – Allocation of overhead costs of pre-processing in the Bo2W scenario

Cost of infrastructure [€/year]	[redacted]
Cost of administration [€/year]	[redacted]
CPUs processed/year	[redacted]
CRT monitors processed/year	[redacted]
Cost of administration [€/product]	[redacted]
CPU dismantling time (minutes)	[redacted]
CRT dismantling time (minutes)	[redacted]
Unit cost infrastructure & administration (€/minute)	[redacted]
CPU overhead cost (€/unit)	1,29
CRT overhead cost (€/unit)	0,83

Environmental model

The environmental model links the various fractions to the proper end-processing with their respective recovery rates. Additionally, when equipment needs to be shipped the impact of transport is added, as will be discussed below. The impact of the dismantling facility itself has been neglected.

4.4.2. Pre-processing of the CRT monitor in the Bo2W scenario

Similar to the MT scenario, the CRT monitor first is manually dismantled. The optimal dismantling depth of a CRT monitor in the Kenyan setting is assessed in chapter 7.1 and makes clear that complete dismantling is most profitable. The PWBs are upgraded by removing the heat sinks and the cables, and are subsequently shipped to Umicore. The cables are sold to a copper smelter abroad. The remaining ferrous metals, aluminium and copper can be melted locally. Similar to the plastics of the CPU, it is assumed that BFR plastics will be incinerated in industrialised countries.

Table 22 – Pre-processing of a CRT monitor in the Bo2W scenario

Component	Pre-processing efficiency	End-treatment	Location
PWBs (upgraded)	100	Umicore PMR	Belgium
Cables	100	Copper smelter	Belgium
Aluminium	100	Aluminium smelter	Kenya
Copper	100	Copper smelter	Kenya
Ferrous metal	100	Ferrous smelter	Kenya
Strontium glass	100	Landfill	Kenya
Leaded glass	100	Non-ferrous recycler	Belgium
Plastics	100	Plastics incineration	Belgium
Phosphors	100	Storage	Belgium

The dismantling of the CRT unit is performed with hot wire techniques. A nickel-chrome wire is wrapped around the separation line between the funnel and the panel glass. The wire is then heated for a minute and the thermal stress causes the glass to crack. The funnel glass can be lifted and the phosphors are removed by suction cleaning. Finally the ferrous shadow mask is separated from the panel glass (Zumbuehl 2006). The leaded glass is treated overseas by a non-ferrous smelter such as Metallo-Chimique. The strontium glass is landfilled locally and the phosphors are shipped to Belgium for storage.

Economic model

The economic model consists of the material revenue and costs that are analogous to CPU Bo2W scenario. The dismantling time per CRT monitor is 20 minutes at the optimal dismantling depth. The transport costs are based on the assessment of next chapter. The allocated costs of the infrastructure and administration is calculated in the previous subchapter and is 0,83 €/unit. Additionally, the cost of the machine to dismantle CRT units is allocated per unit as is shown in Table 23 . With an expected life of X years, a WACC of X %, a purchase cost of X € and the assumed collection levels, the overhead cost due to the equipment per CRT monitor is 0,35 €/unit.

Table 23 – Process equipment cost per CRT monitor in the Bo2W scenario

Purchase cost (€)	
Life estimate	
WACC	
Collection levels (units/year)	
Processing equipment cost (€/unit)	**0,35**

Environmental model

The environmental model is completely similar to that of the CPU in the Bo2W scenario.

4.4.3. Transport

In the following subchapter the economic and environmental importance of the transport of various fractions between developing and industrialised countries is assessed.

Economic model

The cost of transporting containers is shown in Table 24 and is dependent on the mode of transportation, container size and mainly from where to where the container is shipped. Shipping is often not only dependent on the distance, but also on the direction. This is due to the fact that countries, such as China, simply export more than they import. Ships that return are often not fully loaded and hence it is cheaper to transport in that direction.

Table 24 – Transport costs per container

Start-Destination	Mode of transportation	Container size	Cost [€/container]	Source
Nairobi-Mombasa (and reverse)	Truck	20 ft	1.200	WorldLoop
Nairobi-Mombasa (and reverse)	Truck	40 ft	1.800	Estimate
Mombasa-Antwerp	Ship	20 ft	1.300	WorldLoop
Mombasa-Antwerp	Ship	40 ft	1.950	Estimate
Antwerp-Mombasa	Ship	20 ft	1.800	WorldLoop
Antwerp-Mombasa	Ship	40 ft	2.700	Estimate

The loading differences between a 20 feet and 40 feet container are shown in Table 25. Despite that the volume of a 40 feet container is more than twice as big, it can only load 22 % more weight. But the transport costs of a 40 feet container are approximately only 1,5 times as expensive. Hence, for fractions with a high loading density, where the loading is restricted by mass, the 20 feet containers are better. But for materials of lower density the shipping is cheaper in 40 feet containers. In appendix E the density on which the cost of both containers are breakeven is determined as 0,54 tonne/m^3. Below that value it is economically beneficial to ship in 40 feet containers and above in the 20 feet ones.

Table 25 – Loading differences between 20 and 40 feet containers

Container type	Volume [m^3]	Loading restrictions [tonne]
20 feet container	32,9	21,8
40 feet container	67,5	26,7

The weight load and container size for different fractions is shown in Table 26. First the density of the fractions is estimated based on available data or on the dimensions and the mass of the device. The density subsequently is multiplied with the estimated storage efficiency to find the loading density. The PWBs are exceptional because even though that their transport costs would likely be lowered with 40 feet containers, they are shipped in 20 feet containers to avoid cash flow problems.

Table 26 – Load and container size for different fractions

Fraction	Stora	Loading	Cont	Load [ton/	Dimensi	Mas	Sourc

	ge efficiency	density [ton/m^3]	ainer	container]	ons	s	e
PWB	-	-	20	8	-	-	World Loop
Leaded glass	0,9	2,5	20	21,8	-	-	(ICER 2004)
Metals	-	>>0,54	20	21,8	-	-	
Plastics	0,9	0,9*1	20	21,8	-	-	
Cables	0,6	0,6*3,8	20	21,8	-	-	
CPUs	0,75	0,23	40	12 ton 1.200 units	45x19x48	9,9	
CRT monitors	0,65	0,28	40	12,3 ton 1.000 units	33x34x38	12	
CRT units	-	-	40	1.500 units			World Loop
PS	0,7	0,54	20/40		15x8,6x14	1,4	

Based on the above data the transport costs for Antwerp-Nairobi for different fractions are shown in Table 27.

Table 27 – Transport costs of fractions between Antwerp and Nairobi

Fraction	Start-Destination	Cost
Mass restricted 20 feet container	Nairobi-Antwerp	0,11 €/kg
PWBs	Nairobi-Antwerp	0,31 €/kg
CRT units	Nairobi-Antwerp	2,23 €/unit
CPUs	Antwerp-Nairobi	4,93 €/unit
CRT monitors	Antwerp-Nairobi	5,00 €/unit

Environmental model

Transporting fractions from Nairobi to Antwerp requires the shipping of over 11.800 kilometres and the trucking of 500 kilometres over land. Table 28 shows the inventory of the transport which makes use of the ecoinvent data. This data accounts for the primary energy use and makes an allocation of the impact of the required infrastructure. Unlike the economic model, the environmental model does not account for possible differences in the loading of one container between different fractions. The environmental impact is allocated on the distance and the weight.

Table 28 – Inventory of the transport in the Bo2W scenario.

Data	Distance [km]	From-to
Transport, transoceanic	11.800	Mombasa-Antwerp

freight ship/OCE		
Transport, lorry 20-28t, fleet average/CH	500	Nairobi-Mombasa

5. Assessment of the recycling scenarios

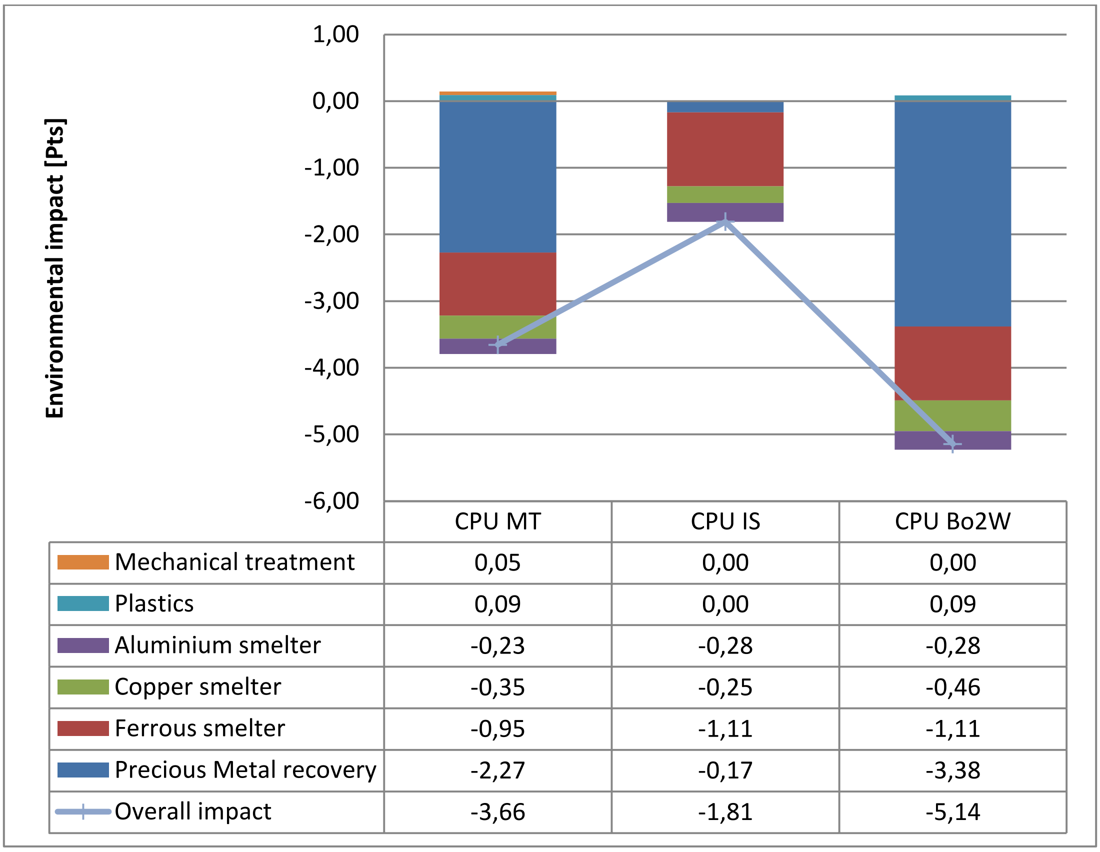
The following chapter shows and interprets the results of the environmental and economic assessment of the recycling scenarios. The goal is to facilitate a clear understanding of the challenges and opportunities of each scenario from both an economic and environmental perspective. The results are further used in chapter 6 to evaluate the Bo2W export scenario and in chapter 7.3 to investigate potential collaboration with the informal sector.

5.1. Environmental assessment

The following section discusses the environmental impact of the recycling scenarios for CPUs and CRT monitors. The results serve as a summary of the LCA and the score is based on the weighting of impact to human health, eco-toxicity and resource depletion. The assessment only considers the products in their disposal phase and avoiding the impact of other processes, such as the mining of gold, results in a negative value.

5.1.1. Environmental assessment of recycling CPUs

The results of the LCA for the MT, IS and Bo2W scenario for recycling CPUs are shown in Figure 20. The Bo2W scenario has the highest avoided impact with a score of -5,1 Pts. The MT scenario follows with an impact of -3,7, but is around 28 % less effective. Informal recycling is far inferior with a score of -1,8, roughly one third of what is possible in developing countries.



	CPU MT	CPU IS	CPU Bo2W
🟧 Mechanical treatment	0,05	0,00	0,00
🟦 Plastics	0,09	0,00	0,09
🟪 Aluminium smelter	-0,23	-0,28	-0,28
🟩 Copper smelter	-0,35	-0,25	-0,46
🟥 Ferrous smelter	-0,95	-1,11	-1,11
🟦 Precious Metal recovery	-2,27	-0,17	-3,38
—+— Overall impact	-3,66	-1,81	-5,14

Figure 20 – Environmental assessment of the recycling scenarios for CPUs

The differences between the scenarios are almost completely due to the precious metal recovery. Figure 21 elaborates on the precious metal recovery of all scenarios. In both the Bo2W and the MT scenario the liberated PWBs end up at an integrated smelter-refiner whose high precious metal recovery rates avoid a lot of impact and only require relatively low processing impacts. But manual dismantling improves the precious metal recovery by almost one half of the MT recovery rates and illustrates that pre-processing certainly is critical. Furthermore, the impact of the required transport to apply the Bo2W philosophy in developing countries is almost negligible.

The Bo2W philosophy is also a signficiant improvement compared with the IS scenario. In the IS scenario the avoided impact is low, because cyanide leaching is only moderately effective for highly concentrated parts and results in overall low gold recovery rates. The emissions due to the cyanide leaching process are found to be rather low when compared with the avoided impact of gold mining. But while the copper recovery rate is high due to the open air burning, this practice clearly is environmentally harmful and offsets the effects of the recycling. In reality, the impact of open air burning is likely worse. Despite that it is modelled as emissions to air in highly populated areas, informal recyclers often stand in the smoke and therefore the health effects will likely be far more harmful.

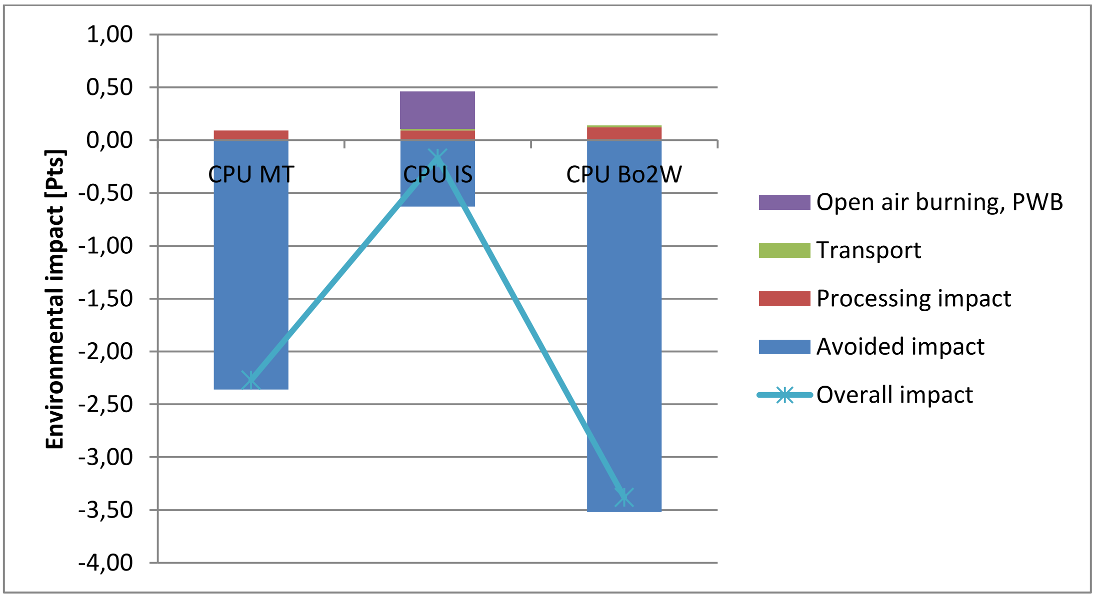


Figure 21 – Environmental assessment of the precious metal recovery for CPUs

Regarding the commodity metals, the recycling scenarios perform almost just as well. The MT scenario is slightly worse for aluminium and ferrous metals recovery because of the lower pre-processing yield. The impact of the mechanical pre-processing itself is low too. The Bo2W and IS scenario are similar to each other, except for the copper recovery. The same amount of copper is recycled, but Figure 22 shows that open air burning of cables in the IS scenario is far worse than controlled incineration. Making the same note as for the burning of PWBs, the health effects likely are far worse because individuals at the dump site will inhale air with highly concentrated levels of heavy metals and dioxins.

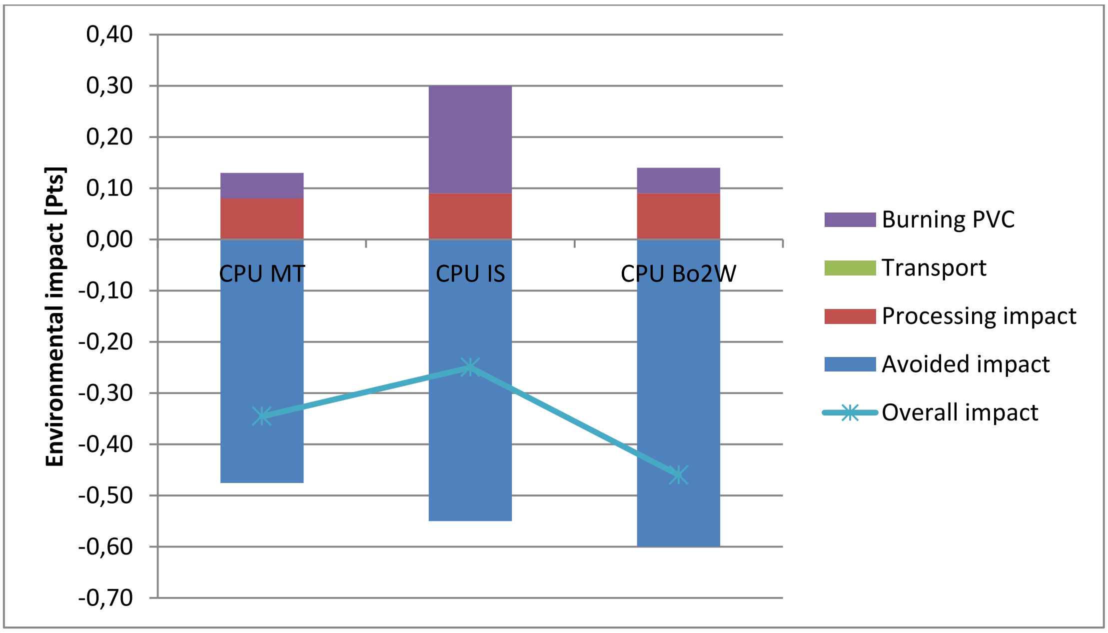
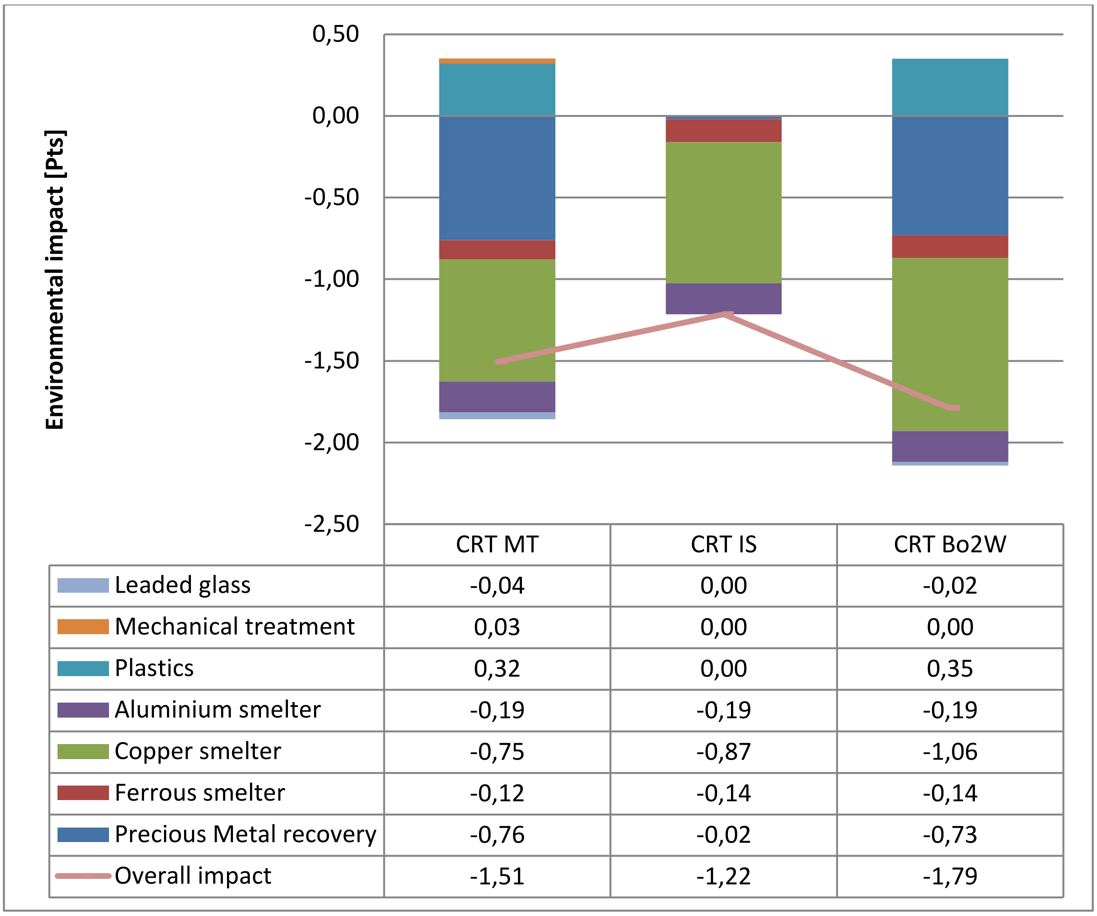


Figure 22 – Environmental assessment of the copper recovery for CPUs

The environmental impact of the plastics varies between the recycling scenarios and seems to be an order of magnitude less important than the metals when incinerated with energy recovery and flue gas treatment. The impact of landfilling in the IS scenario seems lower than that of incinerating, but this is due to restrictions of the model that do not account for leaching of hazardous substances.

5.1.2. Environmental assessment of CRT monitors

Figure 23 shows the environmental impact of the recycling scenarios for CRT monitors. With a score of -1,8 Pts, the Bo2W scenario is also the most environmental friendly scenario for CRT monitors. The MT follows close with a score of -1,5 Pts. Although the model does not take the dumping of leaded glass into account, the impact is worst in the IS scenario.



	CRT MT	CRT IS	CRT Bo2W
🟦 Leaded glass	-0,04	0,00	-0,02
🟧 Mechanical treatment	0,03	0,00	0,00
🟦 Plastics	0,32	0,00	0,35
🟪 Aluminium smelter	-0,19	-0,19	-0,19
🟩 Copper smelter	-0,75	-0,87	-1,06
🟥 Ferrous smelter	-0,12	-0,14	-0,14
🟦 Precious Metal recovery	-0,76	-0,02	-0,73
— Overall impact	-1,51	-1,22	-1,79

Figure 23 – Environmental assessment of the recycling scenarios for CRT monitors

The recovery of copper from the wires and the yoke has the highest prevented impact and is further broken down in Figure 24. The difference between the MT and the Bo2W scenario is almost completely due to the shredding of the yoke. Again, burning the isolation of wires in open air is far worse than controlled incineration.

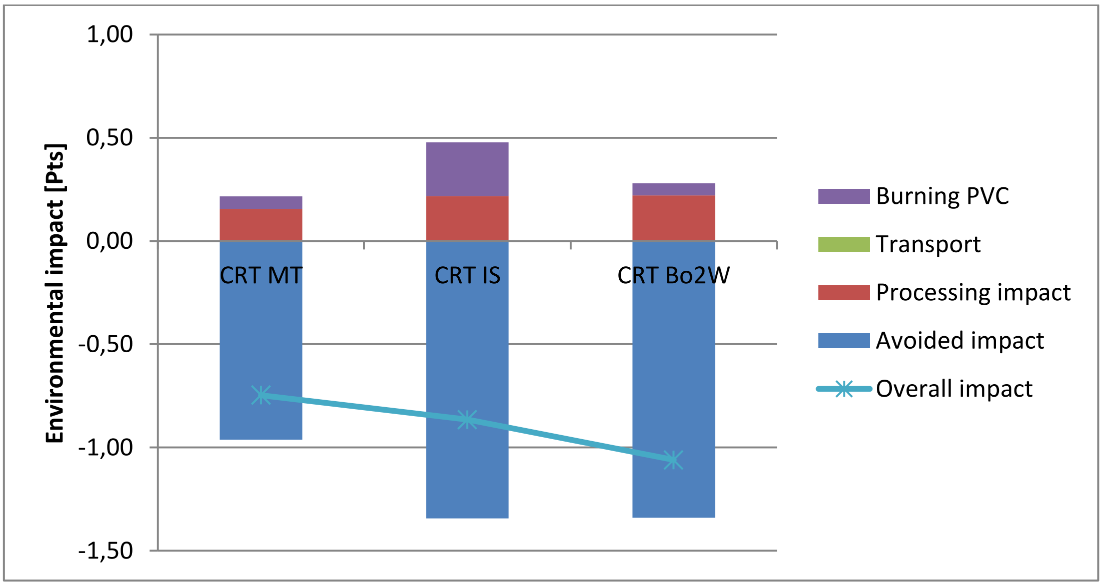


Figure 24 – Environmental assessment of the copper recovery of CRT monitors

Because of the relative low precious metal content, the impact of the PWB is smaller in comparison with the other fractions. Both the Bo2W and the MT scenario dismantle the PWB and send it to an integrated smelter-refiner. Figure 25 shows that the impact of transport is relatively higher than was the case for the PWBs from the CPU, but still is small compared with the benefits. Informal recyclers on the other hand only recover the copper which is about half of the avoided impact. Due to the burning, the benefits of recycling copper are completely offset.

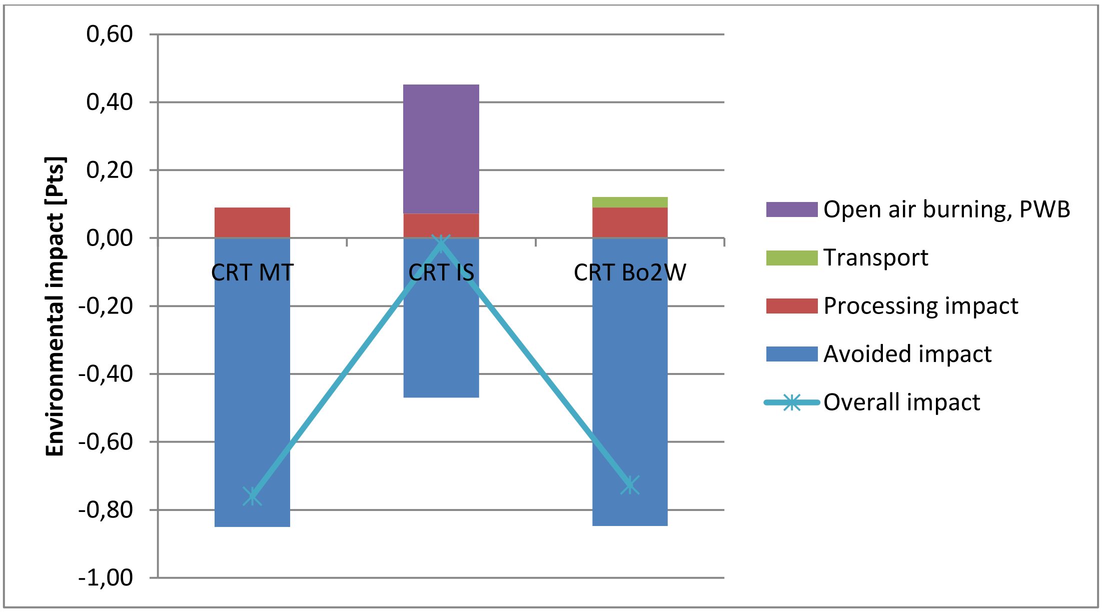


Figure 25 – Environmental assessment of precious metal recovery for CRT monitors

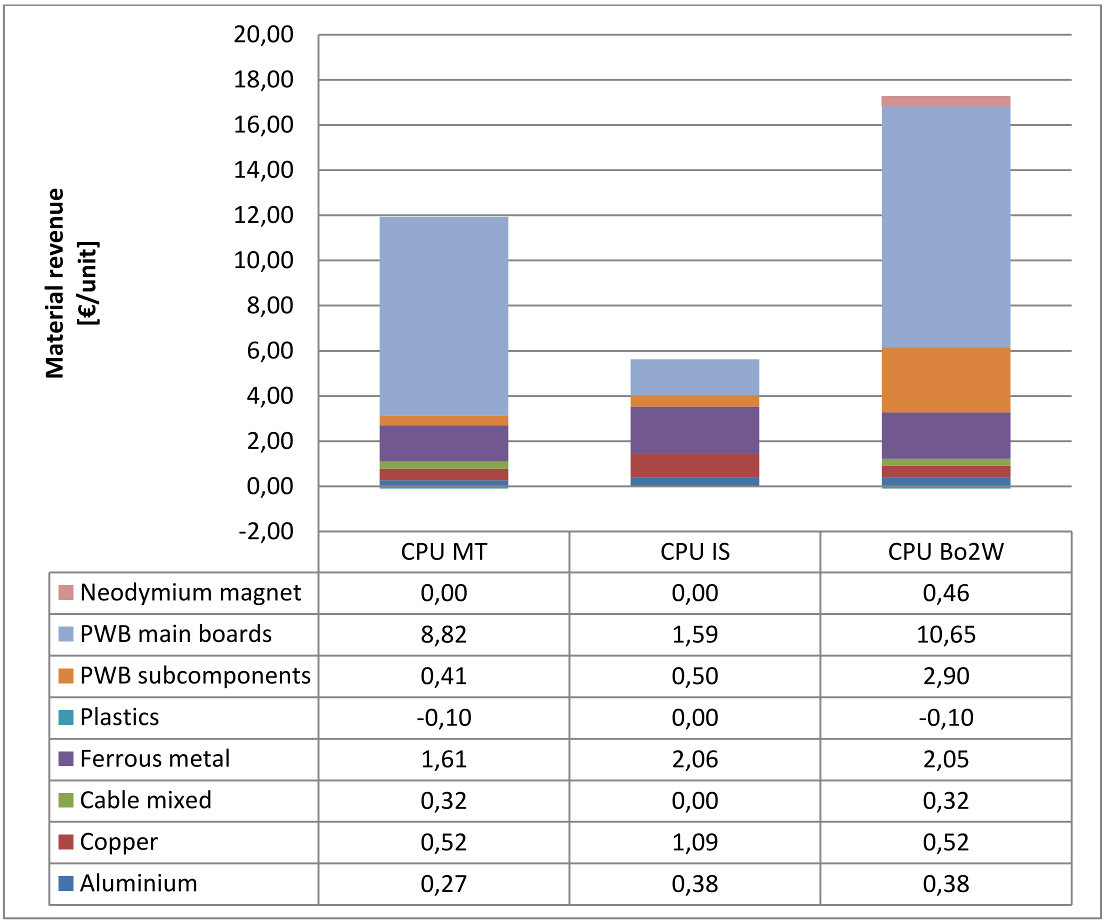
The impact of recycling leaded glass is low compared with the recycling of other metals. But despite that impact of leaching lead from the CRT unit in urban areas is not quantified, recycling likely is a far better solution. The impact of recycling ferrous metals and aluminium are similar between all scenarios. For the plastics, the same note should be made as is done for the plastics of the CPU.

5.2. Economic assessment

The economic assessment of pre-processing is broken down to the revenue that is gained from recovering the materials and the costs due to transport, labour and overhead. As stated in the methodology, the economic assessment takes the perspective of the pre-processor. Hence the material revenue is determined by the value that a pre-processor can earn by selling it to other pre-processors or end-processors.

5.2.1. Economic assessment of recycling CPUs

The material revenue of pre-processing CPUs for the different scenarios is shown in Figure 26. It is clear that the Bo2W scenario is economically superior with a revenue of 17,2 € per unit. The MT scenario follows with a revenue of 11,8 €, while the Bo2W scenario is 45 % higher. Informal recyclers only recover 5,6 €.



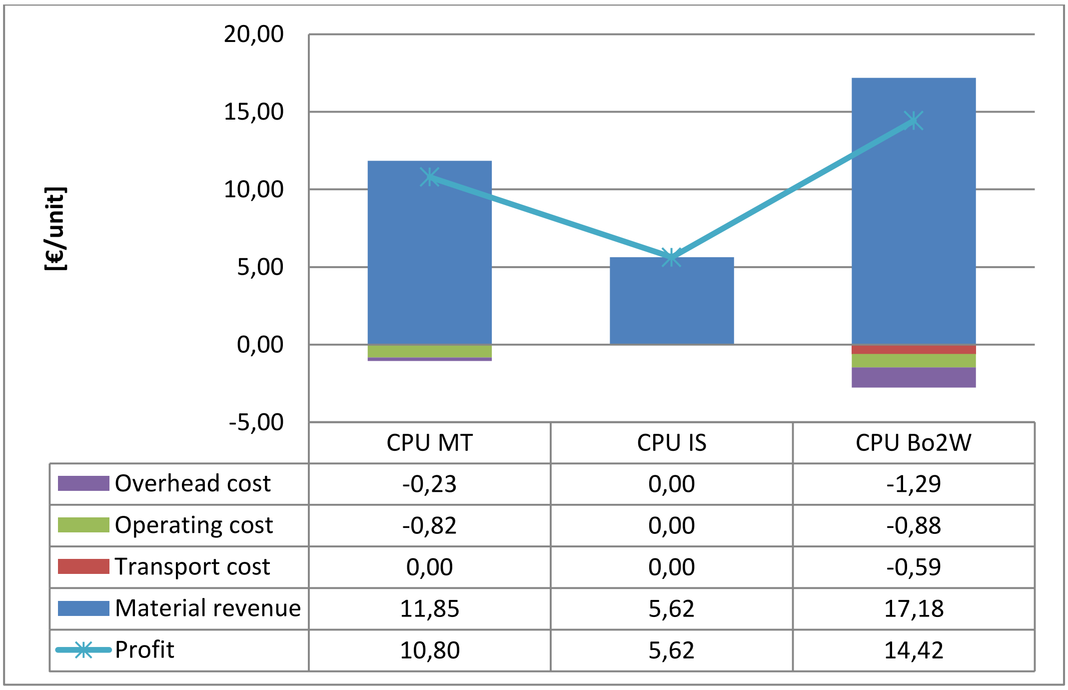
	CPU MT	CPU IS	CPU Bo2W
Neodymium magnet	0,00	0,00	0,46
PWB main boards	8,82	1,59	10,65
PWB subcomponents	0,41	0,50	2,90
Plastics	-0,10	0,00	-0,10
Ferrous metal	1,61	2,06	2,05
Cable mixed	0,32	0,00	0,32
Copper	0,52	1,09	0,52
Aluminium	0,27	0,38	0,38

Figure 26 – Material revenue of the pre-processing scenarios for CPUs

The difference between the scenarios is mainly due to the PWBs. The low recovery efficiencies of precious metals that occur when PWBs are shredded with other WEEE account for a difference of 4,3 € between the Bo2W scenario and the MT scenario. With the estimated recovery efficiencies, the difference between the IS and Bo2W is huge. End-processing PWBs at Umicore gains 11,5 € per CPU more than the cyanide leaching, clearly indicating the improvement potential of informal recycling.

The remaining differences are due to various facts. By dismantling HDDs in the Bo2W scenario Neodymium magnets can be liberated. Informal pre-processors are just as effective as the formal sector to recover commodity metals. Further differences with the MT scenario are due to the recovery yield and differences in value between industrialised and developing countries. In the case of copper, both effects cancel each other out.

Figure 27 summarizes the economic assessment of the CPU scenarios. The profits are 10,8 , 5,6 and 14,1 € for the MT, IS and Bo2W scenario respectively. The Bo2W scenario in the Kenyan setting is 31 % more profitable than the MT scenario in Belgium. The high productivity of the MT scenario is clear from the low operating costs, despite the high wages in Belgium. The costs of the Bo2W scenario illustrate that not only the labour cost, but also the overhead is significant when IT equipment is dismantled. Note that for the allocation of the overhead costs it is assumed that the amount of IT equipment processed are near the capacity of the building, but currently surpasses the amount that can be collected. The transport costs, however, are low when compared with the high material revenue that can be obtained by selecting proper end-processes in industrialised countries.

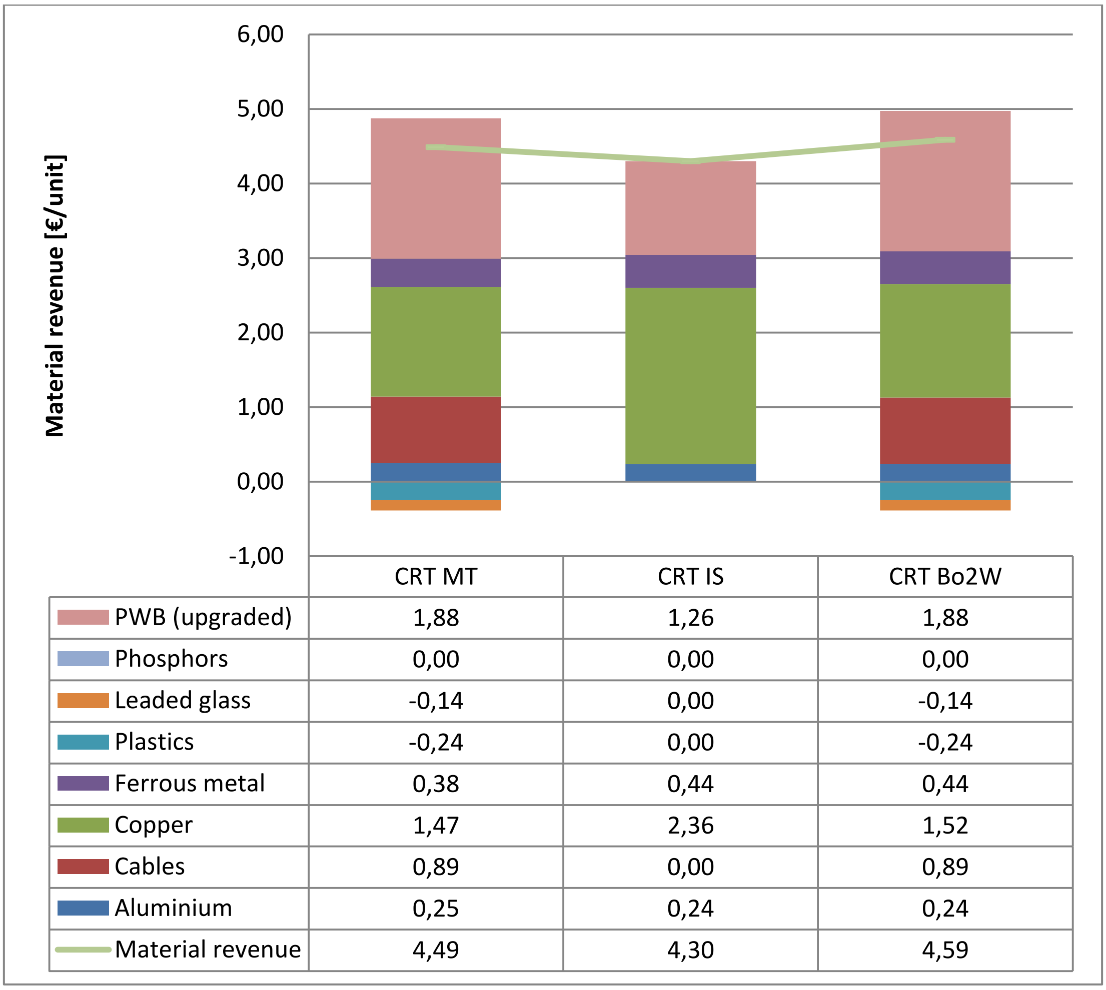


	CPU MT	CPU IS	CPU Bo2W
▬ Overhead cost	-0,23	0,00	-1,29
▬ Operating cost	-0,82	0,00	-0,88
▬ Transport cost	0,00	0,00	-0,59
▬ Material revenue	11,85	5,62	17,18
—✳— Profit	10,80	5,62	14,42

Figure 27 – Economic assessment of the pre-processing scenarios for CPUs

5.2.2. Economic assessment of recycling CRT monitors

The material revenue of the pre-processing scenarios for CRT monitors is shown in Figure 28. In contrast to pre-processing of CPUs, the material revenue of the scenarios does not differ much. The MT, IS and Bo2W scenario have a material revenue of 4,5 , 4,3 and 4,6 € respectively.



	CRT MT	CRT IS	CRT Bo2W
PWB (upgraded)	1,88	1,26	1,88
Phosphors	0,00	0,00	0,00
Leaded glass	-0,14	0,00	-0,14
Plastics	-0,24	0,00	-0,24
Ferrous metal	0,38	0,44	0,44
Copper	1,47	2,36	1,52
Cables	0,89	0,00	0,89
Aluminium	0,25	0,24	0,24
Material revenue	4,49	4,30	4,59

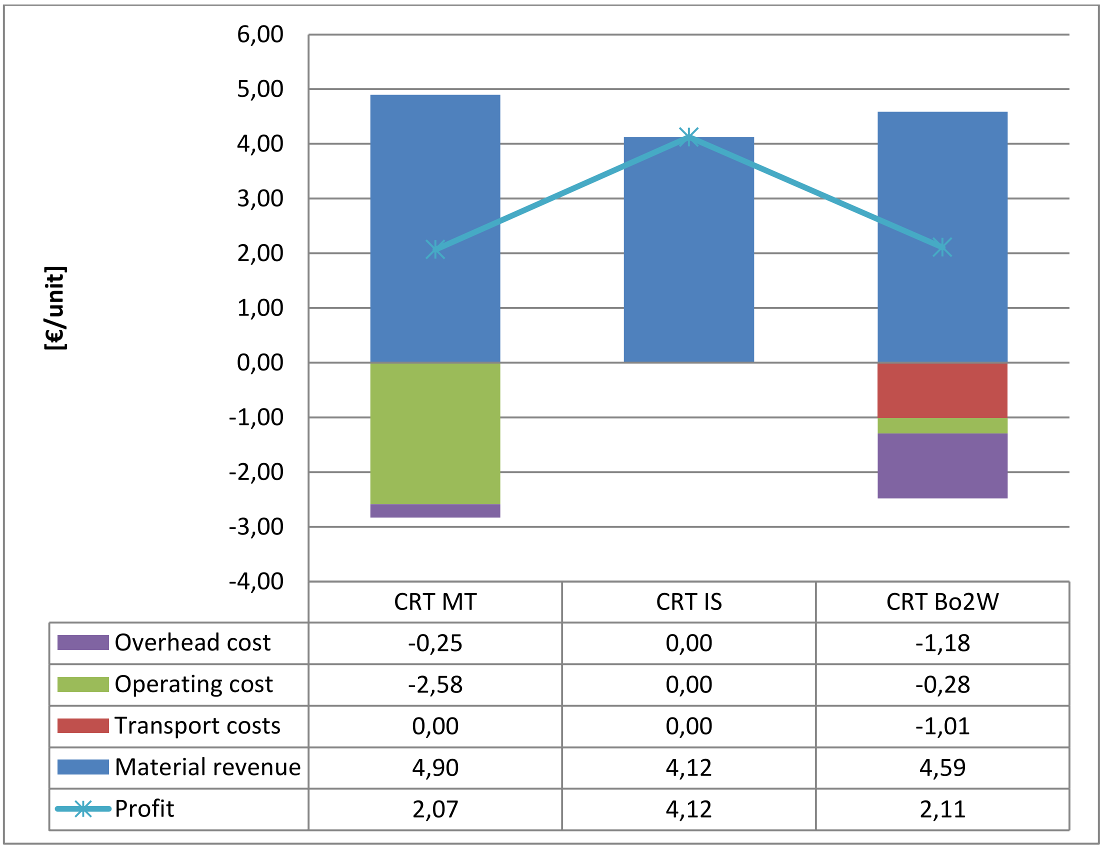
Figure 28 – Material revenue of the pre-processing scenarios for CRT monitors

The most valuable fraction remains the PWB which has a value of 1,9 € after it is upgraded and treated by Umicore. The value is also relatively high in the IS scenario because the gold concentration is low and the burning can liberate most of the copper.

The copper from the yoke and the cables are also of high value. The mechanical treatment of the yoke with other WEEE has lower recovery rates, but the revenue is compensated due to the fact that the copper value is higher in industrialised countries. Informal recyclers burn the cables and also sell the copper.

The revenue from the aluminium and ferrous metals are similar for all the scenarios. The disposal of the hazardous fractions such as the phosphors, leaded glass and BFR plastics, requires the pre-processor to pay for sound treatment. Informal recyclers on the other hand avoid these costs by disposing these fractions.

The economic assessment of the scenarios for CRT monitors is shown in Figure 29. The profitability of the MT, IS and Bo2W scenario is 2,1, 4,1 and 2,1 respectively. The MT scenario has high operating costs due to a 1,5 € labour cost plus a 1,0 € shredding cost per CRT unit. Dismantling the CRT in the Bo2W scenario requires high transport costs to ensure sound treatment for leaded glass and plastics. Manual dismantling, with the associated labour and infrastructure is, however, more cost effective in the Kenyan setting than mechanical treatment in Belgium. The IS scenario has the highest profitability, because they do not pay for the treatment of leaded glass nor use proper equipment to dismantle CRT units.



	CRT MT	CRT IS	CRT Bo2W
🟪 Overhead cost	-0,25	0,00	-1,18
🟩 Operating cost	-2,58	0,00	-0,28
🟥 Transport costs	0,00	0,00	-1,01
🟦 Material revenue	4,90	4,12	4,59
✳ Profit	2,07	4,12	2,11

Figure 29 – Economic assessment of the pre-processing scenarios for CRT monitors

6. Evaluation of the Bo2W export scenario

The following chapter evaluates whether the recycling of CPUs and CRT monitors originating from Belgium could be improved from an environmental and economic perspective by exporting them to countries where they will be manual dismantled according to the Bo2W philosophy. The assessment is subsequently expanded from Kenya to other countries to assess the sensitivity of the results to labour and transport costs. The legislation and other considerations are reviewed. Finally, the outcome is subjected to changes in gold value and dismantling time to assess the robustness of the proposed scenario from an economic perspective.

6.1. Environmental assessment

This section investigates whether the export of IT equipment truly is an improvement of the MT scenario from an environmental perspective. In addition to the environmental assessment of chapter 5.1, the calculations are expanded with the impact of transport. Both CPUs and CRT monitors are shipped from Antwerp to Mombasa by cargo ship km from Mombasa to Nairobi by truck.

The environmental impact of the MT and the Bo2W export scenario for CPUs is shown in Figure 30. Shipping CPUs for 12.000 km accounts for an impact of only 0,2 Pts, but manually recovering the PWBs improves the impact with -1,2 Points. In total, the Bo2W export scenario is 35 % more eco-friendly than the MT scenario.

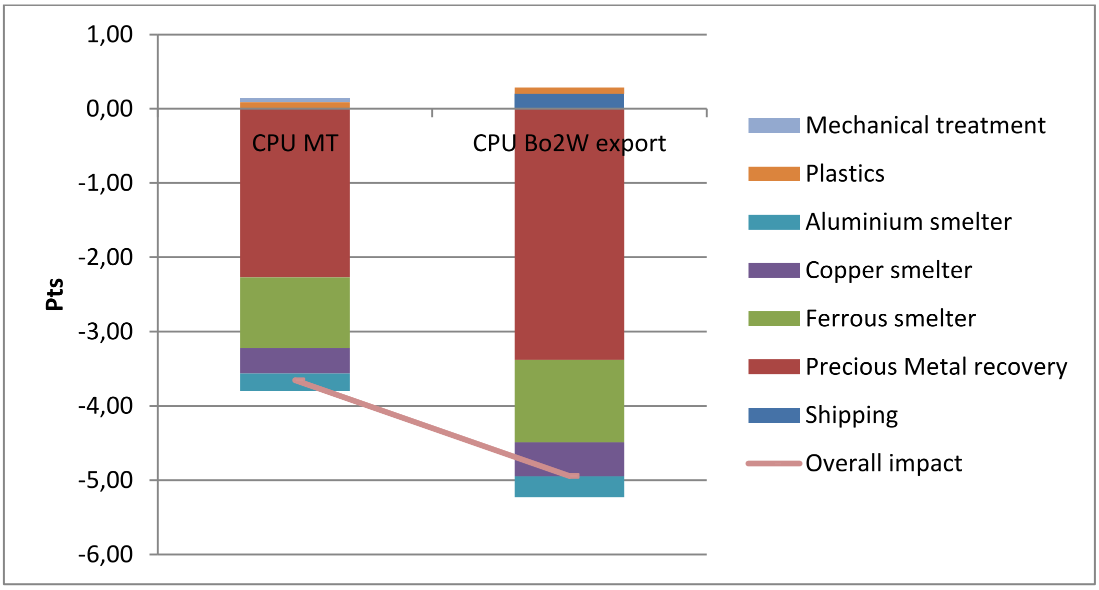


Figure 30 – Environmental comparison between MT & Bo2W export scenario for CPUs

The environmental comparison between the MT & Bo2W export scenario for a CRT monitor is shown in Figure 31. The impact of shipping is not negligible, but not critical either as it makes up for 0,26 Pts. Shipping the CRT monitor to Kenya improves the copper recovery rate, but is merely 2 % better from an ecologic perspective.

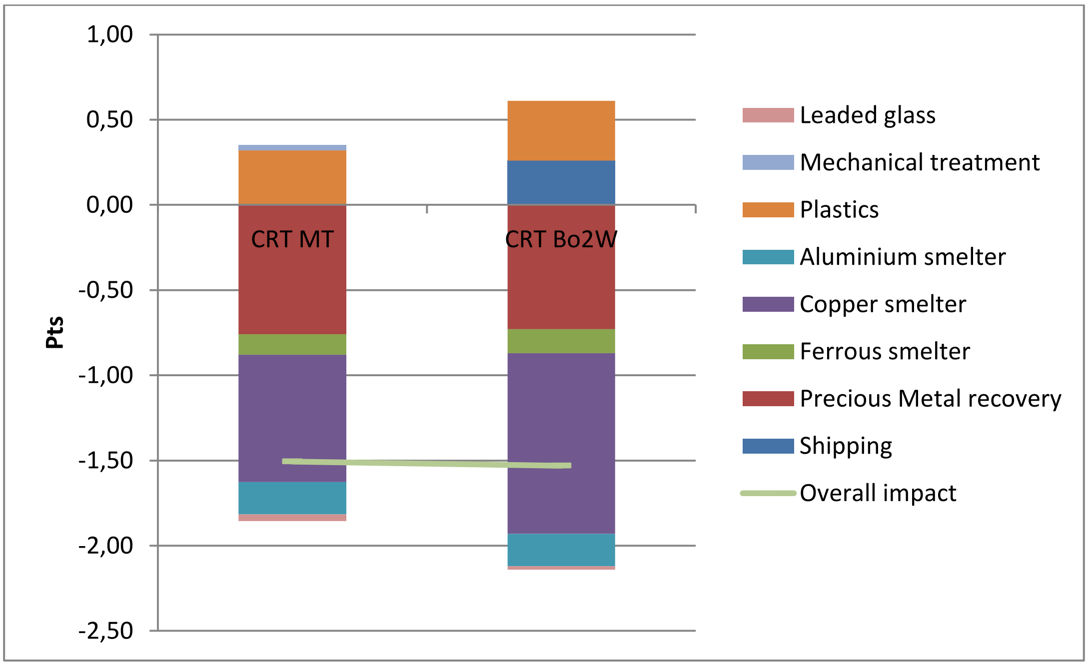
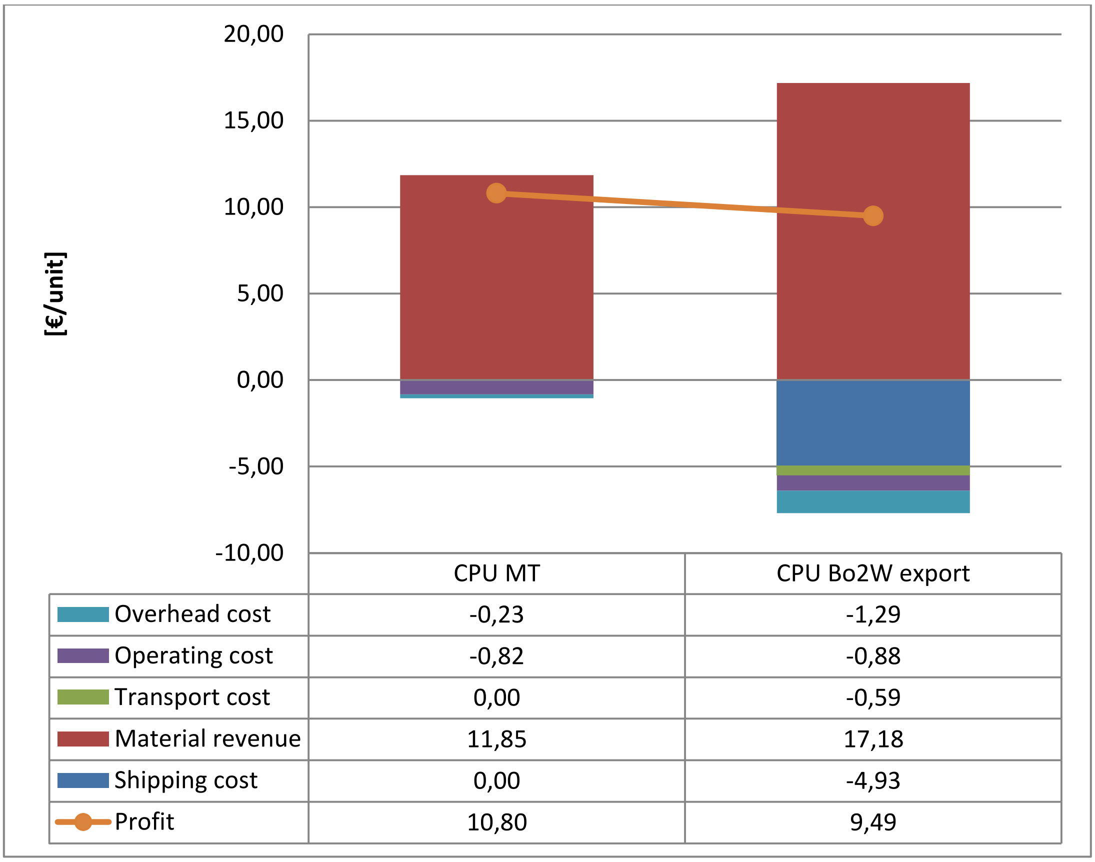


Figure 31 – Environmental comparison between MT & Bo2W export scenario for CRT monitors

6.2. Economic assessment

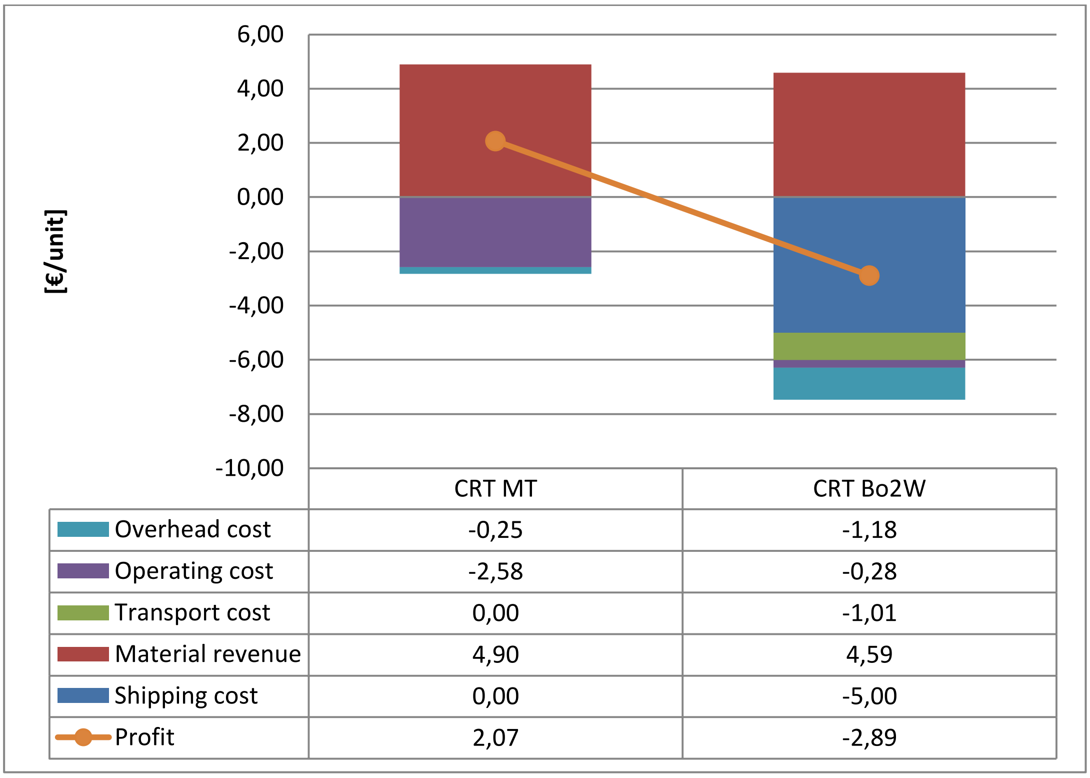
The economic comparison between the MT scenario and the Bo2W export scenario for CPUs can be seen in Figure 32. With the exception of the shipping cost, the material revenue and costs are the same as already discussed in chapter 5.2. The shipment of CPUs from Antwerp to Nairobi in a 40 feet container involves a cost of 4,9 € per unit. The surplus of the material revenue due to manual dismantling is completely absorbed by the shipping cost. Hence, shipping CPUs to Kenya for manual dismantling is not profitable.



	CPU MT	CPU Bo2W export
▬ Overhead cost	-0,23	-1,29
▬ Operating cost	-0,82	-0,88
▬ Transport cost	0,00	-0,59
▬ Material revenue	11,85	17,18
▬ Shipping cost	0,00	-4,93
─●─ Profit	10,80	9,49

Figure 32 – Economic comparison between the MT & Bo2W export scenario for a CPU

The economic comparison between the MT and Bo2W export scenario for CRT monitors is shown in Figure 33. Similar to the export of the CPU, the only addition is the shipping cost which accounts for 5,0 € per unit. Because the profitability of the MT and Bo2W scenario were already similar, the shipment would result in substantial losses.



	CRT MT	CRT Bo2W
🟦 Overhead cost	-0,25	-1,18
🟪 Operating cost	-2,58	-0,28
🟩 Transport cost	0,00	-1,01
🟥 Material revenue	4,90	4,59
🟦 Shipping cost	0,00	-5,00
● Profit	2,07	-2,89

Figure 33 – Economic comparison between the MT & Bo2W export scenario for CRT monitors

6.3. Assessment for different countries

As shown in the bar diagrams above, shipping IT equipment barely affects the environmental benefits of the Bo2W scenario regardless of the distance. But the shipment is the most important driver regarding the economic feasibility of the Bo2W export scenario. Furthermore, the wages will influence the operating costs of dismantling. Hence, as an alternative to a sensitivity analysis of the transport and labour costs, this section expands the calculations from Kenya to other countries. It is assumed that the overhead costs will remain similar to the Kenyan setting and will only differ with the dismantling depth.

The chosen alternative locations are Hungary (Budapest), China (Shanghai) and Kenya (Mombasa). The transport costs differ between countries and are dependent on the direction of shipment. Table 29 summarizes the transport cost for the different countries. Only the costs for the 20 feet container type are shown because the 40 feet type is approximately 1,5 times as expensive.

Table 29 – Additional transport costs

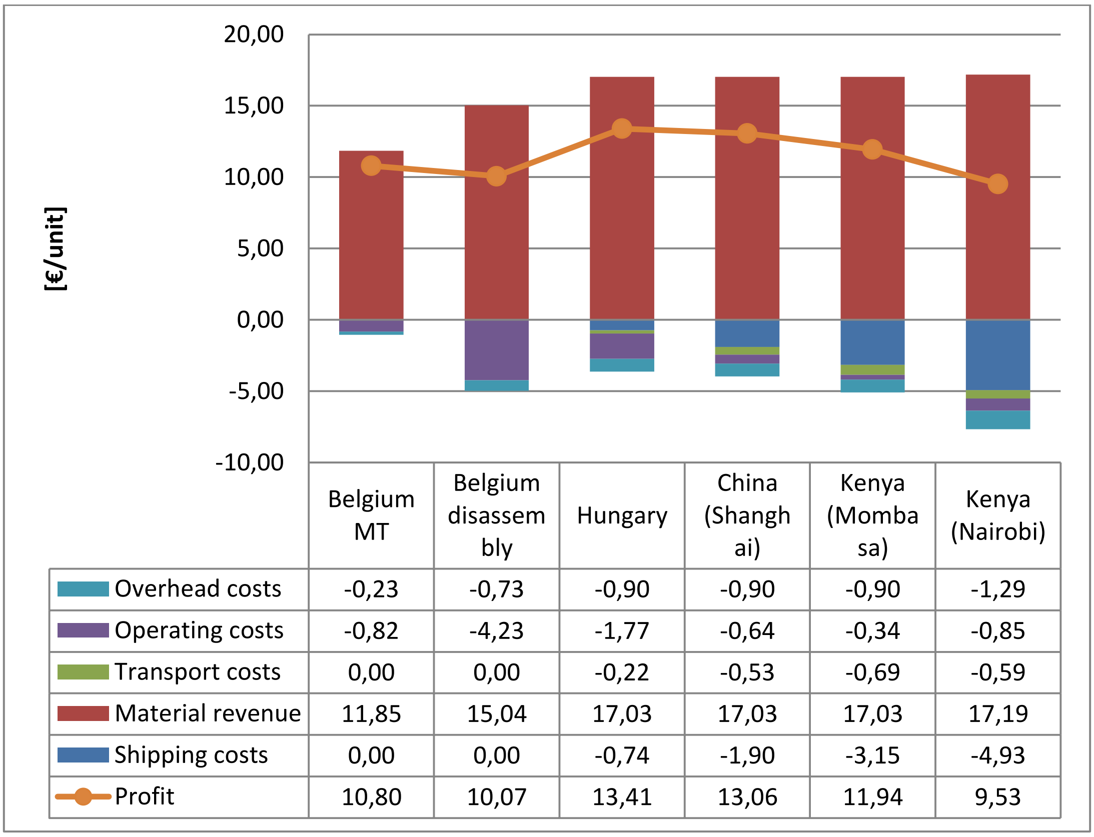
Start-Destination	Mode of transportation	Container type	Cost [€/container]	Source
Budapest-Antwerp	Truck	20	500	Inquiry
Antwerp-Budapest	Truck	20	500	Inquiry
Shanghai-Antwerp	Ship	20	1.230	Worldfreightrates
Antwerp-Shanghai	Ship	20	770	Worldfreightrates
Mombasa-Antwerp	Ship	20	1.200	WorldLoop
Antwerp-Mombasa	Ship	20	1.800	WorldLoop

The wages used for the recycling of WEEE in the assessed countries are shown in Table 30. It has been observed that due to the working conditions, in Belgium and Kenya recyclers don't work at minimum wages, but at a factor of approximately 2,5. Therefore, it has been assumed that the same factor holds for China and Hungary, although that this may depend on local social security conditions and employment opportunities. The table also shows the optimal dismantling depth which is assessed in chapter 7.1.

Table 30 - Wages

Country	Minimum wage [€/hour]	Used wage (x2,5)	Dismantling depth CPU	Dismantling depth CRT monitor	Source
Belgium	9,23	23	A	A	Eurostat
Kenya	0,33	0,85	B (Mombasa) D (Nairobi)	C	Ministry of Labour Kenya; WorldLoop
China (Shanghai)	0,62	1,54	B	C	Ministry of Labour China
Hungary	1,70	4,25	B	A	Eurostat

The economic comparison between the scenarios for CPUs is shown in Figure 34. The figure illustrates the profitability of MT in Belgium, manual disassembly in Belgium and the Bo2W export scenario for Hungary, China and Kenya. The material revenue and overhead slightly differs between the dismantling scenarios because, depending on the wage, the optimal dismantling depth differs.

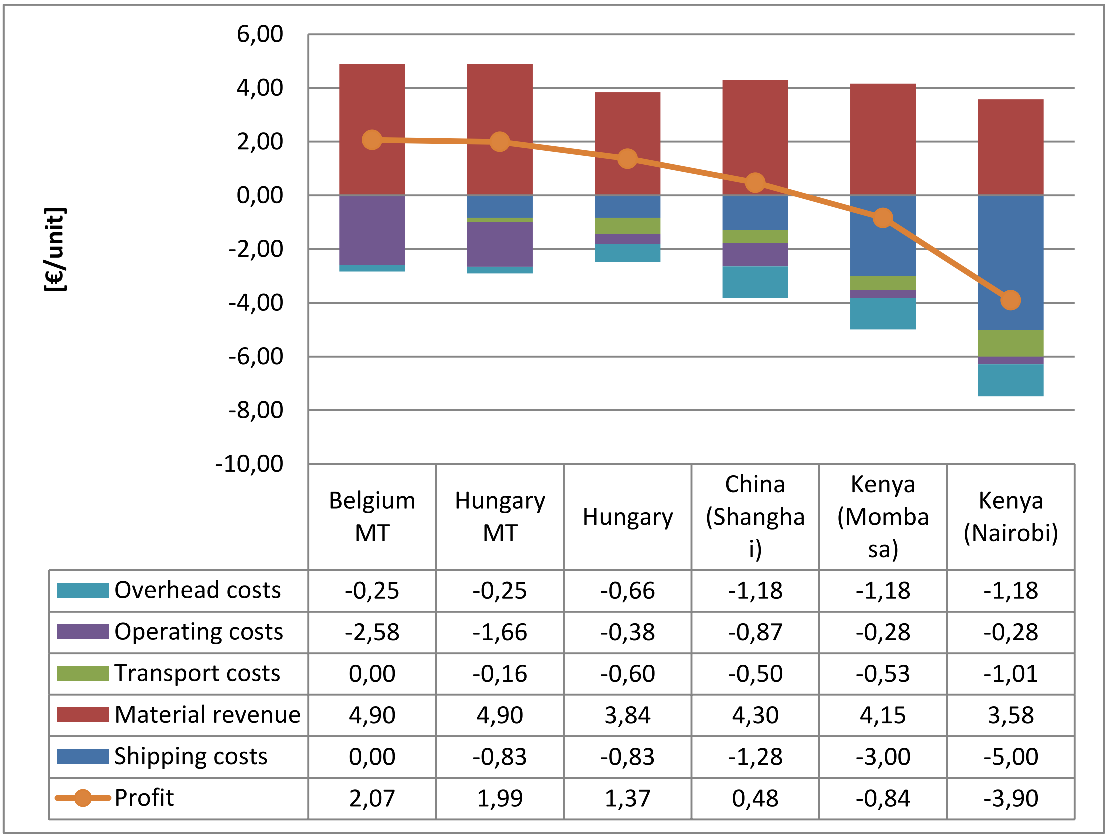


	Belgium MT	Belgium disassembly	Hungary	China (Shanghai)	Kenya (Mombasa)	Kenya (Nairobi)
Overhead costs	-0,23	-0,73	-0,90	-0,90	-0,90	-1,29
Operating costs	-0,82	-4,23	-1,77	-0,64	-0,34	-0,85
Transport costs	0,00	0,00	-0,22	-0,53	-0,69	-0,59
Material revenue	11,85	15,04	17,03	17,03	17,03	17,19
Shipping costs	0,00	0,00	-0,74	-1,90	-3,15	-4,93
Profit	10,80	10,07	13,41	13,06	11,94	9,53

Figure 34 – Economic comparison between MT & Bo2W export scenario of CPUs in different countries

Surprisingly, it is most profitable to export CPUs to Hungary and then apply the Bo2W philosophy. This scenario would result in 24 % higher profits than with mechanical treatment. Dismantling the CPU and all subcomponents, except for the PS and complex parts, in Hungary results in higher operating costs than in China or Kenya, but is offset by the low shipment costs. The Bo2W export scenario is also more profitable in Shanghai and Mombasa than MT in Belgium. This is not the case in Nairobi, because of the exceptional high shipment costs. Recovering the mother board by hand in Belgium is only slightly less profitable than mechanical pre-processing, but this conclusion is very sensitive to the assumptions.

The economic comparison between the MT and Bo2W export scenario for CRT monitors is illustrated in Figure 35. The combined dismantling and mechanical pre-processing in Belgium has high operating costs, but is the most profitable due to high shipping cost to other countries. Despite that dismantling CRT units with hot wire techniques has lower costs in developing countries, it cannot compensate for the high shipping costs. The wages in Hungary make it economically more interesting to sell CRT units to mechanical processors than to treat them manually. Compared with MT in Belgium, the same story holds and it remains less profitable. Even if a mechanical processing plant would be built in Hungary, the lower dismantling cost will not compensate for the initial shipment.



	Belgium MT	Hungary MT	Hungary	China (Shanghai)	Kenya (Mombasa)	Kenya (Nairobi)
🟦 Overhead costs	-0,25	-0,25	-0,66	-1,18	-1,18	-1,18
🟪 Operating costs	-2,58	-1,66	-0,38	-0,87	-0,28	-0,28
🟩 Transport costs	0,00	-0,16	-0,60	-0,50	-0,53	-1,01
🟥 Material revenue	4,90	4,90	3,84	4,30	4,15	3,58
🟦 Shipping costs	0,00	-0,83	-0,83	-1,28	-3,00	-5,00
● Profit	2,07	1,99	1,37	0,48	-0,84	-3,90

Figure 35 – Economic comparison between MT & Bo2W export scenario of a CRT monitor in different countries

6.4. Legislation regarding the export of WEEE

The transboundary movement of hazardous waste is a delicate matter that requires cooperation in international law. Numerous incidents led to a series of conventions of which the Basel Convention on Transboundary Movement of Hazardous Wastes and their Disposal, is the most noteworthy. The legislation that followed from the Basel Convention had the following aims (BAN n.d.):

- To reduce the movement of hazardous waste between countries, especially from developed towards developing countries.
- To reduce the amount of hazardous waste generated.
- To ensure environmentally sound management according to the "principle of proximity", meaning that hazardous waste should be treated as close as possible to the region of its generation.

The export ban amendment of the Basel Convention has not been enforced globally. However, the EU has taken notion of these principles and prohibited the export of hazardous waste to non-OECD countries (countries part of the Organisation for Economic Cooperation and Development). Despite the fact that e-waste also contains valuable substances that can be economically beneficial to recover, the EU prohibits shipment of WEEE to non-OECD countries (EEA 2009). In contrast, the transport of used, but functional devices to non-OECD countries is permitted to aid in the development of those countries. The challenge remains that malicious actors misuse the legislation to ship WEEE (Schluep, Manhart et al. 2011). Within the EU, the shipment of all kinds of wastes is, in principle, possible regardless whether the waste goes for disposal or recovery (EEA 2009).

6.5. Management considerations regarding the export of WEEE

Aside from the legal restrictions, (Manhart 2011) identifies other difficulties that can be expected due to the export of WEEE from industrialised countries towards developing countries. Even though international cooperation of recycling might be economically successful and could create employment opportunities, it cannot justify the unrestricted free trade of hazardous wastes due to the following arguments:

- Currently developing countries are not even able to treat domestically generated WEEE with any concern to safety or to the environment. Hence, treating imported WEEE will likely overstretch the local management capacities and result in negligence of non-valuable fractions or cutting back on social and environmental standards.
- Since not all types of WEEE are economically viable to recycle, the export of WEEE as such would in most likelihood result in the negligence of non-valuable fractions.
- Due to quickly evolving electronic products, the material composition of WEEE is in constant change. Integrated information channels between producers, recyclers and scientists are needed to adapt to these changes, but will be difficult to implement in developing countries.
- Fluctuations in the value of materials can cause instability to international cooperation for the recycling of WEEE.

Additionally, it can be stated that it is important to ensure that WEEE does not end up with the informal sector.

6.6. Sensitivity analysis

As stated in the previous paragraph, an issue of further concern is the possible instability of international cooperation due to the evolving material composition of devices as well as fluctuating resource prices. To assess the sensitivity to the evolving material composition, one could do the same economic and environmental assessment for laptops and LCD screens. Despite that their treatment will be very important for the stability of the Bo2W export scenario in the near future; these calculations could not be performed within the scope of this thesis.

The sensitivity to resource prices, however, is assessed here. Because 80 % of the material revenue of CPUs is determined by their PWBs and thereof most is driven by the gold, Table 31 shows the varying gold prices from 2005 until 2013. The relative ratio of gold compared with the value of 2012 in Figure 36, shows the high volatility on the gold market due to the recent financial and debt crises. The figure also compares the profitability of the MT of CPUs in Belgium to the Bo2W export scenario in Hungary and Mombasa. It clearly shows that the 24 % difference in profits between MT and Bo2W in Hungary in the reference year of 2012 is completely due to momentary peak value of gold. Furthermore, the higher operating costs of manual dismantling can cause the Bo2W scenario to be less profitable. For Hungary and Mombasa this would be the case if gold prices are back again as they were in the case in 2007 and 2009 respectively.

Table 31 – Gold price from 2005 until 2013

Year	Gold $/ounce
2005	513,00
2006	635,00
2007	836,00
2008	870,00
2009	1087,00
2010	1420,00
2011	1531,00
2012	1664,00
2013 (July)	1300,00

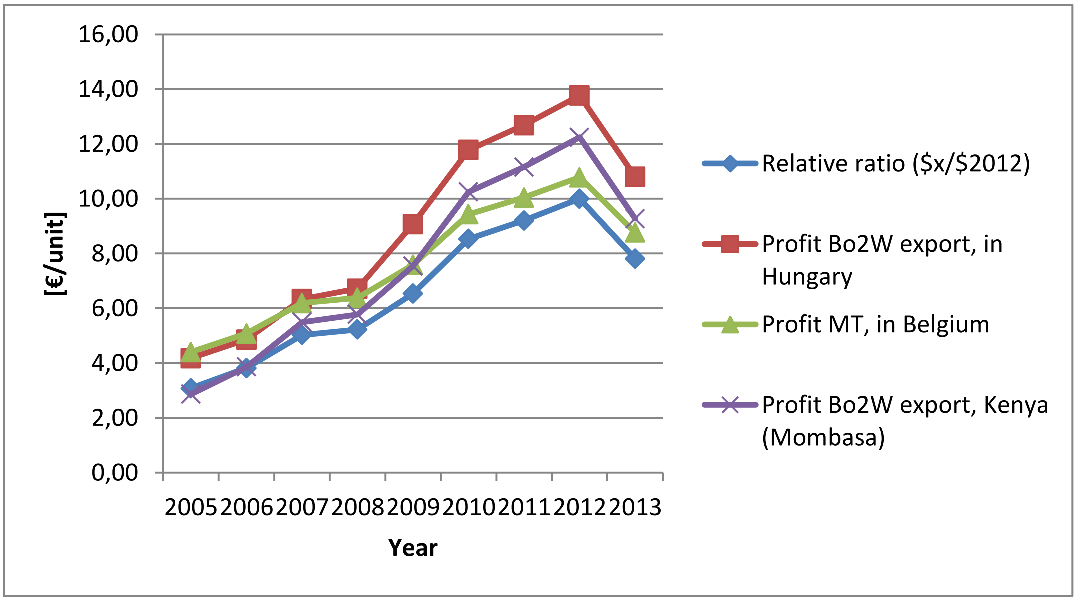


Figure 36 – Sensitivity to gold prices of the profitability of the MT & Bo2W export scenario

As an alternative to international cooperation to improve the economic and environmental performance of recycling IT equipment in industrialised countries, one can assess the required improvements in dismantling time to make manual dismantling profitable. In Figure 37 the profitability of mechanical pre-processing in

Belgium is compared with manual dismantling. Similar as in chapter 7.1, scenario A refers to extracting the motherboard by hand and shredding all subcomponents separately. Scenario B refers to manual dismantling the main unit and all subcomponents, except for the PS. Scenario A and B would be economically superior to the MT scenario if the dismantling time could be reduced below 9 and 14 minutes respectively. Compared with the current estimated dismantling times of 11 and 25 minutes, this would require an improvement of 18 and 44 %. Of course scenario B is to be promoted because it will result in higher recovery rates of precious metals.

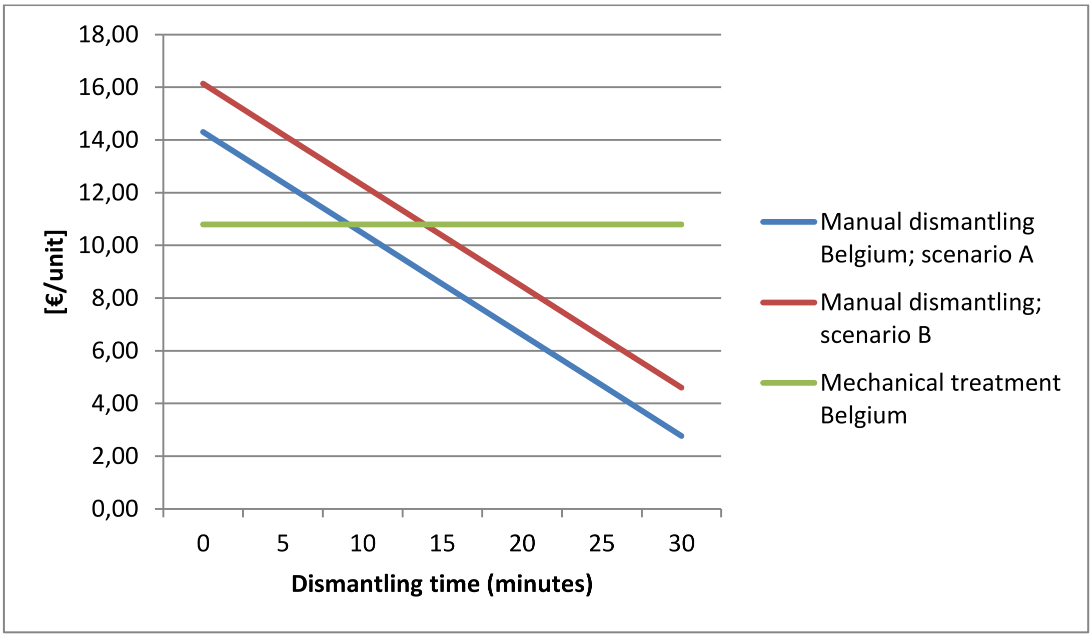


Figure 37 – Sensitivity to dismantling time of a CPU in the Belgian setting

The combination of high recovery rates and quick dismantling times will not likely be achieved by better mechanical pre-processing techniques solely, but will also require design changes of IT devices. Design for recycling and design for disassembly can increase productivity and improve conditions for dismantling products with enclosed valuables. Much can be expected from active disassembly techniques that lend themselves for high levels of automation and can treat multiple products in parallel (Duflou and Dewulf 2013).

7. Improvement of the Bo2W scenario in developing countries

The following chapter investigates opportunities to improve the economic and environmental performance of pre-processing CPUs and CRT monitors in developing countries, but more in particular in Kenya. The topics that are investigated are the optimal dismantling depth of CPUs and CRT monitors, alternative end-processing scenarios for plastics and the economic potential of recovery rare earth element rich components. Furthermore, it is investigated whether collaboration with informal recyclers makes sense from an economic, environmental and social perspective.

7.1. Optimal dismantling depth of a CPU

The following subchapter assess the economically optimal dismantling time of a CPU. For the dismantling of a CPU four different disassembly depths are proposed, ranging from partial to complete dismantling.

A. The dismantling is limited to the liberation of the main subcomponents. The main PWB and the wires are separated and sent to proper end-treatment. The ferrous casing is smelted locally. The HDD, FDD, CDD and PS are sold for mechanical treatment according to their value.
B. The main unit of a CPU is dismantled as in scenario A, but the HDD, FDD and CDD are further dismantled to recover all the PWBs. Complex parts as the motors and the copper coils are sold for mechanical treatment as mixed metals. The PS is not dismantled and sold for MT too.
C. The main unit of the CPU and all subcomponents, including the PS, are dismantled to separate PWBs, wiring and most metals. Only the complex parts are sold for mechanical treatment as mixed metals.
D. The last scenario assumes complete dismantling. Additionally to scenario C, the motors and copper coils are also dismantled.

Table 32 summarizes the different scenarios for the dismantling of a CPU and shows the dismantling times. The dismantling times of the main unit, HDD, CDD and FDD are currently based on videos from YouTube of labourers that dismantle CPUs. The dismantling time of the PS and the complex parts are a personal estimate. The dismantling times will be measured in an internship and the master thesis will be expanded with an addendum to check whether the conclusions remain valid.

Table 32 – Scenarios for the dismantling of a CPU

Scenario	Dismantled	Not dismantled	Dismantling time [minutes]
A	Main unit	HDD, CDD, FDD, PS	11
B	Main unit HDD, CDD, FDD	PS, complex parts	25
C	Main unit, HDD, CDD, FDD, PS	Complex parts	35
D	Main unit, HDD, CDD, FDD, PS Complex parts		60

The time required for dismantling the main unit is 11 minutes. Dismantling the HDD, CDD and FDD to recover the PWBs, complex parts and the casing requires 5, 7 and 2 minutes respectively. The PS is more complex and it is estimated that it takes 10 minutes to recover the main PWB and 20 minutes to free all the subcomponents. Liberating the complex parts, namely the motors and copper coils, is assumed to take 3 minutes per part. In total, this results in a dismantling time of 60 minutes for the complete dismantling.

The material revenue, dismantling and overhead costs of the dismantling scenarios are shown in Figure 38. It is assumed that the dismantling time determines the required infrastructure, hence the overhead cost due to the facility is quantified by multiplying the dismantling time with the estimated cost of the infrastructure per minute. The administrative costs remain allocated per product. Figure 38 shows that dismantling all components, except for the power supply and the complex parts, is the most profitable. The complete dismantling has the highest material revenues, but is less profitable because it needs more infrastructure and dismantling time. However, the profitability only differs 2 % between scenario B and D while the dismantling time is more than doubled. Therefore, scenario D is taken as the reference scenario with the underlying assumption that decision makers will favour doubling the number of employment opportunities, which are highly desired in developing countries, over the slightly higher profits.

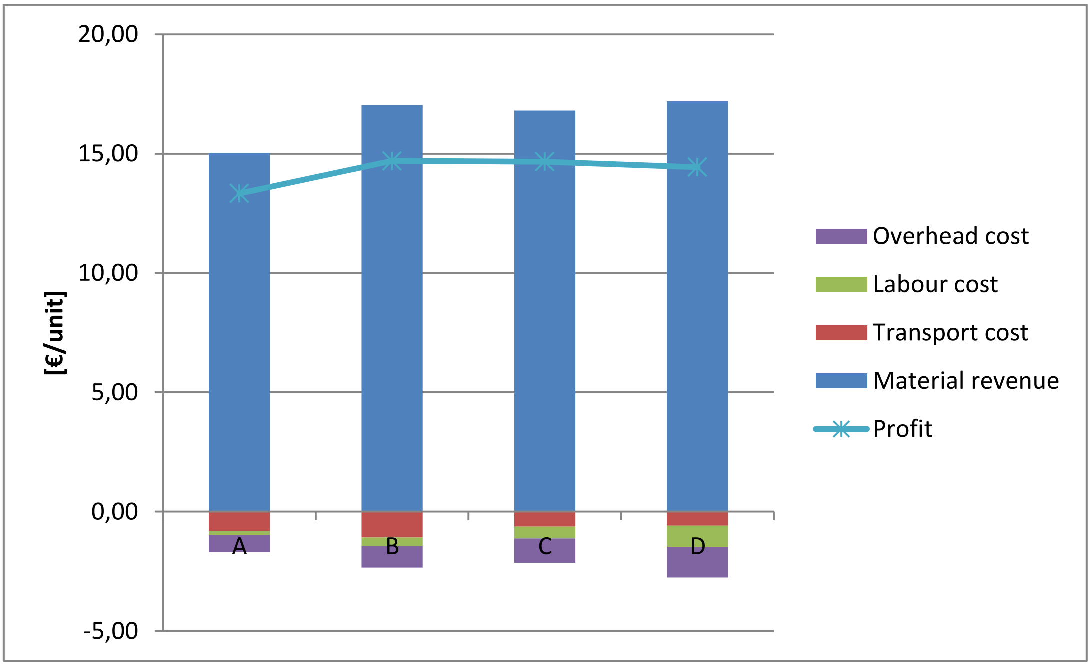


Figure 38 – Economic assessment of dismantling levels of a CPU

To expand the assessment of the dismantling depth to other settings than the Kenyan, a sensitivity analysis of the wage is calculated. The profitability of the different scenarios in function of the wage is shown in Figure 39. Scenario D is optimal if wages are below 0,7. Scenario B is optimal if wages are between 0,7 and 6,7 €, thereafter further dismantling the HDD, FDD & CDD to recover PWBs will be less profitable. The results are used to determine the optimal dismantling depth for the different countries in chapter 6.3. Since the dismantling depth is also dependent on the transport costs, scenario B is even more beneficial for the other settings.

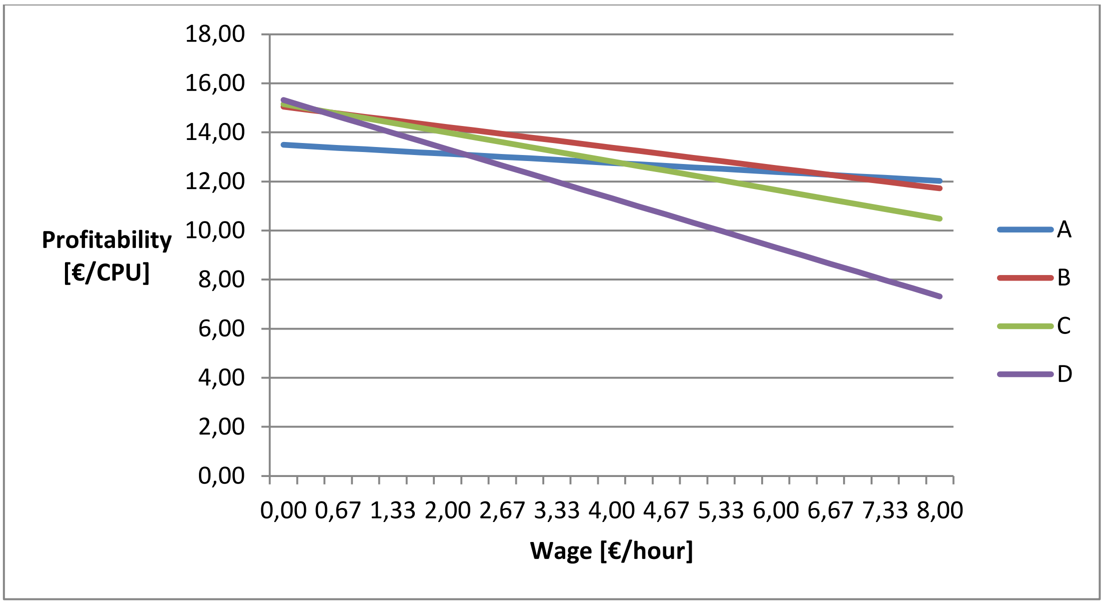


Figure 39 – Influence of wages on the optimal dismantling depth of CPU

7.2. Optimal dismantling depth of a CRT monitor

Analogous to the previous subchapter, the economic optimal dismantling depth of a CRT monitor in the Bo2W scenario is assessed. Three dismantling depths are identified:

A. The CRT monitor is manually dismantled to recover the cables, ferrous parts, plastics and to upgrade the PWB. The yoke is sold for mechanical treatment in Belgium at an estimated value of 2 €/kg. The CRT unit is shipped to a mechanical pre-processor for -0,06 €/kg (Blaser, Schluep et al. 2012).
B. The scenario is similar as scenario A except for the treatment of the CRT unit. The CRT unit is separated with hot-wire techniques to recover the ferrous shadow mask and ship the leaded glass and phosphors for proper treatment overseas.
C. The CRT monitor and CRT unit are dismantled as in scenario B. In addition, the yoke is manually dismantled to separate the copper from the ferrous metal.

Table 33 – Scenarios for the dismantling of a CRT monitor

Scenario	Dismantled	Not dismantled	Dismantling time
A	CRT monitor PWB	Yoke CRT unit	5
B	CRT monitor PWB CRT unit	Yoke	15
C	CRT monitor PWB CRT unit Yoke		20

The economic assessment of the dismantling levels for a CRT monitor is illustrated in Figure 40. Scenario A has the lowest material revenue and by far the highest transport costs because the CRT unit is sold to a mechanical processor. Scenario B has higher material revenue, but the processing equipment necessary for liberating the CRT units causes the overhead costs to rise. But when compared with the transport costs, it is clear that the processing equipment is a valid investment. Scenario C further increases the labour cost and the required infrastructure, but the material revenue more than compensates for these effects.

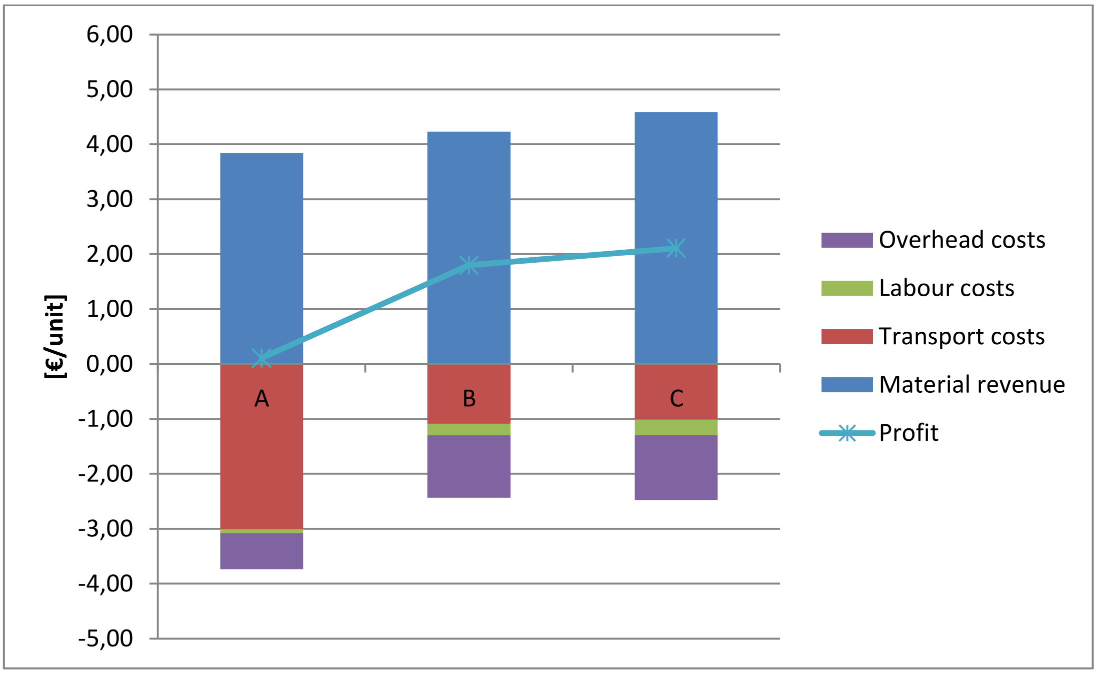


Figure 40 – Economic assessment of dismantling levels of a CRT monitor

Considering that scenario C is not only the most profitable, but also creates more jobs and higher recovery rates due to the complete dismantling, complete dismantling clearly is the optimal scenario in the Kenyan setting. For other countries, the economically optimal dismantling time is also highly dependent on the transport cost and the calculations are included in Appendix F.

7.3. Competition and collaboration with the informal sector

As shown in chapter 5.1, compared with the IS scenario, the Bo2W scenario results in major improvements of the environmental impact and working conditions for dismantlers in developing countries. However, by trying to treat all IT equipment formal recyclers get in fierce competition with the informal sector and it remains difficult to get hold of sufficient devices. Moreover, competing with informal recyclers results in the loss of their income while recycling is one of the few options that they have to sustain themselves and their families. Hence, the question arises whether by trying to solve an environmental issue with the Bo2W philosophy, not an additional social problem is created.

While formal recyclers do create job opportunities under good environmental, health and safety standards, they hardly can be held accountable for the loss of others under worse conditions and who do not respect the environment. However, in the attempt to treat all IT equipment in developing countries with environmental friendly practices, formal recyclers could use their network and knowledge to develop the practices of the informal sector. Instead of mere competition, collaboration might improve the overall environmental performance in developing countries and keep job opportunities for the informal sector. Therefore, the following section investigates three different levels of collaboration, namely:

- Collaboration on the collection of IT equipment
- Collaboration on the collection of environmental significant fractions
- Collaboration on the dismantling of safe IT equipment

7.3.1. Collaboration on the collection of IT equipment

To ensure sound treatment of all e-waste, formal recyclers can try to get a hold of all devices by combining formal and informal collection mechanisms. As informal collection is very effective, it makes sense to combine it with formal collection mechanisms. The competition with the informal sector, however, is very fierce and the informal sector has a dominant position.

The difficulty to buy e-waste from informal collectors lays in the fact that they cooperate more closely with the refurbishing industry. Hence, they typically get more for IT equipment due to the reuse potential of refurbished units or components. There are numerous reports of formal recyclers who cannot compete with the informal sector because recycling simply creates less added value compared to refurbishing (Gmünder 2007; Wang, Huisman et al. 2012). Therefore, to ensure collection it is recommended for formal recyclers to closely cooperate with the refurbishing industry. One approach is to share the collection cost on basis of revenue based cost allocation (Blaser, Schluep et al. 2012), another is by buying non-refurbished components for recycling.

Collaborating with informal collectors keeps employment opportunities for them, but it requires close relationships with the refurbishing industry to be economically viable. This approach remains in competition with informal pre-processors and environmental sound recycling will only be ensured if all pre-processing is done by formal recyclers. This will likely require time and results in job losses to all informal pre-processors. However, instead of taking control over their collection network, collaboration with pre-processors could very well make use of informal collection and ensure sound end-processes while keeping employment opportunities for them.

7.3.2. Collaboration on collection of environmental significant fractions

An approach to find a compromise between ensuring sound treatment for all IT equipment and keeping employment opportunities for the informal sector is to let them dismantle IT equipment, but buy environmentally significant fractions from them. In India, PWBs are successfully bought from informal pre-processors to prevent cyanide leaching practices by giving them training and a financial incentive (Rochat, Rodrigues et al. 2008). However, from chapter 5.1 it follows that aside from PWBs, the impact of burning cables and CRT units are also of concern. This section assesses whether it is economically viable to buy these fractions from them.

By offering informal recyclers a higher price for PWBs, cables and CRT units, this could give them an incentive to trade with formal recyclers and hence unsound practices could be avoided. Figure 41 compares the value of various fractions resulting from dismantling CPUs between formal and informal recyclers. The figure shows that the material value for formal recyclers is way superior for the PWBs, but has a small loss for buying the PS and cables. The PS is of concern too, because informal recyclers likely dispose harmful capacitors and burn copper coils when dismantling it. Overall, buying these fractions from informal recyclers should be economically viable if the assumptions made in chapter 4.3 hold.

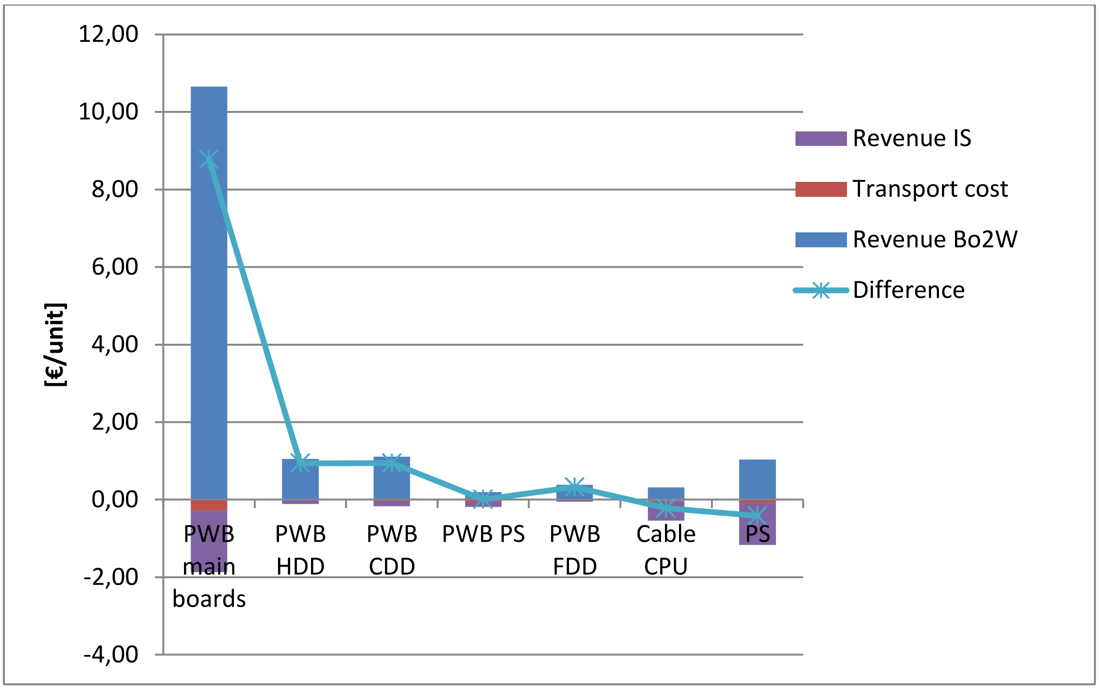


Figure 41 – Economic comparison between the Bo2W & IS scenarios of fractions from CPUs

Figure 42 shows the economic comparison of fractions between the Bo2W and IS scenario from CRT monitors. The cables and the PWBs can be bought at a small loss, but the sound treatment of CRT units requires large financial efforts. Hence, buying fractions from CRT monitors from informal recyclers is not economically viable by itself. However, it could be funded with the profits from CPUs.

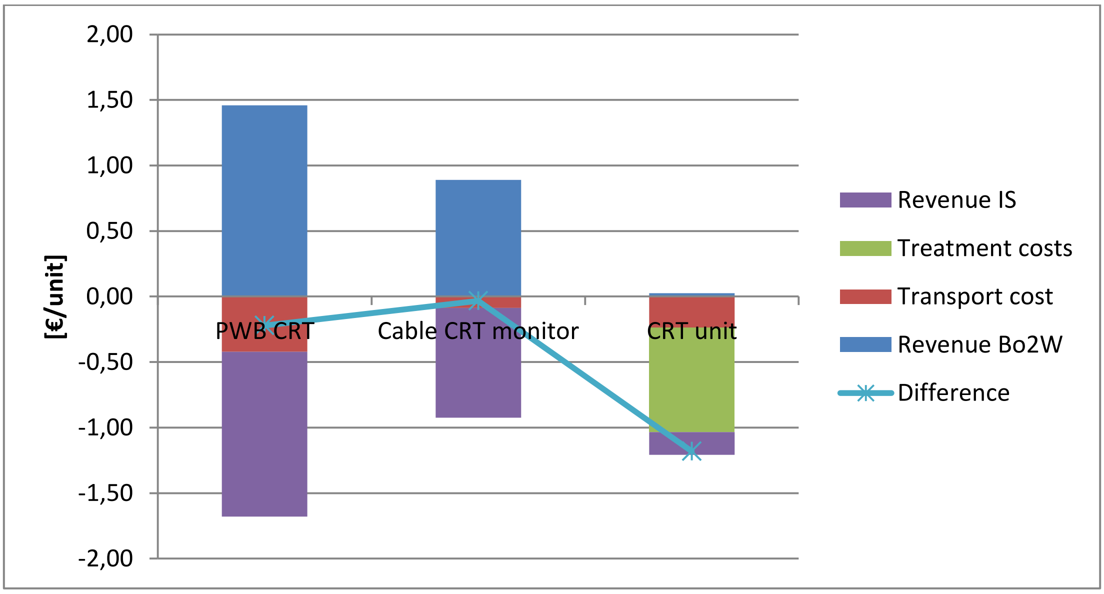


Figure 42 – Economic comparison between the Bo2W & IS scenario of fractions from CRT monitors

In reality, it has been observed that the revenue that informal recyclers can get by selling to Chinese traders exceeds the value that integrated metal smelter-refiners can offer (WorldLoop). Because integrated smelter-refiners recover nearly all the valuable substances, the only possible explanation is that in China they not only recover some gold, but also reuse components. In most likelihood, processors and memory cards will be reused in refurbished equipment. Occasionally, the motherboard or additional cards might be of value too. This shows that close collaboration with the refurbishing industry is critical in order to be economically viable. However, the refurbishing industry in China is likely more professional than in Kenya. Therefore, in absence of a developed refurbishing industry in Kenya, the following strategy is proposed as an economically viable way to prevent the impact of cyanide leaching. First buy PWBs from informal dismantlers at a price that Chinese traders would offer. Subsequently dismantle reusable components and sell these to the traders again. If proper prices can be negotiated, this approach should lead to higher recovery rates of precious metals and be economically viable.

By buying these fractions of informal pre-processors, environmental sound treatment can be ensured and they can hold their jobs. However, it remains unclear how profitable this approach will be and whether it can sustain the treatment of CRT monitors or other devices that may not be profitable to recycle.

7.3.3. Collaboration on the dismantling of safe IT equipment

Ideally, the informal sector would gradually formalize so that dismantlers can enjoy good working conditions while sound end-processes are ensured. Collaborating on the dismantling of IT equipment could provide them with reasonable health and safety measures, stable cash flows and reasonable working hours while having the same environmental impact as the Bo2W scenario.

This approach does require distinguishing between equipment that is safe to dismantle by informal pre-processors and which is not. For example, CRT monitors could be dismantled by them, but CRT units would need to be treated by trained dismantlers with hot-wire techniques in the formal setting. Compared with merely buying CRT units from them, paying pre-processors on a wage basis will keep the profitability just the same as in the Bo2W scenario.

However, it is not clear to what extent that this will be possible. Informal recyclers typically are not educated and, while working with them is not necessarily dangerous, it will require trust from both sides. The estimated wages of informal recyclers in Ghana is 9,5 $ a day at 12 hour working days, or 0,6 € an hour (Prakash, Manhart et al. 2010). Compared with the minimal wage in Kenya of 0,3 €, this is rather high. But it still leaves a margin of one third to attract them and pay them on an hour basis rather than on the fractions that they dismantle. Furthermore, interviews with informal recyclers in China made clear that they desire to formalize due to pressure from the government and the tough working conditions (Wang 2008).

The strategies regarding the competition and collaboration with the informal sector are summarized in Table 34. Without any collaboration, formal and informal recyclers would compete on collection of IT equipment and provide themselves with jobs, but the practices of informal recyclers remain harmful to the environment. In the attempt to ensure sound treatment of all IT equipment, formal recyclers can try to collect everything with formal and informal collection mechanisms. Fierce competition on the collection will ultimately result in job losses to informal pre-processors and requires close collaboration with the refurbishing industry. Collaborating by buying environmental significant fractions from informal pre-processors has potential to ensure sound end-processes for all IT equipment and keep their jobs. Trade on this level will be relatively easy to implement, but the economic viability of this strategy remains unclear. Collaboration on dismantling safe IT equipment could provide win-win situations as informal recyclers can benefit from good social conditions and formal recyclers can ensure sound treatment while being economically viable. The practical feasibility will likely be very challenging and will be subject to conditions that are difficult to foresee.

Table 34 – Overview of the strategies for the collaboration with the informal sector

	None	Collection of IT equipment	Collection of environmental significant fractions	Dismantling of safe IT equipment
Environmental performance	Formal Informal	Formal (Informal)	Formal Informal	Formal Informal
Social performance	Formal Informal: collection & pre-processing	Formal Informal: collection & pre-processing	Formal Informal: collection & pre-processing	Formal Informal: collection & pre-processing +Improved working conditions
Economically viable		Yes Collaboration with refurbishing industry	Unclear Collaboration with refurbishing industry Product dependency	Yes
Practically feasible		In time	Yes	Unclear

In conclusion, the strategy that best respects the environmental, social and economic dimensions is collaboration on dismantling of safe devices. The practical feasibility remains unclear as it is subject to reciprocal levels of trust and additional safety concerns. Collaboration on the collection of environmental significant fractions, however, is easy implementable, but is likely not economically viable. The latter strategy can be used as a transient solution that ensures sound end-processes while the willingness to cooperate on dismantling can be investigated.

7.4. Pre-processing of Rare Earth Elements

For many years, recycling of Rare Earth Elements (REE) was not an issue because of the low value of these materials, low toxicity and a relative stable supply. Recently however, the supply risk of these economic significant elements is found to be high for the EU (Commission 2010). The main reasons are quota of China on the export of REE and additional balance problems because the elements are extracted in groups.

REE are mainly used in electronic devices, but only in small amounts per device. Currently, they don't get recovered in the usual recycling chain and, considering other aspects, drastic improvement in the recycling of REEs are a necessity (Binnemans, Jones et al. 2013). Manual dismantling of IT equipment, however, creates a unique opportunity to separate REE rich components from commodity waste streams.

The environmental inventory of REEs mining and recycling is not yet readily available. Currently, the focus of recycling these critical materials seems to lay in securing future supply. Therefore, the following section does not investigate the environmental impact and only estimates the economic potential of recovering REE from HDD magnets and CRT phosphors.

7.4.1. Permanent magnets in HDDs

Significant amounts of the REE in use are stored in electronic parts. Around 69,4 % of Neodymium in use is found in magnets used for HDD motors, speakers and various others (Curtis 2010). Dismantling HDDs in the Bo2W scenario creates unique opportunities to recover the Neodymium magnets that would be lost to ferrous metals if shredded.

This section briefly estimates the economic value of HDD magnets. From the composition data it is known that the magnet weighs 21 gram (Gmünder 2007). Because the magnets are composed out of a $Nd_2Fe_{14}B$ crystalline structure, Neodymium composes for about 31 % of the weight.

Different manufacturers have used a narrow material distribution over the years for applications such as HDD magnets. Hence, one of the recycling options is to directly melt NdFeB magnets and used them as master alloy for the production of new magnets (Binnemans, Jones et al. 2013). The economic value of NdFeB magnets is therefore assumed to be approximate to virgin the material value. With an economic value of 69 €/kg for Neodymium (Metalpages 2013), the magnets are assumed to be worth 21,5 €/kg or 0,4 € per unit.

7.4.2. Phosphorous dust from CRT units

While 69,2 % of Yttrium in use is found in phosphors for CRT screens and lighting (Curtis 2010), little research is executed on the recovery of REEE from CRT screens. However, it has been shown that 96% of Europium and Yttrium could be recovered by leaching with sulphuric acid at room temperature (Resende and Morais 2010).

The maximum material value is estimated in Table 35 (Resende and Morais 2010; Metalpages 2013). The potential value is 21,0 € per kg phosphors, but as a typical CRT monitor only contains about 3 gram of phosphors it is at most worth 0,06 € per CRT monitor. Moreover, the estimate does not take into account the processing, which likely is not yet commercially viable. Therefore the value of REE for phosphors is neglected in the assessment of chapter 5.1.2.

Table 35 – Maximum value of phosphors from CRT screens

Chemical composition	Composition [%]	Value [€/kg]
Yttrium	17,0	61
Indium	0,5	422
Europium	0,8	1.538
Total	**100,0**	**21,0**

7.5. Alternative end-processing of engineering plastics

The engineering plastics that are used for the housing of IT equipment are one of the biggest waste fractions on a weight basis. In the product characterisation in chapter 4.1 it is assumed that the casing of both CPUs and CRT monitors consists out of BFR containing ABS. On average, however, CPUs contain around 44 % ABS, 22 % PC/ABS and a fragmented mix of plastics. Plastics in CRT monitors are less fragmented and contain 69 % ABS and 20 % PC/ABS on average (Martinho, Pires et al. 2012). Additionally, there are big variations among plastics in colour pigments and additives, such as flame retardants. Regarding the end-processing of engineering plastics, the environmental and economic potential of the following scenarios is assessed:

Scenario A: Plastics downcycling at EcoPost in Kenya. EcoPost is a company that aims to prevent the cutting of hardwood in Nairobi by recycling plastics. They recycle both consumer and engineering plastics to make fences and planks out of them (EcoPost 2013). Actually the plastics are not recycled, but ‘downcycled’ because the resulting material is inferior to the technical potential.

Scenario B: Plastics incineration in Belgium. Incinerating plastics with energy recovery and proper flue gas treatment is used as the reference scenario in the economic and environmental model because the plastics are assumed to contain hazardous BFRs which cannot be recycled under European legislation.

Scenario C: Plastics recycling in Belgium. Proper recycling of plastics is possible if the plastics can be effectively separated on type, colour and additive content. In contrast to BFRs, all phosphorous based flame retardants (PFRs) can be reapplied. Combining manual dismantling with analysing techniques such as sliding-spark spectroscopy and Fourier transform infrared analysis can identify 95 % of all plastics with high certainty. The use of 100 % recycled PC/ABS with PFRs in new applications is considered as technically feasible. Furthermore, the process is economically viable for plastics from flat screen TVs in industrialised countries (Peeters, Vanegas et al. 2013). Regarding the economic and technical feasibility of recycling plastics from CRT monitors, this topic still requires further research.

7.5.1. Economic potential

This subchapter assesses the economic potential of the scenarios for end-processing engineering plastics in developing countries. The assessment is very limited as it only compares the potential revenue and transport costs. The data in Table 36 shows that recycling engineering plastics can significantly increase the revenue. In the case of CRT monitors where the plastic shell weighs 2 kg on average, the margin is in most likelihood big enough to allow for costs due to identification, additional processes and the relative ratio of recyclable engineering plastics. Further research is required, but the economic potential indicates that, in most likelihood, it is worth the effort.

Table 36 – Economic potential of plastics end-processing

Scenario	Kind of plastics	Material value [€/kg]	Transport costs [€/kg]
EcoPost downcycling	All	0,15	-
Plastics incineration	All	-0,12	-0,13
Plastics recycling	ABS: black PC/ABS: blend (PIE 2013)	1,70 2,30	-0,13 -0,13

7.5.2. Environmental potential

This subchapter assesses the environmental impact to the extent that is possible with the current available data. The assumptions and restriction of the model are first explained and subsequently the results are interpreted. The scope is limited to ABS plastics and the assessment is assumed to be representative for other engineering plastics too.

Downcycling of plastics at EcoPost

The downcycling of plastics in Nairobi has the aim to prevent the cutting of hardwood. The avoided impact hence results from the processing of wood and of avoiding the cutting of a tree. Despite large differences between the stiffness of wood and ABS, the fences and planks of EcoPost are designed with common dimensions and are not to be used for structural applications. The functional unit to compare between the two materials is therefore not the bending stiffness, but the used volume. The avoided product of recycling one kilogram of ABS is modelled as 0,8 kg of *sawn timber, hardwood, planed, air/kiln dried, u=10%, at plant/RER* from the ecoinvent database.

The required input is the electricity needed for the recycling of the plastics. According to the EcoInvent data this can be modelled as 0,6 MegaJoule per kilogram ABS of *Electricity, medium voltage, production CH, at grid/CH S*.

The model is limited as the inventory does not take into account any effects due to possible BFRs. Plastics that contain BFRs form highly toxic dioxins and furans when exposed to thermal stress. Hence shredders or granulation equipment for the recycling should be equipped with a flue gas system (Nnorom and Osibanjo 2008). In all likelihood this is not present in the installation of EcoPost. Additionally, even if emissions by melting would be negligible, leaching of these substances from the plastic fences should be considered. Unfortunately these effects could not be quantified and are excluded in the model.

Incineration of plastics in Belgium

The environmental model of plastics incineration is the same as is used for Bo2W scenario and the reader is referred to chapter 4.2.5.

Plastics recycling in Belgium

Recycling plastics in Belgium requires the same input as the downcycling of ABS in Kenya, but avoids the primary production of ABS. The impact of producing ABS is based on the EcoInvent data *Acrylnitrile-butadiene-styrene copolymer, ABS, at plant*.

Interpretation

The results of Figure 43 should be interpreted with care. It is clear that the avoided impact of ABS recycling is more beneficial than preventing the cutting of hardwood, despite the required transport. The model of both the downcycling and recycling do not take into account emissions of shredding. In industrialised countries these would likely be limited with flue gas systems similar as is the case with controlled incineration, but they likely are worse in developing countries. Furthermore, it is unclear how big the impact is of leaching hazardous substances.

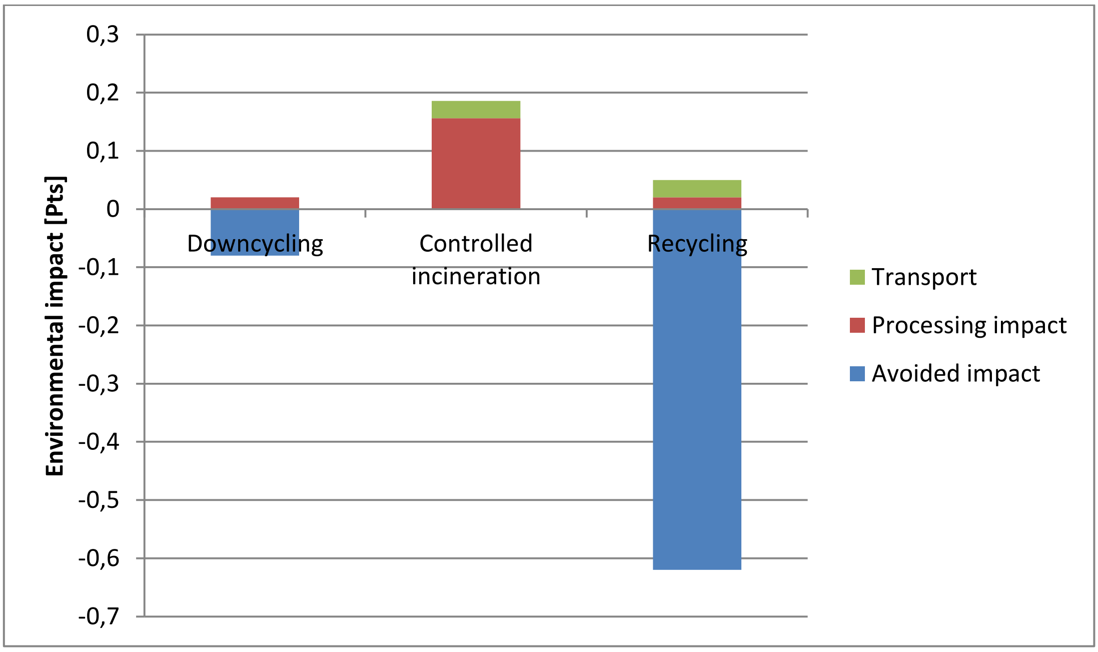


Figure 43 – Environmental assessment of different end-processing scenarios for ABS

In conclusion, this limited economic and environmental assessment indicates that recycling ABS in developing countries has high potential. In most likelihood, the high economic value will compensate for additional costs and recycling ABS under controlled conditions will improve environmental performance.

8. Conclusions

The goal of this final chapter is to summarize all findings and to draw conclusions for the respective research objectives (RO).

8.1. RO1: assessment of the recycling scenarios

The assessment of chapter 5 gave more insight in the economic and environmental performance of the MT, IS and Bo2W scenario. For CPUs the Bo2W scenario is the most eco-friendly mainly due to the fact that most precious metal-rich components can be liberated and sent to integrated smelter-refiners. Losses of precious metals are significant in the MT scenario due to shredding and the environmental impact is one third worse. Informal pre-processors are effective for commodity metals, but their burning and leaching processes severely offset the benefits of recycling.

The profitability of recycling CPUs is highest for the Bo2W scenario. The manual dismantling achieves relatively high material revenues which offset the labour, transport and overhead costs. MT has lower costs for dismantling IT equipment, but its high productivity comes at the expense of losing precious metals. The revenue of informal recycling is below the full potential due to the ineffective leaching methods.

Regarding the environmental performance of recycling CRT monitors, the MT and Bo2W scenario are very similar. Due to incineration of PWBs and cables, the impact of the informal sector is inferior. If the impact of leaching hazardous substances from leaded glass and BFR plastics would be taken into account and matters would even be worse.

However, because informal pre-processors do not use the required equipment for safe dismantling of CRTs or pay for the proper disposal of leaded glass and plastics, they are the most profitable. Dismantling CRT monitors in the MT scenario causes higher operating costs than is the case in developing countries. However, the high transport costs offset these effects and hence the MT and Bo2W are just as profitable.

8.2. RO2: Evaluation of the Bo2W export scenario

The environmental assessment shows that transporting IT equipment is not a critical factor and the Bo2W philosophy can significantly lower the impact to the environment, human health and resource depletion. The impact of the Bo2W export scenario remains very product dependent as international cooperation barely improves the recycling impact for CRT monitors, but in the case of CPUs with 35 %.

The economic assessment makes clear that the cost of shipping is critical. However, shipping to low wage countries such as Hungary, China and Kenya (Mombasa), can be up to 24 % more profitable than mechanically processing CPUs. This is not the case for CRT monitors where the shipping cost are high compared to extra profits that the Bo2W scenario can provide.

Regarding the European legislation on the export of WEEE, shipping to non-OECD countries such as China and Kenya is not to be promoted. Despite the economic and environmental benefits in the case of the CPU, the effects should not be generalised for WEEE in general. The aims of the Basel Ban to decrease the amount of hazardous waste generated and transported across boundaries remain valid for CPUs or other precious metal rich devices. Transport of WEEE within the EU is legally permitted and the principles behind the Basel Convention will likely not be harmed as the EU evolves to a well-governed internal market.

If then CPUs would be transported to low wage countries within the EU such as Hungary, the considerations of (Manhart 2011) remain to be taken to heart. The management capacities should not be overstretched by imported equipment so that all local WEEE will still be treated. It will also require treatment of less valuable fractions. Nevertheless, it seems likely that in time free trade with good governance will solve these imbalances.

The economic robustness of international cooperation is likely sensitive to future developments in products, but further research is needed to quantify the effects. The volatile gold market already challenges the profitability of the Bo2W export scenario for CPUs. However, to achieve similar environmental performance, dismantling time should be reduced by 44 % before manual dismantling in Belgium would be more profitable than mechanical treatment.

To conclude it can be stated that, concerning IT equipment generated in Belgium, in the short term shipping to low wage countries within the EU allows for significant economic and environmental improvements for CPUs. However, the economic viability of such cooperation will remain sensitive to future developments in products and the volatile gold market. Therefore, in the long term a more robust solution would consist of design changes that allow for efficient dismantling techniques with high recovery rates.

8.3. RO3: Improvement of the Bo2W scenario in developing countries

In chapter 7, various opportunities to improve the Bo2W scenario in developing countries are investigated. Dismantling all subcomponents of CPUs, except for the PS and complex parts, results in the economically optimal dismantling depth. However, decision makers can also double employment opportunities by completely dismantling CPUs if they are willing to cut 2 % in the profitability. Furthermore, completely dismantling CRT monitors by liberating components from CRT units and the yoke creates the highest profitability.

In the attempt to ensure sound treatment for all IT equipment, formal recyclers get in fierce competition with the informal sector. Collaborating with informal collectors can keep job opportunities for them, but getting hold of all IT equipment will be tough and requires collaboration with the refurbishing industry. Buying fractions of environmental concern can ensure sound end-processes and keep employment opportunities for collectors and pre-processors. The trade will be relatively easy to implement, but whether it is economically viable for all IT equipment and whether reusable components can be sold for a good price remain unclear. If informal pre-processors could be paid for dismantling safe IT equipment, they can enjoy better social conditions and keep their jobs. Meanwhile formal recyclers can ensure sound processes for all IT equipment while paying them on a wage basis is economically viable. The practical feasibility of cooperative dismantling is unclear as it will be subject to levels of trust and safety concerns. Collection of environmental significant fractions, however, can be used as a transient strategy to gain trust and investigate the potential of close collaboration.

Manual dismantling of IT equipment creates unique opportunities to liberate REE while mechanical treatment currently is not able to recover them. Liberating NdFeB magnets from HDDs is economically beneficial and can be used in the production of new magnets. Recovering REE from CRT phosphors is possible, but it is not clear whether it is commercially viable.

The end-processing of engineering plastics from the casing of CPUs and CRT monitors currently is inferior to its economic and ecologic potential. Methods based on prior identification may result in more profitable solutions that effectively recycle engineering plastics. The matter requires further research as its success will depend on the technical feasibility and the composition of the plastics.

Appendices

Appendix A: CPU composition

Table 37 – Material composition of a CPU

	Subcomponent	Material	Modelled material EcoInvent	Weight (g/unit)
Desktop PC				**9924,9**
	Casing	Steel	Iron and steel, production mix/Us	1544,4
	Housing	Steel	Iron and steel, production mix/Us	3309,9
	Plastic Housing	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER	561,9
	Screws	Steel	Iron and steel, production mix/Us	12,7
	Switches			
		Plastics general	Polypropylene, granulate, at plant/RER	5,8
		Stainless steel	Chromium steel 18/8, at plant/RER	1,0
		Copper	Copper, at regional storage/RER	1,9
	Speakers			
		Copper	Copper, at regional storage/RER	3,9
		Iron	Iron and steel, production mix/Us	16,6
		Other		1,0
	Flat wires			118,8
		PVC	Polyvinyclchloride, at regional storage/RER	44,8
		Copper	Copper, at regional storage/RER	74,0
	Connector flatwire			67,2
		PP	Polypropylene, granulate, at plant/RER	7,8
		ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER	45,8
		PM rich	Precious metal PC connector (flatwire)	13,6
	Round wires			
		PVC	Polyvinyclchloride, at regional storage/RER	8,8
		Copper	Copper, at regional storage/RER	13,6
	Connector roundwire			
		PP	Polypropylene, granulate, at plant/RER	1,0
		ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER	3,9
		PM rich	Precious metal content connector pin	1,0
	Motherboard	PWB	Precious metal content Desktop PC Motherboard	905,7
	Battery	Battery	Battery, LiIo, rechargeable, prismatic, at plant/GLO	4,9
	HDD			495,0
	CDD			933,0
	FDD			382,0

	PS			1345,0
HDD				**495,0**
	PWB	PWB	Precious metal content HDD pwb	41,4
	Casing	Aluminium	Aluminium, production mix, wrought alloy, at plant/RER	185,3
	Magnet	NdFeB		21,2
			Iron and steel, production mix/US	16,0
			NeodymiumOxide	7,0
	Iron plate	Iron	Iron and steel, production mix/US	47,7
	Steel	Stainless steel	Copper, at regional storage/RER	52,9
	Motors			
		Aluminium	Aluminium, production mix, wrought alloy, at plant/RER	9,5
		Iron	Iron and steel, production mix/US	19,3
		Copper	Copper, at regional storage/RER	6,3
	Disks	PM rich	Precious metal content HDD disk	35,1
	Aluminium wrought	Aluminium	Aluminium, production mix, wrought alloy, at plant/RER	33,3
	Reader	PM rich	Precious metal content HDD reader	14,2
	Iron	Iron	Iron and steel, production mix/US	4,8
	Screws	Iron	Iron and steel, production mix/US	4,8
	Connectors	PM rich	Precious metal content HDD connector	3,4
	Brass	Brass	Brass, at plant/CH	1,7
	Waste	Other		5,0
PS				**1345,0**
	Casing	Steel	Iron and steel, production mix/US	533,6
	PWB	PWB	Precious metal content PS PWB	167,0
	Transistors	PM rich	Precious metal content PS transistor	20,7
	Heatsink	aluminium	Aluminium, production mix, wrought alloy, at plant/RER	84,3
	Transformer	ferrite	Ferrite, at regional storage	88,2
		plastics general	Polypropylene, granulate, at plant/RER	24,3
		copper	Copper, at regional storage/RER	47,1
	Copper coil	copper	Copper, at regional storage/RER	41,6
		ceramics		45,6
		plastics general	Polypropylene, granulate, at plant/RER	6,7
		ferrite	Ferrite, at regional storage	5,6
	Capacitors	capacitor Al-el		5,0
	Wires	PVC	Polyvinyclchloride, at regional storage/RER	33,5
		copper	Copper, at regional storage/RER	60,5
	Internal connectors	PP	Polypropylene, granulate, at plant/RER	3,1
		ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER	18,7
		PM rich	Precious metal content connector pins	5,4
	External connectors	PM rich	Precious metal content PS connector	9,5
		Plastics general	Polypropylene, granulate, at plant/RER	15,7
		Iron	Iron and steel, production mix/US	2,3
	Screws	Iron	Iron and steel, production mix/US	12,0
	Copper alloy	Brass	Brass, at regional storage	6,1

	Waste	other		33,2
	Iron	Iron	Iron and steel, production mix/US	3,1
	Ventilator/PWB	PWB		3,4
		Iron	Iron and steel, production mix/US	16,3
	Wires 2	PVC	Polyvinyclchloride, at regional storage/RER	0,0
		Copper	Copper, at regional storage/RER	1,0
	Copper coil	Copper	Copper, at regional storage/RER	8,3
		ceramics		9,1
		Plastics general	Polypropylene, granulate, at plant/RER	1,3
		Ferrite	Iron and steel, production mix/US	1,1
	Plastic	ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER	30,3
		Copper	Copper, at regional storage/RER	1,3
FDD				**382,0**
	Steel	Steel	Iron and steel, production mix/US	225,7
	Aluminium	Aluminium	Aluminium, production mix, wrought alloy, at plant/RER	53,8
	PWB	PWB	Precious metal content PWB FDD	44,0
	Copper	Copper	Copper, at regional storage/RER	0,4
	Reader	PM rich		10,9
	Screws	Steel	Iron and steel, production mix/US	3,4
	Plastic	ABS		8,6
	Brass	Brass		2,1
	Copper coil	Copper	Copper, at regional storage/RER	7,8
		Iron	Iron and steel, production mix/US	11,5
	Motors	Iron	Iron and steel, production mix/US	10,5
		Copper	Copper, at regional storage/RER	3,1
		Plastics general	Polypropylene, granulate, at plant/RER	0,6
CDD				**933,0**
	Casing	Steel	Iron and steel, production mix/US	531,9
	Plastics	Plastics general	Polypropylene, granulate, at plant/RER	182,8
	PWB	PWB	Precious metal content PWB CDD	98,2
	PWB (w iron)	PWB	Precious metal content PWB CDD (w iron)	5,0
	Readers	PM rich	Precious metal content CDD Reader	18,6
	Iron	Iron	Iron and steel, production mix/US	14,2
	Aluminium	Aluminium	Aluminium, production mix, wrought alloy, at plant/RER	2,7
	Screws	Steel	Iron and steel, production mix/US	6,3
	Stainless Steel	Stainless steel	Chromium steel 18/8, at plant/RER	4,5
	Wires	PVC	Polyvinylchloride, at regional storage/RER	0,3
		Copper	Copper, at regional storage/RER	0,6
	Waste	Other		4,2
	Motors	Copper	Copper, at regional storage/RER	7,0
		Iron	Iron and steel, production mix/US	31,4
		Stainless steel	Chromium steel 18/8, at plant/RER	9,1
		Plastics general	Polypropylene, granulate, at plant/RER	16,1

Appendix B: CRT monitor composition

Table 38 – Material composition of a CRT unit

Component	**Material**	**Weight (kg/unit)**	Comment
Shell	ABS	2,030	
explosion protection unit	Steel	0,210	
Yoke		0,600	Assumed ratio
	Copper	0,400	
	Plastic	0,100	
	Steel	0,100	
Metal parts	Steel	0,540	
PWB		- 1,600	
	PWB CRT	1,250	
	Aluminium	0,250	
Wire		0,660	Assumed ratio
	Copper	0,231	
	PVC	0,429	
Plastic	Plastic	0,290	
Rubber	Plastic	0,050	
CRT unit		5,600	

Table 39 – Material composition of a CRT unit

Component	**Material**	**Weight**	**Comment**
Phosphorescent powder	Phosphors	0,003	
Shadow mask	Steel	0,455	
Electron gun		0,096	
	Steel	0,070	Assumed ratio
	Plastic	0,010	Assumed ratio
	Copper	0,016	Assumed

			ratio
Funnel glass	Leaded glass	1,681	
Panel glass	Barium/strontium glass	3,156	
Frit glass	Leaded glass	0,200	Estimate
Neck glass	**Leaded glass**	**0,050**	

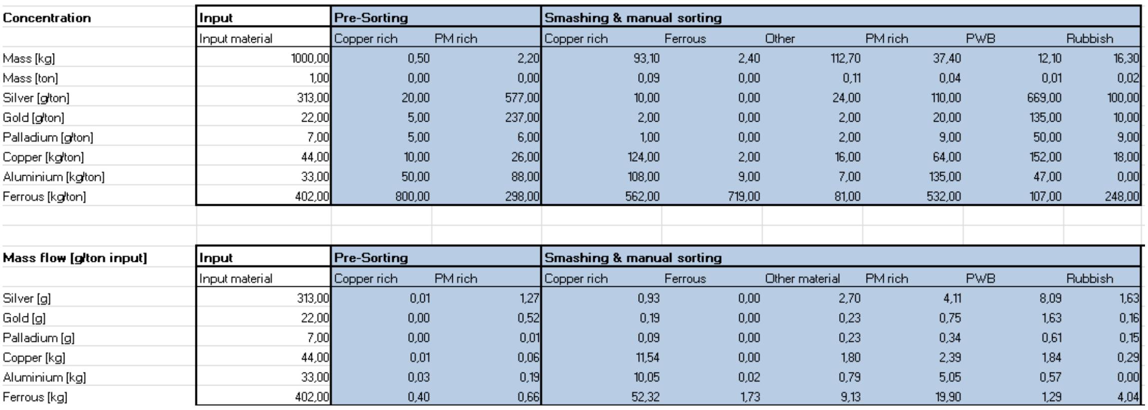
Table 40 – Spectral composition of CRT phosphors (Resende and Morais 2010)

Chemical composition	Composition (%)
Y	17,00
In	0,49
Ce	0,02
Nd	0,01
Sm	0,02
Eu	0,76
Al	4,55
Si	10,44
S	17,38
K	2,36
Ca	0,80
Mn	0,39
Fe	0,54
Zn	31,40
Sr	0,82
Zr	0,15
Ir	0,42
Pd	0,07
Ba	2,15
Pb	7,53

Appendix C: Recovery rates of mechanical pre-processing

The recovery rates of mechanical pre-processing are based on data available from the addendum of (Chancerel, Meskers et al. 2009). Table 41 and Table 42 show the mass flow analysis of part A and B of mechanical pre-processing. The tables on top represent the original data and contain the mass and the concentrations of each flow. That information is used to determine the remaining input material that enters part B of the process. With the assumption that smashing does not cause significant precious metal losses, the recovery rates of precious and other metals is determined of part B.

Table 41 – Concentration and mass flow of part A of mechanical pre-processing



Concentration	**Input**	**Pre-Sorting**		**Smashing & manual sorting**					
	Input material	Copper rich	PM rich	Copper rich	Ferrous	Other	PM rich	PWB	Rubbish
Mass [kg]	1000,00	0,50	2,20	93,10	2,40	112,70	37,40	12,10	16,30
Mass [ton]	1,00	0,00	0,00	0,09	0,00	0,11	0,04	0,01	0,02
Silver [g/ton]	313,00	20,00	577,00	10,00	0,00	24,00	110,00	669,00	100,00
Gold [g/ton]	22,00	5,00	237,00	2,00	0,00	2,00	20,00	135,00	10,00
Palladium [g/ton]	7,00	5,00	6,00	1,00	0,00	2,00	9,00	50,00	9,00
Copper [kg/ton]	44,00	10,00	26,00	124,00	2,00	16,00	64,00	152,00	18,00
Aluminium [kg/ton]	33,00	50,00	88,00	108,00	9,00	7,00	135,00	47,00	0,00
Ferrous [kg/ton]	402,00	800,00	298,00	562,00	719,00	81,00	532,00	107,00	248,00

Mass flow [g/ton input]	**Input**	**Pre-Sorting**		**Smashing & manual sorting**					
	Input material	Copper rich	PM rich	Copper rich	Ferrous	Other material	PM rich	PWB	Rubbish
Silver [g]	313,00	0,01	1,27	0,93	0,00	2,70	4,11	8,09	1,63
Gold [g]	22,00	0,00	0,52	0,19	0,00	0,23	0,75	1,63	0,16
Palladium [g]	7,00	0,00	0,01	0,09	0,00	0,23	0,34	0,61	0,15
Copper [kg]	44,00	0,01	0,06	11,54	0,00	1,80	2,39	1,84	0,29
Aluminium [kg]	33,00	0,03	0,19	10,05	0,02	0,79	5,05	0,57	0,00
Ferrous [kg]	402,00	0,40	0,66	52,32	1,73	9,13	19,90	1,29	4,04

Table 42 – Concentrations and mass flow of part B of mechanical pre-processing

Concentration	Preshredding and manual sorting				Shredding & automated sorting							
	Copper rich	Other material	PM rich (keyboard foils)	PWB	Aluminium	Ferrous	Non-ferrous	Other material	Plastics	PM rich	PWB	Rubbish & filter dust
Mass [kg]	28,70	1,40	0,30	4,90	22,00	329,30	4,30	32,30	264,80	12,90	14,60	7,70
Mass [ton]	0,03	0,00	0,00	0,00	0,02	0,33	0,00	0,03	0,26	0,01	0,01	0,01
Silver [g/ton]	3,00	513,00	5000,00	562,00	2722,00	332,00	423,00	303,00	342,00	662,00	481,00	378,00
Gold [g/ton]	1,00	0,00	0,00	127,00	16,00	27,00	10,00	13,00	24,00	94,00	48,00	24,00
Palladium [g/ton]	0,00	0,00	0,00	48,00	3,00	5,00	5,00	17,00	9,00	21,00	18,00	45,00
Copper [kg/ton]	167,00	1,00	0,00	189,00	33,00	8,00	216,00	37,00	39,00	105,00	153,00	38,00
Aluminium [kg/ton]	12,00	51,00	0,00	44,00	408,00	1,00	134,00	20,00	9,00	103,00	54,00	60,00
Ferrous [kg/ton]	723,00	151,00	0,00	55,00	7,00	861,00	3,00	49,00	4,00	247,00	18,00	208,00

Mass flow [g/ton original input]	Preshredding and manual sorting				Shredding & automated sorting							
	Copper rich	Other material	PM rich (keyboard foils)	PWB	Aluminium	Ferrous	Non-ferrous	Other material	Plastics	PM rich	PWB	Rubbish & filter dust
Silver [g]	0,09	0,72	1,50	2,75	59,88	109,33	1,82	9,79	90,56	8,54	7,02	2,91
Gold [g]	0,03	0,00	0,00	0,62	0,35	8,89	0,04	0,42	6,36	1,21	0,70	0,18
Palladium [g]	0,00	0,00	0,00	0,24	0,07	1,65	0,02	0,55	2,38	0,27	0,26	0,35
Copper [kg]	4,79	0,00	0,00	0,93	0,73	2,63	0,93	1,20	10,33	1,35	2,23	0,29
Aluminium [kg]	0,34	0,07	0,00	0,22	8,98	0,33	0,58	0,65	2,38	1,33	0,79	0,46
Ferrous [kg]	20,75	0,21	0,00	0,27	0,15	283,53	0,01	1,58	1,06	3,19	0,26	1,60

Mass flow [g/ton remaining input]	**Copper rich**	**Other material**	**PM rich (keyboard foils)**	**PWB**	**Aluminium**	**Ferrous**	**Non-ferrous**	**Other material**	**Plastics**	**PM rich**	**PWB**	**Rubbish & filter dust**
Silver [g/ton]	0,00	0,00	0,01	0,01	0,20	0,37	0,01	0,03	0,31	0,03	0,02	0,01
Gold [g/ton]	0,00	0,00	0,00	0,03	0,02	0,48	0,00	0,02	0,34	0,07	0,04	0,01
Palladium [g/ton]	0,00	0,00	0,00	0,04	0,01	0,30	0,00	0,10	0,43	0,05	0,05	0,06
Copper [kg/ton]	0,18	0,00	0,00	0,04	0,03	0,10	0,04	0,05	0,40	0,05	0,09	0,01
Aluminium [kg/ton]	0,02	0,00	0,00	0,01	0,55	0,02	0,04	0,04	0,15	0,08	0,05	0,03
Ferrous [kg/ton]	0,07	0,00	0,00	0,00	0,00	0,91	0,00	0,01	0,00	0,01	0,00	0,01

Recovery efficiencies of Part 2: Preshredding & manual sorting followed by shredding & automated sorting of WEEE								
	Aluminium	Ferrous	Non-ferrous	Copper rich	Plastics	PM rich & PWB	Waste	Control
Ag (%)	0,20	0,37	0,01	0,00	0,31	**0,07**	0,05	1,00
Au (%)	0,02	0,48	0,00	0,00	0,34	**0,14**	0,03	1,02
Pd (%)	0,01	0,30	0,00	0,00	0,43	**0,14**	0,16	1,04
Cu (%)	0,03	0,10	0,04	**0,18**	**0,40**	0,17	0,06	0,98
Al (%)	**0,55**	0,02	0,04	0,02	**0,15**	0,14	0,07	0,99
Fe (%)	0,00	**0,91**	0,00	0,07	0,00	0,01	0,01	1,00

Appendix D: Inventory of cyanide leaching

Table 43 – Spectral composition of the waste solutions

	Waste solution, cyanide leaching [ppm]	Waste solution, silver recovery [ppm]
Ag	455	3
Al	1315	0
As	0	0
Au	6,5	0
Cd	0	0
Cu	185	51
Fe	0	1600
Hg	0	0
Ni	9	0
Pb	4	15
Pd	0	0
Pt	0	0
Sb	0	0
Se	0	0
Sn	6,5	19
Zn	17	0

Table 44 – Particulate matter and spectral composition of fly ash

	Circuit boards [mg/kg circuit boards]	Insulated wire [mg/ kg cable]
Sb	75,4	140,0
As	79,6	ND
Br	3264,0	171,0
Cl	9,3	785,0
Cu	709,0	106,0
Pb	1180,0	964,0
K	68,4	25,6
Na	48,7	42,9
S	26,3	3,0

Sn	134,0	81,2
Zn	80,6	98,2
Particulates < 2,5 µm	15600,0	14740,0
Soot	8952,0	17500,0
Dioxins (toxic equivalent)	92*10^-6	11900*10^-6

Table 45 – Spectral composition of residual ash

	Circuit board		**Insulated wire**	
	Emissions [mg/kg ash]	Emissions [mg/kg circuit board]	Emissions [mg/kg ash]	Emissions [mg/kg cable]
Sb	273,0	191,1	883,0	529,8
As	15,9	11,1	2,3	1,4
Br	2 120,0	1 484,0	366,0	219,6
Cl	210,0	147,0	293 000,0	175 800,0
Cu	13 900,0	9 730,0	47 000,0	28 200,0
Cr	272,0	190,4	47,9	28,7
Ge	1,2	0,8	0,0	0,0
Au	23,5	16,5	0,0	0,0
Fe	6 780,0	4 746,0	730,0	438,0
Pb	3 630,0	2 541,0	16 900,0	10 140,0
Mg	2 950,0	2 065,0	1 250,0	750,0
Mn	45,3	31,7	50,1	30,1
Ni	279,0	195,3	26,3	15,8
Se	4,7	3,3	1,0	0,6
Si	200,0	140,0	0,0	0,0
Sn	2 150,0	1 505,0	217,0	130,2
Ti	2 260,0	1 582,0	0,0	0,0
V	50,1	35,1	6,6	3,9
Zn	180,0	126,0	764,0	458,4
Zr	46,6	32,6	0,0	0,0

Appendix E: Transport costs

This section explains the calculations behind the optimal transport costs. More in particular, it assesses how the density of a product determines whether it is more beneficial to ship on a 20 or 40 feet container.

The calculations assume that there are no scale issues, meaning that the transported amounts always can be stored in full containers. With this assumption, the load of a container is always either volume restricted or mass restricted. When the density exceeds a certain value, containers will be restricted by their maximum weight. The cost per kilogram transported is then determined as the cost of the transport of the container divided by the maximum load weight. If the density is below that value, containers will be restricted by the maximum volume that they can store. The cost per kilogram transported is then determined as the cost of transport of the container divided by storage volume multiplied with density.

Mass restricted cost: € container/ maximum load weight
Volume restricted cost: € container/ (volume * density)

With the volume and mass restrictions of both the containers, Table 46 can be constructed. The calculations assume that the costs of a 40 feet container are always 1,5 times as expensive, which is approximately the case for almost all transports on www.worldfreightrates.com.

Table 46 – Cost of mass and volume restricted transport of both types of containers

Container type	Cost per container [€]	Critical density [ton/m^3]	Mass restricted cost [€/kg]	Volume restricted cost [€/kg]
20 feet	1	21,8 ton / 32,5 m^3 = 0,66	1 € / 21,8 ton = 0,046	1 / (32,5 * ρ) = 0,030/ ρ
40 feet	1,5	26,7 ton / 67,6 m^3 = 0,4	1,5 €/ 26,7 ton = 0,055	1 / (67,6 * ρ) = 0,022/ ρ

Figure 44 shows a graph of the cost per kilogram transported for both kinds of container. The 40 feet container is volume restricted until the density is 0,4 ton/m^3. Before that value the cost per kilogram quickly increases if density would decrease, because more containers would be necessary for the shipment. The same reasoning holds for the 20 feet container where this is the case if the density is 0,66 ton/m^3. The intersection of both lines makes clear that if the density of products is below 0,54 kg/m^3 it will be economically beneficial to ship in 40 feet containers and it the density is above this value in the 20 feet containers.

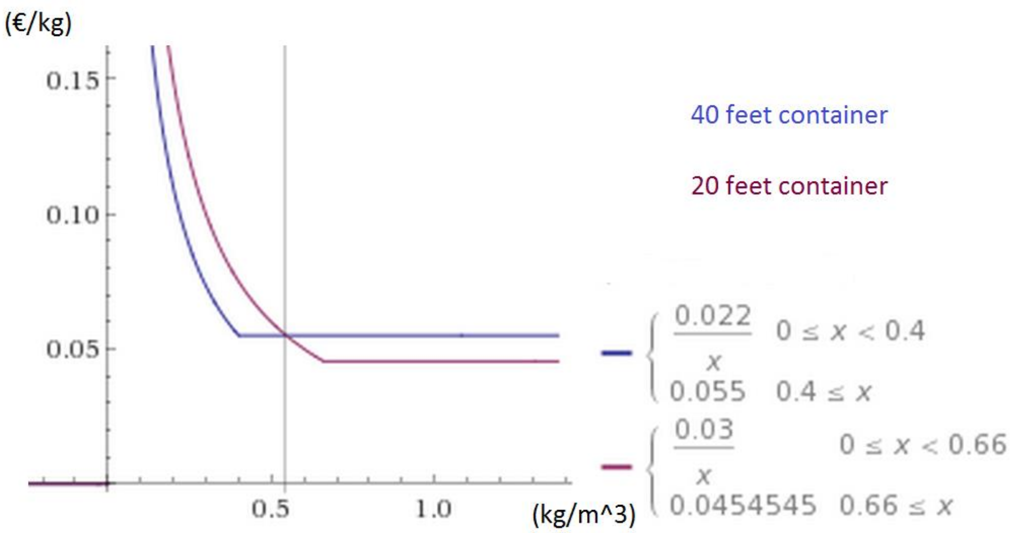


Figure 44 – Transport costs per kilogram for both types of containers

Appendix F: dismantling depth CRT monitors

Table 47 and Table 48 show that the economically optimal dismantling depth of CRT monitors in Hungary and China are scenario A and C respectively.

Table 47 – Economic assessment of dismantling depth of CRT monitors in Hungary

	A	B	C
Material revenue	3,84	4,23	4,59
Transport costs	-0,60	-0,22	-0,20
Labour costs	-0,38	-1,13	-1,51
Overhead costs	-0,66	-1,13	-1,18
Profit	**2,20**	**1,74**	**1,69**

Table 48 – Economic assessment of dismantling depth of CRT monitors in China

	A	B	C
Material revenue	3,84	4,23	4,59
Transport costs	-1,50	-0,54	-0,51
Labour costs	-0,14	-0,43	-0,58
Overhead costs	-0,66	-1,13	-1,18
Profit	**1,53**	**2,12**	**2,32**

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Master's Thesis file

Student: Frank Plessers

Title: Economische & ecologische evaluatie en optimalisatie van recyclage scenario's voor IT aparatuur in ontwikkelingslanden.

English title: Economic & environmental assessment and optimisation of recycling scenarios for IT equipment in developing countries.

UDC: 621

Content in brief:

This master thesis makes an economic and environmental assessment of three commonly applied recycling scenarios for desktop PCs and CRT monitors, namely mechanical treatment in industrialised countries; recycling by the informal sector and the best-of-2-worlds (Bo2W) philosophy in developing countries. Furthermore, compared with mechanical treatment of desktop PCs and CRT monitors in Belgium, it is investigated whether the shipment to developing countries for recycling according to a secured Bo2W scenario can improve the economic and environmental performance. The results are interpreted with consideration of legal aspects, management issues and external conditions. Additionally, this thesis investigates various opportunities to improve the Bo2W scenario in developing countries: The economically optimal dismantling depth of CPUs and CRT monitors is assessed.; The economic and environmental potential of alternative end-processes for rare earth elements and engineering plastics are estimated.; Several strategies to collaborate with the informal sector are evaluated whether they can help to ensure environmentally sound end-processes of all IT equipment generated in developing countries and can keep employment opportunities for the informal sector.

Thesis submitted to obtain the degree of Master in Engineering: mechanical engineering with the option of manufacturing and management.
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