## Delft University of Technology

**Design for Sustainability program**

*The QWERTY/EE concept addresses recyclability and eco-efficiency of take-back and recycling of consumer electronic products, a topic currently receiving large international attention. Through the environmental part of the concept an alternative for usual weight based recycling percentages is presented. In addition, economic effects of take-back and recycling are included in a quantitative eco-efficiency approach for evaluating technological, design and policy strategies. The approach itself and the valuable insights in recycling of consumer electronic products are highly interesting for policy makers, legislators, product designers, manufacturers, recyclers, take-back system operators and scientists. The concept is applied on a large number of products and scenarios, based on extensive environmental and economic modelling of end-of-life processing. The results show how to set priorities to enhance end-of-life performance by properly aligning policy making, system operation, technology and Design for End-of-Life. From this perspective, the recently enacted European Directives on electronic waste, WEEE and hazardous substances, RoHS, are reviewed, indicating substantial room for improvement.*

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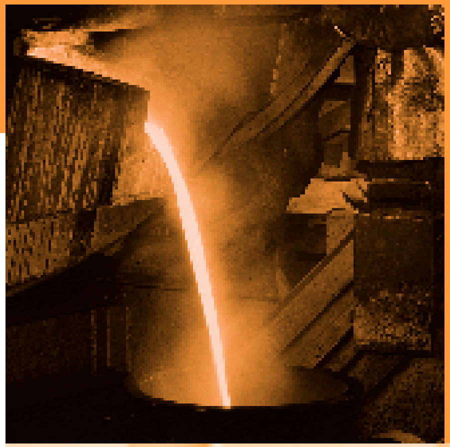

DfS The QWERTY/EE Concept

Jaco Huisman

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**Quantifying Recyclability and Eco-efficiency for End-of-Life Treatment of Consumer Electronic Products**

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***Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products***

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft,
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# *Preface*

I am grateful to the SENTER, IOP – Heavy Metals – Consumer Electronics program and everyone involved for financing and supporting this research.

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It may sound trivial but it has to be written here. This whole Ph.D. effort would be worth nothing if God wasn't present in my life and when some special people weren't close to me. My parents, Lennart and Tijs and my parents-in-law, thank you for praying, supporting and looking after me for so long. Maaike, Jonathan and Job, it would require a much thicker book than this one to describe what I feel and want to say to you. So for now: thank you for who you are.

*Jaco Huisman, 22-4-2003*

# *Summary*

The subject of this thesis, the quantitative environmental and eco-efficiency assessment of the end-of-life of consumer electronics is by definition of a multidisciplinary nature. It is leading to new steps in a field, which is of high societal relevance: end-of-life management and evaluation from a product point of view. The specific scope and goal of this thesis is to enhance the eco-efficient recycling of consumer electronic products. This work intends to address multiple target audiences involved in take-back and recycling.

Take-back systems and products are described from several perspective, these include:

1. The environmental perspective: What are the environmental consequences of end-of-life treatment and which materials and processes to prioritise?
2. The economic perspective: What are the financial consequences of collecting and treating discarded products?
3. The technical perspective: What improvements can be obtained with technological changes in end-of-life processing?
4. The design perspective: How should products be designed to make good end-of-life treatment possible?
5. The policy perspective: What are the appropriate strategies for improving end-of-life performance and how to balance environmental legislation and regulations?

The central problem addressed is whether environmental improvements and the costs involved in take-back and recycling can be described in quantitative units. With these units, applying certain technological improvement options, design changes or policy strategies, can be measured. The subsequent change in 'eco-efficiency' of end-of-life treatment can be prioritised. The improvement options and strategies are evaluated from a product point of view, like for instance: what are the environmental and economic effects of applying plastic recycling for a certain product in a certain take-back system?

The treatment steps of the end-of-life chain: disassembly and shredding and separation of products towards fractions are extensively described, starting with the material decomposition behavior of products. Four groups of products: plastic, glass, metal and precious metal dominated products are addressed. All relevant data on important secondary and waste processing steps have been gathered for each category. The analysis of the stakeholders involved and the main improvement options and strategies that are relevant to consider with a quantitative environmental assessment and eco-

efficiency concept are described. The new concept is entitled QWERTY/EE (Quotes for environmentally WEighted RecyclabiliTY and Eco-Efficiency).

The main technical treatment options considered with QWERTY/EE are CRT glass recycling, plastic recycling, dedicated shredding and separation of metal dominated products and separate collection and treatment of precious metal dominated products. The design strategies evaluated, are focussing on the reduction of the use of critical materials, reallocation of materials and improvement of unlocking properties of parts and components. Finally, the evaluation of policy and legislative improvement options is specifically addressing minimum recycling targets (on a weight basis), minimum collection targets, restrictions on the use of hazardous substances and outlet or treatment control rules for recyclers and secondary material processors.

In first instance, the QWERTY concept is developed to determine environmentally weighted recycling scores rather than weight-based recycling scores. QWERTY takes into account the 'environmental value' of secondary materials and the environmental burden of end-of-life treatment itself. The complex decomposition behaviour of products, described with the so-called 'double ensemble issue' is approximated and integrated into the QWERTY calculations. Application of the QWERTY concept shows how well the primary environmental goals of take-back and end-of-life treatment, reduction of material depletion, controlling potential toxicity and reducing emissions, can be achieved in practice. The concept is proven to be valuable in assessing the effectiveness of end-of-life processing, the consequences of product design and the consequences of proposed legislation on take-back and recycling of consumer electronic products.

A key issue in setting up take-back and recycling systems for discarded consumer electronics is how much environmental gain can be realised per amount of money involved. With the EE (eco-efficiency) extension of the QWERTY concept and the resulting economic calculations, this issue can be quantified. A comprehensive approach including and describing integral costs for the end-of-life chain and the contributions of single processes is developed. The eco-efficiency approach includes two steps:

1. The results are presented in two-dimensional graphs, displaying the 'vector' of a certain change or improvement option. This directly divides between directions with a positive eco-efficiency (higher environmental gain and less costs) and negative eco-efficiency (the opposite). Improvement options or changes leading to a direction towards the 'first quadrant' can be entitled as a positive eco-efficiency and should be promoted. The opposite counts for the third quadrant (higher environmental burden and higher costs).
2. Both the fourth quadrant (higher environmental gain and higher costs) as the second quadrant options (higher environmental impacts but higher financial gain) are to be balanced in terms of environmental gain or burden per amount of money invested or obtained. In fact, based on the size and direction of these 'second quadrant' and 'fourth quadrant' options, the 'quotient' is calculated. The results of the different improvement options in environmental points per amount of money invested can be ranked and related to the consequences of policy strategies.

The resulting QWERTY/EE concept is applied on a large number of cases. Typical example products are chosen and analysed in detail, representing the product categories of plastic-, metal-, glass-, and precious metal dominated products. Also trends in performance for many products and different end-of-life scenarios like plastic recycling, glass recycling and adjusted shredding and separation settings are calculated. The effects of these technological improvements are determined for these products as well as the effects of other improvements at secondary material processors and final waste treatment.

Important conclusions and outcomes are the quantification of the environmental and economic performance of the technical improvement options for around 75 different consumer electronics products:

1. Plastic recycling turns out to be only eco-efficient for large and well-designed housings (no flame retardants and other components present) of CRT-containing appliances already being disassembled. For small and medium sized housings the extra costs of plastic recycling are very high in relation to the environmental improvement realised.
2. Dedicated shredding and separation of metal dominated products only leads to environmental or economic improvements for metal dominated products with a relatively low plastic and high precious metal content.
3. For glass dominated products, an increase in CRT glass recycling results in significant environmental improvements and higher costs, as well
4. Positive eco-efficiencies are calculated for separate collection and treatment of precious metal dominated products. However, economy of scale is a major boundary condition that has to be fulfilled in this case.

The relation and alignment between end-of-life processing and design is also discussed by applying the QWERTY/EE concept on two indicative redesign cases and two highly detailed ones. The cases describe four example products representing the four different product categories. It appears that incremental design for end-of-life plays a limited but not negligible role in improving environmental performance of products in end-of-life. The main improvement options for redesigning products are enabling plastic recycling, delivering better fractions in shredding and separation and in reducing disassembly time and connected end-of-life costs. The improvement potential of incremental Design for End-of-Life is limited due to restrictions other than the environmental life cycle perspective. Costs, functionality requirements, mandatory reliability and safety regulations, limited development times and supply chain aspects decrease the improvement potential of the redesign results considerably. Heavy metals (excluding copper) turn out to have no high influence or priority. In some cases, allowing higher recovery of precious metals is a highly relevant redesign strategy.

The QWERTY/EE concept as such is not primarily developed for design purposes. However, it is proven that the calculation of the various aspects of environmental performance of products and end-of-life processes is valuable for determining the influence and relevance of redesign. It is recommended to further incorporate and develop certain parts of the QWERTY/EE concept for use in existing Design for End-of-Life tools and for design processes in general. The aspect of predicting end-of-life costs of products upfront in the design process is an important recommendation for designers and manufacturers.

The application of the developed methodology on the evaluation of policy strategies as proposed for instance in the European WEEE and RoHS Directives leads to a completely different prioritisation and valuation of implementation strategies currently being promoted. The consideration of the eco-efficiency directions in positive, negative and 'to be balanced' options leads to the conclusion that weight based recyclability targets should be abolished completely and should preferably to be replaced by a balanced set of mandatory collection, treatment and outlet control rules. These rules are to be prioritised and tailored to the product categories concerned. Furthermore, these rules are easier to monitor, are better stimulating actual environmental performance and are much more cost-efficient.

Collection rates should be split per product category. Especially for metal dominated and precious metal dominated products higher percentages should be prescribed. Collection rates enhancing measures must be applied with precaution in order to avoid relatively high costs for collection and transport, especially for small products.

Recyclers should determine when dedicated treatment of metal dominated products is efficient, while environmental and economic optimisation is usually equivalent in this case. A separate collection system for precious metal dominated products with precious metal concentrations above certain thresholds should be prescribed or encouraged under the important boundary condition that sufficient numbers of discarded appliances can be collected.

The application of the QWERTY/EE concept in stakeholder debates is demonstrated to be very useful and is expected to lead to better end-of-life system performance from an environmental point of view. When actually implemented in decision making processes, it will also lead to lower integral societal costs as well. Although recommended, in most cases consensus on which environmental assessment model to apply or which environmental priorities to assign to the different environmental themes is not necessary (except for plastic recycling). Often, 'all arrows are pointing into the same direction', irrespective of a certain method selected.

With the approach outlined in this thesis, the alignment of technology, design and policy is given a powerful and quantitative means to improve the eco-efficiency of take-back and recycling of consumer electronic products.

# *Samenvatting*

Het onderwerp van dit proefschrift, de kwantitatieve milieuwaardering en eco-efficiëntie van afgedankte consumentenelectronica, is per definitie van een multi-disciplinair karakter. Dit onderzoek heeft geleid tot nieuwe inzichten in een gebied van hoge maatschappelijke relevantie: einde levensduur management van afgedankte consumentenelectronica en evaluatie van recycling vanuit een product perspectief. Het thema en doel van dit proefschrift is te komen tot een meer eco-efficiënte recycling van consumentenelectronica. In dit proefschrift worden de verschillende daarbij betrokken doelgroepen aangesproken en geadresseerd.

Het thema van dit proefschrift wordt uitgewerkt vanuit vijf verschillende invalshoeken:

1. Het milieuperspectief: Wat zijn de milieuconsequenties van einde levensduur verwerking en welke materialen en processen hebben daarin de belangrijkste bijdrage en prioriteit?
2. Het economisch perspectief: Wat zijn de financiële consequenties van inzameling en verwerking van afgedankte produkten?
3. Het technisch perspectief: Welke verbeteringen kunnen aangebracht worden en welke veranderingen zijn mogelijk in de thans gebruikelijke verwerkingsstructuren?
4. Het ontwerpperspectief: Hoe moeten produkten ontworpen worden om betere einde levensduurverwerking mogelijk te maken?
5. Het beleidsperspectief: Wat zijn de juiste milieubeleidsstrategieën om de einde levensduur prestaties vanuit milieu en financieel oogpunt te verbeteren en hoe zijn de verschillende strategiëen het beste met elkaar in balans te brengen?

De centrale probleemstelling bij dit alles is de vraag hoe milieuverbeteringen van terugname systemen mede gerelateerd aan de bijbehorende kosten, in kwantitatieve eenheden uitgedrukt kunnen worden. Op basis van deze parameters kunnen beoogde technische verbeteringen, produktherontwerp en milieubeleidsstrategieën geprioriteerd worden en eindelevensduur systemen geoptimaliseerd worden. De verschillende verbeteropties worden geëvalueerd vanuit een specifiek produktperspectief. Bijvoorbeeld: Wat zijn de milieu- en financiële gevolgen van plastic recycling voor een bepaald produkt in een bepaald terugnamesysteem?

Het 'decompositiegedrag' van individuele produkten in demontage, shredden en scheiden is uitvoerig beschreven. Deze belangrijke stap in de eindelevensduurketen is bepaald voor vier verschillende groepen van produkten: plastic, glas, metaal en edelmetaal gedomineerde produkten. Alle relevante data van alle secundaire materiaalstromen en verwerkingstechnologieën zijn verzameld. Op basis hiervan worden de belangrijkste verbeteropties en strategieën uitvoerig beschreven. Het resulterende concept waarmee de berekeningen zijn uitgevoerd is getiteld QWERTY/EE (milieu-gewogen recyclebaarheid en eco-efficiëntie).

De specifiek met QWERTY/EE geadresseerde verwerkingstechnologieën zijn recycling van beeldbuisglas, plastic recycling, speciale shredder instellingen voor metaal gedomineerde produkten en de aparte inzameling en verwerking van edelmetaal gedomineerde produkten. De focus op herontwerpstrategiëen is gericht op de terugdringing van het gebruik van milieurelevante materialen, de configuratie van bepaalde materialen en componenten en de verbetering van ontsluitingsmogelijkheden van onderdelen en componenten. De evaluatie van beleidsinstrumenten en wetgeving is gericht op de thans op gewichtsbasis voorgeschreven minimale recyclingpercentages, op voorgeschreven minimale inzamelhoeveelheden, op het beperken van het gebruik van milieurelevante stoffen en op regels voor het afzetten van secundaire fracties bij bepaalde verwerkers.

Het QWERTY concept is in eerste instantie ontwikkeld om milieugewogen recyclebaarheidsscores te bepalen. Dit is een substantiele verbetering ten opzichte van de huidige gewichtsgebaseerde recyclingpercentages. Zowel met betrekking tot de algemene milieurelevantie als tot het adresseren van specifieke elementen die bij het bepalen van de totale milieuprestaties een rol spelen. QWERTY neemt mee de milieuwaarde van de verschillende secundaire stoffen en de milieubelasting van de procesvoering zelf. Het complexe decompositiegedrag van produkten, het zogenoemde 'double ensemble issue' is benaderd en geheel geïntegreerd in de methode. Toepassing laat zien in hoeverre de primaire milieudoelen van terugname en recycling van produkten in de praktijk gehaald kunnen worden. Deze doelen zijn: het terugdringen van uitputting van grondstoffen, het controleerbaar houden van toxische materialen en het reduceren van emissies. De methode blijkt zeer waardevol in het evalueren van de effectiviteit van eindelevensduurprocessen, van produktontwerp en van het beoordelen van nieuwe wetgeving op het gebied van terugname van electronicaprodukten en recycling.

Een centraal punt in het opzetten van terugname systemen voor afgedankte produkten is hoeveel milieuwinst er behaald kan worden in verhouding tot de bijbehorende kosten. Met de uitbreiding van het QWERTY concept met eco-efficiëntie en de daarbij horende economische berekeningen kan de milieuprestatie in verhouding tot bijbehorende kosten volledig gekwantificeerd worden. Een dergelijk veelomvattende aanpak beschrijft de integrale kosten en milieu-effecten over de hele eindelevensduurketen en de bijdrage van individuele processen. De methode bestaat uit twee stappen:

1. Eco-efficiëntie resultaten worden gepresenteerd in tweedimensionale grafieken. De 'vector' beschrijft een bepaalde verandering in de keten. Richtingen met een positieve eco-efficiëntie (zgn. eerste kwadrant opties: hogere milieuwinst en lagere kosten) en richtingen met een negatieve eco-efficiëntie (zgn. derde kwadrant opties: hoger milieubelasting en hogere kosten) kunnen direct bepaald worden. Verbeteropties met positieve eco-efficiëntie moeten gestimuleerd worden, opties in het 'derde kwadrant' moeten zoveel mogelijk vermeden worden vanuit het perspectief van de integrale einde levensduurketen.

2. De opties in het vierde kwadrant (hogere milieuwinst en hogere kosten) en in het tweede kwadrant (hogere milieubelasting en hogere opbrengsten) moeten afgewogen worden in termen van milieuwinst per bestede hoeveelheid geld. Hier bepalen de richting en de grootte van de vector hier uiteindelijke oordeel: het 'quotiënt'. De resultaten in milieupunten per euro geïnvesteerd kunnen geklasseerd worden en gerelateerd aan de consequenties van verschillende milieubeleidstrategiëen

De resulterende QWERTY/EE methode is toegepast op een groot aantal cases. Typische voorbeeldprodukten zijn gebruikt voor de produkt categorieën plastic, glas, metaal en edelmetaal gedomineerde produkten. Daarnaast zijn mogelijke verbeteropties geanalyseerd voor veel verschillende produkt – verwerkingsscenario's zoals plastic recycling, CRT glas recycling en speciale instellingen voor het shredden van metaal gedomineerde produkten. Ook het effect dat deze opties hebben bij de secundaire materiaalverwerkers is in de berekeningen meegenomen.

Belangrijke conclusies en uitkomsten van de kwantitatieve aanpak en evaluatie van de technische verbeteropties van zo'n 75 verschillende produkten zijn:

1. Plastic recycling blijkt alleen eco-efficiënt te zijn voor grote en goed ontworpen omkastingen van moderne apparaten en alleen indien geen vlamvertragers of andere componenten aanwezig zijn. Voor kleine en middelgrote omkastingen zijn de kosten voor plastic recycling erg hoog in verhouding tot de milieuwinst.
2. Speciale instellingen voor het shredden en scheiden van metaal gedomineerde produkten zijn alleen aantrekkelijk voor die produkten die een relatief laag plasticgehalte en relatief hoog edelmetaalgehalte hebben.
3. Voor glas gedomineerde produkten, leidt een toename van CRT glas recycling tot significante milieuverbeteringen en extra kosten.
4. Positieve eco-efficiënties kunnen worden behaald door apart inzamelen en sorteren plus verwerken van edelmetaal gedomineerde produkten. Een belangrijke randvoorwaarde hier is dat schaaleffecten in voldoende mate gerealiseerd kunnen worden.

De relatie tussen eindelevensduur processen en produktontwerp kan met het QWERTY/EE concept worden gelegd. Aan de hand van twee meer algemene herontwerp cases en twee gedetailleerde herontwerpen zijn vier voorbeeldprodukten uit de vier produktcategorieën behandeld. Hieruit blijkt dat incrementeel herontwerp alleen gericht op de eindelevensduurfase een gelimiteerde, maar niet verwaarloosbare rol kan spelen indien de ontwerprichtingen volgend uit de QWERTY/EE evaluatie opgevolgd worden. De belangrijkste verbeteropties voor herontwerp zijn het beter mogelijk maken van plastic recycling, het creëren van betere fracties in shredderprocessen en in het reduceren van demontagetijden en daaraan gekoppelde kosten. Het verbeterpotentiëel van incrementeel herontwerp voor eindelevensduur van produkten is gelimiteerd door allerlei restricties anders dan het levenscyclusperspectief zelf. Kosten, functionaliteiteisen, verplichte betrouwbaarheid en veiligheideisen, beperkte produktontwikkelingstijden en toeleverancier aspecten verkleinen in belangrijke mate het verbeterpotentieel van herontwerp. Verder blijkt dat de zware metalen (behalve koper) weinig invloed hebben op de prioriteiten voor herontwerp. In sommige gevallen zijn het beter terugwinnen van edelmetaalgehaltes wel van belang in herontwerpstrategiëen.

Niettegenstaande het feit dat het QWERTY/EE concept als zodanig niet ontwikkeld is voor ontwerpdoeleinden, blijkt de methode voor de berekening van milieubelastingen van produkten in de afdankfase van waarde voor het bepalen van de invloed en relevantie van produkt(her)ontwerp. Het is daarom aanbevolen om bepaalde delen van deze methode verder te ontwikkelen en in bestaande 'Design for End-of-Life tools' in te bouwen. Met name de mogelijkheid van het voorspellen van eindelevensduurkosten is belangrijke aanvullende informatie voor ontwerpers en producenten.

De toepassing van het QWERTY/EE concept voor de evaluatie van milieubeleid-strategiëen zoals bijvoorbeeld voorgesteld wordt in de WEEE/RoHS Directives van de Europese Unie leidt tot een andere prioriteitenstelling dan die thans in Europa voorgestaan wordt. De indeling van de resultaten in positieve, negatieve en 'te balanceren' eco-efficiënte richtingen leidt tot de conclusie dat de huidige gewichts-gebaseerde richtlijnen volledig afgeschaft zouden moeten worden. Deze zouden vervolgens moeten worden vervangen door een uitgebalanceerd aantal verplichte inzamel-, verwerkings- en afzetrichtlijnen. Deze richtlijnen moeten bovendien toegespitst worden op de verschillende produktcategorieën. De alternatieve richtlijnen zijn beter controleerbaar, stimuleren beter echte milieuverbeteringen in de einde levensduurketen en zijn aanzienlijk kosten-efficiënter.

Inzamelhoeveelheden moeten voorschreven worden per productcategorie, met name voor metaal en edelmetaal gedomineerde produkten. Het voorschrijven van minimale inzamelhoeveelheden moet voorzichtig toegepast worden om relatief hoge kosten voor transport en logistiek voor met name kleine produkten te voorkomen. Recyclers moet de vrijheid gelaten worden zelf te bepalen wanneer speciale instellingen te gebruiken zijn voor metaal gedomineerde produkten. In deze categorieën wijzen economische en milieuresultaten bijna altijd in dezelfde richting. Een apart inzamelsysteem voor edelmetaal gedomineerde produkten met concentraties boven een bepaalde grens zouden voorschreven moeten worden. Dit onder de belangrijke aanname dat voldoende aantallen hiervan in de toekomst ingezameld zouden kunnen worden.

De toepassing van het QWERTY/EE concept is zeer bruikbaar in discussies tussen verschillende belanghebbenden en het is de verwachting dat toepassing ervan in beslissingsprocessen leidt tot hogere eco-efficiënties van einde levensduurketens. Dat wil zeggen, het leidt tot lagere totale maatschappelijke kosten en verbeterde milieuresultaten. Hoewel aanbevolen, welk milieumodel in de praktijk gekozen wordt, speelt in meeste gevallen geen rol (behalve voor plastic recycling) In bijna alle gevallen wijzen de vectoren dezelfde richting op, onafhankelijk van de specifieke keuze voor een bepaald model.
Met de aanpak zoals beschreven in dit proefschrift is een nieuw en kwantitatief concept ontwikkeld, waarmee technologie, produktontwerp en milieubeleid beter op één lijn zijn te brengen. Deze aanpak kan bijdragen tot een belangrijke verbetering van de eco-efficiëntie van einde levensduurketens van produkten.

# Chapter 1: Introduction

## 1.1 Backgrounds

After many years of attention on cleaner production and end-of-pipe solutions in the environmental field, around 1990 more interest is growing towards the role of products from a life-cycle perspective instead of on production processes only. The last few years environmental concerns related to the disposal of consumer electronic products received a lot of attention. Due to concerns about waste, potential toxicity and spatial problems, legislation on a EU level regarding take-back and recycling of discarded electronic products is recently enacted (Commission of the European Communities 2003a,b). Various stakeholders and parties involved pay much attention at disposed products. Besides governments responsible for waste collection, including national and international policy makers, the awareness by consumers and Non-Governmental Organisations (NGOs) on take-back and recycling is increasing. Producers are concerned about the business consequences and an efficient organisation of take-back systems. Scientists play a role in researching the options for closing material loops, improving end-of-life management and Design For End-of-Life (Stevels 2000a).

This chapter is briefly discussing the backgrounds behind this thesis, the chosen approach as well as the core goal and research questions. In the next Chapter 2, a further elaboration on the issue of end-of-life of consumer electronics will be presented.

The following five perspectives are characterising the end-of-life of consumer electronic products:

1. The environmental perspective. Take-back systems for disposed products are often primarily set-up with a clear environmental intent. This is the case for consumer electronic products in particular, the so-called 'browngoods' that are subject of this thesis (see Section 1.6 for all definitions and terminology used). Also for other products like cars, batteries, bottles, packaging and paper, take-back systems are in place or planned to be organised in the near future.
   The general environmental concerns with respect to discarded consumer electronics are related to conservation of resources, potential toxicity after discarding and the reduction of landfill and incineration volumes. For consumer electronics, the end-of-life stage is relatively of less importance compared to for instance the energy consumption during manufacturing and the use-phase. The special position

of end-of-life is for the reasons outlined above, highly ranked on the societal agenda. The environmental issues related to end-of-life which are discussed in this thesis will be checked with the life cycle perspective, where necessary. The reason for this is to prevent environmental optimisations for the end-of-life stage only, which are leading to higher environmental impacts in other life cycle stages like for instance raw material extraction and manufacturing. The environmental burden of end-of-life compared to the impacts of the total product life cycle will be discussed in Chapter 2.3.2. A typical example of a violation of the life cycle perspective will be for instance presented in Chapter 6.4.3. The various environmental issues and themes related to end-of-life treatment are extensively discussed in Chapter 3.1

2. The economic perspective. In the past, several take-back systems were developed for products with a positive end-of-life value like copiers, medical equipment or computer mainframes. Consumer electronic products usually have a negative end-of-life value. This means that take-back systems for these products will only be developed when driven by legislation. Within given regulations and boundaries, the various recyclers and processors involved tend to maximise their economic interests. Usually, processing configurations like creating material fractions with shredding and separation or disassembly operations, are optimised from an economic perspective. Such an economic optimisation is in many cases not equivalent with environmental optimisation. From a societal point of view, the overall costs for end-of-life treatment of discarded products are preferably to be minimised against maximum environmental performance. The determination of end-of-life costs related to environmental performance is discussed in high detail in Chapter 4 with the introduction of an eco-efficiency approach which is linking both perspectives.
3. The technological perspective. Technology is determining what is physically possible and what boundaries in end-of-life processing are existing. The physics behind end-of-life process steps involved like remanufacturing, reuse, disassembly, shredding and separation, incineration, landfill, metal smelting, plastic recycling or CRT glass recycling are to a large extent determining the environmental and economic performance. Technological improvement options in take-back and recycling like plastic recycling or CRT glass recycling can increase or decrease environmental and economic performance. In many cases, a balancing is needed between lowering environmental burden by applying certain technologies and the amount of money necessary for investments in such end-of-life processing. In Chapter 5 and 7, many examples of technological improvements will be presented which are leading to changing environmental gains and corresponding financial effects.
4. The design perspective. Product design and manufacturing are sometimes regarded as the solution for many environmental problems. At the product creation and design stage, prevention of environmental impacts is related to material extraction and manufacturing, to energy consumption in the use phase and to the environmental consequences of disposal. General ecodesign strategies can improve environmental performance over the life cycle of products by lowering energy consumption, by appropriate material selection, by avoiding the use of certain substances and by optimising product characteristics for end-of-life treatment (van Hemel, 1997). Regarding the last part of the product life cycle, specific 'Design for End-of-Life' strategies can be applied (see Section 1.6 for definitions). These are

addressing the possibilites to create optimal material fractions for further processing, to improve connections between materials and assemblies and by phasing out 'disturbing' substances. Furthermore, also end-of-life costs and disassembly times can be decreased. The relation between Design for End-of-Life and environmental and economic performance is specifically addressed in Chapter 6. In this chapter also specific redesign cases will be presented regarding Design for End-of-Life strategies for consumer electronic products (Eikelenberg 2003).

5. The policy, legislation and system operation perspective. Regulation of take-back system operation includes many important aspects like setting goals and targets, the operationalisation of take-back systems and treatment rules, the way of monitoring and financing. The finance system can be based for instance on visible fees for consumers or being paid by producers on basis of market shares for collective systems. Producers usually directly operate and finance individual take-back systems. The choice for a collective versus an individual system has consequences for the economies of scale of secondary material processing. The way of collecting disposed products, transport distances, the volumes and variety of discarded products as well as the chosen recyclers and secondary processors are to a large extent determining environmental and economic performance (Lucassen 2001).
   The above issues are strongly connected to what is prescribed in actual take-back policies and legislation. In general, policy strategies can be divided in four main strategies: prescribing minimum collection rates, restrictions on the use of hazardous substances and processing, treatment and outlet control rules. The current status of legislation regarding waste of consumer electronics is analysed in eco-efficiency terms in Chapter 7. In this chapter, the relation between these policy strategies and many different eco-efficiency directions is reviewed.

In order to improve end-of-life systems from the first and second perspective, environment and economy, which are linked to each other in Chapter 4, a proper **alignment** with the other three perspectives, design, policy and technology is required. Closely related to (Boks 2002a), in Figure 1.1 the five perspectives are displayed. Environmental and economic achievements are in the centre of this pyramid as the final outcomes of the other three perspectives in the product end-of-life chain: design, technology and policy, legislation and system operation.

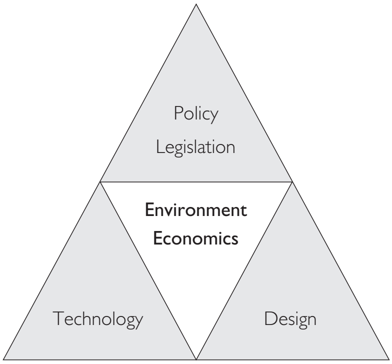


*Figure 1.1 The end-of-life management pyramid*

For the requested **alignment** a robust and proper quantitative approach addressing and linking economic and environmental performance is needed. In other words, comprehensive methodology filled with all relevant environmental and economic parameters and data is necessary to describe the heart of the pyramid. To determine the interrelations between the other three perspectives mentioned with the environmental and economic perspective in the centre, a robust and accurate calculation method quantifying the results of different strategies and end-of-life scenarios would be appreciated by the stakeholders involved in take-back and recycling. In this respect, eco-efficiency plays a key role in balancing environment and economy (Graedel 1995). In 1998, the WBCSD (World Business Council for Sustainable Development 1998) in collaboration with UNEP (the United Nations Environmental Programme) introduced the following definition for eco-efficiency:

> *'Eco-efficiency is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity'.*

Recycling is indirectly addressed in this definition, while 'ecological impacts' over a products life cycle can be reduced by proper end-of-life treatment and 'resource intensity' brought down by closing material loops as far as possible. The eco-efficiency thought has been elaborated on further in many publications, quite often in a qualitative way only based on emotions and non-measurable general principles. However, a quantitative approach based on available facts and best scientific insights is regarded as potentially very beneficial for stakeholder debates and for the comparison of alternatives resulting from the three corners of Figure 1.1 (Porter 1985, Vogtländer 2001, Boks 2002a, Boks 2002b).

The parties or stakeholders involved and their interests in end-of-life are briefly summarised below (Stevels 2002a, Rose 2000a):

1. Consumers: The interests and involvement of consumers are concerns about environmental issues, low costs for disposing products (directly and indirectly) and the avoidance of hassle with products to be discarded.
2. Non-Governmental Organisations (NGOs) are primarily focused on the reduction of the use of hazardous substances and on conservation of resources.
3. Legislators and policy makers are dealing with waste problems in general and sometimes with lack of landfill space or incineration capacity. Furthermore they tend to enhance sustainability with enactments in general and by stimulating the closing of materials loops in particular. The development of regulations includes for instance making producers more responsible for products in their end-of-life phase (extended producer responsibility, EPR).
4. Science and technology are key areas with regard to the development of end-of-life processing technologies, separation techniques and enabling re-application options or upgrading of secondary materials. Furthermore science can show which (innovative) sustainable directions should be followed and can provide the descriptions of future strategies to be promoted.

5. Producers, designers and suppliers are 'responsible' for design, component selection, manufacturing, product architecture and assembly and thus determining the chemical content of products. From their perspective functionality and customer value prevails and end-of-life considerations are subordinate to that. Nevertheless, producers can substantially contribute to improvement of the end-of-life part in the life cycle of products. They can sometimes foster re-use of components and materials or even take-back complete products. Also disassembly times and unlocking properties of materials in end-of-life are closely related to design and production operations.
6. Recyclers, secondary material processors and waste processors are responsible for handling waste and can establish closed loops of materials or take care for energy recovery and waste volume reduction. Furthermore they can optimise environmental and economic value recovery and minimise final waste disposal costs and emissions for certain streams and materials.

An improved **alignment** between the three corners with the heart of the end-of-life management pyramid can be accomplished when the relation between environmental impacts and economic performance of end-of-life is optimised. Tools and methodology addressing the environmental and economic effects in quantitative units of design, policy and technology strategies can substantiate the proposed **alignment** and enhance communications between all parties and stakeholders involved in take-back and recycling (more details will follow in Chapter 4).

A large incentive for take-back and recycling are the recently published European Directives, regarding the Waste of Electric and Electronic Equipment (WEEE) and the Restrictions on the Use of Hazardous Substances (RoHS). These two Directives prohibit the use of certain heavy metals in these products (Commission of the European Communities 2003a) and mainly prescribe recycling targets to be achieved in end-of-life treatment for various product categories (Commission of the European Communities 2003b). More details, in particular on the WEEE Directive, follow in Chapter 2.5.5 and 2.8.2. The result of the enactment of these Directives is a substantial increase in debates and negotiations between the stakeholders involved in take-back and recycling of consumer electronics.

Besides the different positions, described above, three common grounds are present in stakeholder debates (Stevels 2002a):
1. The prevention of damage to the environment.
2. Society has to pay in the end, either directly or indirectly.
3. The prevention of out-of-proportional consequences for individual stakeholders.

This important remark leads to the notion that a quantitative approach for environmental and economic performance would satisfy these common grounds and can clarify ongoing debates and negotiations. The objective of this thesis is to provide in both the data as well as the methodological means to link the above common grounds to the current status of take-back systems and the options to improve environmental and economic performance by means of policy, design and technology strategies.

## 1.2 Research goal and questions

The core goal of this Ph.D. thesis is:

*To determine the performance of discarded consumer electronics in quantitative environmental and economic units and the alignment of treatment, design, policy and legislation and end-of-life system operations in order to improve the eco-efficiency over the end-of-life chain.*

This core goal is leading to the following research questions to be answered and steps to be followed in this thesis. The first question is put forward to describe the 'playing field' and all actors, stakeholders and processes involved. The need for a quantitative approach is addressed in Chapter 2:

Research question 1.

*What are the main factors and stakeholders involved in end-of-life processing of consumer electronics, what are their roles, what environmental issues are relevant and how are these issues currently evaluated?*

The second question directly links to the quantitative description of environmental issues, their relevance and which methodological steps to take to determine product end-of-life performance and recyclability in environmental terms. This will be discussed in Chapter 3:

Research question 2.

*How can recyclability of products be quantified in measurable environmental units and a comprehensive method be developed to describe this end-of-life performance of consumer electronic products for different end-of-life scenarios?*

The third question refers to the extension and combination of the environmental descriptions with economic data and the methodological way of addressing eco-efficiency. This question is also posed assuming that this quantification would help the various stakeholders involved in stakeholder debates with regard to the economic consequences of environmental measures applied and the corresponding efficiency in the environmental and economic results. This will be discussed in Chapter 4:

Research question 3.

*How can a comprehensive and robust eco-efficiency method be developed for end-of-life combining the descriptions of quantified environmental performance with economic consequences and how to enhance the alignment of design, technology and policy with results that are easy to interpret?*

The fourth question refers to the application of the eco-efficiency concept in stakeholder debates and the determining of end-of-life chain performance. The application is focusing on the performance of many different products in different end-of-life scenarios and the improvement potential of certain technological changes (like plastic recycling for instance) from a product point of view as well as a first indication of the priorities of end-of-life processing with regard to policy and legislation. This will be discussed in Chapter 5:

Research question 4.

*What is the improvement potential in eco-efficiency terms resulting from application of the methods developed on many different products and product categories in different end-of-life scenarios and the priorities in this respect to be favoured with end-of-life policy strategies?*

The fifth question concerns the role of product design in the end-of-life chain and the resulting improvement potential of design for end-of-life in particular as well as the design strategies to follow. This will be discussed in Chapter 6:

Research question 5.

*What is the improvement potential of incremental design for end-of-life of certain products from an eco-efficiency perspective and what 'design' strategies can lead to better alignment with technology and policy?*

The sixth question relates to the role of waste policy and legislation as well as take-back system operation. To be addressed is the evaluation of current legislative strategies and how a more eco-efficient balancing of these various strategies should look like. This will be discussed in Chapter 7:

Research question 6.

*What are main priorities from an eco-efficiency perspective for policy, legislation and take-back system operation in order to increase end-of-life system performance and to enhance further alignment with technology and design? What are the main strategies to increase eco-efficiency in end-of-life treatment and how should these be prioritised?*

This thesis is structured around these questions and the steps to take in answering them will be visualised in Section 1.4. But before further discussing the structure of this research, some important remarks are made regarding the scientific nature of this work. The chosen research approach and the many disciplines involved are introduced in Section 1.3.

## 1.3 Multidisciplinary approach

This research is sponsored by and is part of the Innovative Research Programs (IOP) of SENTER a department of the Ministry of Economic Affairs. This particular IOP program, entitled Environmental Technology – Heavy Metals - Consumer Electronics, is started in 1999 with a special focus on reducing risks to the environmental due to heavy metals in consumer electronics (Senter 1997). Within the IOP program, this subproject has a special focus on product design. The product design as the initial starting point was soon extended, while the design perspective is far too limited as already posed with Figure 1.1. The original design perspective is widened to a central position of the performance of products in complex end-of-life systems. In this thesis the focus of the research is also further extended to quantified eco-efficiency methodology development and application on the end-of-life of consumer electronic products in particular. Another reason for extension of the scope is that single environmental themes shouldn't be regarded as purely technically solvable with applying the appropriate design rules. Solving one environmental problem in a products life cycle almost always leads to other problems somewhere else, at times even worse than the original problem. This will be highlighted in Chapter 6 with typical examples in Chapter 6.4.3, Figure 6.10 on material selection and in Chapter 7.8.2, Figure 7.20 with the example of resource depletion of lead-free solders. Moreover, there are multiple chains of actors or systems influenced by environmental measures. In these chains the effectiveness and efficiency of solving single environmental issues must be investigated and balanced.

A very broad and multidisciplinary approach is chosen for this thesis. Not just two or three individual areas of expertise are connected, or one traditional research competence of the author is placed in the middle as a basis from where other research fields can be linked. To the contrary, it is tried to determine the relations between all relevant areas of expertise involved to achieve the core goal set in the previous section. The aim is to develop new environmental and eco-efficiency methodology linking, evaluating and supporting the most relevant aspects of the areas of expertise involved and to achieve alignment of these areas in the development and improvement of take-back systems for discarded products. The areas of expertise involved are:

1. Applied ecodesign
2. Waste processing and process engineering
3. Secondary material processing, metallurgy and resource cycle management
4. Waste management, policy and legislation
5. Electronic product design
6. Environmental assessment and validation, Life-Cycle Assessment (LCA)
7. Financial accounting and economics
8. Logistics and transport

In order to handle these expertise fields, new methodology will be proposed with respect to the interrelations between the different research areas. To support stakeholder debates on environmental priority setting and the efficiency of take-back, a common 'language' for experts in the eight fields above must be developed to connect to the common grounds of the stakeholders described in Section 1.1. This includes prioritisation on relevant substances and materials used in electronics, as well as special focus on certain products and product categories and the recognition of the most important processes. Also determining and predicting integral end-of-life costs for various product and product categories in relation to improvement options in take-back and recycling will be helpful in stakeholder debates. The role of technological improvements in the treatment of streams of discarded consumer electronics and the financial and environmental consequences are of high importance in determining current and future end-of-life strategies. Furthermore, the chosen multidisciplinary approach enables monitoring of take-back systems as a whole on a quantitative environmental and economic basis. From there, also identification of technological or organisational bottlenecks like economies of scale, market matureness and acceptance criteria of secondary processors can be identified in an early stage. Policy strategies, which are contributing to this, should be reviewed and aligned with the technological and design strategies.

One of the challenges of a multidisciplinary approach like this is that the 'overall picture' is very comprehensive. Cooperation and active support from many different experts and groups is an essential requirement. Besides the expertise of the TU Delft on (Applied) Ecodesign, Life Cycle Assessment (LCA) and uncertainty factors in end-of-life (Boks 2002a), within the IOP project, cooperation is started with a number of Dutch institutes and companies. Directly involved are two institutes of the Netherlands Organisation for Applied Research called TNO Environment, Energy and Process Innovation (referred to as TNO-MEP) and TNO Industrial Technology (referred to as TNO-IND) in a subcontracting form (Senter 1997). The expertise fields of these institutes are respectively waste processing and engineering; electronic product design and design for end-of-life. The results of the work of TNO-MEP are published in (Ansems 2002a) and will be further discussed in Chapter 2.4; the work of TNO-IND is published in (Eikelenberg 2003) and will be introduced in Chapter 6. Both publications are written closely related to and supporting the research for this thesis.

Also support for this research is obtained from the Philips Consumer Electronics, Environmental Competence Centre with making available details on product design, product compositions (not only from Philips products) and environmental data acquired by environmental benchmarking of products (like in: Philips Consumer Electronics 2001m) as well as granting access to the LCA database developed by the Philips Centre for Manufacturing Technology, Philips Environmental Standards (CFT-PES), (Philips Consumer Electronics 2002n).

Regarding secondary material processing and metallurgy, collaboration has been set-up with the Department of Applied Earth Sciences, Delft University of Technology on the expertise fields of secondary material processing and metallurgy (Scholte 2002, van den Tweel 2003). Furthermore, the Dutch recycler Mirec, with the expertise field of recycling and shredding and separation and the Ministry of Environmental Affairs and Spatial Planning (VROM) responsible for monitoring the Dutch take-back system (De Straat Milieuadviseurs 2002) are members of the IOP- Heavy metals – Consumer Electronics program and were contributing to this research.

In Table 1.1, all partners are mentioned.

| Institute, company | Expertise fields |
|---|---|
| TU Delft, Design for Sustainability, Applied Ecodesign | Applied Ecodesign, economics of EOL, LCA |
| Philips ECC | Environmental benchmarking, ecodesign, product data and compositions |
| Philips CFT-PES | LCA database |
| TNO-MEP | Waste and secondary processing, shredding and separation settings |
| TNO-IND | (Electronic) product design |
| TU Delft Applied Earth Sciences | Metallurgy, secondary material processing, resource cycle management |
| Mirec | Shredding and separation, stream management |
| VROM | Waste policy and legislation |

*Table 1.1 Main institutes and companies involved in this research*

## 1.4 Scope and positioning

The multidisciplinary approach and the partners involved in this research are determining the scope of this research and the research questions posed in Section 1.2: The electronic products under investigation in this thesis are the so-called browngoods. A more specific name for these products is: high volume consumer electronics (see Section 1.6 for exact definitions and Chapter 2.3.3 for more details). Out of scope are the following product types: small and large IT equipment (grey goods, except for CRT monitors (Cathode Ray Tube) and LCD monitors (Liquid Crystal Display)), medical equipment, household appliances (mixers, magnetrons), whitegoods (freezers, washing machines), electronic tools and toys. These products are often collected together in the same national take-back systems together with the browngoods. The behavior of browngoods in large and complex take-back systems is the prior subject of this research.

The regional scope is in first instance the current Dutch take-back system (NVMP 2002a,b) and the average situation for subsequent secondary material processing and final waste disposal (Ansems 2002a) in The Netherlands. From here also the European situation can be described where necessary.

The time scope is the 2002 situation for end-of-life processing and the products under investigation are derived from the Philips Environmental Benchmarks (for instance in Philips Consumer Electronics 2001m) and are produced in between 1999 and 2002. An important boundary condition is that not enough information is available on older products that are currently discarded and processed. The behavior of 'modern' products with current state-of-the-art recycling techniques is the default starting point of this research.

Another starting point is that the disposed products are regarded as economically or technically so old that higher levels of reuse options are usually not attractive. As is illustrated in (Rose 2001a), for the majority of consumer electronic products, opportunities for **environmentally** justified reuse or lifetime extension are very limited or even counterproductive. This is mainly due to much lower energy consumption levels of new products. In (Rose 2001a) calculations are presented, analysing the reuse potential for a certain product or product category. When a reuse potential is expected, such calculations should precede the assessments made in this thesis. Nevertheless, sooner or later all products will enter the phase that no reuse or remanufacturing potential is present. More information about this issue will be presented in Chapter 2.3. Other criteria regarding the reuse potential of these products are presented in (van Nes, 2003).

From 1999 till now, several methods are developed with different targets at TU Delft. The Design Evaluation (Brouwers 1995) and the End-of-life Design Advisor (ELDA) (Rose 2000) are more design oriented tools. The Metrics for End-of-life Strategy (ELSEIM) (Rose 2001a) is aimed at end-of-life strategies and determines whether it is environmentally friendly to apply reuse, remanufacturing or material recycling (with or without disassembly) and what, from an environmental perspective, for a certain product an optimal life-time is. The Product Material Recycling Costs Model (PMRCM) calculates end-of-life treatment costs and is used for end-of-life scenario evaluation (Boks 2002a). In addition or "on top" of these methods, two new and closely related methods are developed and presented in this thesis: The Quotes for environmentally WEighted RecyclabiliTY (QWERTY) of Chapter 3 and the extension with integral end-of-life costs to eco-efficiency (EE) of Chapter 4 describing environmental impacts and integral end-of-life costs over the full end-of-life chain. Due to the fact that the eco-efficiency concept (EE) is included in the overall calculation sequences it is abbreviated as QWERTY/EE.
In Table 1.2 the position of this research is displayed with respect to predecessors of the method developed in this thesis. These tools and methods are also developed for end-of-life purposes at the TU Delft – OCP Applied Ecodesign group.

| Tool / method | Product Design | System operation | Policy Making | Environmental performance | Economic performance |
|---|---|---|---|---|---|
| Design evaluation (1995) | 0 | + | - | - | 0 |
| ELDA (1996-1999) | + | - | - | 0 | - |
| ELSEIM (2000-2001) | 0 | + | 0 | + | - |
| PMRCM (1998-2000) | 0 | + | 0 | - | + |
| → QWERTY/EE (2000-2003) | + | + | + | + | + |

- : not addressed  0 : partly addressed  + : well addressed

*Table 1.2 Positioning of research*

## 1.5 Structure of this thesis and readers guide

In line with the research questions of Section 1.3, the structure of this thesis is illustrated in Figure 1.2. After this chapter, the first research question will be discussed in Chapter 2 on the end-of-life of consumer electronics. The question on how to quantify environmental performance will be dealt with. After this chapter, two methodology chapters follow respectively on the second and third research question. These Chapters 3 and 4 form the methodological core and calculation framework on recyclability from an environmental perspective (QWERTY) and on balancing economics and environment in a comprehensive eco-efficiency concept (EE).

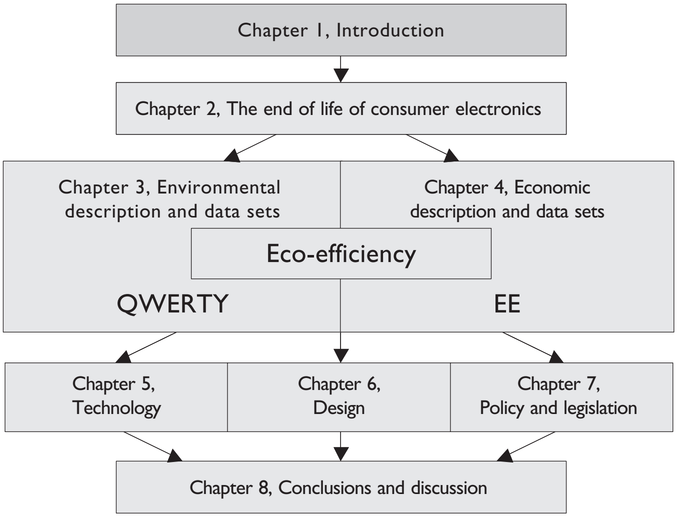


*Figure 1.2 Structure of this thesis*

The Chapters 5, 6 and 7 are addressing respectively the role of technology and end-of-life treatment from a product perspective (Chapter 5), Design for End-of-Life (Chapter 6) and policy, legislation and system operation (Chapter 7). In more detail: In Chapter 5, trends for the various product categories and improvement avenues in end-of-life processing (like plastic recycling and CRT glass recycling) will be discussed related to the environmental and economic performance of individual products. The influence of technological constraints as well as improvement options within these limits will be discussed referring to research question 4. In Chapter 6 will be elaborated on Design for End-of-life and the application of the QWERTY/EE concept on determining design priorities as well as the evaluation of actual redesign cases performed in cooperation with TNO-IND. This refers to research question 5. In Chapter 7 the focus will be on system operation, waste policy and legislation for take-back system. The further alignment of design and technology from the two previous chapters will be incorporated in the evaluation of current take-back and recycling legislation, as posed with research question 6. Also a further discourse on the role of individual stakeholders in current and future take-back systems will be presented. Finally in Chapter 8, overall conclusions and discussion takes place.

In Table 1.3 a 'readers guide' is included illustrating the chapters and sections of special relevance (after reading this chapter). This guide displays the main chapters where specific data, methodology or information can be found for specific target audiences addressed in this thesis.

| Target audience | Most relevant chapters (recommendations in bold) |
|---|---|
| Specific interest in end-of-life of consumer electronics | Everything |
| Core of this thesis | Chapter 2.3; 2.8; 3.3; 3.7; 4.4; 4.7; 5.7; 6.2; 6.7; 7.5 - 7.7, 7.10; 8 |
| General interest in environmental issues | Chapter 2; 3.1-3.4; 4.4; 8.7; **8.8** |
| Manufacturers, producers | Chapter 3.5; 4.5; 5.6-5.7; 6.7; 7.6; 7.9; 7.10; 8; **8.8.1** |
| Designers | Chapter 3.5.5; 6; 8; **8.8.1** |
| Recyclers | Chapter 2.3.5, 2.4; 4.3; 4.4; 5.6-5.7; 7.3; 7.5; 7.7.3; 8; **8.8.2** |
| Policy makers and legislators | Chapter 3.2; 3.3; 3.6; 4.4; 4.6; 7; 8; **8.8.3** |
| Take-back system operators | Chapter 4.4; 4.6; 7; 8; **8.8.4** |
| LCA-experts | Chapter 2.6; 3; 4.6.3; 5.8; 6.3; 7.8; 8; **8.8.5** |
| Metallurgists | Chapter 2.7; 3.3; 6.3.2; 7.3; 7.8; 8; **8.8.5** |

*Table 1.3 Readers guide*

## 1.6 Terminology and definitions

In the previous sections, already many definitions and keywords are introduced. In this section the most important terms and definitions are presented to avoid misinterpretations in the next chapters.

*End-of-life* and the *end-of-life chain* is defined as the part of the life-cycle of a certain product starting with the point of disposal by a customer (this can be a consumer, organisation or business) till the point where materials are re-entering production chains or are finally disposed. A part of this chain is displayed in Figure 1.3. Remanufacturing and reuse also fall under the end-of-life chain but are excluded from this research.

*End-of-life routes* are defined as the activity of treating products, product streams, components, assemblies or *fractions* in *secondary material processing* or *final waste processing* (the arrows in Figure 1.3)

*End-of-life scenarios* are defined as the total set of end-of-life routes for certain products, products streams, components, assemblies or *fractions* with *mechanical treatment, disassembly, reuse, remanufacturing, secondary processing* and *final waste processing* (the total settings and distributions over end-of-life routes in Figure 1.3). In other words when a product is shredded and separated and the resulting fractions are sent to respectively a copper smelter, a plastic recycler and a landfill, then this total set of end-of-life routes is the end-of-life scenario.

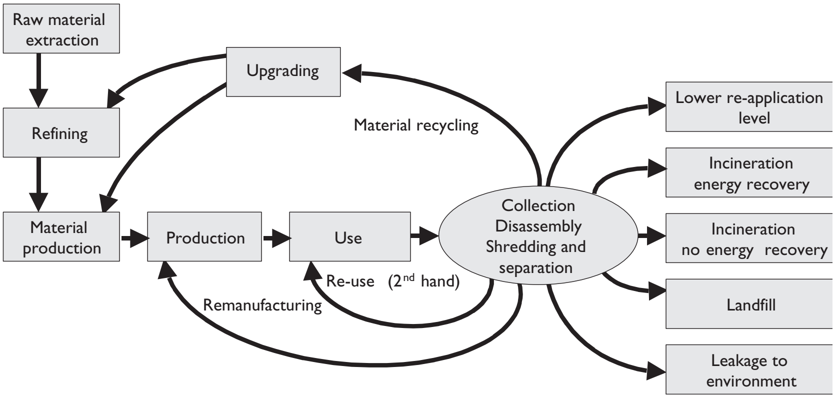


*Figure 1.3 The product end-of-life chain*

*Recycling* is used as a general term for treating (streams of) discarded products in one way or another after discarding by consumers. *Material recycling* is referring to the activity to recover materials by treating streams of discarded consumer electronic products in a central facility either with *mechanical treatment* and, or disassembly.

*Reuse* is defined as the 'second hand' trading of products, assemblies or components for use in its original purpose.

*Remanufacturing* is defined as the activity where reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned and inspected for possible repair and reuse.

*Mechanical treatment* is defined as the (sorting and) shredding of (streams of) discarded consumer electronics followed by separation of materials into *fractions* by processes like magnets, Eddy-Current separation or air tables.

*Disassembly* is either the manual or automated splitting of products in components or fractions (before an optional shredding step) to increase the value of certain fractions or the (obligatory) removal of contaminations and hazardous materials.

*Fractions* are defined as streams of multiple materials with one or more target materials to be recovered at *secondary processes* or as (residue) streams treated by *final waste processors*

*Secondary material processing* is defined as the activity aimed at specific recovery of one or more valuable materials like copper smelting, plastic recycling and CRT glass recycling.

*Final waste processing* is defined as the treatment of products, products streams, components, assemblies or *fractions* by landfill, controlled or uncontrolled, or by incineration of the product, with or without energy recovery.

*State-of-the-art treatment* is defined as the single *end-of-life scenario* reflecting the current average treatment of browngoods within the Dutch *take-back system*. The actual characteristics of this are discussed in Chapter 2.4.4.

*Collection rates* are defined as the percentage of a certain type of products handed and treated in a take-back system versus the total amount of products. Products in stock at consumers are not included in this definition. The non collected products are either exported or treated with MSW.

*Take-back systems* are defined as the total of sets of *end-of-life scenarios* of multiple products streams including collection and logistics of these streams and the corresponding organisational and financing systems.

*Design (for end-of-life)* is defined as the (incremental) product (re)design in order to improve end-of-life performance in environmental or economic terms. Incremental redesign is defined in this thesis as the redesign of products without altering the original product functionality and main specifications, within the technical and economical sboundaries currently applicable.

More definitions and all abbreviations used in this thesis are included in Appendix 1.

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# *Chapter 2: The end-of-life of consumer electronics and environment*

## 2.1 Summary

In this chapter the main factors and processes involved in end-of-life treatment are described. The way to determine environmental and economic behavior of single products within take-back systems and end-of-life processing is introduced. The relationships between the three perspectives: design, technology and policy are highlighted. An important step in the end-of-life chain, the shredding and separation of products into fractions is extensively described. Four different groups of shredding and separation settings are introduced as well as the way to adapt these in the methodology to be developed in the next chapters is discussed. Furthermore extended descriptions of all relevant secondary material processing options and underlying data are discussed.

The main technological, design and policy improvement options and strategies to investigate in this thesis are selected. These options are:

1. Technological improvement options:
   a. CRT glass recycling.
   b. Plastic recycling.
   c. Dedicated shredding and separation of metal dominated products.
   d. Separate collection and treatment of precious metal dominated products.
2. Design improvement options:
   a. Reduce or replace the amount of critical materials.
   b. Reallocate materials.
   c. Improve the unlocking properties of parts and components.
3. Policy and legislative improvement options:
   a. Prescribing minimum recycling targets.
   b. Prescribing minimum collection targets.
   c. Restrictions on the use of hazardous substances.
   d. Outlet control of secondary material streams.

## 2.2 Introduction

This Chapter 2 introduces the end-of-life stage of consumer electronic products and provides a further description of all main factors, stakeholders and processes involved. This chapter is the platform for the methodology to be developed as it contains the answers to the first research question:

Research question 1:

*What are the main factors and stakeholders involved in end-of-life processing of consumer electronics, what are their roles, what environmental issues are relevant and how are these issues currently evaluated?*

As a consequence, the aim of this chapter is to describe the (environmental) issues connected to disposed consumer electronics. All factors, stakeholders and processes involved in recycling of these products are described. The need and relevance of quantitative environmental and eco-efficiency analysis is determined.

Following this goal, the next steps are followed:

1. Description of the discarding of consumer electronics and the environmental issues connected to this (Section 2.3).
2. Description of the end-of-life processing chain (Section 2.4).
3. Description of the improvement options and how the alignment in the end-of-life chain from an environmental and economic perspective can be increased by:
   a. Technological improvements in end-of-life processing (Section 2.5.3).
   b. Design improvements (Design for End-of-Life), (Section 2.5.4).
   c. Changing policy, legislation and system operation (Section 2.5.5).
4. Description of tools and methods available with regard to environmental validation in general and environmental performance of end-of-life systems specifically (Section 2.6).
5. Description of the need for new and multidisciplinary methodology and the criteria to be met with new methodology and more advanced modelling of the end-of-life chain of consumer electronics (Section 2.7).

## 2.3 Disposed consumer electronics and environment

### 2.3.1 The product life cycle

In this section the product life cycle and the position of the end-of-life phase is discussed. The specific contribution of end-of-life to the total environmental impact over a life cycle is discussed in Section 2.3.2. The waste of consumer electronics within the Dutch situation and the different product categories for end-of-life processing are introduced in Section 2.3.3. The relevant materials in Section 2.3.4 and the 'double ensemble' issue which describes the behavior of material within products streams and complex take-back system is introduced in Section 2.3.5.

In Figure 2.1, the simplified picture of the product life cycle is displayed again. The main phases in this graph are raw material extraction, manufacturing, use-phase and end-of-life phase.

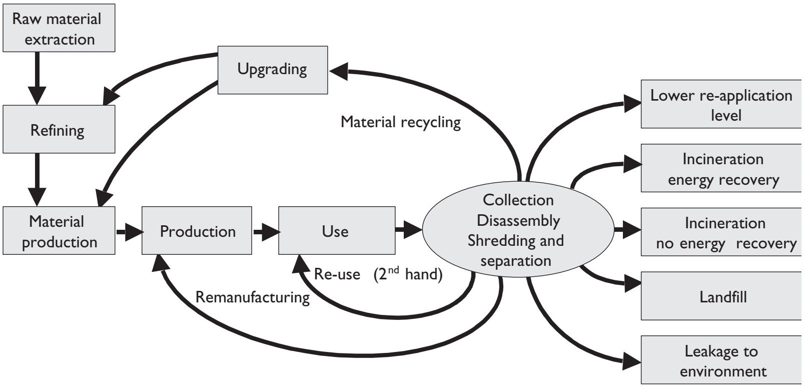


*Figure 2.1 The product life cycle*

The end-of-life phase starts at the point of disposal by a customer (consumer or business) and includes the following end-of-life routes, introduced in a traditional order of preference (Vogtländer 2000, Rose 2000a):

1. Re-use (life time extension)
2. Remanufacturing
3. Materials recycling
4. Lower level of reapplication (immobilisation, road pavement, building industry)
5. Incineration with energy recovery
6. Incineration without energy recovery
7. Controlled landfill
8. Uncontrolled landfill
9. Emission or leakage into the environment

The first two options will not be considered within the scope of this thesis. As already stated in Chapter 1.4, discarded consumer electronic products are regarded as economically or technically so old that higher levels of reuse options are usually not attractive (Rose 2001). This is valid for the products presented in Section 2.3.3, Table 2.1. The reuse options usually occur for products ending up in the second hand circuit, which is well developed for TVs and monitors for instance. This reuse can be regarded as a delayed disposal. The remanufacturing options are currently mainly applied for large IT equipment and for medical systems, product categories falling out of the scope of this thesis. In (Rose 2001) it is shown that for almost all consumer electronic products under investigation in this thesis, life time extension and remanufacturing are not preferable from an environmental perspective excluding two specific product categories: LCD monitors and cellular phones. Also by (van Nes 2003) a limited percentage of products is described with a reuse or remanufacturing potential. However, especially for the cellular phone, the wear-out life cycle (time from buying till disposal) is much shorter than the technology cycle (development of new product functionality and development). Therefore, the only products expected to have a substantial environmental and economic remanufacturing potential are the LCD monitors. For all other product categories, material recycling seems the final solution. After lifetime extension of products suitable for reuse of remanufacturing, these products will also be discarded sooner or later. Thus, for the development of new methodology as will described in Section 2.7 and later on in Chapter 3 and 4, product reuse and remanufacturing are excluded.

### 2.3.2 Position of end-of-life

The position and relevance of end-of-life in the total life cycle of an average consumer electronic product is presented in Figure 2.2. This graph is very generic, for some products (TVs), the use phase is far more environmentally burdening, for other products this is for instance the manufacturing stage (LCD monitors). The average figure 2.2 is based on the Eco-Indicator '99 approach, which will be introduced later in Section 2.6.2. The assumptions behind the determination of environmental impacts with single indicators are discussed in Chapter 3.4 in detail. The environmental impact of raw material extraction, manufacturing and the use phase (energy consumption) is set at 100% (excluding end-of-life). On average the environmental impact of raw material extraction is around 20%, the value for production and manufacturing (of components, assemblies and products from raw materials) is on average around 25%. Due to energy consumption over the full life cycle at the consumers, the environmental impact of the use phase is the most contributing at around 55%.

When end-of-life scenarios are compared with this 100% value, the disposal with Municipal Solid Waste (further referred to as MSW or the 'waste bin') of an average product results in an environmental impact of 3%. However, when under state-of-the-art recycling environmental value of materials is recovered, then a minus 13% is obtained. This minus is due to the fact that new primary material extraction is prevented in comparison to a 'non-recycling' scenario. In fact, the two end-of-life scenarios presented reflect the relevance of collection and treatment versus disposal.

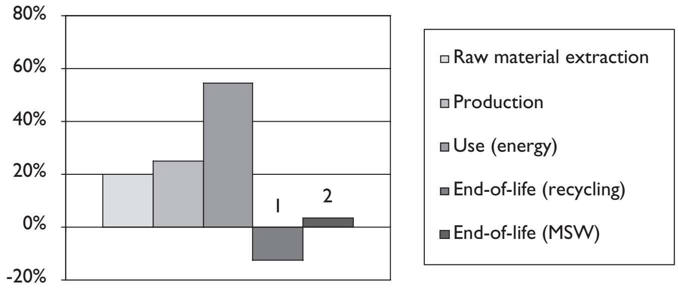


*Figure 2.2 Contribution of end-of-life to the life-cycle environmental impact*

This result is in contrast to (Boks 2002a) where is stated that the end-of-life phase only contributes around 2% to the total environmental burden of the life cycle. The following aspects cause the difference in results:

1. In (Boks 2002a) due to the older and more limited LCA database regarding end-of-life, in which only disposal as such with MSW is taken into account. This leads to a similar bar compared with the second bar of Figure 2.2. However, state-of-the-

art recycling would recover environmental value and prevent new material extraction and therefore a negative value is appearing. The allocation behind this will be further discussed in Chapter 3.3.1. The prevention of new material extraction is around – 13% of the total environmental impact and including all other environmental burdens of processing.
2. The calculations in (Boks 2002a) are based on the Eco-Indicator '95. In this method; no land-use and resource depletion values are present and very limited characterisation factors are available for the environmentally relevant substances present in consumer electronics. These issues are included in the more modern Eco-Indicator '99, which leads to Figure 2.2 (See Section 2.6 and Chapter 3.4.2 for more details on this LCA method).
3. Due to miniaturisation and lower energy consumption in standby and on-modes the relative importance of the raw material and production values and of end-of-life are continuously increasing over time.

Despite the significance of the '13% recovery of environmental impact' in state-of-the-art recycling, still the use-phase remains the most important. Ecodesign should therefore primarily be focused on reduction of energy consumption in the use phase and in comparison, less emphasis on the end-of-life phase. Also certain measures intended for improving environmental performance in the end-of-life phase should not interfere or enlarge the environmental burden in the use-phase and to a lesser extent in the production and manufacturing stage. This issue will be further discussed in Chapter 6 when actual redesign cases focused on improving end-of-life are presented.

### 2.3.3 Waste of consumer electronic products

Since the start of the Dutch take-back system, operated by NVMP (NVMP 2001a,b), the collection rates of discarded products have increased. In the system not only the high volume consumer electronics are collected but also whitegoods, IT equipment and household appliances. In 2001 it is estimated that 9 kton of browngoods or consumer electronics is collected on a total of 15 kton discarded appliances. For TVs a collection amount of 9 kton of an estimated 21 kton discarded appliances is described (De Straat Milieuadviseurs 2002). It is known that appliances not collected are only for a small percentage ending up in MSW (around 10%). The other appliances either remain in stock by consumers (bottom-of-the-drawer-effect) or appearing in the second hand circuit or are exported (De Straat Milieuadviseurs 2002, McLaren 1999). In Chapter 7 more details are presented on the collection rates and the 'leakage' streams of products.

In Table 2.1, some example products are presented for the different product categories of the browngoods under investigation. The products mentioned in the table will be investigated on their behaviour in take-back systems. The consumer electronic product categories and the alignment of technical, design and policy strategies in end-of-life processing relevant to optimise environmental and economic performance of these individual product categories will be extensively discussed in this thesis. In Chapter 5.6 more details on all products used in the calculations later on will be presented.

| Product Category | Example products |
|---|---|
| Plastic dominated | Portable audio, fax, audio systems |
| Glass dominated | TVs, CRT monitors |
| Metal dominated | VCR, DVD player, LCD projector |
| Precious metal dominated | Cordless and cellular phones |

*Table 2.1 Example products for the browngood product categories*

### 2.3.4 Environmentally relevant materials

In Table 2.2 the main environmentally and economically relevant materials in end-of-life processing of consumer electronics are presented (Griese 2001, van Houwelingen 1996, Deckers 1998a,b, Ansems 2002a).

| Abbreviation | Material | Abbreviation | Material |
|---|---|---|---|
| Ag | Silver | **Fe** | **Ferro** |
| **Al** | **Aluminium** | **Glass** | **Glass** |
| As | Arsenic | Hg | Mercury |
| Au | Gold | Liquid Crystals | Liquid Crystals |
| Be | Beryllium | Ni | Nickel |
| Bi | Bismuth | **Other** | **f.i. wood and cardboard** |
| Br | Bromine | Pb | Lead |
| Cd | Cadmium | Pd | Palladium |
| Ceramics | Ceramics | **Plastics** | **aggregated, excl. PVC** |
| Cl | Chlorine | **PVC** | **PVC** |
| **Cu** | **Copper** | Sb | Antimony |
| Cr | Chromium | Sn | Tin |
| **Epoxy** | **Epoxy** | Zn | Zinc |

*Table 2.2 Main materials in consumer electronics*

The materials in bold are main materials, the other materials generally have much lower concentrations. In this list, the flame-retardants are placed under the bromine content. The influence of these flame-retardants on end-of-life processing like incineration is not well known or modelled. Therefore the possible environmental effects of flame-retardants are connected to the bromine content in the product or fraction under investigation. A more detailed list can be found in Appendix 1.

### 2.3.5 The double ensemble issue

In many cases, the environmental performance of single product in end-of-life processing cannot be determined as such. The reason is that as a result of shredding and separation or disassembly operations (not for reuse of remanufacturing purposes), not single products are treated, but material streams. This is referred to as the ensemble issue (Boks 2002a). The product streams are transformed into fractions to be treated in a subsequent process, a secondary material processor or final waste processor. In fact, another ensemble issue occurs. A copper smelter for instance does not treat 'single fractions' but fractions of multiple sources. A combined copper smelter for instance takes in both fractions from secondary origin as well as primary materials from ores. This 'double ensemble issue' is displayed in Figure 2.3.

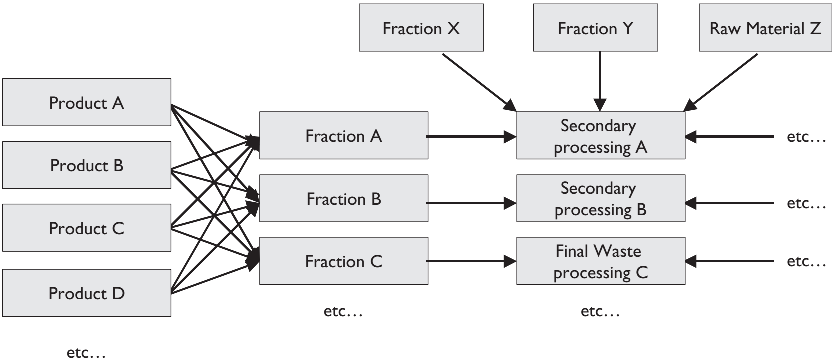


*Figure 2.3 The double ensemble issue*

Figure 2.3 is important for the quantification of environmental and economic performance of end-of-life treatment. The goal of this thesis is not only to determine system performance of large product streams and multiple environmental processing steps as a start for the environmental and economic calculations, but in the first place the performance of individual products and materials in given product and material streams in take-back systems as a whole. This **product perspective** can then in turn lead to evaluation of take-back systems. As later on will be discussed, this is an important starting point for connecting the areas of expertise involved. In practice, it seems impossible to track each individual product and material in the steps displayed in Figure 2.3. As a consequence it seems not realistic to describe the behaviour of single products or materials in a complex end-of-life system based on actual 'behaviour'. However, it is feasible to make a first order estimate on the double ensemble issue. This is represented in Figure 2.4. (In fact there are multiple materials in one product, multiple products in one productstream, multiple productstreams are converted to multiple fractions and multiple fractions are treated by multiple processing options).

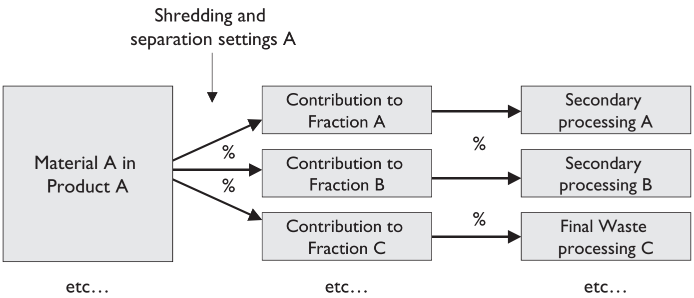


*Figure 2.4 Solution to the double ensemble issue*

The 'solution' or first order estimate for the double ensemble issue is to use average distribution tables for certain settings in shredding and separation for a certain product stream. This comprises the description of the distribution of materials over the end-of-life chain. In detail, this distribution of all materials over the various fractions results in so-called 'contributions to fractions' which on their turn are assumed to be treated as real fractions in subsequent secondary material or final waste processing. The distribution tables are a first order estimate of the chance of appearance of a certain material in a certain fraction. When calculated for all materials within a product, the contribution of the product as a whole to the resulting fractions is obtained. These imaginary 'contributions to fractions' are treated as real fractions in subsequent processing steps. In this secondary or final waste processing, again average distribution tables are used to describe the amounts of materials respectively recovered, ending up in other new fractions sent towards other processing (like slags) or emitted to air, water or soil. In fact, mass balancing of all materials present in the product under consideration is applied, describing the estimated routes of all materials in all processing steps involved.

Due to the focus on the performance of products in this thesis, calculations are starting with individual products and not with product streams. As a consequence both environmental as economic performance for all materials in a certain product under investigation over all relevant end-of-life processing steps can be related to this one single product. Subsequently, the contribution of many single products to a total system can be determined. Later on in this thesis with the development of environmental and eco-efficiency methodology it will be shown that this choice and 'solution' with respect to the double ensemble issue is crucial and is resulting in better understanding of the behavior of products in complex end-of-life systems and the aimed alignment of technology, design and policy. Particularly in Chapter 5 the solution to the double ensemble issue will be shown as very useful for determining the average behavior of individual products in complex end-of-life processing.

The above solution to the double ensemble issue is a crucial step within this thesis. Due to the high influence of this solution to the results presented later in this thesis, the subsequent distribution tables are checked by other experts on multiple occasions as will be presented in the Section 2.4.3.

In Chapter 3, more details will follow on connecting quantitative environmental descriptions to the behavior of products in end-of-life and in Chapter 4.3.6, more details will be presented on how to allocate economic penalties for materials in these 'contributions to fractions' in a certain end-of-life process like a copper smelter. In the next section, the shredding and separation settings and the required distribution tables will be discussed for the description of the left part of Figure 2.4. Also a short introduction of the secondary and final waste processes involved will be given.

## 2.4 The end-of-life chain

### 2.4.1 Collection of end-of-life products

In the Dutch system it is chosen to use municipal depots and retailers (old for new) as main collection points. In practice most discarded appliances are collected at the municipalities, to a lesser extent at retailers and just for a small percentage directly at so-called regional storage senters (RSS). The products collected at municipalities are sent to the RSS, the products collected at retailers are or sent to an RSS or trough a distribution centre (DC) towards recyclers (De Straat Milieuadviseurs 2002, NVMP 2002a,b). In Figure 2.5, these main routes are presented.

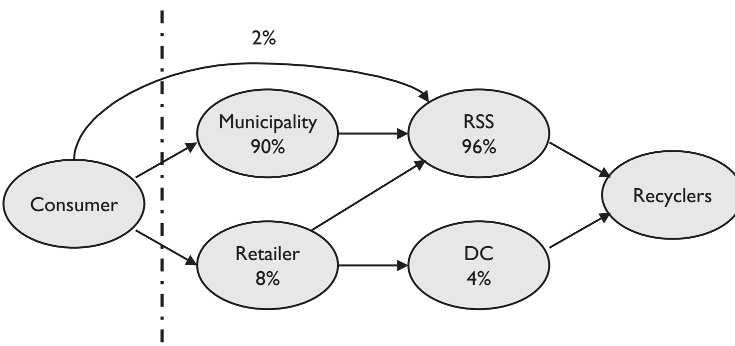


*Figure 2.5 Simplified routes for the Dutch take-back system*

In other European countries like Sweden, Belgium and Germany also other systems are used to collect disposed products like curb side pick-up, collection points at petrol stations and supermarkets, separate systems per producer or in rare cases even by postage (WEEE Executing Platform 2002).

With regard to collection rates, in Table 2.3 information on the streams of products is presented. Notice the high amount of appliances still in stock by consumers ('discarded' but not thrown away or handed in). The data on the amount of appliances within the second hand circuit is highly uncertain. For TVs a limited amount of appliances is treated via MSW. For other browngoods it is known, especially for small appliances that a substantial percentage ends up in the waste bin (around 35%). All data are derived from (De Straat Milieuadviseurs 2002).

| Category | Televisions (kton) | | Other browngood (kton) | |
|---|---|---|---|---|
| Year | 1998 | 2001 | 1998 | 2001 |
| Disposed | 14 | 21 | 20 | 25 |
| Bottom-of-the-drawer (in stock) | 43 | 38 | 74 | 54 |
| Collected and recycled | N.A. | 9 | N.A | 9 |
| Other (estimated) | N.A. | 1,7 | N.A. | 6 |
| MSW (estimated) | N.A. | 0,9 | N.A. | 4 |

*Table 2.3 Amounts of TVs and other browngoods collected in The Netherlands*

### 2.4.2 Disassembly

Disassembly is usually applied to CRT containing appliances (TVs and monitors) and to products suspected of containing batteries or hazardous materials and components (like LCD screens or PCB containing condensators). Disassembly costs for various products are dependent on measuring of disassembly times. For a broad variety of products these disassembly times are derived from (Brouwers 1995, Salemink 1998). The resulting disassembly times can be very different for 'long existing and well-developed' products with similar functionalities which are on the end of the design of their technology cycle. More advanced forms of disassembly like the use of ADSM (Active Disassembly using Smart Materials) based on self-disassembly with shape memory materials looks promising. A lot of research is already available (Chiodo 1999, Wiendahl 2001, Arnaiz 2002) but further research is still required to come to commercial applications. Also, the use of robots for automated disassembly is researched intensively and applied in some cases (Stobbe 2002, Kopacek 2002). Besides the standard disassembly operations used for separation of CRTs for glass recycling and large plastic housings for plastic recycling, the more advanced options are out of scope of this research.

### 2.4.3 Shredding and separation

The distribution tables mentioned in Section 2.3.5, as well as all underlying mass and energy balances of the end-of-life processing are extensively described in literature. These data are gathered by TNO-MEP and integrated in the calculations that will be described in this thesis. This data, published in (Ansems 2002a,b) is obtained from many literature sources and from contacts with Dutch and German recyclers. Other data sources on the matter are (Nordic Council of Ministers 1995a,b; European Trade Organisation for the Telecommunication and Professional Electronics Industry 1997; Zhang 1997). Out of all literature sources and based on the TNO-MEP research, three calculation modules were derived describing the distribution of all environmentally relevant materials over all fractions and end-of-life routes. Three types of shredding and separation settings, with process-step sequences representing best available technology in Europe are implemented in the calculation sequences used for this research. The three modules are:

1. Treatment of CRT containing appliances: Disassembly of housings and picture tubes (CRTs), followed by shredding and separation of the remaining, for CRT-containing browngoods. With this simplified picture as a result six fractions are creat-

ed: a plastics, glass, aluminium, ferro, copper and residue fraction. In Appendix 4, a more detailed process tree for this treatment is presented.

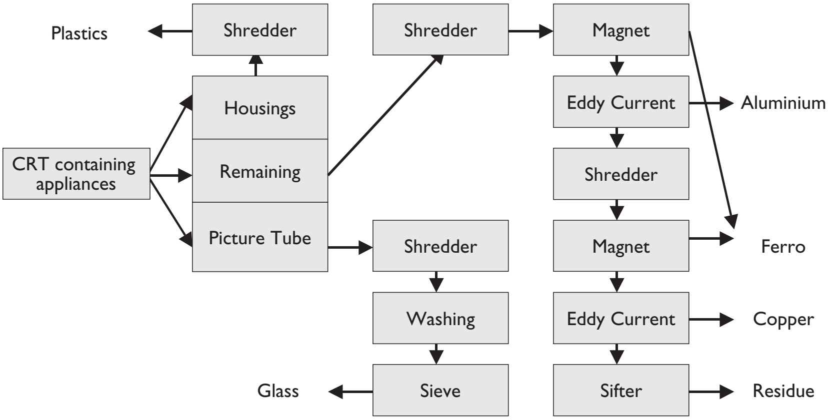


*Figure 2.6 Shredding and separation CRT containing appliances*

2. Shredding and separation of other browngoods (non-CRT appliances). This treatment is similar to the shredding and separation of the remaining of Figure 2.6. These streams are normally treated together when present at the same treatment facility. The result of this processing is four fractions: an aluminium, ferro, copper and residue fraction.

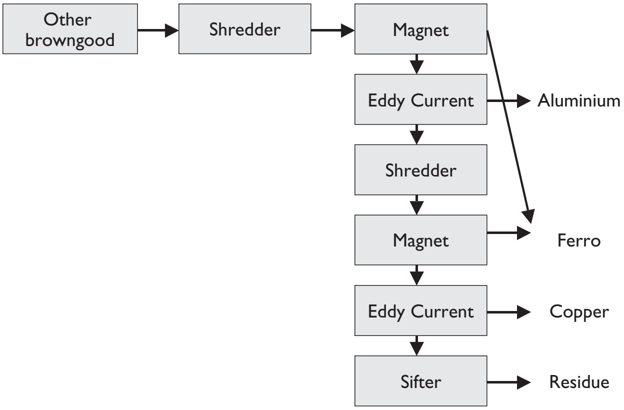


*Figure 2.7 Shredding and separation of other browngoods*

3. Special settings for shredding and separation to be applied after separate collection from the non-CRT stream of cellular phones are displayed in Figure 2.8. These settings are aiming at preventing losses of high precious metal concentrations to other fractions than the copper fraction. The result is a small ferro fraction and a large relatively 'contaminated' copper fraction with all valuable materials present.

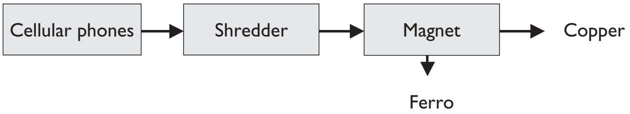


*Figure 2.8 Shredding and separation of cellular phones*

In addition to the TNO-MEP research, a fourth setting is included. Based on (Mirec 2002a) also the dedicated shredding and separation settings for metal dominated products are described:

4. Dedicated shredding and separation of modern metal dominated products with a low plastic content. These settings can be applied when batches of metal dominated products are collected separately and for which a relatively high precious metal content is expected. Most precious metals are present in the copper fraction.

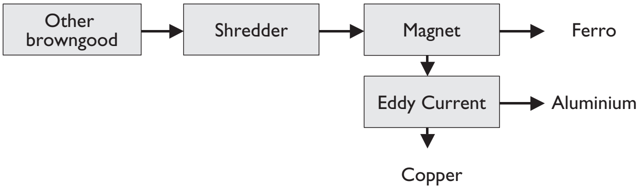


*Figure 2.9 Shredding and separation of modern metal dominated products*

The four general types of shredding and separation settings are converted to average distribution tables for the diversion of materials to each 'contribution to fraction' (further referred to as 'fraction'). The influence of these shredding and separation settings on the environmental and economic results will extensively be discussed in the next chapters. The first three calculation modules are also previously introduced in (Huisman 2001b) and evaluated by (Mirec 2002a).

### 2.4.4 Secondary material and final waste processing

The secondary material processes under investigation in this thesis and relevant for the fractions created by recyclers in the Netherlands are:

1. Copper smelter
2. Iron smelter
3. Aluminium smelter
4. CRT glass recycling
5. Ceramic industry (glass replacing Feldspar)
6. Building industry (glass replacing sand)
7. Plastic recycling
8. Cement kiln (for residue fractions)
9. MSW incineration (with and without energy recovery)
10. Landfill (under controlled and uncontrolled conditions).

Distribution tables and process descriptions for all these processes are derived from (Ansems 2002a) and included in this research and the underlying calculation sequences as presented in the next two chapters. Also the main transport distances, energy consumption for processing and other relevant parameters like recovery percentages are known and included. The environmental parameters involved in these processes are described in Chapter 3.4. The economic parameters involved are introduced in Chapter 4.3. More information is presented in Appendix 3 and 4.

## 2.5 Improving end-of-life system performance

### 2.5.1 Goals per stakeholder

In Chapter 1.1 the most important groups of stakeholders are introduced. The main goals of the stakeholders involved in end-of-life processing and take-back systems are enumerated below:

1. The goals of authorities and legislators should be to set meaningful environmental criteria in policies and legislation (per branch and/ or product category). The current situation regarding relevant policy strategies will be introduced in Section 2.5.5 and Section 2.8.
2. The goals and interests of producers (including designers) is to evaluate the effects of their products in end-of-life, sometimes including the effects of (re) design efforts. Predicting end-of-life costs as well as the option to audit recyclers, when a take-back system is realised, is important information from a business point of view to minimise end-of-life costs.
3. Recyclers and secondary processors can calculate tariffs and can predict the eco-efficiency effects of for instance technology improvement options considered. Also their role in closing material loops and their corresponding environmental relevance can be substantiated.
4. Consumers, consumer organisations and NGOs can examine whether sufficient environmental gain is realised for the money invested. Also the effectiveness of all kinds of green demands, perceptions and corresponding price tags should be measured.

In theory, the contributions of the various stakeholders should aim at maximising take-back system performance. In practice however, as addressed in the next section on Environmental Value Chain Analysis, single stakeholders tend to maximise their own interests, which doesn't necessary mean maximising societal benefits over the end-of-life chain.

### 2.5.2 Environmental Value Chain Analysis

Besides the interests described in the previous section, more insight is required in the role of the stakeholders and processes involved. Environmental Value Chain Analysis (EVCA) is a tool to gather more information on the streams of money, information, activities and products between different players of stakeholders (Rose 2001). The interests and goals of all stakeholders involved can be visualised in more detail. From there strengths and weaknesses of for instance a take-back system can be found. One of the benefits of EVCA is that it is possible to show where financial burden is really being placed (like fees from consumers to producers to recyclers and municipal waste processors) and whether this stimulates better environmental behaviour. In Figure 2.10 the four main groups of stakeholders are presented: the government, producers, consumers and recyclers. All activities, information, services and product streams are displayed in this graph.

Figure 2.10 must be seen as a general representation of the environmental value chain. In specific cases like for instance cellular phone recycling, also retailers, network operators and refurbishers play an important role and should be displayed separately.

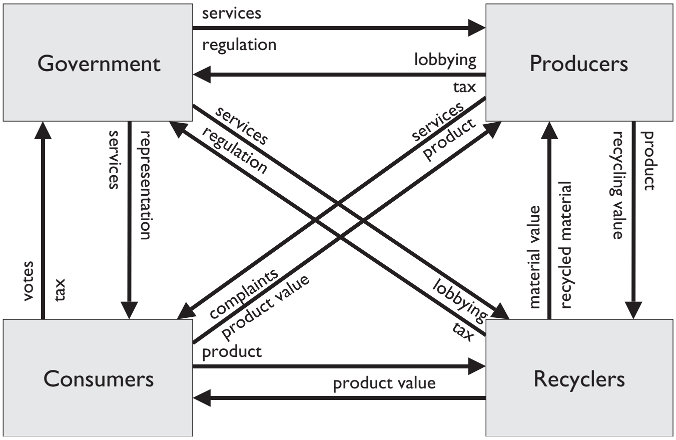


*Figure 2.10 Environmental Value Chain Analysis*

With a comprehensive eco-efficiency concept related to the main goal of this research (Chapter 1.2), the consequences of changes in the end-of-life chain induced by the stakeholders can be quantified. These improvement options per stakeholder are described in the next sections.

### 2.5.3 Technological improvement options

There are many technological improvement options possible to increase environmental and economic performance of end-of-life processing. For all processes described earlier in Section 2.4, changes or additions in processing are possible. This comprises other sorting and handling techniques, increasing disassembly efficiency or applying other disassembly techniques like Active Disassembly using Smart Materials (ADSM), (Chiodo 1999), use of robots for automated disassembly of valuable components from PWBs, changes in settings of shredding and separation process equipment, smelting techniques, more advanced flue gas cleaning at the thermal processes involved, pyrolysis or more dedicated processes for specific materials and fractions like glass recycling and plastic recycling. From this list three main technological improvement options are chosen as examples. The examples are mentioned on top of or in addition to the current end-of-life processing status in The Netherlands (further referred to as state-of-the-art recycling):

1. Plastic recycling is often regarded as a good way to increase recyclability of consumer electronics. On a weight basis, major improvements can be realised in recyclability scores. The question is however if this is true in all cases also when 'real' environmental and economic performance is determined. For many example products and different settings or end-of-life scenarios this should be determined. (This will be done later on in Chapter 3.5.6, Chapter 4.5.5 and Chapter 5.7.1 and 5.8.2). Plastic recycling includes colour sorting, cleaning and upgrading, which is relatively expensive depending on the types of plastics to be processed. It is expected that especially the size of the plastic housings has a high influence on the costs of plastic recycling while normally a disassembly step is required. Also, the availability of markets for secondary plastics play an important role.
2. CRT glass recycling (further referred to as glass recycling) is often not carried out due to a variety of reasons (Boks 2002a). The status of glass recycling in The Netherlands (Mirec, 2002b) will be discussed in Chapter 4.3.7. Currently only 15% of the CRT glass collected in The Netherlands is re-applied in new cone-glass. In fact, changing outlets towards more glass recycling is both a technological improvement options and an outlet control policy issue. No incentives exist at the present supporting the re-application of disposed CRT glass in new CRTs. This issue will be further discussed in Chapter 7.4.5, 7.5.3 and 7.10.2.
3. Dedicated shredding and separation of metal dominated products with a low plastic content. These settings can be applied when batches of metal dominated products are collected separately or sorted from the regular browngoods stream and when relatively high precious metal contents are expected. Two main effects, not losing highly valuable materials to other fractions (residue fraction) and not diluting the same valuable materials too much (copper fraction too large) are to be balanced. This issue will be elaborated on in Chapter 5.3.5.
4. Separate collection and treatment of precious metal dominated products (cellular phones and cordless phones). This requires substantial amounts of these products to be collected separately. The technological improvement option (which is in fact only shredding and the removal of some relatively large ferro parts) is already introduced in Figure 2.8. This option is not only a technological improvement option, but is also influenced to a large extent by collection, logistics and system operation. In Chapter 5.5.5 and 7.5.5 will be elaborated on this issue.

In Section 2.7, one of the most important processes involved, the copper smelter, as well as the base metal production will be further explained. In Chapter 7.8, more details regarding possible improvement options at metal smelters will be presented.

### 2.5.4 Design improvement options

Besides, the in general, technological improvement options presented in the previous section, also the influence of design, or more specific Design for End-of-Life, will be determined using actual redesign cases. These cases are worked out in detail by cooperation with TNO-IND (Eikelenberg 2003). The alignment of design in general will be discussed in Chapter 6, including the place of the methodology developed in the next two chapters in Design for End-of-Life procedures.

The main strategies for specific design for end-of-life are:

1. Reduce or replace the amount of critical materials. This strategy incorporates volume and weight reduction where possible. Furthermore the use of heavy metals can be avoided when components with less toxic substances are available. Also alloys containing toxic or disturbing elements for further processing can be prevented where possible. In Chapter 7.8, with the example of lead-free soldering as one of the restrictions on the use of hazardous substances, this will be further discussed.
2. Reallocate materials. With this strategy, cleaner fractions can be obtained. Based on analysis of problem areas within the product under investigation, in some cases reconfiguring of components or assemblies might be an option.
3. Improve the unlocking properties of parts and components. Both for shredding and separation as for disassembly, the unlocking properties of materials and components play an important role. The amounts of materials ending up in the 'wrong' fractions can be decreased by changing product architecture in general and by changing types, sizes or form of the connections between components or assemblies involved.

### 2.5.5 Policy improvement options

A very important incentive for take-back and recycling in the EU are the WEEE Directive and RoHS Directive, enacted in February 2003, regarding the end-of-life of electric and electrical products. This Waste of Electric and Electronic Equipment (WEEE) Directive prescribes mainly recycling targets to be achieved in end-of-life treatment for various product categories and a minimum collection rate for the total take-back system per country (Commission of the European Communities 2003b). Closely related, the RoHS Directive (Restrictions on the use of Hazardous Substances) prohibits the use of certain heavy metals and certain brominated flame-retardants in electric and electronic products (Commission of the European Communities 2003a).

The transposition of the WEEE Directive in national legislation and subsequent take-back systems must be performed by the EU member states before August 2005. In the WEEE Directive a high emphasis is given on prescribing **weight** based recyclability targets. The main strategies to improve take-back system performance from a legislative perspective are in general:

1. Prescribing recycling targets. This includes minimum percentages to be achieved with end-of-life processing per product category. In Table 2.4, these percentages are presented. (Commission of the European Communities 2003b). However, four very important questions regarding the scope of this thesis arise:

   a. Are the weight based recyclability targets the right means to improve end-of-life system performance for an environmental perspective and is this strategy also efficient from an economic perspective?
   b. Are the prescribed recycling targets unambiguous? Are the weight-based recyclability targets objective or subject to interpretation?
   c. Can different levels of re-application of materials be taken into account?
   d. Can a weight-based recyclability be measured and monitored in practice in take-back systems in place?

   A further elaboration on weight based recyclability targets will be presented in Section 2.8.2.

| Product category | Minimum recycling percentage | Minimum recovery percentage |
|---|---|---|
| Large household | 75% | 80% |
| Small household/ tools and toys | 50% | 60% |
| IT equipment | 65% | 75% |
| CRT containing | 70% | 75% |

*Table 2.4 Minimum recycling and recovery percentages in the WEEE Directive*

2. Prescribing minimum collection targets. In the WEEE Directive, a collection amount of 4 kg per inhabitant per annum is prescribed. The main questions regarding this strategy are:
   a. Are the collection targets the right means to improve end-of-life system performance for an environmental perspective and is this strategy also efficient from an economic perspective?
   b. What are the options for collection rate enhancing measures and the corresponding environmental and economic consequences also in respect to the logistic part of take-back systems?
   c. How can these targets be monitored?
   d. Which product categories are more important than others and can this be covered with prescribing collection targets?
3. The restrictions on the use of hazardous substances (RoHS-Directive). Also here the question is whether it is the appropriate and efficient means to improve environmental performance in end-of-life processing.
4. Outlet control of secondary material streams is hardly addressed in the WEEE Directive. This includes the prescription of which end-of-life routes are allowed for the various fractions resulting from shredding and separation like export or landfill bans. Secondly, end-of-pipe measures are an option regarding certain processes involved in end-of-life processing. The consequences of neglecting this important strategy will extensively be discussed in Chapter 7.6 and 7.7.

Besides the technological, design and policy improvements, also consumer behaviour and logistic changes can play a role. In this respect only certain specific logistic changes are described in this thesis in Section 5.7.4 and Section 7.7.2 Consumer behaviour is out of scope of this research.

In the next section, environmental validation and LCA methods are discussed. After this section, the descriptions of primary and secondary metal streams will be introduced. The questions introduced regarding the different policy and legislation strategies will be discussed in more detail in Section 2.8. In the concluding section, the gap between current policy strategies and actual environmental and economic performance in the end-of-life chain will be highlighted.

## 2.6 Environmental validation

### 2.6.1 Environmental validation methods

Determining on a quantitative way what the environmental effects of certain activities in our modern society are, is not easy. For instance, the overwhelming complexity and variety in ecosystems and the effect of 'disturbances' is impossible to capture in 'simple' models. Many approaches exist in order to approach the complex environmental reality:

1. Common sense. The most simple and maybe most effective method is common sense. With counting and measuring physical data, a good idea of what is good for the environment can be obtained. One of the practical forms is for instance the environmental benchmarking like in (Philips 2002m). With this benchmarking, environmental accounting is done based on physical data like energy consumption (in Watts) or weight (in kg). However no indications can be found on what issues are more environmentally relevant than others. Also Mass Flow Analysis (MFA), (Lave 1995) or Substance Flow Analysis (SFA), (Socolow 1994) fall under these 'common sense' approaches.
2. Environmental weight or factor methods. By counting materials, packaging and substances and by applying simple weight factors, environmental weight factors are obtained which can be compared. This method can be used in companies for quick scans. Also here, no good relation is established between actual environmental impacts and the very subjective weight factors developed by a limited group of people.
3. Life Cycle Assessment (LCA). The most sophisticated environmental validation method is LCA (Heijungs 1992, SETAC 1993, Goedkoop 2000). This method determines the relation between environmental impacts from a functional unit (a product or technique) towards environmental impacts and effects. Through weighting of the environmental effects a single indicator in points (or millipoints mPts) can be derived. In Figure 2.11 the methodology and the steps involved are further illustrated.

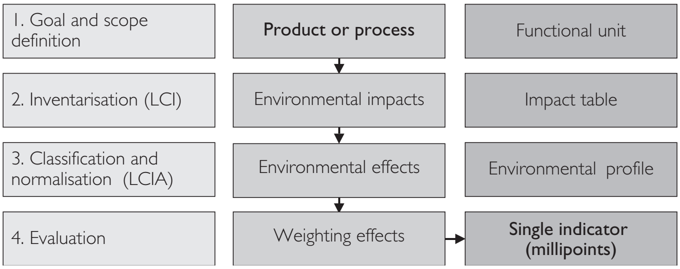


*Figure 2.11 LCA methodology*

Since the early initiatives in LCA many methodological improvement and underlying research has been carried out. This research is mainly focused on expanding Life-Cycle Impact Assessment (LCIA) and Life-Cycle Inventories (LCI). LCIA determines, groups and translates environmental impacts, like emissions towards environmental effects, like greenhouse effect or ozone layer depletion. LCI determines all environmental impacts of processes and steps involved to deliver a certain functional unit or product like the primary production of for instance 1 kg of primary copper. In the next section, the main LCA methods will be mentioned as well as their advantages and disadvantages. Firstly the general advantages and disadvantages of applying LCA are discussed.

Advantages:
1. The holistic approach and the life-cycle perspective. Assessment of multiple environmental impacts and subsequent weighting and determining priorities is possible.
2. State-of-the-art scientific research on all kinds of environmental aspects (toxicology, climate studies, epidemiology, geosciences, etc.) is connected to this approach.

Methodological disadvantages:
1. Subjective weighting. There is always subjective weighting involved in determining the weighting factors of Figure 2.11. In Section 2.3.6 will be elaborated on this main disadvantage.
2. Time scope and regional scope problems. Emissions and the subsequent environmental damage are related to the time frame of emissions and to the region where the emissions take place (an emission of eutrophicating substances is more relevant in The Netherlands than in the middle of the Sahara).
3. System boundaries. The determination of where system boundaries between multiple product systems are is sometimes very difficult. This counts especially for recycle systems (Ekvall 1997). In Chapter 3.3.1, a solution on this for evaluation of end-of-life systems is presented.
4. Rebound effects. With LCA no assessment is made on the value and consequences of the functional unit. When for instance two functional units are compared and one of them is ten times more expensive for a consumer, the consequence is less financial space to buy other products and probably lower environmental impacts (Vogtländer 2001).

Application disadvantages:
1. Applying full LCA is complicated and the procedures are time consuming.
2. Experts are needed for data collection, interpretation and publication according to the rules
3. Data requirements are very high in terms of amount, accuracy and reliability.
4. Results including subjective weighting are not permitted to be used in commercial communication according to ISO 14042 (ISO 14040).

### 2.6.2 LCA methods and choices

With respect to the central goals of this thesis as presented in Chapter 1.2 a choice must be made for a default environmental assessment method to be used as a default in this thesis. The environmental values to be used for end-of-life can be derived from any comprehensive LCA-method that leads to these scores, but also methods focussing one a single environmental effect, like, for instance, eco toxicity or resource depletion, can be used. The methods to be taken into consideration are discussed in this section:

1. The damage based Eco-Indicator '99 is used as the default method. In Figure 2.12 this method is displayed.

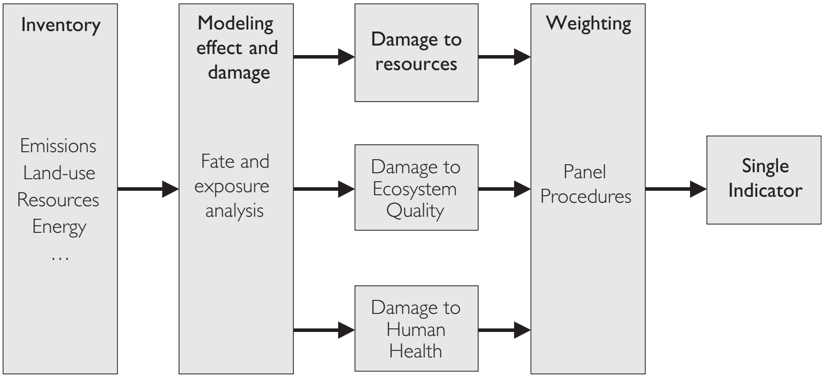


*Figure 2.12 The Eco-Indicator '99 method*

The Eco-Indicator '99 is a so-called damage based approach. In contrast to the traditional category based approaches (which follow the structure of Figure 2.11), a damage based approach tries to link the inventory phase to damage to ecosystems, human health and resources instead of categories like greenhouse effect, heavy metals, ozone layer depletion (which are a part of the damage assessment).

In the Eco-Indicator '99 also three types of perspectives play a role in the fate and exposure analysis, the damage assessment and the final weighting sets. These perspectives reflect different attitudes towards the environment, based on so-called 'Cultural Theory' (Hofstetter 1998):

a. The individualistic perspective: Only scientifically proven causal relationships are taken into account
b. The hierarchic perspective: All proven causal relationships and all facts and relations with sufficient scientific support are included.
c. Egalitarian perspective: The precaution principle is fully taken into account. All possible relations and effects are included even when highly doubted.

In this thesis the hierarchic perspective and corresponding average weighting set is applied because it is the most accepted choice and closest approximation of real environmental burdening. The weighting factor for resource depletion for minerals however is adjusted to 5%. The reason for this is discussed more extensively in Section 2.7.5. The reasons are that still substantial discussion goes on whether or not to include this damage category (some people regard resources depletion of minerals as just an economic problem). Furthermore, for some materials involved in consumer electronics the resource depletion characterisation factors are highly uncertain (for instance for nickel, tin and gold). In Section 2.7.5 more details will be presented regarding this issue.

The results of applying the Eco-Indicator '99 method are checked on their consistency with applying sensitivity analysis on the results also shown per individual damage category:

a. The subset in the Eco-Indicator '99 method for Ecosystem Quality (EQ) is used to acquire insights in the overall impacts of end-of-life treatment on ecosystems.
b. The subset in the Eco-Indicator '99 method for Human Health (HH) is used to acquire insights in the overall impacts of end-of-life treatment on humans.
c. The subset in the Eco-Indicator '99 method for Resource Depletion (RD) is used to acquire insights in the overall impacts of end-of-life treatment on resources.

2. The Danish EDIP'96 method (Wenzel 1997) is regarded up to day as a still rather modern, classic problem oriented approach. The advantage of the method is that comprehensive weighting sets are included. Therefore, this method is used as the first method to evaluate the results in this thesis on their sensitivity towards the use of the environmental assessment method. The weighting set however is excluding resource depletion.

3. The Eco-Indicator '95 is incorporated to check 'backwards compatibility' with respect to the new Eco-Indicator '99 method. Compared to more sophisticated and further developed LCA-methods, the method is 'old-fashioned' and will therefore not be used to check consistency of the results in the sensitivity analyses.

4. The EPS 2000 method (Steen, 1999) is incorporated and is in comparison with the Eco-Indicator '99 also a damage-oriented approach but with a very high focus on resource depletion. Also this method will not be used for consistency checks while the resource depletion aspects can also be covered with the Eco-Indicator '99, resource depletion damage category itself.

5. The Dutch CML method (Heijungs, 1992) is integrated as well. This method is lacking a weighting set by itself. Therefore a weighting set developed at TNO (Tukker, 1999) is applied.

Other available environmental assessment methods are the Swiss Ecopoints '97 (Braunschweig 1998) and the Fraunhofer IZM Toxic Potential Indicator (TPI), (Middendorf 2000, Nissen 2000). These methods will not be used in this thesis, because they are not included in the LCA software (Pre, 2002) and the default database used (Philips Consumer Electronics 2002n).

### 2.6.3 Subjectivity in LCA

An important consideration with respect to the use of LCA methods and methodologies for providing environmental values is the subjectivity related to the weighting of different environmental effects. As mentioned before, in this case ISO 14040 prohibits comparisons of products based on single environmental scores. However, the following considerations are relevant for the scientific character of using single scores in this thesis.

1. Subjectivity is inherent to environmental validation of any kind. When applying a concept like LCA with such a holistic perspective it seems logic to apply the methodology from the beginning to the end. No weighting means no prioritisation at all, which is probably even less 'scientific'.
2. In LCA, subjectivity is not only connected to the weighting steps, but also to the selection of environmental impact categories and methodology as a whole. The arguments for not applying a final weighting step should be applied to the methodology as a whole or not at all. Furthermore with the exclusion of weighting, the suggestion is made that both the incomplete methodology and data collected for a certain comparison is of an objective nature, which is not the case. For instance of the evaluation of flame-retardants, this issue is highly significant.
3. The weighting steps are derived from panel procedures (Goedkoop 2000) consisting of representative of all stakeholders involved in environmental validation. When consensus and agreement amongst all parties involved is reached, no major objectives against weighting and application of LCA remain. In (Bras-Klapwijk 1999) a practical approach is presented to deal with reaching agreement among stakeholders involved on the methodology to follow in product comparisons and policy issues.
4. Uncertainty in LCA results is not only originating from model-uncertainties but sometimes to a much larger extent from data-uncertainties or even due to a severe lack of inventory data.
5. The alternative for LCA is not to apply any priority setting of environmental impacts and themes at all. This alternative however is a violation of the important life cycle perspective and can lead to higher environmental impacts.
6. The influence of the weighting step can be determined by comparing results under single environmental categories and whether these results are in line with each other. This will be done for all main results and conclusions drawn in this thesis. As shall be proven later on, the various methods available show the same trend in the results in almost all cases.

With the choices made above, a starting point is created for evaluating all kinds of environmental impacts in end-of-life processing. Regarding the core goal of this thesis, streamlined environmental validation is needed to reach the proposed alignment of design, policy and technology. The use of the chosen environmental assessment method and the subsequent environmental results will be proven not to be very sensitive to the uncertainties and subjectivity describe before. In Chapter 3.6, Chapter 4.6.3, Chapter 5.8, Chapter 6.6.4 and 6.7.4 and Chapter 7.10.3, special attention is given to sensitivity of the results with respect to the chosen environmental assessment method.

The proposed alignment and quantitative environmental validation requires connecting environmental indicators to the behavior of products and individual materials as displayed in Figure 2.3 and 2.4 and will be further discussed in Section 2.8. In order to do this another connection has to be made: modelling the complex behavior of materials in primary and secondary production processes. This includes both the origin as (supposedly) final destination after creating fractions containing the metals present in consumer electronics. Also this information on the environmental 'value' of primary and secondary materials is essential in order to describe the end-of-life chain in quantitative terms and to determine the relevance of material recycling.

## 2.7 Interconnected primary and secondary material streams

### 2.7.1 Modelling base metal production

In this section, the complexity of treating secondary streams and determining environmental indicators of secondary processing is discussed. As later on will be shown, the metal content of consumer electronics has a high contribution to the environmental performance in end-of-life treatment. The sub stages in the end-of-life chain where secondary materials and especially where copper fractions are treated, will be shown to dominate environmental performance in many cases. Not only the secondary part of metallurgical processes, also the environmental assessment of primary metal extraction is relevant for this thesis, as this determines the need for closing material loops.

Furthermore, as will be shown later on, primary and secondary metal streams are often treated together in smelting and refining operations. In many cases, secondary materials streams in general should be fit as good as possible in primary production routes. As a result, robust and global descriptions of metal production routes and subsequent environmental validation are an important ingredient for determining the environmental performance of end-of-life treatment of consumer electronics. Besides the environmental consequences of secondary processing, it is also important to determine to what extent new primary material extraction is avoided to determine the effectiveness of recycling operations. Thus, regarding environmental validation it is essential to have accurate LCIs on the base metal production of the most important metals involved in consumer electronics: copper (Cu), lead (Pb), tin (Sn), zinc (Zn), the precious metals, silver, gold and palladium (Ag, Au, Pd), nickel (Ni) and to a lesser extent due to their use in lead-free soldering also bismuth (Bi) and antimony (Sb), which is also used in flame-retardants.

Regarding secondary material processing and metallurgy, collaboration has been started with two graduate students of the Department of Applied Earth Sciences, Delft University of Technology (Scholte 2002, van den Tweel 2003). By means of an actual case study, the LCA comparison of lead-free soldering versus traditional soldering, the global and global metal production has been modelled and connected to the Eco-Indicator '99 methodology (Scholte 2002). More backgrounds on the results for lead-free soldering are presented in Chapter 7.8. In this chapter the focus will be on the modelling of the environmental impacts related to base metal production on a global scale.

### 2.7.2 Interconnectedness of metal production

The production of metals is often thought to originate from single and clearly distinguishable raw material sources. This may lead to significant errors in calculating the environmental impact, because strong interconnections between metal production systems exist here. Significant parts of the silver production route are for example originating from 'by-products' of lead and copper mining. Lead and zinc are often mined together with bismuth as a by-product. Bismuth is also obtained from copper mining. In Figure 2.13 a part of the interconnections are displayed for the production of tin, copper, silver, lead, zinc and bismuth. The underlying process steps of mining operations, melting and refining furnaces have been extensively discussed in (Scholte 2002) for the models involved in lead-free soldering.

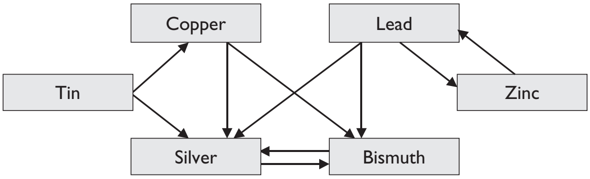


*Figure 2.13 Interconnections in base metal production*

Environmental data on metal production are often based on individual processes like a single copper smelter, where in reality the production of concentrates, secondary streams, intermediates and metals takes place on a global market. Essentially, global modelling of the base metal production would be the most accurate way to come to Life Cycle Inventories (LCI) for base metals to be used in environmental assessment. This is achieved with the research of (Scholte 2002, van den Tweel 2003) and the outcomes are integrated in the calculations presented later on in this thesis.

### 2.7.3 Global and dynamic modelling of base metal production

In order to come to such global modelling of base metal production, all relevant steps determining Figure 2.13 must be known in terms of environmental impacts and distributions of materials over each step individually. Left alone confidentiality reasons, it is practically impossible to have actual mass balances of each individual process step in the world (Chapman 1983). Therefore a theoretical modelling and mass balancing must be applied on the total number of similar process steps involved and the thermodynamic characteristics of these processes.

The methodology used to accomplish this illustrated in Figure 2.14. The proposed 'grey-box' model is essential to adequately describe the production routes as well as the interconnections between the metal cycles and is incorporated within a static model. The effects of global production of metals as well as time dependencies of the system are incorporated within the dynamic model, which is modelled with a software tool called Matlab. The modelling carried out by (Scholte 2002) is based on geological data and on data of all processes and refining steps involved. For all production routes for the base metals under consideration, the type of processing is determined as well as the input and output streams (ore and types of ore used as input and the production of base metals). Mass balances are constructed based on the type of smelter operation (which type of furnace is used) and the way of refining (pyrometallurgical or hydrometallurgical). The resulting mass balances for all production routes are built on split factors to follow the behavior of primary and secondary inputs.

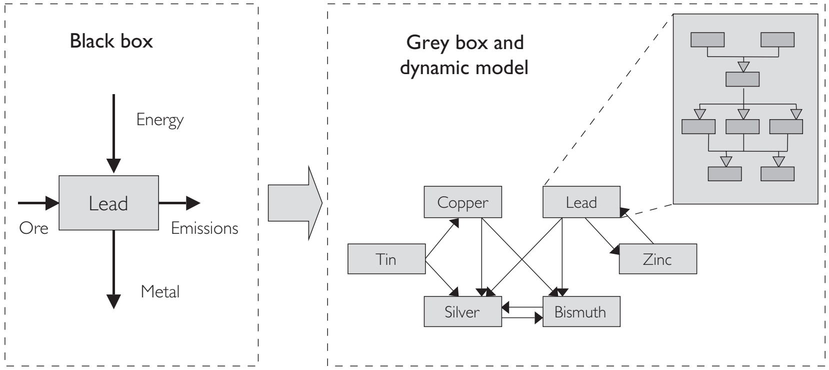


*Figure 2.14 Dynamic mass balancing*

The resulting static mass balances are corrected with a technique called data-reconciliation (Veverka 1997). The mass and energy balances of the resulting static modelling are the basis for a dynamic model built in Mathworks Simulink (Matlab 1992). With this dynamic model time dependencies and disturbances of the metal production systems are described. Further information on this matter can be found in (Scholte 2002, Verhoef 2003a,b).

### 2.7.4 Allocation problems

Many processes of the above static and dynamic modelling of metal production are involved in more than one metal production system. Environmental burdens of such a process must be allocated to the products. In (ISO 14040) allocation rules are found to deal with this problem. These rules can have significant impact on the results. The allocation rules are revised by (Ekvall 2001) for application in end-of-life systems.

Within current LCA studies interconnections between metals are generally not included, thus neglecting the importance of those intermediates for the production of certain important metals present in low concentrations. These interconnections give rise to allocation questions in making an environmental assessment. The three main routes are:

1. Allocation on basis of physical parameters like energy consumption
2. Allocation on a mass basis
3. Allocation on a economic basis

Allocation on a mass basis is advantageous for ores of diverse mineral composition, such as copper, zinc or lead ores. It reflects that besides copper, zinc or lead the processing of these ores introduces other metals into the system, for which no specific ores and extraction routes are available. The most preferred allocation route based on physical relationships is followed as far as possible in (Scholte 2002, van der Tweel 2003).

### 2.7.5 Modelling resource depletion

Another uncertain element in determining Life Cycle Inventories is the modelling of resource depletion. The modelling of resource depletion of minerals in the Eco-Indicator '99 method is based on the so-called surplus energy method. The effect of increasing energy consumption versus the amounts of materials extracted is displayed in Figure 2.15. With this method the extra energy required for mining equal amounts of metal under decreasing ore concentrations is described. In fact the slope of the curve at the current moment in time is used as a characterisation factor for the mineral resource depletion of the metal under consideration.

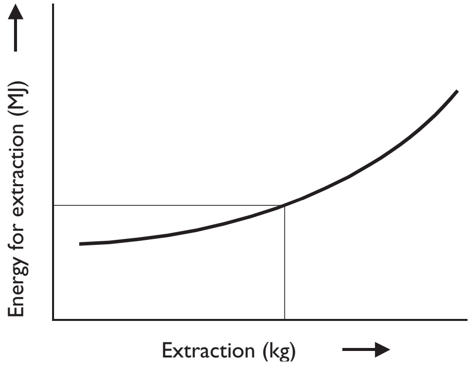


*Figure 2.15 Surplus energy method in Eco-Indicator '99*

The Eco-Indicator '99 approach is different from more traditional approaches based on the quotient of global metal consumption versus reserve base. The determination of the reserve base of minerals is subject to many different interpretations. From a methodological point of view, with the surplus energy method, the discussion on how much metal reserves are still available is avoided. The extraction and connected speed of increasing energy needed to acquire the same amount of metal over time is regarded as a better reflection of environmental damage. However in practice, for some metals the uncertainty in average ore concentrations and the slope of the curve in Figure 2.15 is very uncertain (Chapman 1983). This leads to overestimates of the mineral depletion values in particular for gold and nickel.

The above effect is one of the reasons to lower the weighting factor for resource depletion of minerals to 5% as discussed in Section 2.6.2. The uncertainty in resource depletion factors in the Eco-Indicator '99 methodology is also confirmed by (Spriensma et al. 2002). The decrease in weighting factor is applied to keep the resource depletion aspect included in the methodology on one hand and to avoid overestimation on the other hand. The sensitivity of the results as a result of this choice is checked where necessary. From this it is known that mainly the contribution of gold and nickel is lowered significantly and that the consequences for other metals are negligible.

In Chapter 7.8, with the discussion on the policy strategy of restrictions on hazardous materials, the lead-free soldering example will be used to discuss the above issue in more detail. With the descriptions of product behavior in end-of-life treatment, the choice for a quantitative environmental validation as well as the descriptions of base metal production and secondary processing, the main ingredients for a comprehensive quantitative environmental validation from a product perspective are in place. In the next section, the further development into methodology and the criteria or needs to fulfil are discussed.

## 2.8 The need for a quantitative approach

### 2.8.1 Description of the end-of-life chain

In this section the first research question of Chapter 1.2 is addressed:

Research question 1:

> *What are the main factors and stakeholders involved in end-of-life processing of consumer electronics, what is their role, what environmental issues are relevant and how are these issues evaluated?*

The main factors involved are shortly described from a product life cycle perspective and the position of end-of-life in this cycle. Also the issue and quantities of electronic waste are mentioned as well as a description of the ensemble issue and the right way to deal with this issue for evaluation of single products. Furthermore an extended description of the end-of-life chain including all relevant processes and activities has been presented as well as the possible improvement options from a design, technology and policy perspective.

Already in Section 2.5.5, the main policy strategies regarding discarded consumer electronics are introduced. One strategy is discussed in detail because it leads to important starting points for new methodology in the next chapters of this thesis. This strategy, the current status of prescribing recyclability targets will be mentioned and the gap between these definitions and actual environmental impacts during end-of-life will be sketched. In Section 2.8.3 the shortcomings of weight based recyclability are related to new methodology to be developed.

### 2.8.2 Recyclability definitions

The WEEE Directive (Commission of the European Communities 2003b) contains the following weight based recyclability definition:

*'The rate of component, material and substance reuse and recycling shall reach a minimum of x % by weight of the appliances.'*

The 'x' is already displayed in Table 2.3 for the various product categories. This definition seems driven by waste prevention in terms of weight only. Toxic materials, plastics and precious metals are not really contributing to this definition due to their relative low weight in consumer electronics.

The definition of recyclability in the draft WEEE directive is called material recycling efficiency in this thesis (MRE). This MRE is frequently applied in environmental accounting, operation of end-of-life systems and product development. However, major operational questions appear: is an average recyclability rate for products and brands falling under the same WEEE category sufficient for compliance? What sampling frequency is required for characterising the output flows of a recycling process? Who will monitor the quality and reliability of recyclability re-ports generated by recyclers and material processors? Should losses at material processing facilities like copper smelters be taken into account when calculating recyclability? Is the quality or re-application level of the secondary use of materials of importance? An environmental alternative for weight-based recyclability would lead to answers to these questions.

Weight based recyclability definitions are also subject to many different interpretations as well. The current WEEE Directive allows a lot of different interpretations of recyclability (MRE):

1. Material recycling efficiency based on the amount of materials treated by a recycler per total amount collected/ discarded.
2. Material recycling efficiency based on the amount of materials not sent to landfill per total amount of materials collected and discarded.
3. Material recycling efficiency based on the total amount of materials sent to secondary material processing, which is the weight of the fractions sent to the corresponding processors, e.g. the weight of copper fraction to the copper smelter and the aluminium fraction sent to a aluminium smelter.
4. Material recycling efficiency based on the amount of target materials sent to secondary material processing (the weight of the copper in the copper fraction sent to a copper smelter).
5. Material recycling efficiency including energy recovery based on one of the above definitions including energy recovery: for instance 18% of the combustible waste to be counted as recovered in addition to the amount of materials recovered like in (Ploos van Amstel Milieuconsulting 1997).
6. Material recycling efficiency based on the amounts of materials actually recovered and reapplied in its original form: e.g. the amount of copper and other recoverable materials in the copper fraction multiplied with the average recovery for copper and the other recovered materials at the copper smelter under consideration (this will be further referred to as the strict MRE definition).

Besides these 6 definitions, other mixed forms are imaginable. The disadvantages of the weight based recyclability definitions are already becoming clear. For instance every product entering the gate of a recycler, independent of its further treatment is accounted as being recycled with the first definition. It seems that the 'recycling definition' as meant in the WEEE Directive is closest to the third definition, but even then it is still not clear what is meant with 'other purposes'. Is a residue fraction to be used as a fuel in a cement kiln included in one way or another? Is a glass fraction used to replace feldspar in the ceramic industry counted or a plastic fraction used in road pavement/ asphalt included or not? As the implementation in national law is left to the individual Member States, it is feared that different definitions will be used per country. This may lead to unequal positions for instance for recyclers allowed to sent glass to a processor with a lower level of reapplication in one member state compared to other recyclers bound to stricter definitions in another member state. As a consequence, there will be also differences in costs for secondary treatment for different recyclers leading to unequal economic positions, which are in principle not allowed by the EU.

All the above definitions are not addressing actual environmental value. In an ideal situation and in order to have a more accurate definition, the following criteria should be dealt with:

1. System boundaries play a role when calculating recyclability scores. For example, when calculating an average recovery, is the produced volume, the discarded volume or the collected volume used as 100%? The WEEE rightfully sets targets for collected volume/discarded volume for collection and recovered volume/collected volume for processing. However, no target for discarded volume/produced volume is set, whereas still a wide gap exists between what is known to be discarded and what is produced. Many products disappear due to 'bottom of the drawer' effects or for instance due to exports.
2. Materials sent to a secondary processor, which are not recovered towards their original level of re-application, should be evaluated on their real environmental effects.
3. Materials that are recovered but that cannot reapplied due to market constraints, which happens for instance with CRT glass recycling should be evaluated on their actual environmental impacts and not their potential environmental gain.
4. The grade or reapplication level of secondary materials should be taken into account as well. Glass recycled to produce new CRT glass should be rated higher than secondary glass reapplied in the building materials as replacement for sand. This issue cannot be addressed with the current recyclability targets.
5. How to value relatively high environmental and economic burdens in end-of-life processing for instance for the use of additional chemicals for plastic recycling or for energy consumption or transport? In other words, 100% recycling can always be realised but against other environmental sacrifices and very high costs.

### 2.8.3 The basic nature of the approach of this thesis

The approach of this thesis as will be presented in the next chapters, is appealing to the common grounds for all stakeholders as described in Chapter 1.1 and also in line with the original intent of the WEEE Directive. Two important remarks are made as an introduction to the next two chapters:

1. The WEEE Directive is primarily set up out of environmental motives. The description of treatment performance and evaluation should therefore primarily take place in environmental terms.
2. The current WEEE Directive has not taken into account costs or efficiency aspects. This economic performance is highly relevant for all stakeholders involved. Therefore the question: how much environmental improvement is realised against which costs will be addressed in this thesis as well in a quantitative way.

The gap between the 'prescriptions' of the WEEE Directive and actual environmental performance will be extensively addressed in Chapter 3, where the development and introduction of methodology will take place. This replaces the multiple interpretations of weight-based definitions by one unambiguous environmental weight based definition. The economic efficiency, quantitative economic assessment and integral end-of-life costs calculations will be connected to this and will be introduced in Chapter 4.

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# Chapter 3: The QWERTY concept

## 3.1 Summary

The QWERTY concept (Quotes for environmentally WEighted RecyclabiliTY) focuses on the determination of environmentally weighted recycling scores rather than weight-based recycling scores. The concept describes the environmental performance of treatment of discarded products. It turns out to be very powerful in assessing the effectiveness of end-of-life processing, the consequences for design of products in relation to recyclability issues and the consequences of proposed legislation on take-back and recycling of consumer electronic products.

QWERTY takes into account the 'environmental value' of secondary materials and the environmental burden of end-of-life treatment itself. In this chapter the basic mathematical procedures for calculating QWERTY scores are presented as well as the application on a plastic dominated product for which several end-of-life scenarios are considered. The complex decomposing behaviour described in Chapter 2 into fractions has been modelled and integrated into the QWERTY calculations. With the application of the QWERTY concept is shown how well environmental goals of take-back and end-of-life treatment, reduction of material depletion, controlling potential toxicity and reducing emissions are reached in practice. The example of the plastic dominated product portable audio product, the Soundmachine shows its additional value to the alignment of policy and take-back system operation, technology and design in order to increase environmental performance of end-of-life treatment of consumer electronics.

## 3.2 Introduction

### 3.2.1 Backgrounds

Due to increased attention for producer responsibility and take-back of products, the environmental performance of end-of-life processing of products has become important. Until now, product recyclability has mostly been calculated on a weight basis only, which is a poor yardstick from an environmental perspective and it is scientifically very inaccurate and it can lead to incorrect conclusions regarding the initial environmental goals. Moreover, calculations based on weight-based recyclability are likely to lead to incorrect decisions. This notion has led to the development of the concept of

Quotes for environmentally WEighted RecyclabiliTY (QWERTY) for calculating product recyclability on a real environmental basis. Proposed take-back and end-of-life processing legislation for the electronics industry, the so-called WEEE Directive (Commission of the European Communities 2003b), has primarily been set up out of environmental motives. The description of treatment performance and evaluation of recyclability targets, should therefore also take place in environmental terms. Currently this is only the case in a very limited way.

A substantial amount of previous research has been conducted on mass balancing of disposed electronic equipment in end-of-life and the environmental consequences (Nordic Council of Ministers 1995a,b, European Trade Organisation for the Telecommunication and Professional Electronics Industry 1997, Zhang 1997). Nevertheless, still limited overall environmental insights exist. Important aspects for analysis are detailed product compositions (trace amounts of potentially toxic materials), specific behaviour of products in end-of-life processing (shredding and separation characteristics) and data from for instance primary and secondary metal smelters (recoveries of precious metals, heavy metal leakages). These data are rarely integrated in a comprehensive environmental evaluation of the end-of-life phase of consumer electronic products. With the current QWERTY approach, all the elements mentioned before are integrated into one environmentally based recyclability concept. In literature also some methods are already available, describing recyclability or recoverability indicators, but, without exception, they are all focusing on single issues, themes or target groups, like for instance the designer or the recycler (Mathieux 2001, Stobbe 2001, Hermann 2002a,b). In comparison with these 'performance indicators', the strength of the new and in itself unique QWERTY concept lies in its 'rethinking-character' of recyclability in terms of real environmental value of materials instead of recovered weight.

### 3.2.2 Objectives

This Chapter 3 is focused on the development of a consistent methodology for the description of environmental performance of disposed consumer electronics. This development is needed to determine what is summarised in the core research goal and the subsequent research question 2 from Chapter 1. This question directly links to the methodological quantitative description of environmental issues, the relevance and which steps to take to determine product recyclability in environmental terms:

Research question 2:

> *How can recyclability of products be quantified in measurable environmental units and a comprehensive method be developed to describe this end-of-life performance of consumer electronic products for different end-of-life scenarios?*

As a consequence, the main objective of this chapter is to develop a comprehensive method for quantitatively describing the recyclability of consumer electronic products in environmental terms for different end-of-life scenarios. Following this goal, a number of items should be covered with an accurate measure of this performance:

1. The concept should describe to what extent material loops can be closed, that is to describe in environmental measures how much material value is conserved.
2. The concept should describe how much unwanted emissions to the environment are avoided on the short and long term. This applies for instance to leaching of heavy metals from landfill sites.
3. The concept should be based on best available insights and state-of-the-art environmental validation.
4. The concept should address the level of re-application or grade and recovery of secondary materials.
5. The concept should give a proper description of the environmental performance of end-of-life treatment systems including the environmental load of logistics, energy consumption of processing and upgrading of materials.
6. The concept should indicate and prioritise where environmental improvements can be realised in end-of-life processing and which materials should be prioritised as well as analysis of which processes contribute the most.
7. The concept should determine from an environmental perspective what the best avenues for product (re)design for end-of-life are.
8. The concept should lead to an evaluation of the currently prescribed weight based recyclability targets in legislation.

The QWERTY concept, as explained in this chapter is capable to cover all these issues. In three publications (Huisman, 2000a,b; Huisman, 2001a), the concept has been applied to several case studies, enabling for example comparison with the application of the traditional weight-based recyclability (MRE). In (Huisman 2003a) the mathematics behind the concept are published. In this chapter all underlying equations and basic assumptions of the QWERTY approach are comprehensively presented as well as the application on evaluation of end-of-life processing, design and take-back policies.

### 3.2.3 Position of this chapter

The focus of this chapter is on the development of the QWERTY concept. But the first aim is to develop consistent environmental metrics. Therefore, in Section 3.3, the general ideas behind the QWERTY concept, the definition and underlying formulas will be introduced. In Section 3.4 the environmental and product data required for application of the concept are discussed. The aim of the Soundmachine example of Section 3.5 is to illustrate the usefulness, application bandwidth and limitations of the QWERTY methodology. In Section 3.7 extensive discussion will be presented on the data quality of the environmental parameters used as well as on the use of single environmental scores and the application of multiple environmental assessment methods. Finally, conclusions will be drawn in Section 3.7.

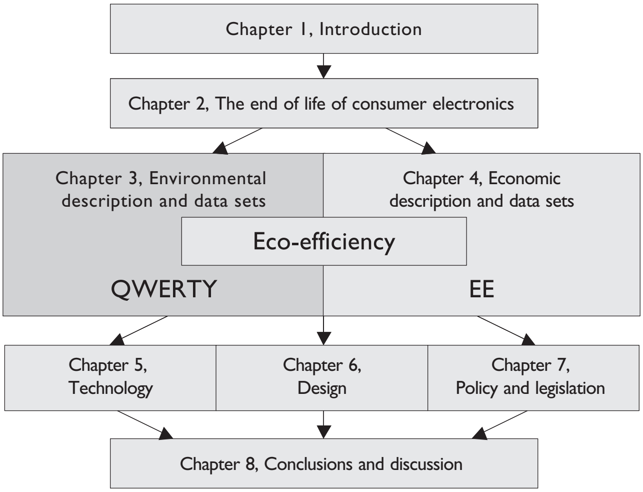



*Figure 3.1 Position of Chapter 3*

In Figure 3.1, the position of this chapter is presented. In the next chapters the application fields of QWERTY are further highlighted in detail. In Chapter 4, the QWERTY concept will be expanded with an economic leading to a comprehensive eco-efficiency method. In Chapter 5, trends for the various product categories and improvement avenues in end-of-life processing (like plastic recycling and glass recycling) will be discussed. Also the influence of technical constraints as well as improvement options within these limits will be mentioned in more detail. In Chapter 6, the focus is on Design for End-of-life and to what extend it can improve end-of-life performance. In Chapter 7 the focus will be on system operation and legislation, and further alignment of technology, design and policy will be presented.

### 3.2.4 Assumptions and terminology

In this chapter, environmental value is defined as the value or load that is calculated for a certain material or material processing using an environmental assessment model as described in Chapter 2.6. End-of-life routes are defined as the additional processes after disassembly or shredding and separation as mentioned before in Chapter 2.4.3. End-of-life scenarios are defined as a set of (different) end-of-life routes for the material fractions resulting from shredding and separation and/ or disassembly. All data, results and graphs presented in this chapter are based on the following assumptions:

1. State-of-the-art recycling is defined as the current settings in shredding and separation technologies and the destination of the resulting fractions to relatively modern smelters for the copper, ferro and aluminium fractions and residue fractions to modern MSW incineration.

2. Shredding and separation behavior of products is based on the distribution tables derived from (Ansems 2002a) and checked by TU Delft Geosciences and Mirec (Mirec 2002a).
3. Data are representing the Dutch take-back system.
4. Plastic recycling of housings is assumed to be technically possible. It is also assumed that other mixed plastics cannot be recycled due to the large variety in types and relatively low amounts.
5. The state-of-the-art recycling graphs and results are based on the occurrence of plastic within the other fractions, mainly the residue fraction to be treated in a MSW-incineration plant if not stated otherwise.

## 3.3 The QWERTY concept, basic equations and assumptions

### 3.3.1 The general idea behind QWERTY

The general idea behind the development of the QWERTY concept is to determine an environmentally justified alternative for Material Recycling Efficiency (MRE) and can be summarised as follows:

Instead of measuring recyclability in terms of weight recovered per kilogram of product, the QWERTY score is based on the net 'environmental value' recovered over the 'total environmental value' of a product.

To achieve this, the different material fractions of a product are weighed on an environmental basis, including the environmental impacts of end-of-life treatment itself. In either case, MRE or QWERTY, the recyclability of a product cannot be determined 'as such', but depends on an assumed end-of-life scenario for this product. As every end-of-life scenario has an (positive or negative) environmental impact, the aim of the QWERTY concept is to relate environmental scores to realistic best and worst-case end-of-life scenarios. To do this, a QWERTY score is always determined in relation to a well-defined theoretical best-case scenario, 'minimum environmental impact', and worst-case scenario, 'maximum environmental impact'. For the determination of the environmental impact of a product within an end-of-life scenario, the recovery percentage of the processing techniques and the associated environmental scores for recycling or treatment of non-recovered material fractions are calculated.

The starting point is that the disposed product, economically or technically so old that reuse or remanufacturing are not attractive. As considered in (Rose 2001), for the majority of consumer electronic products, opportunities for environmentally justified reuse or lifetime extension are very limited or sometimes even counterproductive. This last remark can be the case due to lower energy consumption levels of new products. In (Rose 2001) calculations are presented, analysing the reuse potential for a certain product or product category. When a reuse potential is expected, such calculations should precede the application of QWERTY.

This issue is previously addressed in Chapter 1.4. In this chapter, the starting point is material recycling according to the following scheme. Figure 3.2 illustrates the starting point for the further explanation of the QWERTY context. Here, it is shown that material fractions leaving the pre-treatment, shredding and separation or disassembly stage can for instance end up as materials either to landfill, directly emitted, incinerated, or to be used as substitution for primary materials. The latter case is what is usually referred to as recycling. The conventional approach of calculating weight-based recyclability scores, only addresses this route by taking the weight percentage of materials ending up in this fraction, without taking into account the environmental load of previous pre-treatment, shredding, separation and upgrading steps. Furthermore, the remaining fractions can still cause potentially toxic materials to be emitted to the environment whereas on a weight basis it is suggested that a good end-of-life performance is obtained.

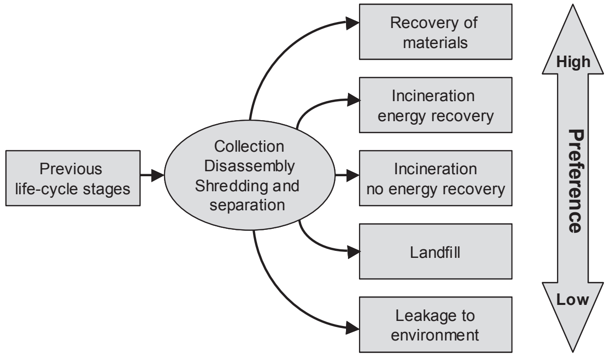



*Figure 3.2 Simplified end-of-life treatment structure*

The QWERTY concept addresses, besides the amount of material ending up in each fraction, also the 'environmental value' of each material fraction for every end-of-life route. Also the level of re-application or grade can be taken into account as explained later with Figure 3.4 for CRT glass. The replacement of primary materials can vary substantially for different materials because of differences in the prevented environmental load. In particular for precious metals for instance, higher environmental values exist than for the base metals like copper, aluminium and ferro. This is due to substituting the relatively high environmental load of the corresponding primary material production. Notice that the 'order of preferences' in Figure 3.2 is a general order often given for products as a whole. For specific materials or material fractions the environmentally preferred order can be different than depicted in Figure 3.2 as will be explained further in this chapter.

To calculate QWERTY scores, first the minimum environmental impact or maximum 'environmental recyclability' is defined representing a 'best case' end-of-life scenario for the product or product stream under investigation. Secondly also a 'worst case' end-of-life scenario or maximum environmental impact for the same product is determined. Then the relevant actual end-of-life treatment is determined and the distances between this scenario and the minimum and maximum values is measured. As the worst-case is set at the 0% level and the best case at the 100% level, consequently the actual environmental impact is a percentage in between in Figure 3.3.

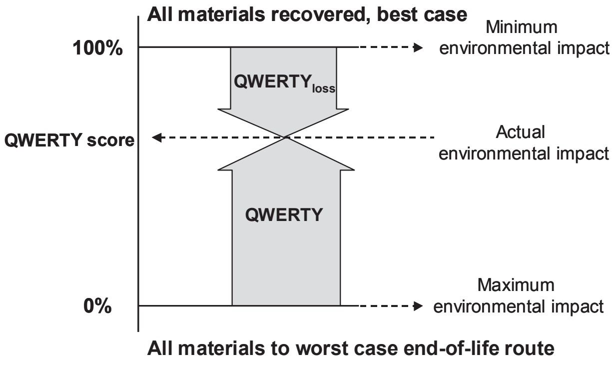



*Figure 3.3 Calculating QWERTY scores*

The result is the QWERTY score. The individual contributions of every material to the final score can also be determined. The whole procedure can also be applied to product categories, single components, assemblies or even product streams.

### 3.3.2 Definition of the minimum environmental impact

The minimum environmental impact or minimum environmental impact as depicted in Figure 3.3, is 'the best possible case' and defined as all materials recovered completely without any environmental burden to achieve this. More precisely: every material is recovered in its initial amount and grade without any environmental burden of treatment steps. Obviously this is an unreachable, and therefore a fixed theoretical optimal situation. Equation 3.1a and 3.1b describe this definition of the minimum environmental impact.

3.1a $$EVW_{\min,i} = m_i \times EV_{subst,i}$$

3.1b $$EVW_{\min} = \sum_{i=1}^{\infty} \left(m_i \times EV_{subst,i}\right)$$

With:

$EVW_{min,i}$ is the defined minimum environmental impact, maximum recovery of environmental value for the weight of material i;

$EV_{subst,i}$ is the environmental substitution value for the extraction of raw material for material i, measured with a relevant environmental impact assessment score;

$m_i$ is the weight of material i within the product;

$EVW_{min}$ is the total defined minimum environmental impact minimum environmental value for the complete product.

The environmental substitution values in Equation 3.1 can be measured with any suitable environmental assessment method (as further explained in Section 2.6 and Section 3.4). Equation 3.1 describes the avoided environmental impact associated with the recycling and subsequent reuse of all materials in a product. This part of the environmental impact is taken into account by determining the environmental value of primary material that is actually substituted and must therefore not be extracted from ores (metals) or to be manufactured (in case of plastics). It might be helpful to note that in all equations a positive environmental impact means environmental burden, whereas a negative one means an avoided environmental burden, which is referred to as an environmental gain. Therefore the $EV_{subst,i}$ and $EV_{min}$ are usually negative values.

The basis for the minimum environmental impact can be subject to choice. The current choice for the minimum environmental impact only depends on the product material composition and the corresponding original environmental value and is independent of many possible treatment scenarios. In case of including a reuse or remanufacturing potential, the choice could be altered with the environmental value connected to the components or complete product. Within the scope of this thesis, focusing on material recycling, the choice is made to start with the environmental value of the materials present in the product.

### 3.3.3 Definition of the maximum environmental impact

The definition of the maximum environmental impact or maximum environmental impact is the 'worst-case scenario' and is defined as every material ending up in the worst possible (realistic) end-of-life route, including the environmental burden of pretreatment: collection, transport, disassembly and shredding and separation into fractions. Important in this definition is that not one single end-of-life route for the product as a whole is selected, but the total set of, sometimes, different end-of-life routes for every material.

The reason for not choosing a single end-of-life route for the complete product is that some materials have very high environmental impacts on landfill sites due to high leaching percentages and high toxicity values for emissions to soil and water (for instance known for lead, nickel and antimony). Whereas other materials, with high toxicity values for emissions to air (for instance mercury, cadmium and arsenic), can have high transferrals to the gas-phase in incineration processes, combined with relatively low capturing percentages within the flue gas cleaning system and thus possibly resulting in high environmental impacts. In other words, this definition is reflecting the fact that the order of end-of-life treatment preferences is different for every material (see also Vogtländer 2001).
Calculations have shown for this definition that the highest environmental impacts for most materials occur in two routes, either uncontrolled landfill with maximum leaching to water and soil over a 100 year time period (which is a common worst case assumption in this field), or in incineration, without energy recovery and limited traditional wet flue gas cleaning, including all leaching from slag from residues. Accidentally,

materials can have high environmental impacts in one of the other 'realistic' scenarios (like for instance plastics in metal smelting operations). As a mathematical consequence, in the Equations 3.2a and 3.2b, the highest 'worst case' or maximum environmental impact will be selected by taking the maximum environmental impact value for material i out of the all 'realistic' end-of-life routes. Due to inclusion of state-of-the-art processing for instance for metal smelters, the maximum or worst case scenario will be lower than taking into account for instance metal smelters in other parts of the world like in China. In Chapter 7.8, an example will be given of the environmental consequences of a smelter with a less modern flue-gas cleaning.

Another practical benefit of this definition is that the total maximum environmental impact value can only be exceeded under 'unrealistic' conditions. In the calculation of the contribution of different materials to the total QWERTY score, no negative values occur. These negative values are basically not a mathematical problem within the concept, but can be difficult to interpret in practice.
Scenarios excluded in this definition are the 'unrealistic' scenarios, like for instance uncontrolled incineration without any gas cleaning (which can cause instantaneous health and safety problems and is obviously prohibited). The definitions of the maximum environmental impact are given in Equations 3.2a and 3.2b.

3.2a $$EVW_{\max,i} = m_i \times \left(EV_{\max eol,i} + EV_{pretr,i}\right)$$

3.2b $$EVW_{\max} = \sum_{i=1}^{\infty}\left(m_i \times \left(EV_{\max eol,i} + EV_{pretr,i}\right)\right)$$

With:

$EVW_{max,i}$ is the defined maximum environmental impact/ for the weight of material i;

$EV_{max\ eol,i}$ is the maximum environmental impact for material i in the end-of-life scenarios under investigation, e.g. the 'worst case scenario (usually or incineration without energy recovery, or uncontrolled landfill).

$EV_{pretr,i}$ is the aggregated environmental value for material i undergoing pre-treatment steps (f.i. transport and storage, complete shredding and separation);

$EVW_{max}$ is the total defined maximum environmental impact or maximum environmental value for the complete product.

The reason for including the pre-treatment part in the definition is the fact that the energy needed for pre-treatment and the energy needed for shredding products can be substantial. For the current definition where the part of the maximum environmental impact depends on certain processing steps, the assumed pre-treatment is possibly dominated by the energy to shred the disposed products into small pieces. This energy consumption is to a large extent independent of the product composition and a relatively stable value.

### 3.3.4 Determining the actual environmental impact

The actual environmental impact of a certain product (see also Figure 3.3) in a certain end-of-life scenario is represented by Equations 3.3a and 3.3b. The actual impact for the total amount of material i, is the sum of all this material ending up at the end-of-life destinations as represented by Figure 3.2, multiplied with the corresponding environmental value for this direction. Here, all pre-treatment, shredding and separation and recovery steps are included. The environmental value of recovered material, as well as the 'environmental costs' for all necessary shredding and separation steps are represented this way.

3.3a $$EVW_{actual,i} = m_i \times \left( EV_{pretr,i} \times x_i + rec_i \times grade_i \times EV_{subst,i} + \sum_{j=1}^{\infty} \left( EV_{eol,ij} \times y_{ij} \right) \right)$$

3.3b $$EVW_{actual} = \sum_{i=1}^{\infty} \left( m_i \times \left( EV_{pretr,i} \times x_i + rec_i \times grade_i \times EV_{subst,i} + \sum_{j=1}^{\infty} \left( EV_{eol,ij} \times y_{ij} \right) \right) \right)$$

With:

| | |
|---|---|
| $EVW_{actual,i}$ | is the defined actual environmental value for the weight of material i for the end-of-life scenario under consideration; |
| $x_i$ | is the percentage of material i undergoing the defined pre-treatment steps; |
| $rec_i$ | is the percentage of material i being recovered and substituting its corresponding primary material; |
| $grade_i$ | is the grade in which material i is occurring after recovery (only relevant for recovered material with a different level of re-application compared to the original material) see Section 3.3.5; |
| $EV_{eol,ij}$ | is the environmental value for material i going into end-of-life route j; |
| $y_{ij}$ | is the percentage of material i ending up in end-of-life route j; |
| $EVW_{actual}$ | is the defined actual environmental value for the complete product and the end-of-life scenario under consideration. |

In Equation 3.3, the pre-treatment steps and the actual recovery of materials is described separately from possible end-of-life routes. Although in the end probably only a part of a material fraction is actually recovered, the product is likely to undergo the end-of-life treatment as a whole. Therefore all environmental burden of pre-treatment steps is allocated to the whole product on a weight basis. The $EV_{eol,ij}$ represents the environmental value of the part of material i which ends up in a certain end-of-life route, for instance incineration. The total amount of material i ending up in each end-of-life route plus the actual amount of i that is recovered, must equal 100% as represented by Equation 3.4. Usually the $EV_{pretr,i}$ and the $EV_{eol,ij}$ are positive values, the $EV_{subst,i}$ is a negative value.

3.4 $$\sum_{j=1}^{\infty} y_{ij} = 100\% - rec_i$$

### 3.3.5 Level of re-application: grade versus recovery

In Equation 3.3, a very important parameter is the grade of secondary materials in comparison with the original grade. Except metals that are recovered in their original grade at their primary smelter, all other secondary materials are usually not recovered in their original form. For metals recovered at a smelter this value for the grade will be 100%. For metals used in alloying produced at other smelters or end-of-life routes, the grade will be lower than 100%.

Plastics for instance are usually not recovered with the same quality of the original material due to degradation. For materials undergoing degradation, quality loss and a resulting lower re-application level, it is defined as the quotient of the environmental value of the secondary material over the environmental value of primary material. In the case of CRT glass, which is not very often used in its original form, the influence of the grade in relation to recovered environmental value is significant. It is often re-applied in a lower quality for instance as a replacement for Feldspar in the ceramic industry or as replacement for sand in the building industry. For all these options, the connected (primary and secondary) environmental value is calculated and plotted in Figure 3.4.

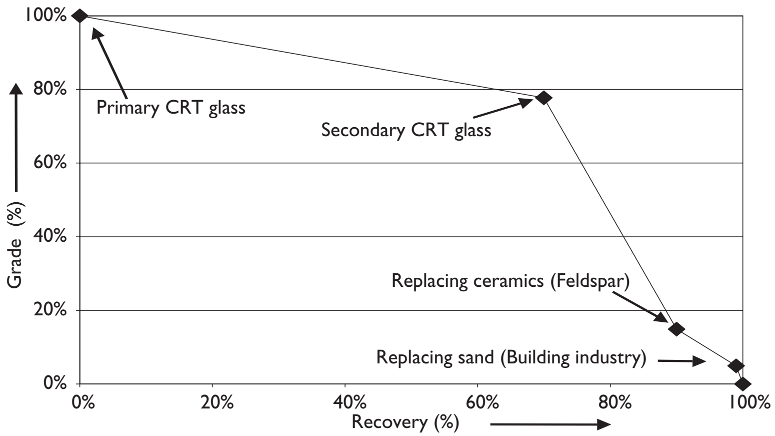



*Figure 3.4 'Environmental grade' versus recovery for CRT glass*

In the methodology proposed, the original or primary production value represents a grade of 100%. Four points are shown in Figure 3.4 representing a lower environmental value with respect to the original environmental value. These points are the value for primary CRT glass with 100% grade. Due to the fact that this situation cannot be reached without environmental burden connected to cleaning and upgrading processes, this situation never can be realised in actual practice. The second point is in practice the best achievable situation with 70% material recovery and re-application to produce new CRT glass. The third point and fourth point are respectively representing the replacement of feldspar in the ceramic industry and sand in the building industry. The environmental values connected to these two lower levels of re-application are substantially lower, respectively 20% and 5%. It can be concluded from Figure 3.4 that for CRT glass the level of re-application is an important parameter.

Note that the chosen definition for grade is based on **environmental** reasoning and not on the more common 'concentration' based definition, used for instance in metallurgy. For instance for recovery of copper back to the original so-called copper A-grade (99,99%), the 'environmental grade' is in this thesis 100%. However, the similarities between the two types of definition are large, when Figure 3.4 is compared to the similar graphs for recovery – grade functions as discussed for instance in (Zhang 2000) based on the classical 'concentration' approach. This is due to fact that the higher the concentration, the higher the quality or grade of the fraction of material under investigation and also the higher the environmental value. In other words, the concentration of original material is often in line with the corresponding environmental value.

A weight based recyclability definition cannot address properly loss of environmental value due to lower levels of re-application of materials. However, with the application of Equation 3.3 and the inclusion of the various points of the above graph in the calculations, this issue very well be dealt with in the QWERTY concept.

### 3.3.6 Determination of the actual QWERTY score

With the determination of the actual environmental impact, a figure is calculated that represents an absolute value for the weighted environmental impacts of a particular product in the end-of-life stage. With this absolute figure it is not yet transparent whether the results are good or bad from an environmental perspective. A normalisation step is performed to obtain QWERTY scores that can easily be interpreted (and thus be compared with traditional weight-based recyclability scores). The product's actual end-of-life performance is always positioned in between the upper and lower boundaries and leads to the QWERTY value by applying Equation 3.5. Similarly, the $QWERTY_{loss}$ is the distance of the actual environmental impact from the minimum environmental impact, as represented by Equation 3.6.

3.5a $$QWERTY_i = \frac{(EVW_{actual,i} - EVW_{\max,i})}{(EVW_{\min} - EVW_{\max})}$$

3.5b $$QWERTY = \sum_{i=1}^{\infty} \left( \frac{(EVW_{actual,i} - EVW_{\max,i})}{(EVW_{\min} - EVW_{\max})} \right)$$

And:

3.6a $$QWERTY_{loss,i} = \frac{(EVW_{\min,i} - EVW_{actual,i})}{(EVW_{\min} - EVW_{\max})}$$

3.6b $$QWERTY_{loss} = \sum_{i=1}^{\infty} \left( \frac{(EVW_{\min,i} - EVW_{actual,i})}{(EVW_{\min} - EVW_{\max})} \right)$$

With:

| | |
|---|---|
| $QWERTY_i$ | is the amount in which material i contributes to the total QWERTY score (in percent); |
| QWERTY | is the QWERTY score for the complete product; |
| $QWERTY_{loss,i}$ | is the amount in which material i contributes to the total QWERTY loss score (in percent); |
| $QWERTY_{loss}$ | is the QWERTY loss score for the complete product. |

3.7 $$QWERTY + QWERTY_{loss} = 100\%$$

The QWERTY score expresses the environmentally weighted recyclability of a product in a certain end-of-life scenario; the $QWERTY_{loss}$ score expresses the 'distance' to the best possible performance. Both scores can also be expressed per individual material present in the product, which is one of the main strengths of this concept, because it leads to a quantification of the environmental improvement potential. In practice, Equation 3.7 also helps to check whether the assessments made with the QWERTY calculations were consistent and the mass balances applied correctly.

In order to make comparisons with the traditional way of addressing recyclability, the most common equation for material recycling efficiency is given in Equations 3.8a and 3.8b. As stated before, the definition of MRE in many legislative documents is ambiguous. For instance the energy recovery from plastics is in some cases (very arbitrary) taken into account as 50% material recovery and in other cases even as a 100% material recovery (Kalisvaart 2000). In this thesis, this definition of weight-based recyclability is used in a strict from: only materials actually recovered at a secondary material processor (for instance also copper recovered at a ferro smelter) and thus preventing new primary material production is taken into account. This definition is already presented and discussed in Chapter 2.8.

3.8a $$MRE_i = m_i \times rec_i$$

3.8b $$MRE = \sum_{i=1}^{\infty} \left(m_i \times rec_i\right)$$

With:

| | |
|---|---|
| $MRE_i$ | is the contribution of the weight of material i to the Material Recycling Efficiency; |
| MRE | is the total Material Recycling Efficiency for the whole product weight and the corresponding end-of-life scenario under consideration. |

## 3.4 Environmental data

### 3.4.1 Introduction

In the previous section the generally applicable equations of the QWERTY concept are given. The practice of assessing environmental aspects of disposed consumer electronic products leads to a number of requirements necessary to evaluate the end-of-life of consumer electronic products. These requirements deal with the following issues:

1. Choices regarding environmental assessment methods (Section 3.4.2).
2. Use of LCA-software, inventories and databases (Section 3.4.3).
3. Product compositions and levels of detail (Section 3.4.4).
4. Description of end-of-life scenarios (Section 3.4.5 till 3.4.11).
   a. Collection and transport (Section 3.4.5)
   b. Shredding and separation (Section 3.4.6)
   c. Incineration (Section 3.4.7)
   d. Landfill (Section 3.4.8)
   e. Copper smelter (Section 3.4.9)
   f. Other secondary material processing (Section 3.4.10)
   g. Transport distances (Section 3.4.11)

### 3.4.2 Choices for LCA and related methods

The basic QWERTY concept described in Section 3.3 uses 'environmental values' (see Equation 3.1-3). These values can be derived with any comprehensive method that produces these scores, but also methods focusing on one single environmental effect, like, for instance, eco toxicity or resource depletion, can be used. In Chapter 2.6 the relevant methods are already presented. As a default choice, the Eco-Indicator '99 is used (Goedkoop 2000), but in addition also other sets of LCA-methods are incorporated in the QWERTY calculation sequences and used for detailed analysis and consistency check on the results:

1. The damage based Eco-Indicator '99 is the default method. The hierarchic perspective and average weighting set applies. Within this method, the weighting factor for resource depletion is adjusted to 5% (see Chapter 2.6).
   a. The subset in the Eco-Indicator '99 method for Ecosystem Quality (EQ) is used to acquire insights in the overall impacts of end-of-life treatment on ecosystems.
   b. The subset in the Eco-Indicator '99 method for Human Health (HH) is used to acquire insights in the overall impacts of end-of-life treatment on humans.
   c. The subset in the Eco-Indicator '99 method for Resource Depletion (RD) is used to acquire insights in the overall impacts of end-of-life treatment on resources.
2. The Danish EDIP'96 method (Wenzel et al. 1997) should be regarded as a rather sophisticated, classic problem oriented approach. The advantage of the method is that comprehensive weighting sets are included. Therefore, this method is used as the first method to check QWERTY results on their sensitivity towards the use of the environmental assessment method. The weighting set excludes resource depletion.

   a. A separate weighting set in the EDIP'96 methods exists for resource depletion only. This set can be used for evaluation of the RD set of the Eco-Indicator '99
3. The Eco-Indicator '95 is incorporated to check 'backwards compatibility' with respect to the new Eco-Indicator '99 method. Compared to modern LCA-methods, the method is 'old-fashioned' and outdated and will therefore not be used to check consistency of the results.
4. The EPS 2000 method (Steen 1999) is incorporated and is in comparison with the Eco-Indicator '99 also a damage oriented approach but with a very high focus on resource depletion.
5. The Dutch CML method (Heijungs 1992) is integrated as well. This method is lacking a weighting set of itself. Therefore a weighting set developed at TNO (Tukker 1999) is applied.

Other available environmental assessment methods are the Swiss Ecopoints '97 (Braunschweig 1998) and the Fraunhofer IZM Toxic Potential Indicator (TPI), (Middendorf 2000, Nissen 2000). These methods will not be used in this thesis, while they are not included in the LCA software (Pré Consultants 2002) and the default database used (Philips Consumer Electronics 2002n). However, in an older publication, a comparison is made including the TPI method (Huisman 2001a).

Further considerations with respect to the use of LCA methods and methodologies for providing environmental values are enumerated below.
1. In LCA there is always a 'subjective' evaluation step involved to weigh different environmental themes and to produce a single end-point score. This is inherent to aggregated environmental scores of any kind. One reason for choosing the Eco-Indicator '99 is that, compared to other LCA methods, it is the most transparent one regarding influence of different environmental perspectives and opinions of all factors that influence the final end-point score (and not only the final weighting step). It is also possible to integrate single themes used in LCA-methods within the QWERTY calculations, which provides the final weighting step not to occur, but it limits the relevance of results to single environmental themes only.
2. The starting point of the QWERTY concept is not the same compared to LCA. The focus of QWERTY is on the product's end-of-life, while LCA methods regard the full life-cycle of products, hence different system boundaries and allocation rules apply. Due to this different starting point, the QWERTY concept regards materials that are not recycled as causing extra environmental load by extra raw material extraction. Due to this choice, many problems with allocation and the definition of system boundaries are prevented (Ekvall 1997). See also Figure 3.2.

### 3.4.3 LCA software, inventories and databases

The following remarks regarding the LCA-software, the Life-Cycle Inventories and databases are important:
1. The environmental scores of the LCA software and default database are used (Philips Consumer Electronics 2002n) in the QWERTY calculations. A broad description and overview of the structure of these calculation sequences is avail-

able in Appendix 1. Environmental scores for emissions to air, soil and water as well as the primary and secondary production values are included for all materials mentioned in Table 2.2 of Chapter 2.3.4 for all above mentioned environmental assessment methods.

2. An important requirement is an environmental database providing environmental values for all relevant end-of-life processing steps and materials (Philips Consumer Electronics 2002n). For all relevant processing of materials, the mass and energy balances must be transferred to corresponding environmental values. Especially for the end-of-life phase of products, there are usually many data gaps within current LCA-databases. The TNO-MEP descriptions of end-of-life processing (see Chapter 2.4.3) are the main source of environmental data. Together with the Philips internal LCA-database a sufficient amount of data on materials, components, end-of-life processing steps, energy consumption, emissions and contribution of related processes is present. On these data will be further elaborated in the Sections 3.4.5 till 3.4.11. The LCA software tool SIMAPRO is used for calculation of all environmental scores (Pré Consultants 2002).
3. Accurate and representative Life-Cycle Inventories (LCI) for the base metals are necessary for sound environmental assessment methods of electronic products. The standard available LCIs on metals are not very well representing the global markets of secondary and primary metals. Therefore in cooperation with the TU Delft, Geosciences Department, new dynamic models and inventories have been produced for the environmental assessment of lead-free soldering. This concerns the important metals, copper, tin, silver, zinc, bismuth, antimony, lead, nickel, gold and palladium (Verhoef 2003a,b, Scholte 2002, van den Tweel 2003). In Chapter 7.8, a more detailed explanation follows on this subject.
4. In the standard Eco-Indicator '99 method, there is no well-developed inclusion of the acute human toxicity part. Till recently, fate and exposure analysis of the behavior of substances in the environment is based on models for organic substances. These models are not applicable on the important inorganic substance like metals. This lack in the methodology is dealt with and has lead to an improvement in the LCA-software (Spriensma 2002) and is also included in the environmental calculations of this chapter. More information on this matter is also presented in Chapter 7.8 for the lead-free soldering example.

### 3.4.4 Product compositions and levels of detail

To apply the theoretical outline of the QWERTY concept, a full and as accurate as possible chemical composition should be known, or at least estimated in cases where only rough figures are available. To deal with this issue in practice, three levels of detail are defined.

1. Level 1: Only the main materials are known, being the copper, ferro, aluminium, glass, plastic and rest content. Experience has shown that with these materials, per product category, good estimations can be made for both the actual product composition (Philips Consumer Electronics 2002a) and the distribution of materials over the relevant end-of-life routes (Huisman 2001a). In practice this means that rough QWERTY assessments can be made, based on the six aforementioned

materials alone. However, exceptions are single products with, in comparison to their product category, high amounts of toxic materials or precious metals.

2. Level 2: The amount of all relevant materials and their average distribution over all occurring fractions are known. This refers to the shredding and separation process descriptions of Chapter 2.4.3. In this case the processing applied to, for instance, the copper fraction is allocated only to the materials recovered from this fraction. The copper lost to other fractions from which it is not recovered only adds to the corresponding value to the QWERTYloss value. In practice this means an estimated average loss due to materials ending up in the 'wrong' fraction, which can be quite substantial.
3. Level 3: Whenever a product composition is known in full detail and the specific distribution of all materials over all fractions and end-of-life destinations is known as well, the equations of Section 3.3 including all environmental values for every material can be applied in their fullest form for every possible material. This will in practice rarely be the case, as analysing product compositions with this level of detail requires substantial effort, which is very costly. Moreover, the decomposition behaviour and mixing of materials within various end-of-life processing steps is usually so complex, that a specific distribution of materials over fractions can't technically be measured. Thus only average distribution percentages of materials over fractions will be known.

Based on the above reasoning, the most accurate assessments in practice will be that of using detailed product compositions, including chemical analysis (level 3) and estimated fraction compositions (level 2). The most frequent method is the estimation of the product compositions on basis of already available analysis and parametric assessments. In this thesis most product compositions are based on this level of detail. Nevertheless, with the important example products used to illustrate the methodology for instance, full chemical analysis is available.

### 3.4.5 Basic environmental parameters: collection and transport

The collection distance for consumers to hand in disposed products at retailers and municipalities is estimated to be 10 km single distance on average and transport per car is assumed. The subsequent transport from retailers and municipalities to so-called regional sorting senters (by 16 ton trucks) and recyclers (by truck 40 ton) has been estimated at around 250 km. Chapter 4.3.2 presents more information on the collection stage with the discussion on logistics costs. With the LCA database, the resulting environmental scores for the transport distances and transport loads are determined for all environmental assessment methods introduced in Section 3.4.2 and included in the QWERTY calculation sequences (see Appendix A).

### 3.4.6 Basic environmental parameters: shredding and separation

As addressed before, the distribution percentages for the fraction compositions are described in (Ansems 2002a) and are obtained from many literature sources and from contacts with Dutch and German recyclers and also in (Nordic Council of Ministers

1995b, van Houwelingen 1996, Zhang 1997, Zhang 2000). These data are checked by experts from (Mirec 2002a) and by experts from Fraunhofer IZM (Stobbe 2002). See Chapter 2.4.3 for more details. In addition, the energy consumption during shredding and separation and concentrating of materials is derived from (Ansems 2002a; van Houwelingen 1996). A typical example for treatment of a regular browngoods stream is illustrated in Table 3.1.

| Process | **Energy consumption** (kWh/ton) |
|---|---|
| Shredder 1 | 20 |
| Shredder 2 | 40 |
| Magnetic Separation | 0,6 |
| Eddy-Current | 5 |
| **Total** | **65,6** |

*Table 3.1 Typical energy consumption of shredding and separation*

The above energy consumption is allocated on all materials undergoing the individual treatment steps on a weight basis. The relevance and contribution of the environmental impacts of this energy consumption are connected with standard LCIs based on average European electricity production (can be very different per country) within the LCA-software and incorporated in the QWERTY calculations. The influence and contribution of this stage to the overall impacts of end-of-life treatment will be discussed in Section 3.5.

### 3.4.7 Basic environmental parameters: incineration

From (Ansems 2002a) also an incineration model for the description of consumer electronic fractions in MSW incineration plants is included. This model is developed at TNO and adjusted to reflect conditions for consumer electronics. The model includes data on distribution of metals to the flue gas, the bottom ashes and flue ashes. Flue gas cleaning efficiencies and leaching from slags of the main elements in electronics is included. This model is directly connected to the QWERTY calculation sequence and the corresponding environmental scores for all elements and materials. In Table 3.2 a part of this model is presented.

| Element | to flue gas | to air | to water |
|---|---|---|---|
| Hg | 93,0% | 0,4220% | 0,0011% |
| Cd | 77,0% | 0,0500% | 0,0555% |
| As | 29,0% | 0,1000% | 0,0002% |
| Se | 68,0% | 0,2000% | 0,0000% |
| Cr | 8,0% | 0,0000% | 0,0007% |
| Sb | 36,0% | 0,0000% | 0,0000% |
| Cu | 4,0% | 0,0000% | 0,0001% |
| Pb | 32,8% | 0,1988% | 0,0011% |
| Zn | 37,0% | 0,2000% | 0,0007% |
| Sn | 33,0% | 0,2000% | 0,0037% |
| Ni | 5,0% | 0,0000% | 0,0074% |

*Table 3.2 Estimated leakage of metals in MSW incineration*

The sensitivity of the QWERTY results to the incineration parameters of the above model will be discussed in Section 3.6.

### 3.4.8 Basic environmental parameters: landfill

From (Ansems 2002a) also a leaching model for the description of consumer electronic fractions in landfill scenarios is included. This model is developed at TNO-MEP and adjusted to reflect conditions for consumer electronics. The model includes many expert data on leaching behavior of the elements involved. Also the treatment of percolation water and the resulting incineration of the cleaning residues is included and integrated in the incineration model of the previous section. Also this model is directly included in the QWERTY calculation sequence and connected to the environmental scores for all elements and materials involved, both for controlled and uncontrolled landfill sites. In Table 3.3 again a part of this model is presented to illustrate the parameters for different materials.

| Element | to soil | to air | to water |
|---|---|---|---|
| Hg | 0,0004% | 0,0000% | 0,0071% |
| Cd | 0,0001% | 0,0000% | 0,0026% |
| As | 0,0001% | 0,0000% | 0,0022% |
| Cr | 0,0001% | 0,0000% | 0,0019% |
| Cu | 0,0002% | 0,0000% | 0,0045% |
| Pb | 0,0001% | 0,0000% | 0,0016% |
| Zn | 0,0000% | 0,0000% | 0,0006% |
| Cl | 0,2933% | 0,1035% | 1,4373% |
| Ni | 0,0002% | 0,0000% | 0,0040% |

*Table 3.3 Estimated leaching of metals in a controlled landfill*

Also in this case the sensitivity of the QWERTY results connected to the above model will be discussed in Section 3.6.

### 3.4.9 Basic environmental parameters: copper smelter

The description of environmental data at an average copper smelter is obtained through (Verhoef 2003a,b; Scholte 2002; van den Tweel 2002). These data are based on global and dynamic mass balancing over copper smelter processes. Included in the QWERTY calculation sequence are energy consumption, average recovery percentages of metals, energy recovery estimates for the plastics in a certain fraction and the final emissions to air, water and soil as well as the treatment of flue gas cleaning sludges. In Chapter 7.8, more details will be presented for copper smelter operations. In Table 3.4, only the average recoveries of metals are made explicit.

| Element | Recovery |
|---|---|
| Cu | 95% |
| Ag | 97% |
| Au | 98% |
| Pd | 98% |
| Ni | 90% |
| Pb | 90% |
| Sn | 90% |
| Cd | 90% |
| Hg | 90% |

*Table 3.4 Average recoveries of metals at a copper smelter*

The dynamic modelling by (Verhoef 2003a,b; Scholte 2002; van den Tweel 2002) is included as well in the QWERTY calculation sequence. The sensitivity of the QWERTY results connected to the above model will be discussed in Chapter 7.8.

### 3.4.10 Basic environmental parameters: other secondary material outlets

1. Aluminium and ferro smelters: Distribution tables from (Ansems 2002a) are known for the main materials directed to emissions to air, water and soil for both processes. Also included are energy consumption, average recovery percentages of metals, energy recovery estimates for the plastics content in a certain fraction and the final emissions to air, water and soil as well as use of auxiliary materials like cokes and lime. All data are connected to the corresponding environmental scores for all environmental assessment methods and included in the QWERTY calculation sequences.
2. Glass treatment: In Chapter 4.3.7, Table 4.6 more details will be presented for the average treatment of old CRT glass in The Netherlands and the percentages of glass sent to various end-of-life options. The basic parameters for glass recycling

are 10 kWh/ton for crushing and separation and cleaning of a glass fraction and 25 MJ/ton for smelting operations (Mirec 2002b).

3. Cement kiln: Residue fractions are often sent to a cement kiln (Ansems 2002a, Verein Deutsche Zementwerke 2001). Again all data are coupled to the corresponding environmental scores for all environmental assessment methods and included in the QWERTY calculation sequences.

| Element | to air |
|---|---|
| As | 0,10% |
| Cd | 0,08% |
| Cr | 0,10% |
| Cu | 0,07% |
| Hg | 4,81% |
| Ni | 0,10% |
| Pb | 0,08% |
| Sb | 0,07% |
| Sn | 0,13% |
| Zn | 0,08% |

*Table 3.5 Emissions to air at a cement kiln*

### 3.4.11 Transport distances and destinations

The default destinations of the fractions resulting from shredding and separation are displayed in Table 3.6. The way and distance of transport is included in the QWERTY calculation sequence. In Section 3.6 sensitivity analysis on the influence of these parameters is conducted.

| Fraction | Destination | Distance (km) | Transport means |
|---|---|---|---|
| Residue | MSW incineration (NL) | 250 | truck 40t |
| Copper | via harbour (NL) | 250 | truck 40t |
| | Copper smelter (CAN) | 8000 | oversea bulk transport |
| Aluminium | Aluminium smelter (NL) | 500 | truck 40t |
| Ferro | Ferro smelter (NL) | 350 | truck 40t |
| Glass | Glass recycler (NL,D) | 250 | truck 40t |
| Plastics | Plastic recycler (B) | 400 | truck 40t |

*Table 3.6 Transport distances and destinations fractions*

## 3.5 Example: application on a Soundmachine

### 3.5.1 Introduction

In this section, a plastic dominated and medium sized Soundmachine (portable audio from 2001) is taken as an example. Besides the used environmental benchmark data (Philips Consumer Electronics 2001e) also the PWB compositions are chemically analysed. So the product composition is known and the level of detail of the QWERTY analysis is the highest possible.

In Section 3.5.2, the product data and composition as well as the behavior in shredding and separation is presented. Then in Section 3.5.3 the QWERTY scores and further discussion on the recovered and lost environmental value will be held. Whereas the contribution of materials are highlighted in Section 3.5.3, the role of the various stages and processes involved will be introduced in Section 3.5.4 and the other end-of-life scenarios applicable on this product in Section 3.5.5. Finally, a discussion on the destination of the plastic content and the environmental consequences is presented.

### 3.5.2 Product data, shredding and separation

In Table 3.7 the product composition is given. The product weight is 3,9 kg, the plastic (ABS) housings weight is 1,3 kg.

| Material | Weight (g) | Weight% |
|---|---|---|
| Aluminium | 47,74 | 1,2% |
| Copper | 414,34 | 10,6% |
| Ferro | 1009,28 | 25,8% |
| Glass | 3,60 | 0,1% |
| Plastics | 2215,51 | 56,5% |
| Other | 228,96 | 5,8% |
| **Total** | **3919,44** | **100%** |

*Table 3.7 Product composition Soundmachine*

In Table 3.8 the estimated contribution to fractions is given. This table is based on the general distribution tables per product category for shredding and separation (which were previously described in Chapter 2.4.3). Most environmentally relevant substances and precious metals are originating from the PWBs. The most important characteristics are a relatively low bromine content and low precious metal content. Besides the housings of 1,3 kg ABS, 0,9 kg of mixed plastics is present and 0,1 kg of PVC originating from internal wiring.

The table shows that not every material appears in the 'right' fraction. Some of the copper for instance is lost to the aluminium and residue fraction. Due to pieces of PWB materials ending up in the residue fraction instead of the copper fraction, also some of the precious metals are lost to the residue fraction.

| Fraction | Ferro (g) | Aluminium (g) | Copper (g) | Residu (g) |
|---|---|---|---|---|
| Aluminium | 0,24 | 39,42 | 2,35 | 5,73 |
| Copper | 3,89 | 20,72 | 324,06 | 65,67 |
| Ferro | 958,82 | 10,09 | 10,09 | 30,28 |
| Glass | 0,02 | 0,02 | 0,36 | 3,20 |
| Plastics | 26,81 | 11,08 | 221,55 | 1956,07 |
| Other | 1,82 | 1,79 | 131,49 | 93,85 |
| **Fraction Weight** | **991,60** | **83,12** | **689,90** | **2154,81** |
| **Fraction %** | **25,3%** | **2,1%** | **17,6%** | **55,0%** |
| Total | | | | **3919,44** |

*Table 3.8 Fraction compositions of the Soundmachine*

The destinations of the four fractions are respectively ferro smelting, aluminium smelting and the copper smelting. The residue fraction is assumed to go to a MSW incineration plant (with energy recovery).

### 3.5.3 QWERTY scores and scenarios

In Figure 3.5 the contribution of the different materials within the described take-back system to the QWERTY definition based on the Eco-Indicator '99 and MRE definition, which is in fact the product composition. Note that for the MRE a very strict weight based definition for recyclability, is used. Comparing the contributions of the different materials shows that the plastics and ferro content are becoming less important and especially copper and lead are becoming more important.

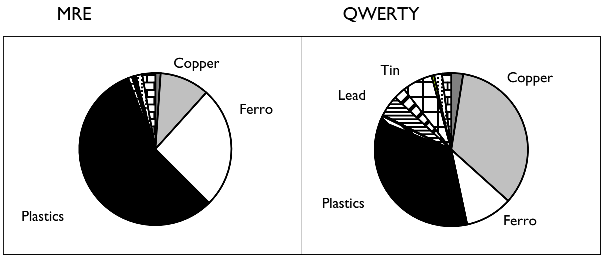



*Figure 3.5 MRE definition versus QWERTY definition*

In Figure 3.6 the 'break-down' of the MRE definition to the recycling percentage gained and lost (based on strict MRE) and the QWERTY value gained and lost are given for the current recycling scenario. Note that with this strict definition, under state-of-the-art recycling without plastic recycling, only 29% weight based recyclability is achieved. When a strict recovery definition is applied (total amount of fractions towards secondary material processors) a percentage of 42% is reached. The WEEE recyclability targets are clearly not met under these strict definitions and is probably only achieved with mechanical plastic recycling. In Figure 3.5 it is shown that the plastics contribute the most to the lost MRE percentage under the strict definition. The question rises, whether a proposed plastic recycling really leads to higher environmental scores. This will be discussed in Section 3.5.6. But first the 'break-down' of the MRE definition in the lost and gained part is depicted.

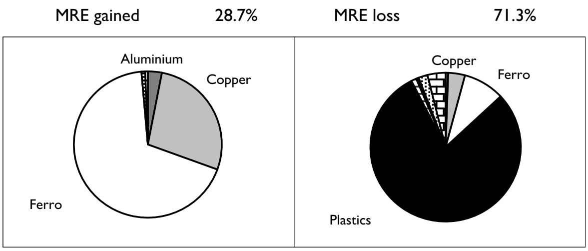



*Figure 3.6 MRE values gained and lost for the Soundmachine*

In Figure 3.7 the same graph is presented for the QWERTY scores. The gained QWERTY percentage is 46%. In the QWERTY percentages the plastic also contribute the most to the lost environmental value but not as much as in the weight based percentages. In the next section more detailed information will be presented about the causes of this loss.

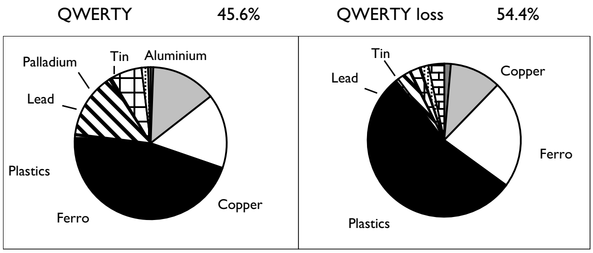



*Figure 3.7 QWERTY values gained and lost for the Soundmachine*

It can be concluded that the environmentally weighted QWERTY scores present a completely different picture than the traditional weight based percentages. The consequences of this important conclusion for design, end-of-life policy and legislation and end-of-life processing are discussed in the thesis, for instance in Chapter 7.3.3. But a graph like Figure 3.7 alone provides not enough information on where environmental gain and loss is created, what the contribution of the various processes are and moreover how much additional environmental value recovery can be realised with improvement options in design, processing or take-back system organisation. In the next sections the QWERTY calculations are extended in order to address these issues.

### 3.5.4 Other end-of-life scenarios

Besides the state-of-art recycling scenario also the environmental behavior of the product within other scenarios can be displayed. In Figure 3.8 the environmental performance of the product within all end-of-life scenarios (the product as a whole goes into one scenario) are shown. The first bar is the theoretical 'best case' value or original material value. The second bar is the 'worst case' scenario or highest environmental values per material – end-of-life route combination. With these two bars, the environmental bandwidth is presented. Also in this figure, the contribution of the different materials is integrated. The 'recycling' bar is the state-of-the-art recycling scenario. Note that recovery of copper adds the most to the recovered environmental value in this bar, whereas the plastics mainly contribute to the environmental value lost. Another important conclusion is that although state-of-the-art recycling is applied, the environmental recovery is far from the 'best-case' scenario mainly due to materials ending up to in the wrong fractions or not being recovered at the corresponding secondary material processor. Also energy required for end-of-life treatment and environmental impacts of transport play a role in this.

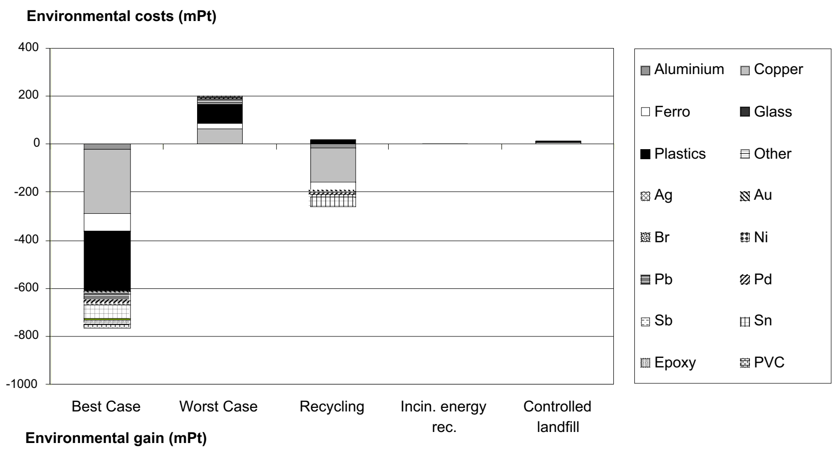



*Figure 3.8 Environmental scores per scenario*

The QWERTY approach is primarily focused on describing the performance of a single product within different end-of-life scenarios. The Figures 3.7 and 3.8 already deliver some information for Design for End-of-Life activities. It shows which materials to prioritise. However, the contribution of single processes to the actual environmental value for the state-of-the-art recycling is not directly clear. Also the reason of the gap between first and the third bar of Figure 3.8 is not substantiated. With the next section, more detailed information is given to the role of the individual processes and materials involved are explained.

### 3.5.5 Contribution of processes and materials

In Figure 3.9 the detailed analysis of the role of different materials in the selected end-of-life scenario is displayed. It is a more detailed representation of the difference between the first and the third bar of Figure 3.8. The left part of the bars is displaying the non-recovered environmental value of the corresponding material. This is for some materials including the grade function representing a lower degree of re-application of the material. The right part of the bars is showing the, mainly inevitable environmental burden of end-of-life processing like energy consumption, transport and emissions.

The aim of Figure 3.9 is twofold. It can be used on forehand in a detailed analysis of the environmental losses connected to the different materials. For the example Soundmachine the main losses connected to the plastics content is caused for two thirds by not recovering material value and for one third by the emissions at the incineration with energy recovery. The second application option is the evaluation of a redesign effort by verifying whether really a reduction in environmental loss is realised for the materials involved. This will be further discussed in Chapter 6.3 with actual redesign cases.

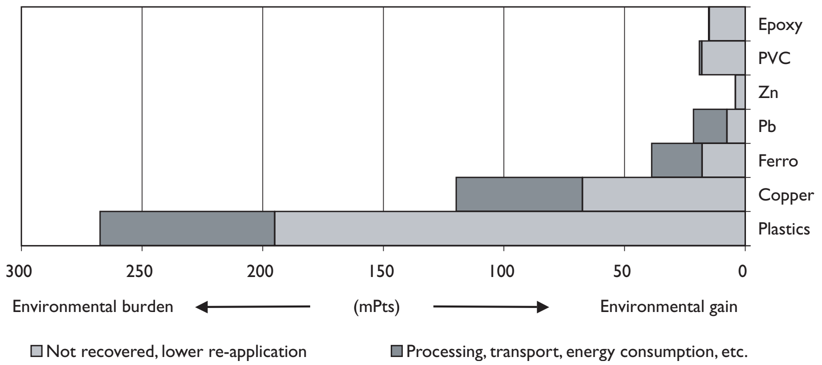



*Figure 3.9 Detailed analysis of losses for the different materials of the Soundmachine*

In Figure 3.9 still the role of the individual process is not clear. For instance emissions at the transport and collection stage are not addressed. In fact, not only the environmental loss as displayed in Figure 3.9, but also the environmental gain due to material recovery is useful information. In Table 3.9 the role of the processes is presented in absolute values.

| Stage | Process | Environmental impact (mPts) |
|---|---|---|
| Collection and 'recycling' | Transport | 8,6 |
| | Shredding and separation | 4,0 |
| Final Waste | Incineration (with energy recovery) | 1,8 |
| Secondary Processing | Copper smelter | -200,5 |
| | Aluminium smelter | -15,4 |
| | Ferro smelter | -38,2 |
| **Total** | | **-239,6** |

*Table 3.9 Absolute values per stage for the Soundmachine*

From Table 3.9 it is clear that for this example the copper smelter is the most important stage in the current end-of-life scenario, even for this plastic dominated example product. Nevertheless, still the contribution of processes to the recovery and loss of environmental value connected to the materials is not clear.

In Figure 3.10, this role of the end-of-life processes involved per material is displayed. Environmental gain by recovering environmental value in absolute values is on the left side in this graph. Figure 3.10 displays the third bar of Figure 3.8 in terms of contributions of processes to the environmental value involved. With this graph it is shown that the copper smelter is important for recovery of the environmental value of the materials copper, tin, palladium and gold. Also the burden of processing at the copper smelter is included. For the plastics it is shown that the emissions due to incineration are comparable with the environmental gain due to energy recovery.

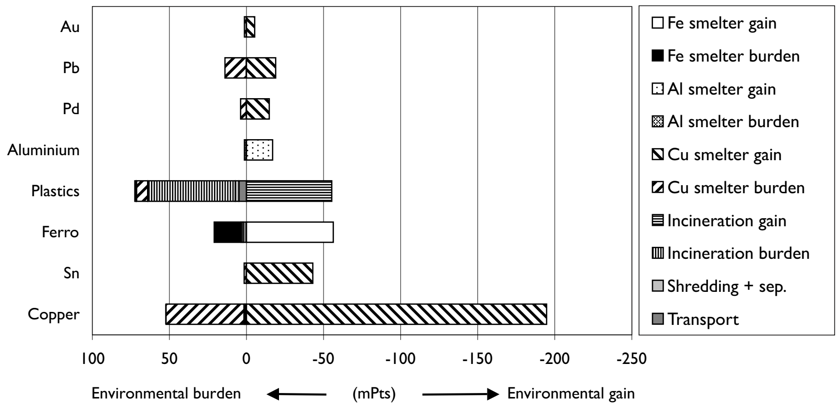



*Figure 3.10 Analysis of the role of the processes involved*

### 3.5.6 Technical improvement option: Plastic recycling

One of the options to increase weight based recyclability scores (MRE) is to apply plastic recycling of the housings (1,3 kg from 3,9 kg total product weight). In Figure

3.11 the QWERTY scores related to four destinations of the plastics involved are calculated. The left four bars are representing the strict MRE definition. The first three bars are respectively incineration of the plastics as part of the residue fraction with MSW without energy recovery, the second is with energy recovery and the third bar is incineration of the residue fraction in a cement kiln and have the same MRE result: 28,7%. Obviously, the plastics don't add to this value. In the fourth bar the plastic recycling is included. In this case an increase in MRE value is obtained of 28,7% towards 54,3%.

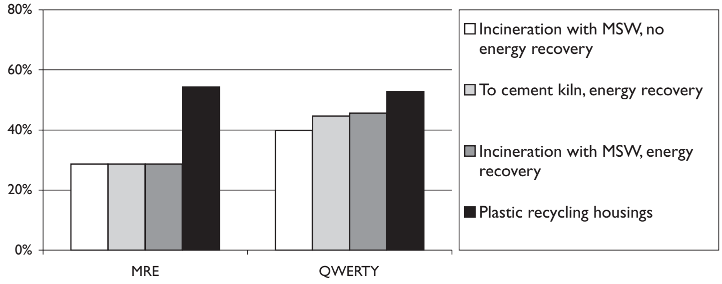



*Figure 3.11 QWERTY scores for various plastic destinations of the Soundmachine*

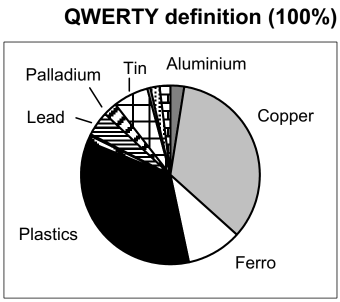
The four bars on the right in Figure 3.11 are the QWERTY percentages. In this case it is shown that the difference in incineration with and without energy recovery is about as large as the difference between incineration with energy recovery and plastic recycling. However, compared to the difference in MRE value, the QWERTY values show relative smaller differences. Furthermore, an important assumption for the plastic recycling scenario is that it is technically possible. Due to contamination and due to the use of mixed plastics this is not the case. This issue of technical boundaries will be discussed in further detail when this same Soundmachine example is used as a screening redesign case in Chapter 6.4. The discussion on the costs involved for plastic recycling of medium sized housings is extensively discussed in Chapter 4.5.5.

## 3.6 Discussion

### 3.6.1 Multiple environmental assessment methods

In these sections the default Eco-Indicator '99 method will be compared with the EDIP'96 method, as the first method to check the Eco-Indicator '99 results. Furthermore comparison with the CML2 method with TNO weighting set is performed. Thereafter, the single environmental themes resource depletion, human health and ecosystem quality used within the Eco-Indicator '99 method will be displayed separately.

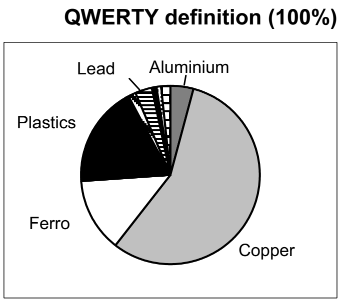
In Figure 3.12, the Eco-Indicator '99 QWERTY results for the Soundmachine are presented again. The contribution of the materials to the definition is illustrated. This is the same as the bandwidth between the best-case and worst-case options and it is the same graph as the right part of Figure 3.6.




| Contributions: | |
|---|---|
| Plastics | 34,3% |
| Copper | 34,1% |
| Ferro | 10,0% |
| Sn | 6,4% |
| Pb | 4,6% |
| Aluminium | 2,5% |
| Pd | 2,5% |
| PVC | 2,0% |
| Epoxy | 1,6% |

*Figure 3.12 Contribution of materials (Eco-Indicator '99)*

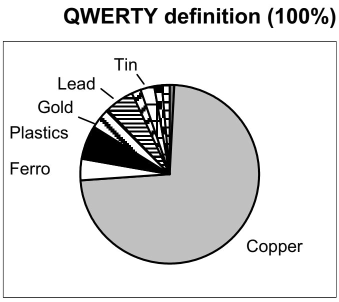
This graph can be compared with the contribution of materials to the EDIP'96 method. This is presented in Figure 3.13.




| Contributions: | |
|---|---|
| Copper | 56,3% |
| Plastics | 18,2% |
| Ferro | 13,6% |
| Aluminium | 4,1% |
| Pb | 2,9% |
| PVC | 1,7% |
| Au | 1,3% |
| Epoxy | 0,8% |
| Sn | 0,4% |

*Figure 3.13 Contribution of materials (EDIP'96)*

Despite the fact that the EDIP'96 method is a completely different approach, the same 10 materials are prioritised first but the ranking order is different, especially for the plastics. The plastics are less important under this method. The mutual ranking of the metals remains comparable to the Eco-Indicator '99 method. One of the underlying reasons for the differences is the inclusion of resource depletion aspects for fossil fuels – plastics in the Eco-Indicator '99 methodology, which is not the case in the EDIP'96 method. The ranking of materials is further discussed in Table 3.10.




| Contributions: | |
|---|---|
| Copper | 72,9% |
| Plastics | 6,0% |
| Pb | 5,4% |
| Ferro | 4,0% |
| Au | 3,8% |
| Sn | 2,5% |
| Pd | 1,5% |
| Zn | 1,3% |
| PVC | 1,3% |

*Figure 3.14 Contribution of materials (CML2-TNO)*

In Figure 3.14 with the TNO weighting set (see Section 3.4.2), the contribution of materials to the QWERTY scores is calculated for the CML2 method. Although this graph looks different in comparison with the two previous LCA-methods, a comparable ranking order appears compared to the EDIP'96 method. The main difference is the very high 'appreciation' of copper and the even lower contribution of the plastics. The reason for this is that the CML-2 method is not very suitable for evaluating inorganic substances, because this is not included in its underlying fate and exposure analysis. It should also be noted that the used method is less suitable for comparison while the weighting set is not very well developed and aligned with the LCA method itself.

| Ranking | Eco Indicator'99 | EDIP'96 | CML2-TNO |
|---|---|---|---|
| 1. | Plastics | Copper | Copper |
| 2. | Copper | Plastics | Aluminium |
| 3. | Ferro | Ferro | Ferro |
| 4. | Tin | Aluminium | Plastics |
| 5. | Lead | Lead | Lead |
| 6. | Aluminium | PVC | Gold |
| 7. | Palladium | Gold | PVC |
| 8. | PVC | Epoxy | Tin |
| 9. | Epoxy | Tin | Epoxy |
| 10. | Gold | Palladium | Palladium |

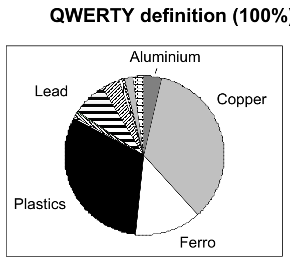
*Table 3.10 Ranking of materials under three environmental assessment methods*

Table 3.10 shows in general a rather similar ranking of the metals involved. The plastics however are valued differently. Despite the differences it is remarkable that the same top-ten appears (there are many more materials present in the product).

Already in Chapter 2 it is stated that the Eco-Indicator '99 will be used as being the most comprehensive and most modern method. Since this default method can also address the three main environmental themes, human health, ecosystem quality and resource depletion, an elaboration is presented on QWERTY scores versus these single environmental themes.

### 3.6.2 Single environmental impact categories

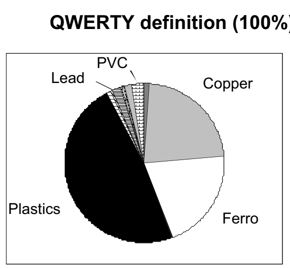
In Figure 3.15 the QWERTY definition is presented for the damage to Human Health category. Again copper, plastics and ferro appear high in the ranking. But in this case lead has a relatively high contribution due to toxicity reasons. It is remarkable that not the materials with high toxicity values have the highest contributions, but copper, plastics and ferro. This is due to the overall 'damage to human health burden' connected to processing of these materials due to energy consumption, etc.




| Contributions: | |
|---|---|
| Copper | 34,8% |
| Plastics | 31,1% |
| Ferro | 13,5% |
| Pb | 6,8% |
| Aluminium | 3,5% |
| Pd | 3,4% |
| PVC | 2,3% |
| Epoxy | 1,7% |
| Au | 1,1% |

*Figure 3.15 Contribution of materials (Eco-Indicator '99 Human Health)*

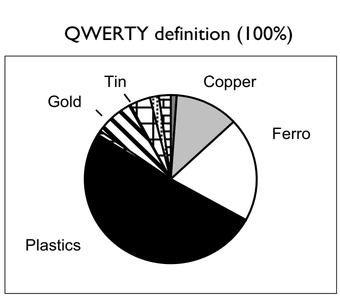
In Figure 3.16 the same contributions are calculated for the damage to Ecosystem Quality of the Eco-Indicator '99. Also in this case the most important materials are plastics, ferro and copper. The reasons are similar compared to the discussion at the 'Human Health' values.




| Contributions: | |
|---|---|
| Plastics | 47,9% |
| Copper | 22,4% |
| Ferro | 20,7% |
| PVC | 2,5% |
| Pb | 1,6% |
| Epoxy | 1,4% |
| Aluminium | 1,2% |
| Other | 0,7% |
| Au | 0,4% |

*Figure 3.16 Contribution of materials (Eco-Indicator '99 Ecosystem Quality)*

At last, in Figure 3.17 the QWERTY definition is displayed for the Resource Depletion part of the Eco-Indicator '99. Again, the most important materials are plastics, ferro and copper. The fourth material in this ranking is gold due to its high resource depletion of minerals potential. It is remarkable that from three different points of view, human toxicity, ecosystem and resource depletion, a rather similar ranking of the most contributing materials appears. The reason for this is the fact that the processing itself (energy consumption, etc.) is more determining than the final weighting set used to integrate these three parts into one single score.




| Contributions: | |
|---|---|
| Plastics | 50.7% |
| Ferro | 20.0% |
| Copper | 12.1% |
| Au | 7.1% |
| Sn | 3.8% |
| PVC | 2.3% |
| Epoxy | 1.5% |
| Aluminium | 1.0% |
| Other | 0.7% |

*Figure 3.17 Contribution of materials (Eco-Indicator '99 Resource Depletion)*

An assessment of the influence of the different environmental assessment methods on 'changes in processing' and the contribution of the end-of-life processes involved is explained in the next section.

### 3.6.3 Plastic recycling and different environmental assessment methods

In Figure 3.18 the same graph as Figure 3.11 is illustrated but this time with the QWERTY scores of the environmental assessment methods as well. This graph points out that the very different values connected to the plastics according to the different methods also lead to different results for plastic recycling.

All methods, except MRE, point out that the energy recovery part is beneficial for the environment and also that plastic recycling is better than no energy recovery of the plastics, under the EDIP'96 method the energy recovery processes incineration with MSW or in a cement kiln is scoring better than the plastic recycling. The reason for this is again that no resource depletion value is connected to the recycled plastics in comparison with the default Eco-Indicator '99 method.

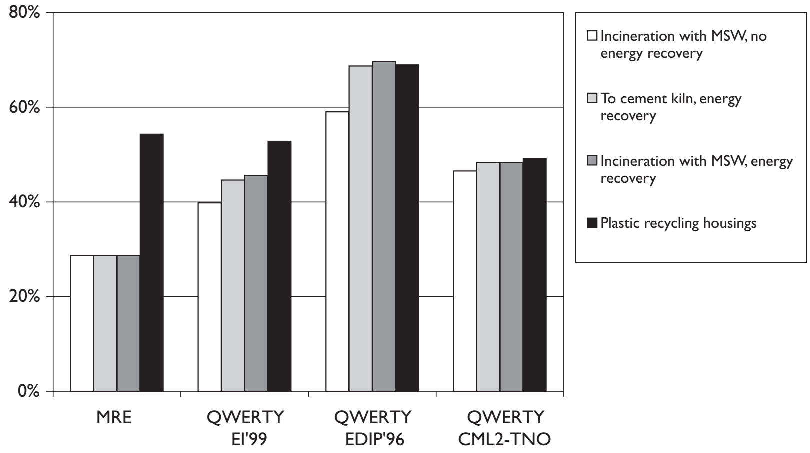



*Figure 3.18 Plastic recycling and multiple environmental assessment methods*

The differences between the various processes under the CML2-TNO method are not very large due to the low appreciation of plastics: according to Figure 3.14 only 8,5% of the contribution is originating from the plastics. From this graph and the 'defects' in the CML2 method as described in the previous section, it is chosen not to use this method as a check on the Eco-Indicator '99 results. The EDIP'96 method is the most suitable method for evaluation of the default Eco-Indicator '99 method, taking into account the lack of addressing resource depletion. When necessary, the single environmental themes human health, ecosystem quality and resource depletion are addressed separately with the Eco-Indicator '99.

In the next chapters the same comparisons will be made for example products representing the other product categories. It is expected that the differences between the various environmental assessment methods will be less great due to the comparable 'appreciations' of the other materials and metals than the plastics. Whether this expectation is right will be addressed in more detail in Chapter 5.8.
In the remaining of this section the sensitivity of the results due to data uncertainty and data-quality will be discussed.

### 3.6.4 Sensitivity analysis

In this section the sensitivity of the results with regard to the most important parameters is discussed. These main parameters or settings are:

1. Transport distances
2. Recovery percentages
3. Incineration and landfill settings
4. Energy consumption at shredding and separation

The effect of transport distances is on the results is very limited. An assumed increase of 100% longer distances leads to a decrease in the QWERTY score for the example Soundmachine under Eco-Indicator '99 for state-of-the-art recycling with less than 1% (from 45,6% to 44,9%). Already in Figure 3.10 and Table 3.9 the limited role of transport is visible. Also when applying another environmental assessment method this low sensitivity appears. This is displayed in Figure 3.19 for the EDIP'96 method.

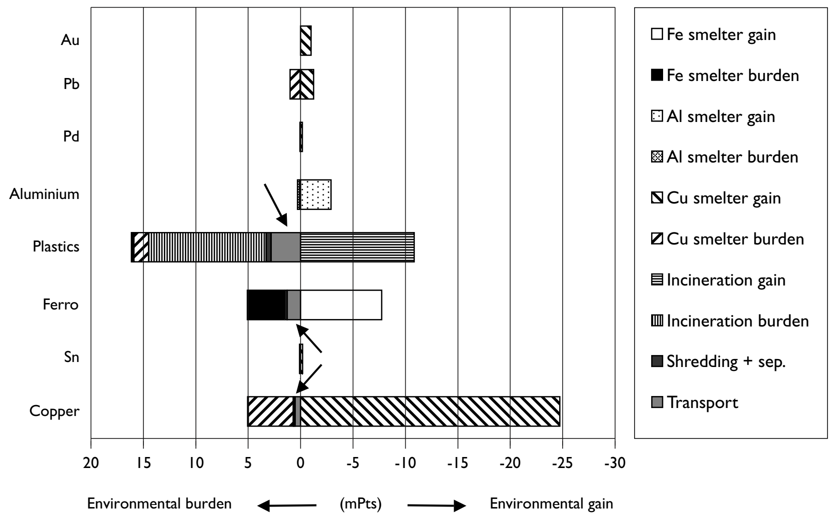



*Figure 3.19 Analysis of the role of transport (EDIP'96)*

In Figure 3.19, for the doubled transport distances, only two small 'blocks' appear (see the arrows in Figure 3.19). Also note that this Figure 3.19 is very similar to Figure 3.10 for the Eco-Indicator '99. Although materials are weighted differently by the environmental assessment methods, this apparently doesn't count for the valuation of the contribution of processes.

The second set of important parameters in the calculations are the recovery percentages at the copper smelter. The sensitivity of the results is calculated for the relative increase in recovery of 50% per metal and is displayed in Table 3.11. The increase in QWERTY score is limited again: from 45,6% to 46,4%. The reason is that the recovery percentages are high already.

| Material | Recovery % old | Recovery % new |
|---|---|---|
| Copper | 95,0% | 97,5% |
| Silver | 97,0% | 98,5% |
| Gold | 98,0% | 99,0% |
| Palladium | 98,0% | 99,0% |
| Nickel | 90,0% | 95,0% |
| Lead | 90,0% | 95,0% |
| Tin | 90,0% | 95,0% |
| Cadmium | 90,0% | 95,0% |
| Mercury | 90,0% | 95,0% |

*Table 3.11 Assumed increase in recovery percentages*

Another important set of parameters to check is the incineration and landfill settings. For the incineration description of Table 3.2, the effect on the results of a 50% less efficient gas-clean-up is calculated.

The effect is less than 0,1% on the QWERTY scores both for the state-of-the-art recycling scenario as for the incineration of the product as a whole.

The sensitivity of the results regarding the landfill settings from Table 3.3 is more significant. The underlying leaching percentages of (Ansems 2002a) are highly uncertain. Therefore, assuming an increase in this leaching percentage results in the following (absolute) numbers: For controlled landfill of the product as a whole, the environmental impacts are changing from 9,2 mPts per Soundmachine to 14,3 mPts (50% increase) and for uncontrolled landfill (not allowed in the Dutch situation) leads to an increase from 15,7 mPts to 80,0 mPts (+500%) per Soundmachine. Compared to the values of state-of-the-art recycling it still means a limited role for the controlled landfill scenario as a whole (see Figure 3.9). The increase in environmental burden for the uncontrolled landfill scenario is significant. However compared to the environmental gain with recycling, the influence on the results of a residue fraction in state-of-the-art recycling to landfill is limited to 0,5% for controlled landfill and 6% for uncontrolled landfill (the bandwidth of Figure 3.8 is around 1000 mPts = 100% QWERTY).

The effect of the energy consumption of shredding and separation is very limited and can already be seen in Figure 3.10 as well. A 100% increase in energy needed would only lead to a decrease in the QWERTY scores of 0,5%.
The results of this sensitivity analysis are displayed and ranked in Table 3.12

| Parameter | Max. effect |
|---|---|
| Landfill uncontrolled: factor 10 higher leaching | 6% |
| Doubled transport distances | 1% |
| Increased recoveries at copper smelter (50% lower loss) | 1% |
| Landfill controlled: factor 10 higher leaching | 0,5% |
| Doubled shredding and separation energy | 0,5% |
| Incineration: 50% less cleaning efficiency | 0,1% |

*Table 3.12 Sensitivity analysis of the Soundmachine results*

It can be concluded that except for the uncontrolled landfill scenario, the sensitivity of the results regarding the main parameters is low.

In Chapter 7.8, a more detailed discussion on the sensitivity of the results regarding the influence of the copper smelter and the Life-Cycle Inventories (LCIs) on the base metal production takes place. In Chapter 2, already the influence of the distribution tables on the fraction compositions is discussed. In case of products with high amounts of environmentally relevant substances of a high precious metal content, this results in moderate uncertainties in the outcomes. This issue will be further discussed in Chapter 5 when other example products are presented and in Chapter 6 when the influence of design and the options to increase the amount of materials to the right fractions will be discussed.

## 3.7 Conclusions

### 3.7.1 Application bandwidth

The QWERTY concept is a prime method to assess a product's end-of-life treatment from an environmental point of view. From both an environmental and a scientific perspective it is to be preferred over conventional, weight-based approaches to assess recyclability scores. The main advantages of the QWERTY concept include weighing the different material contents with respect to their environmental impact and the option to integrate the environmental losses, caused by a variety of treatment steps. Furthermore, the opportunity to include more than one environmental assessment model meets the wishes of the different stakeholders where many different preferences regarding environmental assessment models exist. In that sense, the basic QWERTY equations are independent of personal preferences for assessing environmental impacts. Depending on the availability of data, QWERTY scores can explain in detail where the environmental impact of products in the end-of-life stage originates, and where the best potentials for improvements lie. It has been explained that even with limited product and process data, very meaningful results can be generated (Huisman 2000a,b, Huisman 2001a).

The practical application of the QWERTY concept is manifold. In industrial applications, the concept supports priority setting as regards the environmental relevance of different materials. This in turn enables the determination of design avenues, technology investments and appropriate material recovery focusing in general. It is also obvious that the QWERTY concept is a good alternative for the MRE definitions in particular and for the different possible interpretations of the WEEE recyclability targets.

### 3.7.2 Results

With the Soundmachine example it is demonstrated that the QWERTY analysis leads to detailed information on both the role of materials and processes involved in end-of-life treatment. A disadvantage is the use of single environmental indicators. The influence of different environmental assessment shows that the weight given to the various materials doesn't differ significantly, except for the plastics. The Eco-Indicator '99 method is chosen as the default method. With this method also the human health, ecosystem quality and resource depletion perspectives can be addresses individually. The influence of the environmental assessment methods on the contribution of the individual processes involved is very low.

Another important remark is that the QWERTY concept produces both **absolute** and **relative** values. It is not only developed to deliver a relative recyclability percentage: in the remainder of this thesis it will also be used to further compare different end-of-life scenarios for many different products.

In the next Chapter 4, the QWERTY concept will be expanded with an economic part. The result will be a comprehensive eco-efficiency concept, which could help the ongoing discussions on the do's and don'ts in the end-of-life of consumer electronics.

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# *Chapter 4: Eco-efficiency of end-of-life*

## 4.1 Summary

A key issue in setting up take-back and recycling systems for discarded consumer electronics is how much environmental gain can be realised per amount of money invested. With the eco-efficiency approach and resulting calculations as presented in this chapter, this issue can be quantified. The approach is an extension of the QWERTY concept with calculations on economic value instead of environmental value. The resulting eco-efficiency calculations are presented in two-dimensional graphs in which one axis represents economic costs and revenues; the other axis represents environmental burden and gain.

The graphs are based on two steps: a 'vector approach' to divert between positive and negative eco-efficiency directions and a 'quotient approach' for balancing of environmental and economic performance from a system point of view . They illustrate the eco-efficiency effects of, for instance, changes in take-back system operation, like applying new technologies, changing collection infrastructures, the consequences for the various stakeholders involved and how return behavior can influence system performance. The examples for plastic, metal, precious metal and glass-dominated products show that improvement avenues in design, technology and policies and take-back system operation are different for these four categories. It is shown that a concept like this is very useful in determining possible optimisation routes for discarded consumer electronics and the influence of the various drivers and enablers.

## 4.2 Introduction

### 4.2.1 Goal and position of this chapter

This Chapter 4 is focused on the methodological aspects of applying a comprehensive eco-efficiency concept for end-of-life. The development of a concept like this is needed to determine what is summarised in Chapter 1 with research question 3. This question refers to the extension and combination of the environmental descriptions with economic data and the methodological way of addressing eco-efficiency. This question is also posed assuming that this quantification would help the various stakeholders involved in stakeholder debates with regard to the economic consequences of environmental measures applied and the corresponding efficiency in the environmental and economic results:

Research question 3.

> *How can a comprehensive and robust eco-efficiency method be developed for end-of-life combining the descriptions of quantified environmental performance with economic consequences and how to enhance the alignment of design, technology and policy with results that are easy to interpret?*

Therefore the main goal of this chapter is to develop a comprehensive eco-efficiency method for end-of-life of consumer electronic products, addressing both the environmental and economic performance in a quantitative way.

In Figure 4.1, the position of this chapter is presented. The QWERTY concept of Chapter 3 is duplicated for 'economic value'. The resulting approach includes both the economic and environmental part and is abbreviated as QWERTY/EE (Eco-Efficiency). In Section 4.2 the backgrounds of QWERTY/EE and the position towards existing eco-efficiency concepts is discussed as well as the essential criteria to be met in the concept. Thereafter, the economic data of all relevant end-of-life processing and activities necessary for an accurate economic description of the end-of-life of consumer electronics are highlighted, as well as the equations needed to integrate 'the economics' in QWERTY/EE. Then in Section 4.5, a plastic dominated Soundmachine is used as an example to illustrate the application and boundaries of the eco-efficiency concept. Finally in Section 4.6, the methodological robustness and some remarks on the usefulness of the methodology as a policy instrument are made.

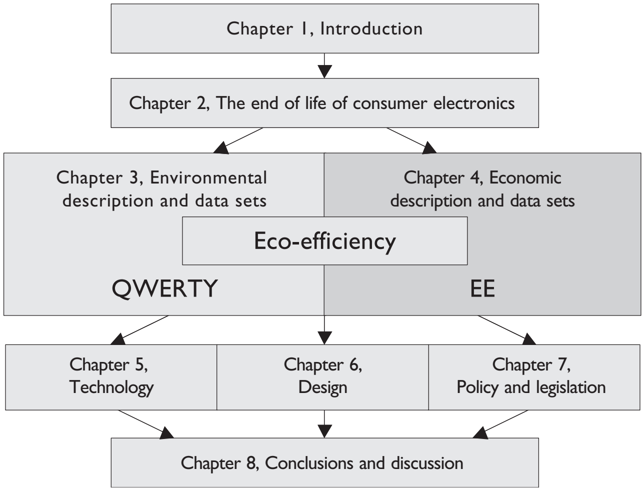


*Figure 4.1 Position of Chapter 4*

The focus of this chapter is on the eco-efficiency **methodology**. So, the first aim of the Soundmachine example is primarily meant to illustrate the usefulness, application bandwidth and limitations of this methodology. In the next chapters the application fields of QWERTY/EE are further highlighted in detail. In Chapter 5, trends for the various product categories and improvement avenues in end-of-life processing (like plastic recycling and glass recycling) will be discussed by applying the eco-efficiency methodology developed in this chapter. In Chapter 6, the focus is on the role and contribution of Design for End-of-life. In Chapter 7 the focus will be on system operation and legislation. In this Chapter 7, the results of the eco-efficiency calculations and direction for changes in design and technology are discussed from a policy perspective.

### 4.2.2 Backgrounds

First of all, a comprehensive and quantified eco-efficiency approach would help support ongoing discussions about responsibilities, organisation and financing of the take-back systems in practice and the relation with the environmental consequences (Stevels 1999, Hermann 2002a,b). Often the efficiency and effectiveness of achieving the initial goals of take-back and recycling is overlooked (Franz 2002). The aim of the QWERTY/EE approach is to address these issues on a quantitative way as will be demonstrated in the next sections.

QWERTY/EE as presented in this chapter is primarily focused on improving the end-of-life chain performance as a whole. The contributions of the various stakeholders should be in accordance with maximising system performance. In practice however, as addressed in Chapter 2.5.2, single stakeholders tend to maximise their own interests and financial profits over their part of the end-of-life chain, which doesn't necessarily mean maximising the overall end-of-life chain on economic performance. With a comprehensive eco-efficiency concept the consequences of individual goals per stakeholder can be quantified (Stevels 1999b) and ongoing discussions on the efficiency of end-of-life treatment can be performed more objectively. These individual goals are repeated shortly:

1. The goals of authorities and legislators are to set meaningful criteria in policies and legislation (per branch and/ or product category). Furthermore the eco-efficiency concept can help in monitoring system performance and efficiency and effectiveness of measures taken.
2. The goals and interests of producers (including designers) is to evaluate the effects of their products in end-of-life, sometimes including the effects of (re) design efforts. Predicting end-of-life costs as well as the option to audit recyclers, when a take-back system is in place, can be realised.
3. Recyclers themselves can calculate tariffs and can predict the eco-efficiency effects of for instance technological improvement options.
4. Consumers, consumer organisations and NGOs can examine how much environmental gain is realised for the money invested. Also the effectiveness of all kinds of green demands and corresponding price tags can be measured.

### 4.2.3 Existing concepts combining environment and economy

Until now, only a few consistent assessments are published on both the environmental part and economic part of end-of-life processing of consumer electronic products. These will be discussed in this section. Combining economic and environmental results to evaluate whether one really achieves better environmental performance for the amount of money being invested is seldom being incorporated in comprehensive and consistent methodology. Probably one of the reasons are the many existing definitions for eco-efficiency. In (Stevels 1999, Boks 2002b) these different definitions are discussed in more detail. Only a few methods are combining economic and environmental results:

The most relevant and comprehensive quantitative approach is developed by BASF (UBA 1996, Saling 2002). Regarding this eco-efficiency analysis method, the following remarks are made:

1. It uses 2D graphs for representation of a cost indicator and an environmental impacts indicator.
2. Goal, scope and backgrounds: The analysis is primarily targeted at customer benefits from a life-cycle perspective. It uses the same approach regarding comparison of 'functional units' as in (ISO 14040).
3. The BASF method is starting from an environmental profile of a product or functional unit. From that a time consuming LCA can be performed and on top an eco-efficiency analysis, even more time consuming, where costs are included.
4. In the BASF approach, environmental impact categories are in first instance build on the following categories: Energy consumption, emissions, material consumption, toxicity potential and abuse and risk factors (in fact representing a new environmental theme). The result is an environmental fingerprint.
5. It does not specifically zoom into end-of-life issues.

Although the BASF method is well developed and consistent, it is also focusing on full life cycles of functional units and therefore less applicable on end-of-life issues. Furthermore, it is not possible to make streamlined calculations with this method.

Also by (Hermann, 2002a,b), an economic and environmental indicator approach is developed for the end-of-life of products, called ECO2 indicators. Advantage of the approach is the focus on end-of-life. The method as such shows many similarities with the QWERTY approach of Chapter 3.3 in defining minimum and maximum values for environmental impacts of end-of-life treatment. Nevertheless, also within this LCA based approach some disadvantages exist. First of all, no weighting of impact categories is applied making the outcomes difficult to interpret while only individual subcategories reflecting single environmental themes are specified. Also the 'economic side' only consists of potential benefits from electronic waste, without describing any additional costs like for treatment, transport and shredding and separation. Furthermore no comprehensive data sets are gathered especially on the economic part of the calculations.

Another existing LCA based concept is the Eco-costs Value Ratio (EVR) (Vogtländer 2000a) also developed at TU Delft. The central idea behind this approach is depicted in Figure 4.2. With EVR, environmental effects are transformed into virtual pollution prevention costs, called 'eco-costs'. The application of EVR on end-of-life issues is highlighted in (Vogtländer 2000a,b).

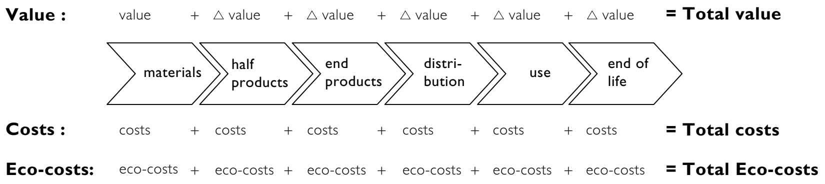


*Figure 4.2 The idea behind the Eco-costs/ Value Ratio*

In this EVR-approach some similar choices are made to deal with allocation problems, which where already discussed in Chapter 3.3.1 and Figure 3.2. The main characteristic of the EVR method is that in fact LCA scores are monetarised into one-dimensional values. The resulting values are not representing actual prices, but 'virtual prevention costs'. In contrast with the EVR approach, in QWERTY/EE the preference is to maintain a strict distinction between economy and environment. Other disadvantages of EVR are that not all environmental effects can be transformed into monetary units. Furthermore for many emissions and corresponding environmental effects the question remains whether a virtual economic accounting method can properly address the distance to a 'sustainable situation'. The EVR method is in fact not an eco-efficiency concept but an one-dimensional monetarisation of LCA results. Within the scope of this thesis however, a strict distinction between environmental impacts and economic value is preferred. Therefore, actual environmental performance is treated 'as such' and not transferred into other units like monetary ones.

Apart from the already mentioned advantages and disadvantages of these methods, the following criteria are formulated to which a comprehensive eco-efficiency concept on end-of-life of consumer electronics should comply. They are presented in Table 4.1:

| Criteria |
| --- |
| Single environmental scores included or LCA-based? |
| Specifically developed for end-of-life evaluation? |
| Suitable for multiple stakeholder evaluations? |
| Multiple weighting sets incorporated? |
| Basic environmental data sets available? |
| Basic economic data sets available? |
| Basic technical descriptions of end-of-life scenarios? |

*Table 4.1 Criteria for a comprehensive eco-efficiency method for end-of-life*

In Section 4.7, the QWERTY/EE method will be compared with existing methods regarding the above criteria. Next to these criteria or requirements also the following results should be generated in the specific case of discarded consumer electronics:

1. Performance of single products in other end-of-life options, like incineration and landfill, but also the effects of plastic recycling or glass recycling already discussed from an environmental perspective in Chapter 3.3.5 and Chapter 3.5.6.
2. Contribution of individual materials and material fractions in this performance, hence generating improvement avenues in design, policy, technology and system organisation. This is related to research question 4 of Chapter 1.2.
3. The consequences and contributions of single stakeholders or stages like the influence of transport, copper smelting, cement kiln and other secondary processors, to the total end-of-life chain to the overall system performance.
4. The consequences for system organisation. Visualising the influence of logistics, economies of scale due to collective versus individual systems, collection rates, etc. The environmental perspective on this is earlier addressed in the sensitivity analysis of Chapter 3.6. However, the economic contribution of this is expected to be much larger as will be introduced in Section 4.3.2.
5. Optimising the technical correlation between recyclers and secondary material processors and final waste processors: Which materials should end-up in which fractions to be treated by which secondary material processors. This will be addressed in Section 4.3.4 till 4.3.7.
6. Policy makers: The relation between certain measurements, policies or legislative actions and the corresponding environmental performance and economic effects, can be determined. In simple words: How much environmental revenue can be realised per amount of money invested? This is addressed with research question 6 and will be elaborated on in the example of Section 4.5.5 and with many different examples and a more general discussion in Chapter 7.

On all of these aspects will be further elaborated in Section 4.5 with the example of the Soundmachine, already introduced in Chapter 3.5.

### 4.2.4 The basic idea behind eco-efficiency of end-of-life

In Figure 4.3 the basic idea behind the eco-efficiency calculations of the QWERTY/EE approach is visualised. The Y-axis represents an economic indicator (this can be an absolute one, for instance in euros or dollars, or a relative one, in percentages, market share, etc.). The X-axis represents the environmental indicator (this can also be absolute, in points or other environmental scores, or a relative one as well). In Figure 4.3 the choice is made for **absolute** economic values: €'s and absolute environmental scores (Eco-Indicator'99 points).

End-of-life scenarios for one and the same product (or for a product stream) can be displayed as points in Figure 4.3. In order to achieve higher eco-efficiencies, the options should lead to a change from the reference or starting point into the direction of the upper right part of Figure 4.3 (point A). Such options describe certain changes in end-of-life treatment or applying certain technological improvements like plastic recycling for instance. However, options with a direction towards the down-left part of Figure 4.3 should be avoided (higher costs and higher environmental impacts), because from the point of reference a lower eco-efficiency is realised (point B). The other two points C and D are leading to the same environmental improvement but also higher costs compared to the reference point. When point C and D are comparable, one could say that in general direction C is more eco-efficient than direction D, because the same environmental improvement is realised against less costs. The approach sketched with Figure 4.3 makes it possible to compare multiple scenarios for single products and multiple products with in one scenario.

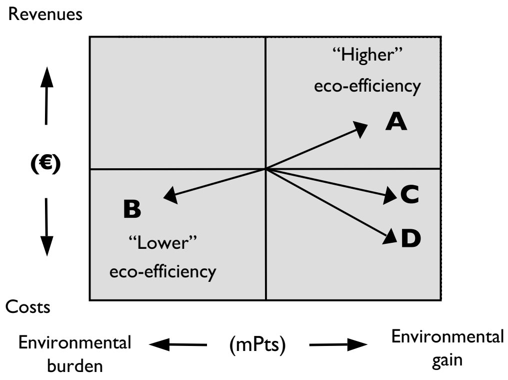


*Figure 4.3. Example two-dimensional eco-efficiency graph*

Application of the eco-efficiency method includes two important steps:
It is started with a '**vector approach'**. This means that in first instance four directions or quadrants are selected. When for example plastic recycling of housings is applied and the resulting vector is directed to the first quadrant (point A) of Figure 4.4, a 'positive eco-efficiency' is realised, compared to the original situation (reference point) without plastic recycling. The opposite counts for the third quadrant. Options and directions is this case should be avoided from both an environmental as an economic standpoint.
The second step is a **'quotient approach'.** Very often options to be evaluated are leading to a direction in the fourth quadrant and sometimes in the second quadrant. This is when an environmental improvement is realised and financial investments are needed to obtain this. In this case, when multiple options are appearing in the fourth quadrant, the **'quotient approach'** can be applied to determine how much

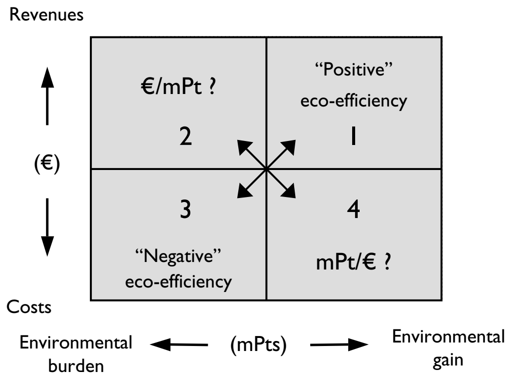


*Figure 4.4. The four quadrants of two-dimensional eco-efficiency graphs*

(absolute) environmental improvement (mPts) is realised per amount of money invested (€). In the second quadrant, higher revenues or lower costs are obtained against higher environmental impacts. When a certain option leading to a vector in the second quadrant is reversed, the result will appear in the fourth quadrant and can be treated as such.

The chosen 'vector approach' to display eco-efficiency in 2D graphs, is directly decisive for options or changes in the first and third quadrant as a first step. Subsequently the 'quotient approach' should be applied for all options appearing in the fourth quadrant (and sometimes in the second quadrant, but this situation doesn't occur frequently in this thesis). The resulting **'mPts per €'** can be used to rank the different options available. With this ranking it can be determined in what options to invest at first. In Chapter 5, the focus will be on the application of the eco-efficiency method and 2D graphs on the behavior of multiple products in several end-of-life scenarios. In Chapter 7.5, the two steps will be further discussed and the 'quotient approach' will be applied extensively in order to rank different improvement options and to relate them to the different policy strategies. This enhances the further alignment of design, technology and policy. In this chapter, the application of the eco-efficiency method will be discussed with the example of a Soundmachine.

In Section 4.3 all economic parameters, data availability and backgrounds will be presented to come to the economic indicators of the QWERTY/EE approach, which leads to the results in the above figures for the vertical axis. In Section 4.4 the economic and environmental data from Chapter 3 (results for the horizontal axis) are combined.

## 4.3 Economic data

### 4.3.1 Introduction

In this section, all integral costs and revenues involved in the end-of-life chain are described in order to derive results for the vertical axis. The way in which the environmental results for the horizontal axis of Figure 4.3 and 4.4 are generated with the QWERTY concept of Chapter 3 is also applicable on the economic part of the eco-efficiency calculations. The way of thinking in terms of environmental value can be extended on economic value. The economic values necessary for determination of the Y-axis are based on integral costs for all parts of the end-of-life chain. Costs and revenues are defined as the actual amounts of money paid or obtained from other parties including interests and margins in the end-of-life chain between the various stages. These stages are depicted in Figure 4.6. Margins for one party are included in the costs calculated to another party for delivering a certain service or for processing fractions or materials. The calculations are based on integral costs, including those cases where also revenues are created due to material recovery, for instance at a copper smelter (see Section 4.3.6). Figure 4.6 illustrates the main individual stages in the end-of-life chain for the economic part of eco-efficiency that is in line with Chapter 3. Besides addressing absolute costs and revenues, also cost efficiency can be calculated (as an equivalent of the relative QWERTY scores of Chapter 3, representing the efficiency of recovering economic material value).

In Figure 4.5 the 'break-down' of the original economic material value is displayed. This original value is defined as the economic value present in the discarded product as such, assuming that this value could be recovered completely (comparable with the definition for minimum environmental impact or maximum environmental value recovery in Chapter 3.3.2). From an economic perspective it is preferred to minimise costs over the chain for final waste treatment (left) and to maximise material recovery (right) at the same time. In detail, the economic values of different end-of-life scenarios can be determined. With Figure 4.5, many different end-of-life scenarios can be investigated on their economic performance and which routes are relatively cheap or relatively expensive.

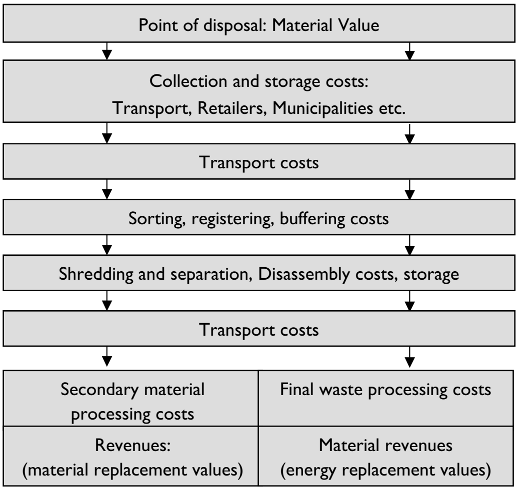


*Figure 4.5 The economic bandwidth*

In the next sections, all stages of Figure 4.5 are described in economic terms. Both the mathematics (where necessary) as the main economic parameters are given per stage. Not all data included in the QWERTY/EE software are shown due to confidentiality agreements. However, in the underlying calculations and resulting examples, these data are incorporated. Furthermore, also discussion on the robustness, scope, accuracy and sensitivity of the data used is mentioned wherever necessary.

### 4.3.2 Collection and transport

In Figure 4.7 the main transport routes within the Dutch EE&E system are displayed. The main route is from consumer to municipality towards Regional Sorting Stations (RSS) and finally to recyclers.

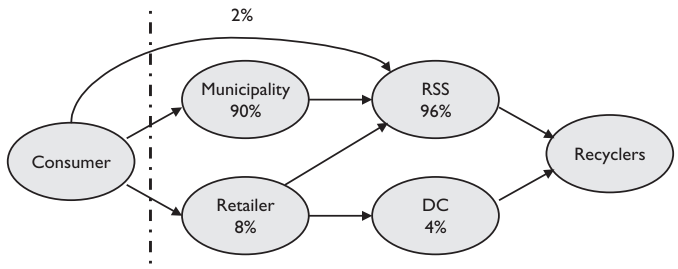


*Figure 4.6 Collection routes for the Dutch E&EE system*

In Table 4.2 the main economic data for these various collection and transport scenarios are presented. Data are derived from (Boks 2002), (NVMP 2002a) and from Dutch and German recyclers (Stobbe 2002).

| Scenario | Costs/kg |
|---|---|
| Dutch E&EE system, CRT, consumer - recycler | € 0,26 |
| Dutch E&EE system, Non-CRT, consumer - recycler | € 0,65 |
| Dutch E&EE system, CRT, municipality/retailer - recycler | € 0,06 |
| Dutch E&EE system, Non-CRT, municipality/retailer - recyc. | € 0,12 |
| Pick-up on demand, CRT, consumer - recycler | € 0,46 |
| Pick-up on demand, Non-CRT, consumer - recycler | € 7,60 |
| Second waste truck, average costs, consumer - recycler | € 0,59 |
| Postage, max 31 kg, average 20kg | € 0,75 |
| Retailer brings new product, pick-up old, average costs | € 0,16 |

*Table 4.2 Collection and transport cost for various scenarios per kg*

The first two options are average integral costs for CRT containing and non-CRT containing appliances ('browngoods', see Chapter 1.6 for the right definitions) within the Dutch E&EE system, including estimates for the costs of consumers handing in products at retailers and municipalities. The percentages of products following each route are displayed in Figure 4.6. The options 3 and 4 are excluding these costs for consumers. Besides these 'regular' costs, also other options are mentioned to compare different logistic systems other than the current settings for the Dutch E&EE system. These options are further discussed with actual examples in Chapter 7.

Table 4.2 shows relatively high costs for small appliances and dedicated scenarios like the 'pick-up on demand' scenario. The data are for relatively dense populated areas (Dutch and German situation). For other countries where average distances are longer, the transport costs can be significantly higher. The costs are primarily dominated by labour cost and secondly by fuel prices. When the data from Table 4.2 is combined with collection rates per collection/ logistic scenario, also system performance can be determined. An example of this will be given in Section 4.5.4. Note that the contribution of transport is much higher to the economic side of the end-of-life chain than the environmental side as presented in Chapter 3.6.4.

### 4.3.3 Storage, sorting, disassembly and shredding and separation

Economic parameters for shredding and separation are mainly based on energy consumption of the processes involved. Furthermore storage, sorting, analysis and overhead costs are known (Mirec, 2002a). For regular electronic fractions and non-CRT containing fractions, a rather constant, average integral costs of € 0,14 per kg are derived from these data.

Disassembly costs for various products are dependent on measuring of disassembly times. For a broad variety of products theses disassembly times have been determined by the Philips environmental benchmarks (Philips 2002b). The resulting disassembly times can be very different for comparable and even 'long existing en well-developed' products. Disassembly costs are determined for all products individually and based on average disassembly times per disassembly operation necessary. An integral hour-rate of € 36, € 0,60 per minute, € 0,01 per second is taken into account. In the QWERTY/EE calculations, a list of 150 different operations, derived from (Salemink 1998) is included. To illustrate this, a typical result for a TV set is displayed in Table 4.3.

| Operation | Seconds |
|---|---|
| TV mains cords + back covers | 50 |
| Chassis | 15 |
| Speakers | 10 |
| Deflection Unit | 15 |
| CRT | 80 |
| Front cover | 30 |
| **Total** | **200** |

*Table 4.3 Example disassembly times for CRT containing appliances*

### 4.3.4 Incineration

Incineration costs (in a MSW incineration plant) are obtained from AVR Chemie (AVR Chemie 2001), from the Philips DFND (Design for Non Disassembly) project (Deckers 1998) and from German sources (Fraunhofer 2002). The costs are divided in general incineration costs per ton and extra penalties costs for unwanted elements. In order to determine the costs for a fraction the following equations counts per material. In principle, the exact contribution of a certain product being shredded and separated to for instance a residue fraction being incinerated is per definition impossible to determine. However a first order approximation can be made as follows with Equation 4.1:

4.1 $$IC_{inc} = \sum_{i}^{\infty} IC_{inc,i} = \sum_{i}^{\infty} \left[ \left( \frac{m_i}{m} \right) \times TC_{inc} + \left( \frac{m_i - UD_i}{m} \right) \times P_i \right]$$

With:

$IC_{inc}$ is the integral costs paid for incineration of the material fraction;
$IC_{inc,i}$ is the contribution of material i to the integral costs for incineration;
$m_i$ is the weight of material m in the fraction;
m is the weight of the fraction;
$TC_{inc}$ is the general treatment costs for the fraction (set at 250 €/ton, (Fraunhofer 2002a));
$UD_i$ is the threshold for material I for which above a penalty has to be paid;
$P_i$ is the penalty paid for material i, only if $m_i > UD_i$.

With Equation 4.1, the material contribution of a certain product to a certain fraction has been calculated. For this contribution, the penalties are estimated for every material taking into account an estimated concentration in this contribution as the concentration for which has to be paid. The resulting penalty is allocated on the material under consideration. In practice, the penalties will usually be lower due to dilution of penalty elements when multiple fractions or contributions to fractions come together. However, the opposite can occur as well. When two contributions to one material fraction are combined, with both contributions containing the same penalty element, then the threshold is taken into account for the two contributions instead of for the whole fraction, resulting in a too low penalty.

In Table 4.4 the penalty elements and thresholds as set in the calculations are given.

| Material | Threshold % | Penalty € per % per ton |
|---|---|---|
| Cu | 1,0% | € 16 |
| Ag | 1,0% | € 40 |
| As | 1,0% | € 40 |
| Br | 1,0% | € 40 |
| Cd | 0,05% | € 8.000 |
| Cl | 1,0% | € 16 |
| Cr | 1,0% | € 16 |
| Hg | 0,001% | € 16.000 |
| Ni | 1,0% | € 16 |
| Pb | 1,0% | € 16 |
| Sb | 1,0% | € 40 |
| Se | 1,0% | € 40 |
| Sn | 1,0% | € 40 |
| Zn | 1,0% | € 16 |

*Table 4.4 Penalties in MSW incineration*

### 4.3.5 Landfill

Landfill costs (in a MSW controlled landfill) are also obtained from AVR Chemie (AVR Chemie 2001), from the Philips DFND (Design for Non Disassembly) project (Deckers 1998) and from German sources (Fraunhofer 2002). The costs are divided in general landfill costs per ton and extra penalties costs for unwanted elements. Again, in order to estimate the costs for a fraction the following equations counts per material. In principle, the exact contribution of a certain product being shredded and separated to for instance a residue fraction being incinerated is impossible to determine. However a first order approximation for the landfill cost can be made as follows in Equation 4.2:

4.2 $$IC_{landfill} = \sum_{i}^{\infty} IC_{landfill,i} = \sum_{i}^{\infty} \left[ \left( \frac{m_i}{m} \right) \times TC_{landfill} + \left( \frac{m_i - UD_i}{m} \right) \times P_i \right]$$

With:

$IC_{landfill}$ is the integral costs paid for landfill of the fraction;
$IC_{landfill,i}$ is the integral costs for material i to the integral costs of landfill;
$m_i$ is the weight of material i in the fraction;
m is the weight of the fraction;
$TC_{landfill}$ is the general treatment costs for the fraction (set at 140 €/ton for controlled landfill and 64 €/ton for uncontrolled landfill, (Fraunhofer 2002a));
$UD_i$ is the threshold for material i;
$P_i$ is the penalty paid for material i, only if $m_i > UD_i$.

Like with Equation 4.1 also with Equation 4.2, the material contribution of a certain product to a certain fraction can be calculated. For this contribution, the penalties are

| Material | Threshold % | Penalty € per % per ton |
|---|---|---|
| Cu | 1,0% | € 20 |
| Ag | 1,0% | € 40 |
| As | 1,0% | € 40 |
| Be | 1,0% | € 40 |
| Br | 1,00% | € 45 |
| Cd | 1,0% | € 40 |
| Cl | 1,0% | € 15 |
| Cr | 1,000% | € 20 |
| Hg | 0,0% | € 40.000 |
| Ni | 1,0% | € 20 |
| Pb | 1,0% | € 20 |
| Sb | 1,0% | € 40 |
| Se | 1,0% | € 40 |

*Table 4.5 Penalties in MSW landfill*

estimated for every material taking into account an estimated concentration in this contribution as the concentration for which has to be paid. The resulting penalty is allocated on the material under consideration. The penalties are determined and 'allocated' to the corresponding amount of material under the assumption that the corresponding fraction as a whole doesn't fall under another waste-category (like categories for which special treatment costs must be paid). In Table 4.5 the main penalty elements and thresholds as set in the calculations are given.

### 4.3.6 Copper smelter

Economic data from copper smelter processes are obtained from (Mirec 2002, Deckers 1998, Boks 2002a, Fraunhofer 2002). Integral costs at a copper smelter can be calculated with Equation 4.3 (Lewis 1978, van Houwelingen 1996). Costs and revenues are integral in the following Equation 4.3. It represents the amount of money paid by copper smelters to recyclers that deliver copper fractions.

4.3 $$IC_{copper} = \sum_{i}^{\infty}\left(\left(\left(\frac{m_i}{m}\right) - UD_i\right) \times \left(\left(LME_i \times AF_i\right) - RC_i\right) - TC_{copper}\right)$$

In which:

$IC_{copper}$ is the integral costs and revenues paid/received from a copper smelter;
$m_i$ is the weight of material i in the fraction;
$m$ is weight of the fraction;
$UD_i$ is the Unit Deduction for material i (above this threshold revenues are received);
$LME_i$ is metal prices for material i at the London Metal Exchange (LME, see Section 4.3.8);
AF is Adjustment Factor, the percent of the LME price offered by the smelter ;
$RC_i$ is the refining charge to be paid for material i;
$TC_{copper}$ is the general treatment charge to be paid for fractions delivered at the smelter.

All units are in %, €, and kg.

Equation 4.3 counts for the valuable metals copper, gold, silver and palladium. For some other metals penalties must be paid, analogue to the situation described in Section 4.3.5. Equation 4.4 represents this:

4.4 $$IC_{copper,pen} = \sum_{i}^{\infty} IC_{copper,pen,i} = \sum_{i}^{\infty}\left[\left(\frac{\left(m_i \quad UD_i\right)}{m}\right) \times P_i\right]$$

With:

$IC_{copper,\ pen}$ is the integral penalty costs paid for the fraction/ lot at the copper smelter
$IC_{copper,\ pen,i}$ is the total penalty for material i to the integral costs of the copper smelter

$m_i$ is the weight of material m in the fraction
m is the weight of the fraction
$UD_i$ is the penalty threshold for material i
$P_i$ is the penalty paid for material i, only if $m_i > UD_i$

### 4.3.7 Specific secondary material processing routes

1. Ferro smelting: For the processing of ferro fractions, an integral treatment charge of 0,41 €/kg is applied. Revenues for iron recovered are only 0,12 €/kg. Only for separately collected stainless steel a higher revenue is paid of € 2,10. Other metals present in a ferro fraction are or lost to slags, or ending up in the steel. In Equation 4.5 the economic consequences of the ferro fraction are represented:

   4.5 $$IC_{ferro} = TC_{ferro} \times m - LME_{ferro} \times m_{ferro}$$

   With:
   $IC_{ferro}$ is the integral costs and revenues paid/received from a ferro smelter;
   $m_{ferro}$ is the weight of material i in the fraction;
   m is weight of the fraction;
   $LME_{ferro}$ is metal prices for iron at the London Metal Exchange (see Section 4.3.8);
   $TC_{ferro}$ is the general treatment charge to be paid for the fraction delivered at the ferro smelter.

2. Aluminium smelter: Usually a flotation process is applied for concentrating the aluminium fraction. The resulting residue fraction (also containing circuit board materials) is sent back to the recycler. The default treatment charge is assumed to be 600 €/ton. Revenues are 1370 € per ton aluminium recovered.

   4.6 $$IC_{aluminium} = TC_{aluminium} \times m - LME_{aluminium} \times m_{aluminium}$$

   With:
   $IC_{aluminium}$ is the integral costs and revenues paid/received from an aluminium smelter;
   $m_{aluminium}$ is the weight of material i in the fraction;
   m is weight of the fraction;
   $LME_{aluminium}$ is metal prices for iron at the London Metal Exchange (see Section 4.3.8);
   $TC_{aluminium}$ is the general treatment charge to be paid for the fraction delivered at the aluminium smelter.

3. Cement kiln: Mixed plastics or residue fractions are often processed in cement kilns. In Germany a large amount of mixed plastics are processed this way. As a default value the treatment charge for a mixed plastics/ residue fraction is set to 0,10 €/kg. Acceptance criteria are usually not applicable for residue or mixed plastic fractions originating from shredding and separation of consumer electronics (Ansems 2002a), (Verein Deutsche Zementwerke 2001).

4. Plastic recycling: Colour sorting, cleaning and upgrading is relatively expensive depending on the types of plastics to be processed. For recycling of ABS for instance, treatment costs for the plastic fraction are 0,40 €/kg. The material value for original ABS is around 1,50 €. However, for secondary ABS a much lower value is paid due to degradation and loss of quality. Furthermore, recovery percentages are not very high (see Section 3.4.8 and Equation 4.9). This result in the fact that only large plastic housings (monitors and TVs) are possibly economically feasible for plastic recycling, under the assumption that economies of scale are realised and the markets for secondary plastics become more mature (Boks 2002a). In Chapter 5.5.1, the options for plastic recycling and resulting eco-efficiency calculations will be presented.

5. CRT-glass recycling: In Table 4.6, the current status of glass recycling in The Netherlands is displayed (Mirec 2002b). Only 15% of the CRT glass collected in The Netherlands is actually re-applied in new cone-glass. Expected is that it is technically possible to recycle 70% of old CRT glass including the re-application of cone-glass towards cone glass and screen glass towards screen glass. Precondition however, is that contracts with CRT glass manufacturers provide in a stable and secure outlet for this secondary material. The prices presented in Table 4.6 are based on actual market prices. In Chapter 5.5.2 the eco-efficiency results of increased glass recycling will be presented.

| Treatment option | % | Replaces | Costs (kg) | Revenues (kg) | Net costs (kg) |
|---|---|---|---|---|---|
| Building industry | 35% | Sand | € 0,11 | € 0,01 | € 0,10 |
| Uncontrolled landfill | 40% | - | € 0,06 | € 0,00 | € 0,06 |
| CRT glass recycling incl. pretreatment | 15% | Cone glass | € 0,37 | € 0,30 | € 0,07 |
| Ceramic industry | 10% | Feldspar | € 0,13 | € 0,04 | € 0,09 |

*Table 4.6 Treatment percentages old CRT-glass, costs and revenues*

### 4.3.8 Revenues for materials

In Table 4.7, the September 2002 LME metal prices are given.

| Metal | Price (kg) | Metal | Price (kg) | Metal | Price (kg) |
|---|---|---|---|---|---|
| Ag | € 141 | Fe | € 0,07 | Pb | € 0,50 |
| Al | € 1,37 | Hg | € 0,15 | Pd | € 10.639 |
| Au | € 10.319 | In | € 161 | Pt | € 17.300 |
| Bi | € 8,47 | Mg | € 1,82 | Sb | € 1,69 |
| Cd | € 56,32 | Mn | € 0,79 | Sn | € 3,90 |
| Co | € 15,27 | Mo | € 10,60 | Ta | € 804 |
| Cu | € 1,59 | Ni | € 7,36 | Zn | € 0,81 |

*Table 4.7 LME metal prices (09/2002)*

A few other revenues or replacement values for other materials, not displayed in Table 4.7 or Section 4.3, are also included in the QWERTY/EE software.

## 4.4 Combining economic and environmental data in 2D-graphs

### 4.4.1 The X-axis: environment

All steps necessary in order to incorporate all data presented in Section 4.3 in a comprehensive eco-efficiency method will be discussed in this section. As discussed in 4.2, the default choice for the X-axis of Figure 4.3 is a single environmental indicator. The results are directly obtained from calculations as illustrated in Chapter 3. In first instance no relative, but **absolute** values are taken. The 'environmental ingredients' are described in Chapter 3.4. As a default choice, the Eco-Indicator '99 method is taken, with 5% weighting of the impact category Resource Depletion for Minerals. For more details see Chapter 3.4.1.

### 4.4.2 The Y-axis: economics

Like in Chapter 3, also economic minimum and maximum boundaries are defined to keep the economic calculation sequence in line with the environmental calculations of Chapter 3. For the minimum boundary (maximum revenues or lowest costs) the definition is recovery of the initial economic value of the materials in the product (or stream) under consideration, without any losses due to treatment activities. Like the environmental part, this is a theoretical and unreachable situation. In the case of the maximum boundary condition (maximum costs or lowest revenues), the highest costs per realistic process per material under consideration are taken. With these two definitions, the same approach as in Chapter 3 can be followed. In other words the economic potential of a certain product or product stream over the end-of-life chain can be followed. Like in Chapter 3, an economic value gained versus lost account can be made. Due to this choice, also relative values ('cost-efficiency') can be calculated as will be shown in Section 4.4.4. Furthermore, also an easy comparison can be made between the environmental effects of a certain stage in the end-of-life chain and the economic effects. This will be discussed in detail in Section 4.5.9.

The minimum costs/ maximum revenues as depicted in Figure 4.6, are 'the best possible case' and defined as all materials recovered as such. More precisely: every material is recovered in its initial amount and grade without any economic costs of treatment steps. Again, this is an unreachable, and therefore a fixed theoretical optimal situation. Equation 4.7a and 4.7b describe this definition of this lower boundary, which represents the original economic material value within the product under consideration.

4.7a $$IC_{\min,i} = m_i \times IC_{subst,i}$$

4.7b $$IC_{\min} = \sum_{i=1}^{\infty} \left( m_i \times IC_{subst,i} \right)$$

With:

$IC_{min,i}$ is the best case economic value, minimum costs, for the weight of material i;
$IC_{subst,i}$ is the maximum economic substitution value for the extraction of raw materials for material i;
$m_i$ is the weight of material i within the product;
$IC_{min}$ is the total defined lower boundary minimum economic value for the complete product or fraction under consideration.

The economic substitution values in equation 4.7 are based on the economic material values of primary materials. In all equations positive economic values represents costs, negative values represent negative costs or revenues. Therefore the $IC_{subst,i}$ and $IC_{min}$ are usually negative values.

Comparable with the choice made for the minimum environmental value, the economic value is also based on the product's material composition and the corresponding replacement value. See Chapter 3.3.2 for more details on this choice. The definition of the worst case or maximum costs is the maximum costs per material ending up in the worst possible (realistic) end-of-life route, including the costs of pre-treatment: collection, transport, disassembly and shredding and separation into fractions. Again, it is important in this definition that not one single end-of-life route for the product as a whole is selected, but the total set of, sometimes, different end-of-life routes for every fraction. Also, reason for not choosing a single end-of-life route for the product as a whole, is that some materials have high penalties only in specific scenarios. For more details see Chapter 3.3.3.

The definitions for the worst-case economic value or highest costs are given in equations 4.8a and 4.8b.

4.8a $$IC_{\max,i} = m_i \times \left(IC_{\max eol,i} + IC_{pretr,i}\right)$$

4.8b $$IC_{\max} = \sum_{i=1}^{\infty} \left(m_i \times \left(IC_{\max eol,i} + IC_{pretr,i}\right)\right)$$

With:
$IC_{max,i}$ is the worst case economic value, maximum costs, for the weight of material i;
$IC_{max\ eol,i}$ is the maximum economic value for material i in the end-of-life scenarios under investigation, e.g. the 'worst case scenario;
$IC_{pretr,i}$ is the aggregated economic value for material i undergoing pre-treatment steps (f.i. transport and storage, complete shredding and separation);
$IC_{max}$ is the total defined maximum costs for the product or fraction under consideration.

The reason for including the pre-treatment part in the definition is the fact that energy consumption for processing and recovering materials and transportation costs should be incorporated and these costs can be significant.

The actual costs for a certain product, see Figure 4.6, in a certain end-of-life scenario is represented by Equations 4.9a and 4.9b. The actual costs for the total amount of material i, is the sum of all this material ending up at the end-of-life destinations as represented by Figure 4.6, multiplied with the corresponding economic value for this direction.

4.9a $$IC_{actual,i} = m_i \times \left( IC_{pretr,i} \times x_i + rec_i \times grade_i \times IC_{subst,i} + \sum_{j=1}^{\infty} \left( IC_{eol,ij} \times y_{ij} \right) \right)$$

4.9b $$IC_{actual} = \sum_{i=1}^{\infty} \left( m_i \times \left( IC_{pretr,i} \times x_i + rec_i \times grade_i \times IC_{subst,i} + \sum_{j=1}^{\infty} \left( IC_{eol,ij} \times y_{ij} \right) \right) \right)$$

With:

$IC_{actual,i}$ is the actual economic value for the weight of material i for the end-of-life scenario under consideration;

$x_i$ is the percentage of material i undergoing the defined pre-treatment steps;

$rec_i$ is the percentage of material i being recovered and substituting its corresponding primary material;

$grade_i$ is the grade in which material i is occurring after recovery (only relevant for recovered material with a different level of re-application compared to the original material, this factor represents the percentage of the original economic value that is paid for the secondary material);

$IC_{eol,ij}$ is the environmental value for material i going into end-of-life route j;

$y_{ij}$ is the percentage of material i ending up in end-of-life route j;

$IC_{actual}$ is the defined actual environmental value for the complete product and the EOL scenarios under consideration.

In Equation 4.9, an important parameter representing the grade of secondary materials in comparison with the original grade is used. Except metals that are recovered in their original grade at their corresponding primary smelter, other secondary materials are usually not recovered in their original form. In particular plastics are usually not recovered with the same quality of the original material due to degradation. Also glass for instance, is not very often used in its original form, but in a lower quality or as a slag former in thermal processes as described in Section 4.3.7. So for metals recovered at a corresponding smelter this value will be 1, for materials undergoing degradation or quality loss, it is the quotient of the economic value of the secondary material over the economic value of primary material.

Equation 4.10 represents the total actual economic value to be used in Equation 4.9. For the integral costs of end-of-life of consumer electronics in this thesis the following steps are incorporated: Collection and transport costs, shredding and separation, concentrating, analysis and overhead costs. Furthermore, copper, aluminium and ferro smelter, glass recycling, plastic recycling, ceramic and building industry. Finally final waste processing: (controlled and uncontrolled) landfill, incineration (with and without energy recovery and cement kiln are included.

4.10 $$IC_{EOL} = IC_{collection} + IC_{transport} + IC_{shredding} + IC_{copper} + IC_{ferro} + IC_{aluminium} + IC_{glass} + IC_{ceramic} + IC_{building} + IC_{plastic} + IC_{landfill} + IC_{incineration} + IC_{cementkiln}$$

With:

| | |
|---|---|
| $IC_{collection}$ | is the integral costs for collection; |
| $IC_{transport}$ | is the integral costs for transport; |
| $IC_{shredding}$ | is the integral costs for shredding, separation and analysis/overhead costs; |
| $IC_{copper}$ | is the integral costs or revenues at the copper smelter; |
| $IC_{aluminium}$ | is the integral costs or revenues at the aluminium smelter; |
| $IC_{ferro}$ | is the integral costs or revenues at the ferro smelter; |
| $IC_{glass}$ | is the integral costs or revenues at glass recycling; |
| $IC_{ceramic}$ | is the integral costs or revenues at the ceramic industry; |
| $IC_{building}$ | is the integral costs or revenues at the building industry; |
| $IC_{plastic}$ | is the integral costs or revenues at plastic recycling; |
| $IC_{landfill}$ | is the integral costs for MSW landfill (controlled or uncontrolled); |
| $IC_{incineration}$ | is the integral costs for MSW incineration (with or without energy recovery); |
| $IC_{cement\ kiln}$ | is the integral costs for cement kiln. |

The total amount of material i ending up in each end-of-life route plus the actual amount of i that is recovered, must equal 100% as represented by Equation 4.11. The Equation is used to check the Equations 4.9 and 4.10 in the QWERTY/EE software and to make sure no materials are 'lost' in the calculations and that the mass balances are correct.

4.11 $$\sum_{j=1}^{\infty} y_{ij} = 100\% - rec_i$$

### 4.4.3 Calculating take-back system performance

From Equation 4.10 also system performance can be calculated in two ways:

1. First of all the single results of different end-of-life scenarios for one and the same product as defined in Equation 4.10b can be multiplied with the collection percentage for every scenario. In this the general collection rate for a total system is 'translated' to the chance that a certain product is collected and treated within a certain take-back system. The result shows the average individual performance of the product, fraction or product stream within the take-back system. In other words the general average collection rate is converted and linked to the performance of individual products and this is done for every end-of-life scenario under consideration.
2. Secondly, the performance of a large number of product – end-of-life scenario combinations can be multiplied with the total numbers of products going into each direction.

An example regarding the first option is highlighted in Section 4.5.5. An example regarding the second option is given in Section 4.5.8

### 4.4.4 Calculating cost efficiency

As with the determination of the actual environmental impact, with Equation 4.10 an actual economic value is determined for a product in a certain take-back system. This value represents an **absolute value** in euros, which, in contrast to the absolute environmental values of Chapter 3, is usually more transparent than the millipoints used as environmental scores. However, also cost efficiency can be calculated: A normalisation step is performed to obtain relative cost efficiency scores. The product's actual end-of-life performance is positioned in between the 'best case' and 'worst case' scenarios of Equation 4.7 and 4.8. This leads to cost efficiency values by applying the same equations as in Chapter 3.3.5 by replacing EVW (Environmental Value Weight) with IC (Integral Costs/revenues) and QWERTY with cost efficiency. With the results also the contribution of individual materials to the 'costs bandwidth' can be determined. Similar to Chapter 3.3.5, also the economic 'gain' percentage and economic 'loss' percentage per material can be determined.

## 4.5 Example: application on a Soundmachine

### 4.5.1 Introduction

In this section, the plastic dominated and medium sized Soundmachine (portable audio from 2001) is taken as an example. In Chapter 3, already a detailed QWERTY analysis of this product is conducted. The product composition is known in high detail.

In addition to the QWERTY analysis of Chapter 3, also the main costs and cost scenarios will be highlighted. Cost efficiency and the analogue with Chapter 3 is discussed in Section 4.5.3. The costs per end-of-life sub-stage are shown in Section 4.5.4. In Section 4.5.5, the example of mechanical recycling of plastics versus incineration with energy recovery will be given. Consequences of increasing collection rates and costs per stakeholder are mentioned in Chapter 7.7. Finally, the possibilities of comparing the performance of the chosen product within different take-back systems will be mentioned in Section 4.5.2.

### 4.5.2 Costs and revenues

In Figure 4.7 the economic equivalent of Figure 3.6 of Chapter 3.5.3.is depicted.

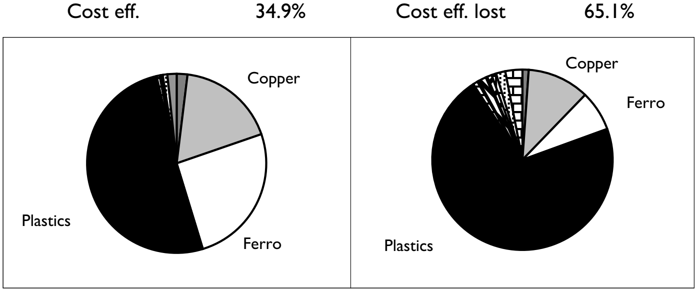


*Figure 4.7 Cost efficiency of the Soundmachine*

In Figure 4.7, it seems remarkable that the lost 'costs' are comparable with the contribution of materials to the MRE-loss value of Figure 3.5 in Chapter 3.5.3. The reason is that the most significant activities and thus costs from transport and shredding and separation are allocated to the product as a whole on a weight basis. The costs for incineration of the residue fraction results in a high contribution of the plastics in this graph. In Chapter 7.9 the costs per stage will be discussed.

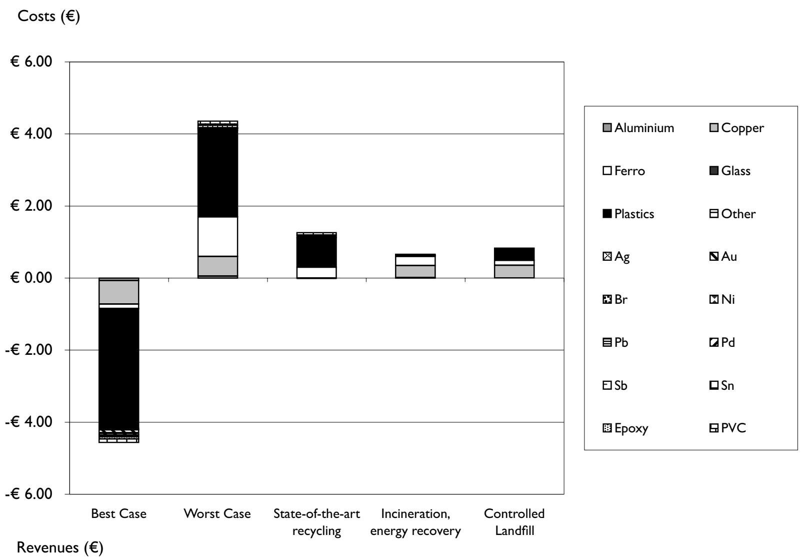


*Figure 4.8 Cost scenarios*

Figure 4.8 shows the economic equivalent of Figure 3.7 from Chapter 3.5.4. Besides the state-of-art recycling scenario (3rd bar) also the economic behavior of the product within other scenarios can be displayed. In Figure 4.8 the economic performance of the product within other relevant end-of-life scenarios (the product as a whole into one scenario) are shown. Again, the first bar is the theoretical 'best case' value or original economic material value. The second bar is the 'worst case' scenario or highest economic values per material – end-of-life scenario combination. With these two bars, the economic bandwidth is presented which is the same as the right graph in Figure 3.7. Also in this figure, the contribution of the different materials is integrated. Also here, an important conclusion is that although state-of-the-art recycling is applied, the economic recovery (in fact only net costs are realised) is far from the 'best-case' scenario. In this case mainly due to shredding and separation and transport costs.

### 4.5.3 Eco-efficiency, the bridge to system performance

When the eco-efficiency concept as described in Section 4.2.3 is applied, a graph like Figure 4.9 can be drawn. This graph is the result of combining Figure 4.7 and Figure 4.8. The basic idea behind the graph within Section 4.2.4 is filled with all the environmental and economic data of this chapter. Again on the vertical axis, costs (below) and revenues (above) are displayed in monetary units (€'s). On the horizontal axis, environmental burden (left) and environmental gain due to preventing new material extraction (right). The points in this graph represent the different scenarios to which a product can end up. The point 100% collection and recycling is the state-of-the-art recycling process.

The logistics costs are based on the logistics costs excluding the consumer part (4th option of Table 4.2 and the left side of Figure 4.6). The costs of consumers handing in products at municipalities and retailers are excluded. These costs can be very high. The 'consumer part' is estimated to be € 1,18 in this particular case. Also the difference between incineration with and without energy recovery is relatively large. This also means from an eco-efficiency perspective that for plastics dominated products like this Soundmachine, at least energy recovery should take place when incinerated.

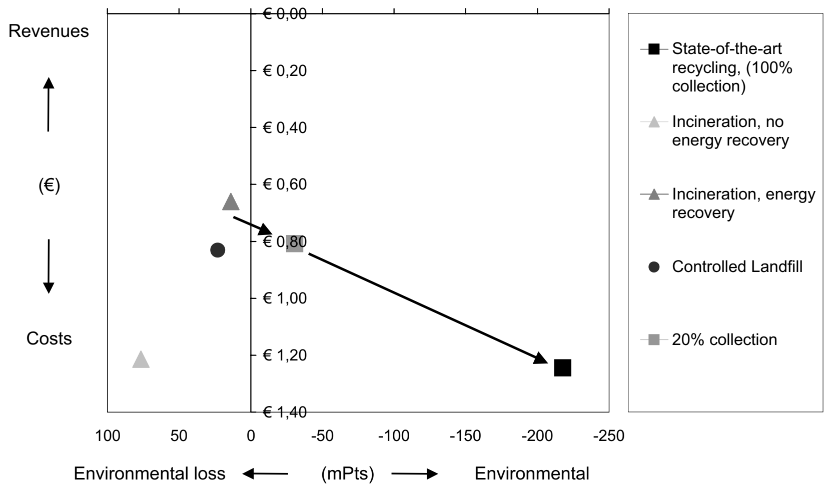


*Figure 4.9 Eco-efficiency of all relevant end-of-life options*

With Figure 4.9, also the effect of increasing collection rates can be visualised. The first arrow, from 0% collection (which is in fact a 100% disposal with MSW; a mix of 23% landfill and 77% incineration) towards 20% collection results in higher environmental gains against slightly higher costs for the system as a whole. If it would be possible to collect 100% of the discarded products, than a significant increase in environmental gain is realised against higher costs (first arrow plus second arrow). The total costs within the system are increasing in this case from 0,70 € per Soundmachine (4 kg) to 1,23 €, excluding the costs for consumers to hand in a product like this. In Section 4.5.3, a further comparison is made regarding the increased collection rates, a direction falling in the fourth quadrant.

From this graph three more detailed questions arise:
1. What are the costs per end-of-life stage? (Section 4.5.4)
2. What will be the effect of plastic recycling on the results? (Section 4.5.5)

3. What is the relation between the plastic recycling option and the increase collection rate option in eco-efficiency terms (also Section 4.5.5).
4. What is the effect of changes in logistics on the system performance? (Section 7.7.2)
5. What are the costs per stakeholder, also related to increasing collection rates? (Chapter 7.9.2)

### 4.5.4 Costs per end-of-life stage: Hidden and indirect costs

Besides the eco-efficiency graph of Figure 4.9, in which the overall system performance is displayed, also the individual costs per end-of-life stage can be determined. This is illustrated in Table 4.8.

| End-of-life stage | Integral costs | Costs | Revenues |
|---|---|---|---|
| Transport and collection | € 0,48 | € 0,48 | € 0,00 |
| Shredding and separation | € 0,55 | € 0,55 | € 0,00 |
| Sorting and handling | € 0,27 | € 0,27 | € 0,00 |
| Incineration, energy rec. | € 0,07 | € 0,07 | € 0,00 |
| Copper smelter | -€ 0,08 | € 0,38 | -€ 0,46 |
| Aluminium smelter | € 0,00 | € 0,05 | -€ 0,05 |
| Ferro smelter | -€ 0,05 | € 0,04 | -€ 0,09 |
| **Total** | **€ 1,24** | **€ 1,84** | **-€ 0,60** |

*Table 4.8 Integral costs per stakeholder/ end-of-life stage*

The most relevant stages are the first ones for this Soundmachine (see the first column with net values). Transport and collection costs as well as shredding, separation and overhead costs have the highest contributions. Recovered material value is much lower and mainly originating from the copper smelter (from recovery of both copper and precious metals). Note that in the second and third column, the costs and revenues are displayed. For the copper fraction, a € 0,47 revenue against € 0,35 costs are realised. Furthermore a small amount is paid for incineration with energy recovery of the residue fraction.

### 4.5.5 Is plastic recycling eco-efficient?

In the case of the Soundmachine, disassembly of the encasings of 1,3 kg on a total product weight 3,9 kg is assumed (120 seconds average disassembly time). Costs involved are already mentioned in Section 4.3.7. A reason for plastic recycling might be to increase weight based recyclability. In this case, under a strict definition, without plastic recycling 29% is realised and with plastic recycling 54%.

The economic and environmental calculations result in Figure 4.10, which is similar to Figure 4.9, but containing an extra arrow for plastic recycling of the housings. It is clear that although plastic recycling is leading to higher environmental gain (change to the right on the environmental axis), also much higher integral costs are occurring (change from € 1,23 to € 2,19 on the vertical axis). The QWERTY scores are increased from 46% to 53%. The assumptions made in Chapter 3.6.3 and in Section 4.3.7 for plastic recycling are also including economies-of-scale for plastic recycling. This is far from reality at the moment for the Dutch and European situation. In (Boks 2002a) it is proven that this can have large consequences for the integral costs involved. Also many technical problems exist in this area. The result is that the eco-efficiency direction of Figure 4.10 is a 'best case' scenario for plastic recycling. In reality, due to immature markets the eco-efficiency direction will be much more downwards than the optimal direction shown in this graph.

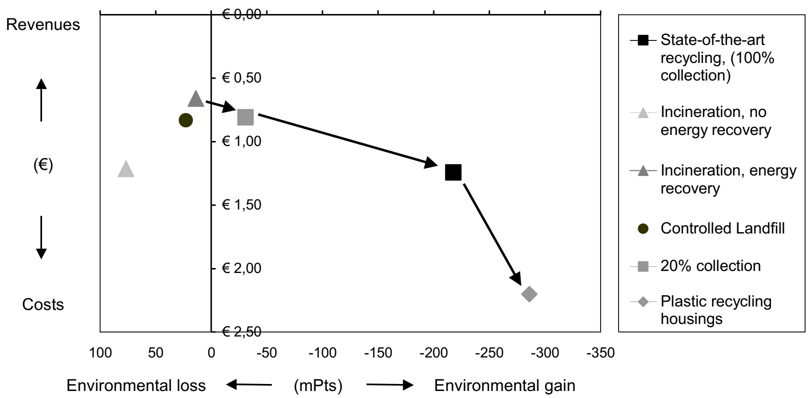


*Figure 4.10 Eco-efficiency of plastic recycling*

Figure 4.10 is used to demonstrate the usefulness of the **'vector approach'**. Avoiding incineration without energy recovery for instance, results in a higher eco-efficiency. It is also clear that the second arrow leads to relatively high environmental returns for the extra costs compared to the application of plastic recycling of the housings as displayed with the third arrow. Both options are 'fourth quadrant' results and need balancing of environmental gain over costs with the **'quotient approach'**. The application of the latter is extensively discussed in Chapter 7.5 for many other cases and products.

## 4.6 Discussion, using QWERTY/EE as a waste policy instrument

### 4.6.1 Economic sensitivity analysis and data quality

Sensitivity analysis regarding the environmental part is already discussed in Chapter 3. In this section, sensitivity of the economic results is discussed. Assumptions, scope and boundaries of the economic part of the eco-efficiency calculations are very important. In this chapter, data on all relevant stages for treatment of discarded consumer electronics are presented. Main data on collection and transport, storage, shredding and separation, secondary material processing and final waste treatment are included. The fact that almost all basic data are derived from actual processes and activities and not from theoretical modelling results in a high grade of reality. More robust data can be obtained by observing multiple similar processes instead of data of single processes. However, due to time constraints, this was not feasible. The copper smelter data are for instance originating from one smelter. Minor differences can occur when another smelter would have been selected and evaluated.

The inclusion of (sometimes indirect) costs for instance for penalty elements in both final waste processing as for the secondary material outlets, leads to comprehensive and actual data. The main discussion items on using specific versus general data, the sensitivity of the results and the use of another environmental assessment methods are listed below in the next three sections:

### 4.6.2 Specific and current data versus general data

Specific versus general data. Most data is derived from Dutch and German sources.

1. Collection data and transport costs are for dense populated areas. When the same data is applied on less populated countries, a serious underestimate of collection and transport costs is likely to appear. The costs are primarily determined by labour costs and secondly by fuel costs, so for instance in the US these costs would be slightly lower due to lower fuel prices. Collection costs can also substantially higher in sparsely populated areas due to economies of scale effects and larger transport distances. Collection and transport costs have often the highest contribution in the integral costs of end-of-life treatment.
2. Most data are from 2001 or 2002. In some cases, technological developments are causing rapid improvements. These developments are mainly taking place in shredding and separation, disassembly and plastic or CRT glass recycling. More details on the uncertainty in future economic parameters can be found in (Boks 2002a). The data used in this chapter are in almost all cases based on state-of-the-art technology.
3. Immaturity of secondary glass and plastics markets causes technical problems (acceptance criteria can not be met) and secondary streams are often not large enough to be economically of great interest for plastic of glass producers. Legislation prescribes an extended producer responsibility for taking back discarded products, but doesn't contain the obligation of taking back secondary product streams by suppliers like CRT or plastic producers. This often leads to higher prices that are not reflecting 'real market values'.

### 4.6.3 Sensitivity and different environmental assessment methods

In this section the sensitivity of the results regarding the choice for an environmental assessment method is discussed:

In Figure 4.14, the eco-efficiency results for the Soundmachine are displayed for another environmental assessment method than the Eco-Indicator '99: the EDIP'96 approach. Comparing Figure 4.14 with Figure 4.9, shows more or less the same trends for all end-of-life options. Compared to Figure 4.9 for the Eco-Indicator '99, the landfill options have higher environmental impacts compared to the incineration options according to the EDIP'96 method. The plastic recycling scenario in relation to the state-of-the-art options with energy recovery, leads to less environmental improvement compared to the Eco-Indicator '99 method. The resulting eco-efficiency direction is even more 'downwards' than under the Eco-Indicator '99 method. The reason here is already mentioned in Chapter 3.6.1, Figure 3.12: in the EDIP'96 method no resource depletion of fossil fuels is included.

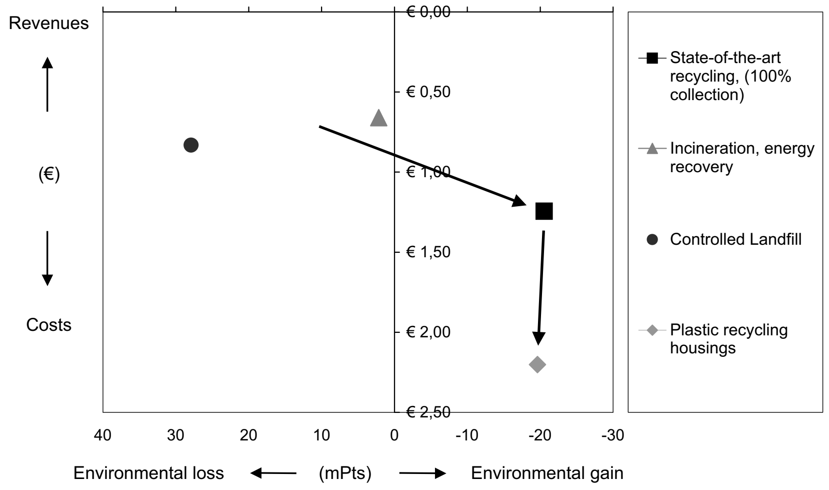


*Figure 4.11 Eco-efficiency of the Soundmachine, (EDIP'96)*

Note that the EDIP'96 method is a completely different approach (category based) than the Eco-Indicator '99 method (damage based). See Chapter 3.6 for more details on the environmental assessment methods used in this section.

### 4.6.4 Sensitivity regarding other aspects

In this section the sensitivity of the results regarding other aspects is discussed

1. A very important aspect is economies of scale. In all examples within this chapter, economy of scale is assumed to be reality. This regards the current situation for the shredding and separation processes and the subsequent treatment for the metal and residue fractions. For the glass en plastic fraction towards their respective recycling processes, 'real market values' and sufficient stream sizes are assumed. In the case of plastics, for the start-up periods, high investments costs occur compared to an economy of scale situation. Immaturity of secondary CRT glass and plastics markets also causes that economies of scale are not realised. This can result in higher integral costs than presented in Section 4.3.7 and 4.5.5.
2. Collection rates of consumer electronics in some cases rapidly increase due to the development of take-back systems in several countries. Also changes in the compositions of the streams collected are expected, leading to large changes of uncertainty in the costs per kg treated within a certain take-back system. For instance in

the Dutch E&EE system, the numbers of small appliances being collected are still raising every year (but is still relatively low compared to larger appliances).
3. Changes in amounts of plastics (van Schijndel 2002) by material substitution and dematerialisation have a strong influence on the treatment costs per kg. Use of precious metals is decreasing, however due to miniaturisation the concentrations can increase by changing PWB designs, which was already discussed in Chapter 2.
4. Changes in product compositions and categories have influence on the costs side. For instance the application of LCD screens instead of CRT screens change the production volumes of CRT glass in the future, while on the same time an enormous amount of 'historical glass' cannot probably be used as secondary material for new CRTs. Secondly, also miniaturisation of PWBs has a large effect on the concentrations of environmentally relevant materials (including precious metals) in disposed products.
5. Markets for some materials are mature, whereas other are not well developed or even absent, for instance for glass and plastic recycling. Also market prices over time can play a substantial role in the economic parameters. In (Boks 2002a) it is shown that for precious metal dominated products, the LME price for palladium can have a tremendous influence on what the optimal recycling infrastructure should be. The concentrating of materials (copper) to meet minimum acceptance criteria (copper smelter) or prevention of diluting valuable materials to other fractions (palladium) is influenced by the palladium price.

### 4.6.5 Using eco-efficiency as a policy instrument

In this section, already a few general remarks are made regarding the application of the above eco-efficiency concept as a policy instrument. In Chapter 7, this will be discussed in more detail.

1. The first target of the concept was to estimate the system performance as a whole, the options for improvement, the role and contribution of the individual stakeholders and the relative importance of the various substages in the total picture. The methodological development makes it possible to determine the right avenues for eco-efficient improvement of end-of-life chains. The current neglect of efficiency and effectiveness in proposed policy and legal measures can now be dealt with, which is very relevant from a societal perspective.
2. If a concept like this is applied to monitor end-of-life system performance in practice, then an upfront agreement can be made among the stakeholders involved on the main assumptions, the most important economic parameters and on the use of an environmental scoring method. Moreover, if such agreements are in place, the normalisation and weighting schemes should be developed and fixed by all parties (Bras 1999).
3. Sensitivity analysis on the most uncertain factors should always be applied to determine under which circumstances the conclusions drawn could change.
4. In negotiations between parties, the selection of improvement options should obviously start with the most eco-efficient directions. In Chapter 7, the different types of eco-efficiency changes are further discussed closely related to Figure 4.4 and the two steps involved. For instance for all 'fourth quadrant' directions, a rank-

ing can be made for those options with the highest environmental returns on investment. How to deal with this is presented in Chapter 7.5.

## 4.7 Conclusions

Generally it can be concluded that addressing costs and revenues in relation to environmental costs and revenues on a quantitative way, is a powerful concept in rethinking about the eco-efficiency of the end-of-life of consumer electronic products. Furthermore, better in-sights in the system performance and the demands and constraints of secondary material processors are obtained. The concept places the best possible and state-of-the-art environmental measuring in an economic context, addressing the environmental effectiveness of for instance the WEEE Directive in relation to actual costs efficiencies. The value and applicability of the concept will be further enhanced in the next chapters.

With the examples of the Soundmachine, it is shown that the eco-efficiency concept as a whole is very useful in determining the 'overall performance picture' as well as the influence of single aspect and issues on this. The following aspects were briefly addressed in a quantitative way:

1. Performance of a single product in different end-of-life scenarios.
2. Contribution of individual materials and material fractions to this performance.
3. The consequences and contributions of single stakeholders.
4. The eco-efficiency effects of possible changes in
    a. Design (for instance: which materials to prioritise?)
    b. Policy (for instance: how to monitor system performance?)
    c. Technology (for instance: what is the effect of plastic recycling?)
    d. Logistics and system organisation (for instance: what is the effect of changing collection infrastructures?)
5. Optimising the relation between recyclers (fractions) and secondary material processors or final waste processors.
6. The basic question: Where to invest first in general?

In Section 4.2.3 other eco-efficiency related methods were discussed. In Table 4.9 these are repeated again including the position of the QWERTY/EE method in this:

| Criteria | Method | BASF | ECO2 | EVR | QWERTY/EE |
|---|---|---|---|---|---|
| LCA-based? | | + | + | + | + |
| Specifically for end-of-life evaluation? | | - | + | - | + |
| Suitable for stakeholder evaluations? | | o | - | + | + |
| Multiple weighting sets | | + | - | + | + |
| Basic environmental data sets available? | | + | - | + | + |
| Basic economic data sets available? | | - | - | + | + |
| Basic technical data on end-of-life included? | | - | - | - | + |

*Table 4.9 Position of QWERTY/EE towards other methods; +: included; o: not known; -: not included*

The main characteristics in comparison with existing methods is that the QWERTY/EE calculation sequences start at the point of disposal of products and that the application options are more extended: Also the inclusion of 'pre-cooked' technical descriptions for end-of-life processing, like a landfill and leaching model or incineration model as well as availability of basic environmental and economic data is as an important criteria.

The application of the QWERTY/EE on these issues will be discussed into more detail in the next chapters: In Chapter 5, the focus is on the technical side of end-of-life like the influence of technical constraints and developments from a **product perspective** and on trends for the different product categories in end-of-life processing. In Chapter 6, the focus is on improvement strategies by changing product design and the evaluation of improving end-of-life performance of disposed products. In Chapter 7 the focus is on system operation, legislation and logistics. Many options for which the **'quotient part'** of the 2D eco-efficiency approach applies, are discussed in more detail.

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# *Chapter 5: Technological improvement options from a product perspective*

## 5.1 Summary

The QWERTY/EE method of Chapter 4 is applied on a large number of examples. In addition to the plastic dominated product of the previous chapter, the example products for the categories of metal-, glass-, and precious metal dominated products are discussed. Furthermore trends in performance for many other products within various end-of-life scenarios under multiple environmental assessment methods are determined. The effects of technological improvements in plastic recycling, CRT glass recycling and adjusted shredding and separation settings are determined for the example products. Also the effects of other improvements at secondary material processors and final waste treatment are determined with the QWERTY/EE approach.

Important conclusions and outcomes are the quantification of the environmental and economic performance of the technical improvement options for multiple products. Plastic recycling seems only to be eco-efficient for large housings without flame-retardants or other contaminations which already undergoing disassembly due to the presence of a CRT or LCD. For small and medium sized housings the extra costs of plastic recycling are very high in relation to the realised environmental improvement. Dedicated shredding and separation of metal dominated products doesn't lead to substantial environmental or economic improvements. For glass dominated products, an increase in CRT glass recycling results in significant environmental improvements. The same counts for separate collection and treatment of precious metal dominated products with a sufficient precious metal content like cellular phones. However, economies of scale are a major assumption that has to be fulfilled in this case as well.

Another important conclusion is that although the different environmental assessment models prioritise the different materials within disposed products sometimes in a different order, the results of technological changes on a system level are very similar. The analysis of more than 75 different products clearly shows groups in state-of-the-art recycling performance in both environmental and economic terms and the distinction between the various product categories. From there also the evaluation takes place of further technical improvements in relation to the state-of-the-art recycling or current best-case situation. Even more, with the QWERTY/EE concept it is made possible to the select and rank improvement options within current and future

end-of-life processing and to determine which options bring very little environmental gain in practice.

## 5.2 Introduction

### 5.2.1 Objectives

This Chapter 5 focuses on the application of the QWERTY/EE method presented in Chapter 3 and Chapter 4, on a large number of examples. The aim is to determine the economic and environmental performance of a set of example products, which are regarded as typical for their product category. Where in Chapter 3 and 4, already the example of a plastic dominated Soundmachine is given, in this Chapter 5, similar results will be presented for a metal dominated DVD player, for a glass dominated 17-inch CRT-monitor and for a precious metal dominated cellular phone. The focus is on the eco-efficiency of single products and product groups in the Dutch take-back system, which is considered to be based on recycling processes that are currently the best available technology. On top of this, the eco-efficiency results of applying technical improvement options on around 75 different products will be described in order to check whether the example products were really 'typical' for their corresponding product categories.

The fourth research question posed in Chapter 1.2 refers to the application of the eco-efficiency concept and its usefulness in stakeholder debates and determination of end-of-life chain performance.

Research question 4:

> *What is the improvement potential in eco-efficiency terms resulting from application of the methods developed on many different products and product categories in certain end-of-life scenarios and the priorities in this respect to be favoured with end-of-life policy strategies?*

From this the main goal of this chapter is to demonstrate that the application of the comprehensive eco-efficiency concept for end-of-life of consumer electronic products is very useful in determining environmental performance of many different products and product categories as well as the improvement bandwidth of technical changes in end-of-life processing.

### 5.2.2 Position and structure of this chapter

In Section 5.3, the example of a metal dominated DVD player will be discussed. Thereafter, the same calculations will be mentioned for respectively a glass dominated 17-inch CRT monitor in Section 5.4 and a precious metal dominated cellular phone in Section 5.5. In Section 5.6, the results for many different products will be presented also in order to check whether the results of the example products where a good representation of the results for products within these product categories. Furthermore an evaluation on trends over compositions and sizes for many products will be discussed. In the next Section 5.7, some improvement options at shredding and separation will be discussed in further detail and in Section 5.8 and 5.9 the same is done for technical changes at respectively secondary material processors and final waste processors. Finally in Section 5.10 and 5.11 a sensitivity analysis will be carried out and conclusions will be drawn.

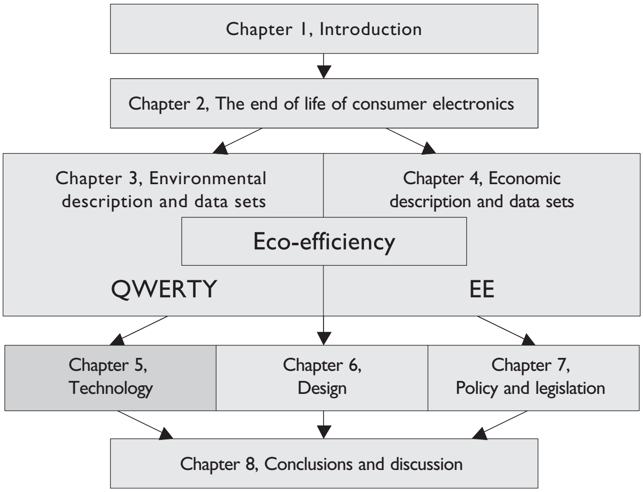


*Figure 5.1 Position of Chapter 5*

In Figure 5.1, the position of this chapter is presented. The eco-efficiency approach developed in Chapter 3 and 4 is demonstrated on a range of products and corresponding improvement avenues. After this chapter, in Chapter 6, the focus will be on the alignment of Design for End-of-life with the technical options and boundaries presented in this chapter. In Chapter 7 the same alignment will be made but then between end-of-life processing, system operation and legislation.

### 5.2.3 Backgrounds and assumptions

In Section 5.3 till 5.5, single examples of products representing their product categories will be discussed. A technical improvement option or scenario is defined as a change in end-of-life processing in relation to state-of-the-art recycling or treatment. The latter is defined as the current average end-of-life processing including collection, disassembly, shredding and separation, final waste processing and secondary material processing applied in the Dutch take-back system. Partly, this is already described in the two previous chapters. All data, results and graphs presented in the Sections 5.3 till 5.7 are further based on the following important assumptions:

1. State-of-the-art recycling is based on current shredding and separation technologies as earlier presented in Chapter 2.4.3. Shredding and separation behavior is based on the distribution tables derived from (Ansems 2002a) and checked by TU Delft Geosciences and Mirec (Mirec 2002a).
2. Data are representing the Dutch take-back system.

3. Economies of scale for glass and plastic recycling are realised as well as for sorting metal dominated products for dedicated shredding and separation and separate collection for cellular phones and other precious metal dominated products.
4. Costs for consumers for handing in products at municipalities or retailers are excluded from the integral costs unless stated otherwise.
5. All graphs and results are based on the occurrence of plastic within the other fractions, mainly the residue fraction to be treated in a MSW-incineration plant if not stated otherwise.
6. On all example products of Section 5.3 till 5.5 and on some products within Section 5.6 and 5.7, chemical analysis of the PWBs is performed. The Ecoscan files on which the Philips environmental benchmarks are based, deliver the data on all other components. The two combined result in full product compositions. See also Chapter 3.4.4 for more information on this matter.
7. For the other products in Section 5.6 and 5.7 without chemical analysis of PWBs, good estimates are available based on the types of PWB materials, the level of integration of components and the amounts and types of components attached to the boards (see level 2 description in Chapter 3.4.4).
8. The Eco-Indicator '99, Philips Best-Estimate, Hierarchic Perspective, Average Weighting set, weighting factor Resource Depletion – Minerals adjusted to 5%, is used as a default environmental assessment model (see Chapter 3.4.2).
9. All fractions sent to a subsequent process fall under the acceptance criteria applicable for this process or operation.

### 5.2.4 Approach

Like in Chapter 4, the following structure will be used to determine the environmental and economic performance of the example products of Section 5.3 - 5.5. For the plastic dominated Soundmachine the same order was followed as in Chapter 4:

1. Determination and description of product compositions and main product characteristics
2. Fraction compositions after shredding and separation.
3. Description of environmental performance:
   a. MRE and QWERTY definitions.
   b. MRE and QWERTY values gained and lost.
   c. Environmental impacts per stage for state-of-the-art recycling
   d. Other environmental scenarios for end-of-life
4. Description of economic performance:
   a. Integral costs per stage
   b. Results for other end-of-life scenarios
5. Graphical representation of the eco-efficiency directions
   a. State-of-the-art recycling (default scenario)
   b. Main technical improvement options (like glass or plastic recycling)

For more details on this structure, see Chapter 4.

## 5.3 Example: a metal dominated product

### 5.3.1 Product data, pre-treatment, shredding and separation

In this section, a metal dominated low-end DVD player from 2001 is taken as an example. Product data are obtained from (Philips 2001k). In addition, also the PWB compositions of this product are determined by chemical analysis (Mirec 2002a). In Table 5.1 the resulting product composition is given. The most important characteristics are a relatively high ferro-content: the weight of the metal housings of this product is 1,5 kg on a total weight of 2,6 kg. The precious metal content on the PWBs are on a total product weight: a 110 ppm for Silver, 16 ppm for gold and 3,3 ppm for palladium. The precious metal contents were lower than expected before PWB analysis. The plastics are to a large extent originating from the front panel and DVD-unit. The product architecture and Design for End-of-Life options will be discussed in Chapter 6 in more detail.

| Material | Weight (g) | Weight % |
|---|---|---|
| Aluminium | 23,84 | 0,9% |
| Copper | 97,27 | 3,8% |
| Ferro | 1849,15 | 71,9% |
| Plastics | 460,96 | 17,9% |
| Ag | 0,28 | 110 ppm |
| Au | 0,04 | 16 ppm |
| Pd | 0,01 | 3 ppm |
| Other | 141,96 | 5,5% |
| **Total** | **2573,50** | **100%** |

*Table 5.1 Product composition of the DVD player*

Similar to Table 3.8 of Chapter 3.5.2, the resulting contribution of materials towards fractions can be calculated based on the distribution tables of (Ansems 2002a), (Mirec 2002a). In Table 5.2, the resulting fractions after shredding and separation are displayed. Note that a substantial percentage of the valuable materials copper, gold, silver and palladium end-up in the 'wrong fractions', mainly the residue fraction.

| Fraction | Ferro (g) | Aluminium (g) | Copper (g) | Residu (g) |
|---|---|---|---|---|
| Aluminium | 0,12 | 19,68 | 1,17 | 2,86 |
| Copper | 0,91 | 4,86 | 76,07 | 15,42 |
| Ferro | 1756,69 | 18,49 | 18,49 | 55,47 |
| Plastics | 5,58 | 2,30 | 46,10 | 406,98 |
| Ag | 0,0028 | 0,0028 | 0,2405 | 0,0371 |
| Au | 0,0004 | 0,0004 | 0,0324 | 0,0073 |
| Pd | 0,0001 | 0,0001 | 0,0068 | 0,0015 |
| Other | 0,82 | 0,80 | 18,67 | 121,67 |
| **Fraction Weight** | **1764,13** | **46,14** | **160,78** | **602,45** |
| **Fraction %** | **68,5%** | **1,8%** | **6,2%** | **23,4%** |
| **Total** | | | | **2573,50** |

*Table 5.2 Fraction compositions for the DVD player*

The destinations of the four fractions are respectively ferro smelting, aluminium smelting and the copper smelting; the residue fraction is assumed to go to a MSW incineration plant (with energy recovery). The environmental performance of treating the contributions to the fractions of the DVD player in the above way is described in the next section. The assumptions and boundaries presented in 5.2.3 are applied to derive the environmental results in the next Section 5.2.3.

### 5.2.3 Environmental performance

In Figure 5.2, the contribution of the different materials within the described take-back system to the QWERTY and MRE (product composition) definitions is presented. Comparing the contributions of the different materials in the left MRE graph, with the QWERTY definition on the right, shows that especially the copper and precious metal become more important in the 'environmental product composition', to a lesser extent this also counts for the other environmentally relevant substances lead and zinc.

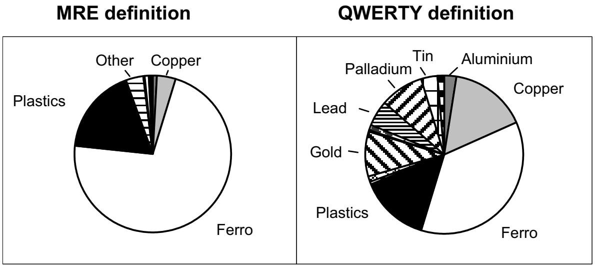


*Figure 5.2 QWERTY and MRE definition for the DVD player*

In Figure 5.3 the contributions of the different materials to the percentages gained and lost under the strict recyclability (MRE) definition is presented for the state-of-the-art recycling scenario. Obviously, the ferro-content contributes the most to the recovered weight and the plastics together with the non-recovered ferro content are the most contributing materials regarding the non-recycled part.

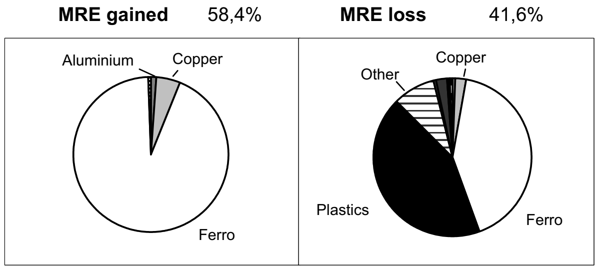


*Figure 5.3 Contribution of materials to the MRE values recovered/lost*

Note that with the strict MRE definition, under state-of-the-art recycling for the DVD player (as introduced in Chapter 2.8.1, only 58 % weight based recyclability is achieved. This is despite the fact that from a weight perspective the DVD player is almost an ideal product within an ideal recycling scenario.

In Figure 5.4, also the contribution of materials under the QWERTY definition is presented. Besides the copper content, also the precious metal content is of increasing relevance under the QWERTY definition in comparison with the MRE definition. Moreover, in comparison with the Soundmachine example of Chapter 3.5.4 and Figure 3.6, a completely different picture appears. The precious metals and other environmentally relevant materials from the PWBs have higher contributions in contrast to the Soundmachine example.

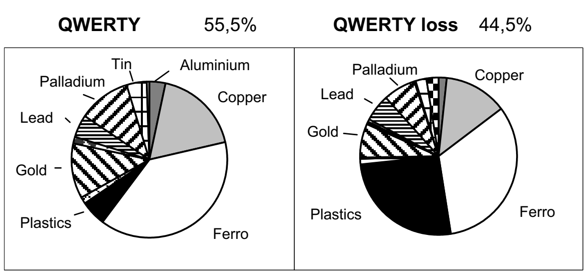


*Figure 5.4 Contribution of materials to the QWERTY values recovered/lost*

The question rises, whether with better shredding and separation settings, tailored to modern metal dominated products as described in Chapter 2.4.3, Figure 2.9, the QWERTY results can be improved by increasing the amount of PWB materials in the copper fractions. This will be discussed later on in Section 5.3.5.

In Table 5.3, the environmental impacts per end-of-life stage are presented. The environmental impacts for collection, shredding and separation and sorting/handling are relatively small compared to the values for the materials recovered at the copper and ferro smelter (negative sign: prevented environmental impacts). It is also remarkable that despite the weight percentage of ferro (73%) most environmental value is recovered at the copper smelter (mainly from the copper and precious metal content) and not at the ferro smelter.

| End-of-life stage | Environmental impact (mPts) |
| --- | --- |
| Transport and collection | 5,6 |
| Shredding and separation | 2,6 |
| Incineration, energy recovery | 0,7 |
| Landfill controlled | 0,0 |
| Copper smelter | -94,4 |
| Aluminium smelter | -7,7 |
| Ferro smelter | -71,3 |
| **Total** | **-164,5** |

*Table 5.3 Environmental impacts per stage for the DVD player*

Besides the state-of-art recycling scenario as displayed in Table 5.3, also the environmental behavior of the product within other scenarios can be displayed. In Figure 5.5 this performance of the DVD player in all end-of-life scenarios (the product as a whole goes into one scenario) is shown. The first bar is the theoretical 'best case' value or original material value. The second bar is the 'worst case' scenario or highest environmental loads per material – end-of-life route combination. With these two bars, the environmental bandwidth is presented. Also in this figure, the contribution of the different materials is incorporated. The 'recycling' bar is the state-of-the-art recycling scenario (third bar). Note that recovery of copper, ferro and precious metals add the most to the recovered environmental value in this case. An important conclusion is that although state-of-the-art recycling is applied, the environmental recovery is far from the 'best-case' scenario mainly due to materials appearing in the wrong fractions or not being recovered at the corresponding secondary material processor. Also energy required for end-of-life treatment like refining and upgrading plays a significant role here, to a lesser extent this also counts for the environmental impacts of all transports. Furthermore some environmental impacts occur from incineration with energy recovery of the residue fraction. In this environmental impact also the partial energy recovery is included.

In Chapter 6 more attention will be paid to the options for Design for End-of-life to decrease the gap between the first and the third bar. The environmental impacts per process step under state-of-the-art recycling are presented for this same DVD player in Figure 6.9, which is a more detailed representation of Table 5.3.

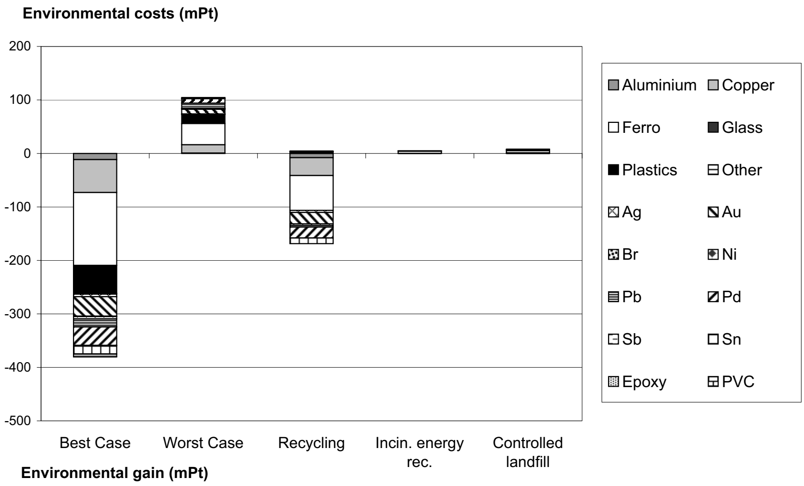


*Figure 5.5 Environmental scenarios for the DVD player*

### 5.3.3 Costs and revenues

In Table 5.4 the costs per end-of-life stage are presented. These costs are based on the descriptions of integral costs in Chapter 4.4. From the QWERTY/EE calculation sequences an € 1,13 costs (second column) per DVD player is derived. The main contributions are from collection and transport, shredding and separation and sorting and handling (excluding costs for consumers to hand in their products). Also revenues of € 0,67 per product (third column) are created. The net integral costs for this example are € 0,46 per DVD player. It is remarkable that the revenues at the copper smelter are substantially higher than the revenues from the ferro smelter. Despite, the high ferro content in this product, also in the economic picture, the copper smelter is the most important process in recovering material value.

| End-of-life stage | Integral costs | Costs | Revenues |
|---|---|---|---|
| Transport and collection | € 0,32 | € 0,32 | € 0,00 |
| Shredding and separation | € 0,36 | € 0,36 | € 0,00 |
| Sorting and handling | € 0,18 | € 0,18 | € 0,00 |
| Incineration, energy recovery | € 0,05 | € 0,05 | € 0,00 |
| Landfill controlled | € 0,00 | € 0,00 | € 0,00 |
| Copper smelter | -€ 0,36 | € 0,12 | -€ 0,48 |
| Aluminium smelter | € 0,00 | € 0,03 | -€ 0,02 |
| Ferro smelter | -€ 0,10 | € 0,07 | -€ 0,17 |
| **Total** | **€ 0,46** | **€ 1,13** | **-€ 0,67** |

*Table 5.4 Integral costs per end-of-life stage for the DVD player*

The integral costs of the previous table can also be determined for other end-of-life scenarios. Figure 5.6 shows the economic equivalent of Figure 5.5. Besides the state-of-art recycling scenario represented with the third bar also the economic behavior of the product within these other scenarios can be displayed. Again, the first bar is the theoretical 'best case' value or potential economic material value. The second bar is the 'worst case' scenario or highest costs per material – end-of-life scenario combination. With these two bars, the economic bandwidth is presented. Also in this figure, the contribution of the different materials is visualised. An important conclusion is that although state-of-the-art recycling is applied, the economic performance (in fact only total costs are realised) is again far from the 'best-case' scenario. In this case mainly due to inevitable shredding and separation and treatment costs at ferro and copper smelting.

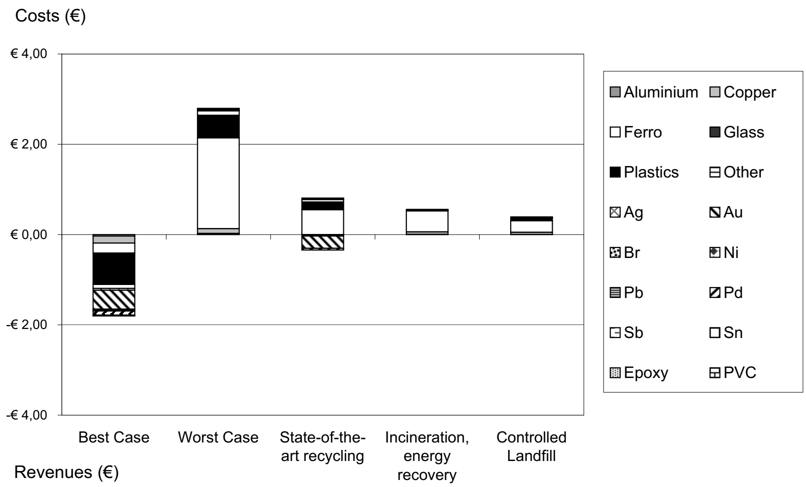


*Figure 5.6 Cost scenarios for the DVD player*

### 5.3.4 Eco-efficiency within the Dutch take-back system

When the eco-efficiency concept of Chapter 4 is applied, Figure 5.7 is obtained for the DVD player in the state-of-the-art recycling scenario. Again on the vertical axis, costs are put below and revenues above in absolute amounts (euros). On the horizontal axis, environmental burden is put on the left and environmental gain on the right in absolute amounts as well (mPts). The points in the graph represent the different scenarios in which a product can end up. The costs of consumers handing in products at municipalities and retailers are excluded. These costs can be very high. This 'consumer part' is estimated to be an extra € 1,34 for this DVD player.

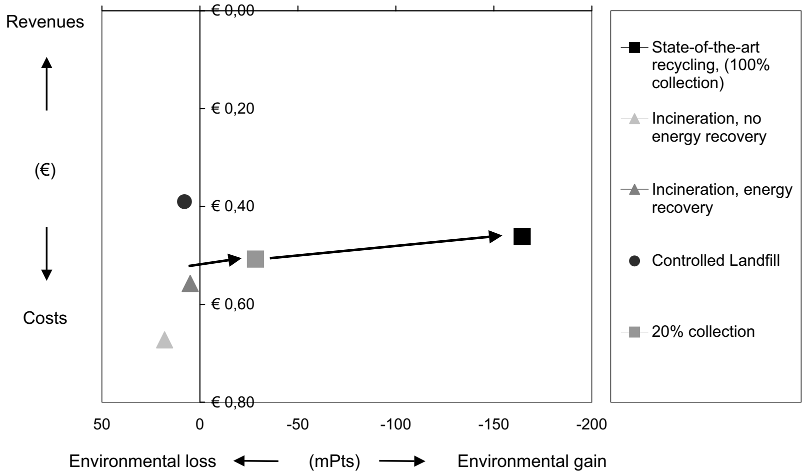


*Figure 5.7 Eco-efficiency of all relevant end-of-life options for the DVD player*

With Figure 5.7, also the effect of increasing collection rates is visualised for the percentages of this product ending up in the different end-of-life scenarios. The graphs are representing the environmental impacts of one-single product and the average percentages of where this product could end-up in. In this way, an estimate can be made for the costs and environmental impacts of a single product under different collection rates.

The effect of increasing collection rates can be displayed in the 2D eco-efficiency graphs as well. The collection rates are translated to the chance for this product to appear in one of the scenarios displayed. Export and other options besides state-of-the-art treatment and disposal with MSW are disregarded in this graph. So, 100% collection and treatment is the state-of-the-art recycling scenario itself and 0% collection means disposal with MSW, which is a mix of 23%, controlled landfill and 77% incineration with energy recovery. Included in the MSW costs are the penalties for too high concentrations of certain materials. These are indirect costs and usually not directly paid by the consumer as part of the integral waste disposal fee. This issue is further highlighted in Chapter 7.9. The collection rates are only based on the streams within the take-back system and not those leaving it by for instance export. At the moment of executing these calculations the effect was not known, but some details can be found in the monitoring reports of the Dutch take-back system (De Straat Milieuadviseurs 2002).

The first arrow in Figure 5.7, from 0% collection and treatment, the 100% disposal scenario, towards 20% collection results in higher environmental gains against slightly lower costs for the performance of this product in the take-back system as a whole. If it would be possible to collect 100% of the discarded example products, than a significant increase in environmental gain is realised against lower costs (first arrow plus second arrow). The total costs for this single product within the take-back system as a whole are slightly decreasing in this case from 0,52 € per DVD player (2,7 kg) to € 0,46. This is excluding the costs to be made by consumers to hand in this particular product at a retailer or municipality. This does not mean that the costs per stakeholder are decreasing for all stakeholders. This effect will be discussed in Chapter 7.9.

### 5.3.5 Eco-efficiency of dedicated shredding and separation

An option to increase both the environmental and economic recovery from metal dominated products is to apply dedicated settings for shredding and separation in order to get more PWB materials in the copper fraction. This means that instead of producing a residue fraction with most of the plastics in it, only an aluminium, ferro and copper fraction are created and some larger plastic pieces are separated from these fractions by handpicking. The result is a more 'contaminated' copper fraction (with a higher total amount but also a higher dilution of precious metals) and a 'cleaner' plastic fraction.

In fact, the question is from both an economic and environmental perspective where the balance lies between not losing high valuable materials to the wrong fraction, or in concentrating materials to recover more value. In order to estimate the shredding and separation performance of a metal dominated product like the DVD player, an expert guess on the distribution of materials is made (Mirec 2002a). In Table 5.5, the corresponding integral costs per stage for this change is depicted.

| End-of-life stage | Integral costs | Costs | Revenues |
|---|---|---|---|
| Transport and collection | € 0,32 | € 0,32 | € 0,00 |
| Shredding and separation | € 0,36 | € 0,36 | € 0,00 |
| Sorting and handling | € 0,18 | € 0,18 | € 0,00 |
| Incineration, energy recovery | € 0,00 | € 0,00 | € 0,00 |
| Landfill controlled | € 0,00 | € 0,00 | € 0,00 |
| Copper smelter | -€ 0,26 | € 0,20 | -€ 0,47 |
| Aluminium smelter | € 0,00 | € 0,00 | € 0,00 |
| Ferro smelter | -€ 0,10 | € 0,07 | -€ 0,17 |
| **Total** | **€ 0,50** | **€ 1,14** | **-€ 0,64** |

*Table 5.5 Integral costs for dedicated shredding and separation for the DVD player*

Table 5.5 shows higher integral costs for the DVD player in this specific scenario. The reasons for this are not only the extra sorting costs (plastic and metal dominated products must be separated in two streams: € 0,10 extra per kg), also the revenues are lower due to decreasing (precious) metal concentrations in the copper fraction. This causes higher treatment charges to be paid for the larger copper fraction and it also leads to a relatively higher so-called unit deduction to be subtracted (lower concentrations of copper and precious metals in the fraction). See also Chapter 4.3.6 and

Equation 4.3 in Chapter 4 (in this Equation, the refining charge (RC) is paid for more material and the unit deduction ($UD_i$) is applied to more valuable material).

Not only the economic results are worsening, the environmental performance is also slightly better for the original treatment of the DVD player with the regular brown-goods stream than in the 'dedicated shredding and separation of metal dominated products' scenario. This is mainly caused by sending more plastics and other environmentally relevant materials to the copper smelter which has a relatively bad flue gas cleaning, whereas in the original scenario more plastics are incinerated in a MSW incineration plant with a more extended flue gas cleaning system.
The net effect is a higher impact for the dedicated shredding and separation scenario although more valuable metals are recovered in this scenario. The energy effect of plastics in both scenarios is included. The resulting 'negative' eco-efficiency direction is visualised in Figure 5.8. In fact, this effect is good example of changing end-of-life processing with the intention of recovering more valuable material, but resulting in application of the 'second law of recycling': You cannot recover all materials present in a product to their original grade without causing any environmental burden of doing so (see also Chapter 3.3.5, Figure 3.4).
In Chapter 6, the (re)design for end-of-life options for this DVD player will be discussed in terms of improving environmental performance and corresponding eco-efficiency effects.

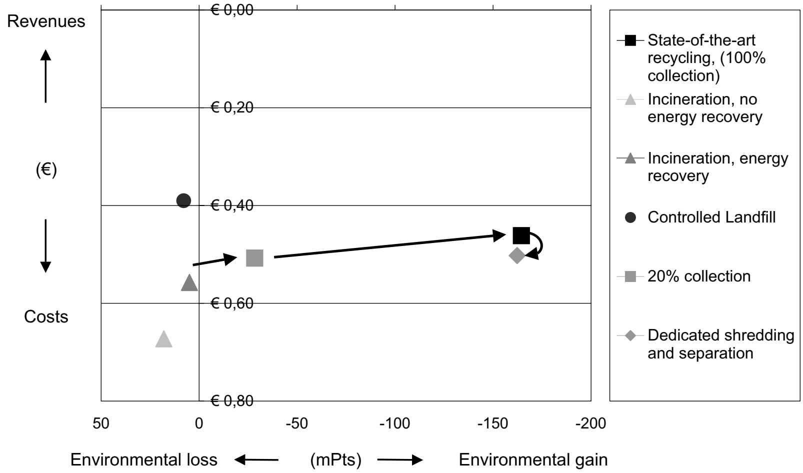


*Figure 5.8 Eco-efficiency of dedicated shredding and separation for the DVD player*

## 5.4 Example: a glass dominated product

### 5.4.1 Product data, pre-treatment, shredding and separation

In this section, a 17-inch CRT-monitor from 2002 will be discussed as a typical example of a glass dominated product. Product compositions are derived through (Philips

2002k). In addition, also the PWB compositions of this product are chemically analysed (Mirec 2002a). In Table 5.6 the resulting product composition is given. The most important characteristic is obviously the high glass content, which is 9,4 kg on a total product weight of 14,7 kg. The precious metal content present in this well-developed product is 133 ppm for silver, 8 ppm for gold and 5 ppm for palladium over the total amount of the electronic fraction (PWBs and wiring). On the total product weight, this is 11 ppm for Silver, 0,7 ppm for gold and 0,25 ppm for palladium.

| Material | Weight (g) | Weight% |
|---|---|---|
| Aluminium | 48,55 | 0,33% |
| Copper | 892,15 | 6,09% |
| Ferro | 1324,08 | 9,04% |
| Glass | 9392,50 | 64,1% |
| Plastics | 2606,62 | 17,8% |
| Ag | 0,16 | 11 ppm |
| Au | 0,01 | 0,7 ppm |
| Pd | 0,00 | 0,3 ppm |
| Other | 385,22 | 2,63% |
| **Total** | **14649,30** | **100%** |

*Table 5.6 Product composition 17-inch CRT-monitor*

For CRT-containing products, disassembly of the CRT and the plastic front and back covers is applied. The remaining is shredded after removing the electron gun, the deflection coil, the degaussing coil and the cabling and wiring. This results in six fractions, with compositions as displayed in Table 5.7 (Ansems 2002a). This table is checked by (Mirec 2002a).

| Fraction | Ferro (g) | Aluminium (g) | Copper (g) | Residu (g) | Plastics (g) | Residu (g) |
|---|---|---|---|---|---|---|
| Aluminium | 0,25 | 40,09 | 7,28 | 0,00 | 0,00 | 0,93 |
| Copper | 8,39 | 44,61 | 697,75 | 0,00 | 0,00 | 141,4 |
| Ferro | 1258 | 26,48 | 26,48 | 0,00 | 0,00 | 13,24 |
| Glass | 46,96 | 46,96 | 93,93 | 9158 | 0,00 | 46,96 |
| Plastics | 31,54 | 13,03 | 260,7 | 0,00 | 1895 | 406,4 |
| Ag | 0,000 | 0,000 | 0,138 | 0,000 | 0,000 | 0,025 |
| Au | 0,000 | 0,000 | 0,0088 | 0,000 | 0,000 | 0,0010 |
| Pd | 0,000 | 0,000 | 0,0033 | 0,000 | 0,000 | 0,0004 |
| Other | 1,34 | 1,47 | 125,1 | 123,1 | 58,03 | 76,26 |
| **Fraction Weight** | **1346** | **172,6** | **1211** | **9281** | **1953** | **685,2** |
| **Fraction %** | **16,16** | **2,07** | **14,54** | **111,37** | **0,133** | **0,047** |
| **Total** | | | | | | **14649** |

*Table 5.7 Fraction compositions from state-of-the-art shredding and separation*

The default destinations of the fractions are respectively ferro smelting, aluminium smelting, copper smelting and incineration with energy recovery of the plastic and residue fraction. The glass fraction is assumed to be treated like presented in Chapter 4.3.7, Table 4.6. This table represents the 2001 average situation for The Netherlands with only 15% recycling of old to new CRT glass, 40% uncontrolled landfill, 35% to the building industry and 10% to the ceramic industry. The environmental performance of the current 'settings' will be discussed in the next section. In Section 5.4.5.the consequences of increasing CRT glass recycling will be mentioned. In Section 5.4.6, the effect of applying plastic recycling of the front and back covers is discussed.

### 5.4.2 Environmental performance

In Figure 5.9, the contribution of the different materials of the CRT-monitor within the Dutch take-back system to the QWERTY and MRE (product composition) definitions is presented.

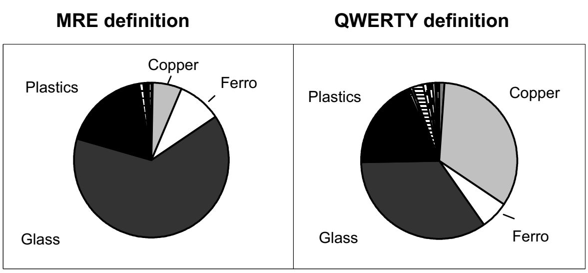


*Figure 5.9 Contribution of materials to QWERTY and MRE definition*

The left pie of Figure 5.9 is the weight based product composition. The right pie represents the 'environmental product composition'. Comparing the contributions of the different materials to both definitions shows a relative increasing importance for the copper content and a decreasing contribution of the glass content. The plastic content remains relatively important in contribution tot the total pie in both definitions. All other materials are of less relevance.

In Figure 5.10 the percentages gained and lost under the MRE definition of Figure 5.9 is shown. The two pies are the gained and lost percentages for the strict MRE definition. The glass content plays an important role in these two pies. Due to the low average percentage for CRT glass recycling, the MRE gained percentage is only 21%. Obviously, the non-recycled glass content, including the amounts to ceramic and building industry, contributes the most to the lost MRE pie on the right.

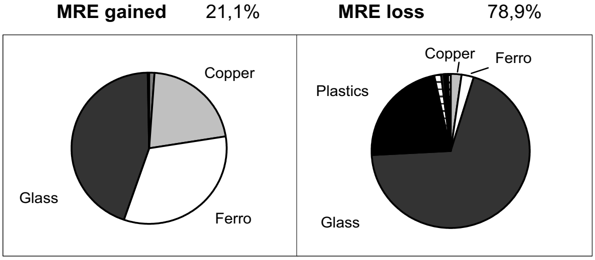


Figure 5.10 Contribution of materials to the MRE values recovered/lost

In the two pies of Figure 5.11, representing the QWERTY definition, copper plays a more important role both in the QWERTY gained and QWERTY lost percentages. The contribution of glass to the QWERTY definition is much smaller compared to the weight based definition. The QWERTY value of the state-of-the-art recycling scenario is 43,4%.

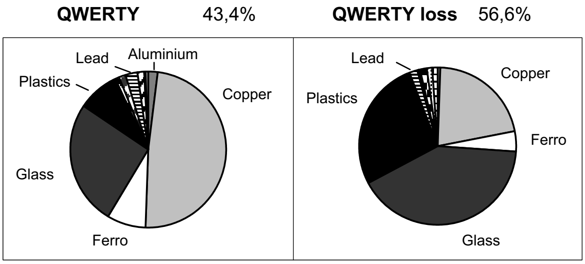


Figure 5.11 Contribution of materials to the QWERTY values recovered/lost

In Table 5.8, the environmental impacts per end-of-life stage are presented. Again, the environmental impacts for collection and transport and shredding and separation are relatively small compared to the recovered values (negative values) at the glass oven and especially the copper smelter. It should be noted again, that despite of the high weight percentage of glass (64%), the most environmental value is recovered at the copper smelter (only from the copper content) and not at the glass processing options: building industry, ceramic industry and glass furnace.

| End-of-life stage | Environmental impact (mPts) |
|---|---|
| Transport and collection | 32,14 |
| Shredding and separation | 3,50 |
| Incineration, energy recovery | 2,38 |
| Landfill uncontrolled | 8,14 |
| Building industry | 7,62 |
| Ceramic industry | -25,29 |
| Copper smelter | -335,36 |
| Aluminium smelter | -15,00 |
| Ferro smelter | -49,94 |
| Glass furnace | -53,67 |
| **Total** | **-425,49** |

*Table 5.8 Environmental impacts per stage*

Besides the state-of-art recycling scenario as displayed in Table 5.8, also the environmental behavior of the product within other scenarios can be displayed. In Figure 5.12 the environmental performance of the 17-inch CRT-monitor within all end-of-life scenarios (the product as a whole goes into one scenario) are shown. The third 'recycling' bar is the average Dutch state-of-the-art recycling scenario. Note that recovery of copper adds the most to the recovered environmental value. Also here, an important conclusion is that although state-of-the-art recycling is applied, the environmental recovery is far from the 'best-case' scenario mainly primarily due to not recycling of glass and plastics. To some extent energy required for end-of-life treatment and environmental impacts of transport plays a role as well.

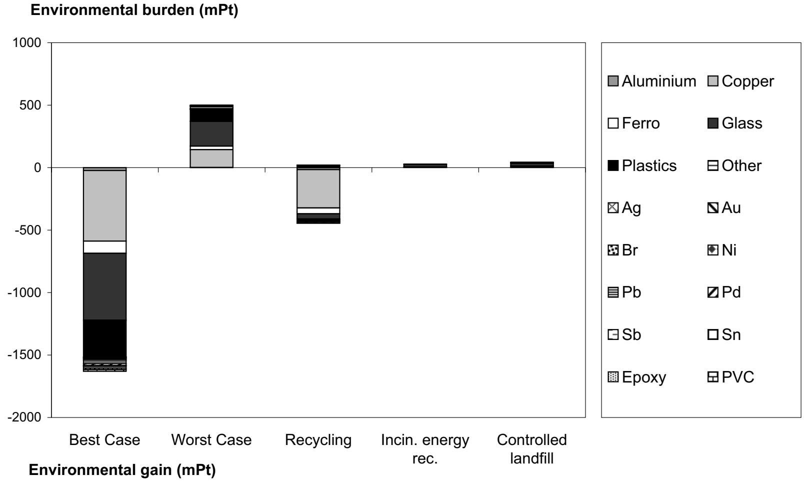


*Figure 5.12 Environmental scenarios*

### 5.4.3 Costs and revenues

In this section, the economic performance of the 17-inch CRT-monitor is discussed. The costs per end-of-life stage are represented in Table 5.9. In contrast with the environmental impacts per stage, the highest costs are caused by respectively disassembly, sorting and handling, collection, shredding and separation. The total disassembly time is estimated at 285 seconds in total by (Philips 2002k) and is checked by (Mirec 2002a). The costs presented are again excluding the costs for consumers to hand in their products. In total, some material value (€ 1,47) is regained at the secondary material processors, but this is substantially lower than the total costs for all operations (€ 7,41) to which the costs for collection and 'recycler' are the highest (€ 5,17). Again, the costs for consumers for handing in products at municipalities or retailers are excluded. The costs of consumers handing in products at municipalities and retailers are excluded. These additional costs are estimated at € 3,03 per 17-inch CRT-monitor.

| End-of-life stage | Integral costs | Costs | Revenues |
|---|---|---|---|
| Transport and collection | € 0,81 | € 0,81 | € 0,00 |
| Disassembly | € 2,85 | € 2,85 | € 0,00 |
| Shredding and separation | € 0,48 | € 0,48 | € 0,00 |
| Sorting and handling | € 1,03 | € 1,03 | € 0,00 |
| Incineration, energy recovery | € 0,13 | € 0,13 | € 0,00 |
| Landfill uncontrolled | € 0,24 | € 0,24 | € 0,00 |
| Building industry | € 0,34 | € 0,34 | € 0,00 |
| Ceramic industry | € 0,08 | € 0,12 | -€ 0,04 |
| Copper smelter | -€ 0,26 | € 0,74 | -€ 1,00 |
| Aluminium smelter | € 0,06 | € 0,11 | -€ 0,05 |
| Ferro smelter | -€ 0,07 | € 0,06 | -€ 0,12 |
| Glass furnace | € 0,27 | € 0,52 | -€ 0,25 |
| **Total** | **€ 5,96** | **€ 7,41** | **-€ 1,45** |

*Table 5.9 Integral costs per end-of-life stage*

Figure 5.13 shows the economic equivalent of Figure 5.12. Besides the state-of-art recycling scenario (third bar) also the economic behavior of the product within other scenarios can be displayed. An important conclusion is that although state-of-the-art recycling is applied, the economic recovery (in fact only net costs are realised) is again far from the 'best-case' scenario. In this case mainly due to the disassembly and collection costs.

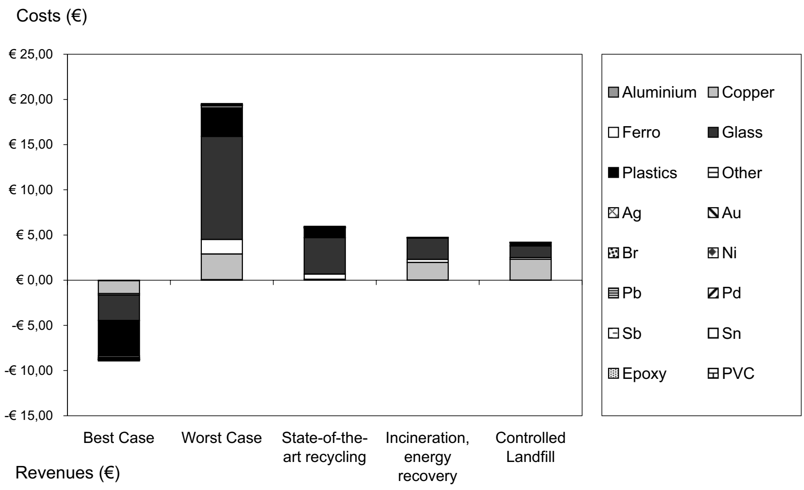


*Figure 5.13 Cost scenarios*

### 5.4.4 Eco-efficiency within the Dutch take-back system

In this section the economic and environmental data are again brought together in the eco-efficiency graphs of Figure 5.14. With this graph, again the effect of increasing collection rates is visualised. The first arrow, from 0% collection towards 60% collection (and 31% incineration and 9% landfill) results in higher environmental gains against slightly lower costs for the take-back system as a whole. If it would be possible to collect 100% of the discarded products, than a significant increase in environmental gain is realised against higher costs (first arrow plus second arrow). The total costs for the system are then increasing from € 5,42 per 17-inch CRT-monitor to (14,7 kg) to € 5,95. This again doesn't mean that the costs per stakeholder are decreasing for all stakeholders. This effect will also be discussed in more detail in Chapter 7.9. What the environmental return per euro invested means is further discussed and related to other options in Chapter 7.5.

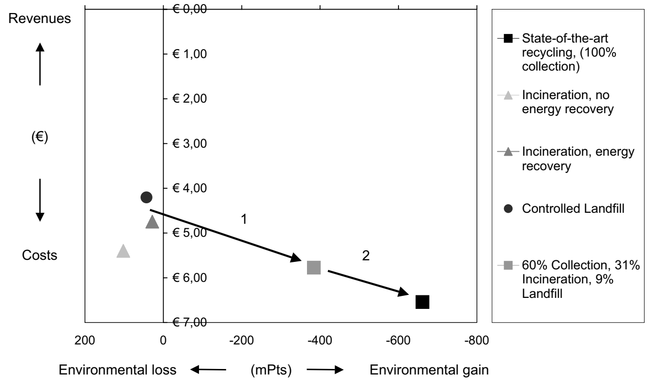


*Figure 5.14 Eco-efficiency of all relevant end-of-life options*

### 5.4.5 Eco-efficiency of increasing glass and plastic recycling

One option to increase both the environmental and economic recovery from metal dominated products is to increase CRT glass recycling. From (Mirec 2002b), the maximum percentages that can technologically be achieved are estimated at 70% recovery of glass back to CRT glass (screen to screen and cone to cone glass), 20% to the ceramic industry (replacement of Feldspar) and 10% to the building industry (replacement of sand) (Mirec 2002b). The resulting eco-efficiency direction is displayed with the fourth arrow in Figure 5.15.

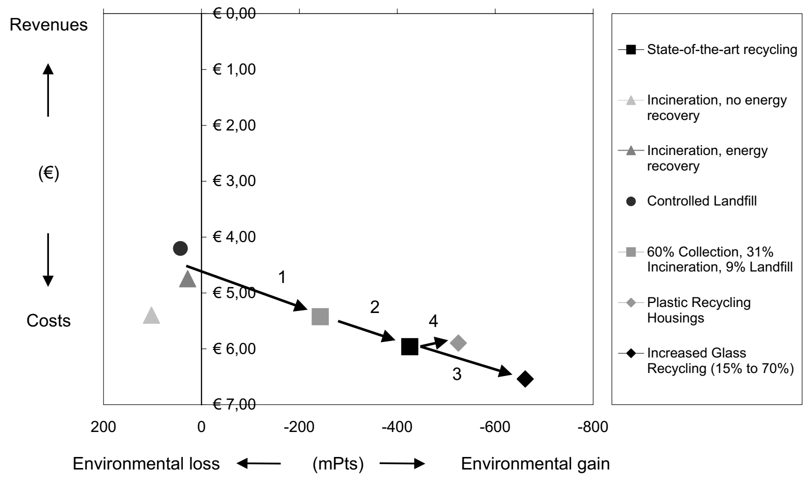


*Figure 5.15 Eco-efficiency of increased glass and plastic recycling*

Figure 5.15 shows a substantial improvement in environmental performance for increased CRT glass recycling (from –425 mPts to –661 mPts). From a cost perspective there is an increase from € 5,95 to € 6,54 per product. These results will be checked later on in Section 5.7.3. What the environmental return per euro invested, in this case 400 mPts/€ means is further discussed and related to other options in Chapter 7.5.

Another option is to increase plastic recycling. Instead of incineration with energy recovery of the plastic fraction, the recycling of 1,9 kg of the front and back-covers is taken into account. The resulting eco-efficiency direction is also displayed in Figure 5.16 with the fourth arrow. The result of this plastics recycling is an environmental improvement of -425 mPts to -525 mPts against almost the same costs (from € 5,95 to € 5,88) as the original scenario with incineration plus energy recovery.

Note that the eco-efficiency direction is 'far more horizontal' (change to the right which leads to 1400 mPts/€ invested) for these larger plastic housings than for the example of the Soundmachine in Chapter 4.5.5. This is due to the fact that the disassembly costs for this product are placed on the disassembly operation of the CRT. In Section 5.7 more products are evaluated on this and in Chapter 7.5 and 7.6.2 a more precise evaluation is presented on the relation between the size of the housings and connected disassembly costs versus environmental gain. Together with the higher absolute environmental improvement, this leads to a much larger 'vector' for CRT glass recycling compared to plastic recycling in Figure 5.15. The role of design in improving end-of-life performance for this 17-inch CRT-monitor as an example for a glass dominated product will be discussed in Chapter 6.

## 5.5 Example: a precious metal dominated product

### 5.5.1 Product data, pre-treatment, shredding and separation

A typical example of a precious metal dominated product is used as an example in this section. A high-end cellular phone from 2000 is taken as an example. The cellular phone is chemically analysed by (Mirec 2000a). The product composition is well known and given in Table 5.10. Despite the high weight percentage of plastics in the products it is still to be characterised as a precious metal dominated product, while its precious metal content is very high: 800 ppm for Silver, 800 ppm for gold and 500 ppm for palladium. Note that the concentration of gold is 50 times as high and even a 160 times higher for palladium compared to the DVD player, which also contained a relatively modern PWB. The product composition is presented for the cellular phone alone, without batteries and adapter.

| Material | Weight (g) | Weight% |
|---|---|---|
| Aluminium | 1,92 | 2,30% |
| Copper | 22,3 | 26,8% |
| Ferro | 2,00 | 2,40% |
| Glass | 4,58 | 5,50% |
| Plastics | 36,7 | 44,0% |
| Ag | 0,07 | 800 ppm |
| Au | 0,07 | 800 ppm |
| Pd | 0,51 | 610 ppm |
| Other | 15,3 | 18,4% |
| **Total** | **83,3** | **100%** |

*Table 5.10 Product composition cellular phone*

Also in this case, the resulting contribution of materials towards fractions can be calculated based on (Ansems 2002a) and (Mirec 2002a). In Table 5.11, the resulting fraction of shredding and separation are displayed. Note that a substantial percentage of the precious metals are appearing in the 'wrong fractions', mainly the residue fraction.

| Fraction | Ferro (g) | Aluminium (g) | Copper (g) | Residu (g) |
|---|---|---|---|---|
| Aluminium | 0,010 | 1,58 | 0,09 | 0,230 |
| Copper | 0,210 | 1,11 | 17,43 | 3,53 |
| Ferro | 1,90 | 0,020 | 0,020 | 0,060 |
| Glass | 0,023 | 0,023 | 0,458 | 4,08 |
| Plastics | 0,444 | 0,183 | 3,67 | 32,37 |
| Ag | 0,0007 | 0,0007 | 0,0566 | 0,0087 |
| Au | 0,0007 | 0,0007 | 0,0533 | 0,0120 |
| Pd | 0,0004 | 0,0004 | 0,0333 | 0,0075 |
| Other | 0,131 | 0,129 | 7,16 | 8,28 |
| **Fraction Weight** | **2,72** | **3,05** | **29,0** | **48,6** |
| **Fraction %** | **3,26%** | **3,67%** | **34,8%** | **58,3%** |
| **Total** | | | | **83,3** |

*Table 5.11 Fraction composition from state-of-the-art shredding and separation*

The destinations of the four fractions are respectively ferro smelting, aluminium smelting and the copper smelting. The residue fraction is assumed to go to a MSW incineration plant (with energy recovery). The environmental performance of treating the contributions to the fractions of the cellular phone in the above way is described in the next section.

### 5.5.2 Environmental performance

In Figure 5.16, the contribution of the different materials within the described take-back system to the QWERTY (right graph) and MRE (left, product composition) definitions is presented.

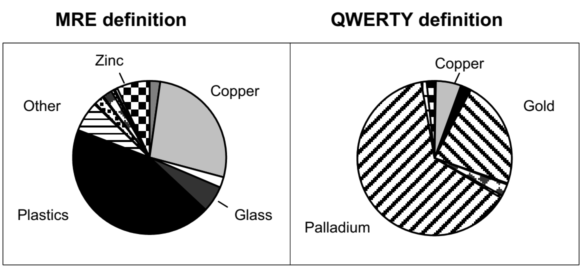


*Figure 5.16 Contribution of materials to QWERTY and MRE definition*

Comparing the contributions of the different materials shows completely different results under both definitions. The high precious metal content, which is not visible in the MRE graph, leads to a very high contribution of palladium and gold in the QWERTY definition. The plastic content is very dominant in the MRE graph, but seems completely irrelevant in the 'environmental product composition'. Actually, this environmental graph clearly displays the complete irrelevance of using weight based recyclability percentages as a monitoring instrument for end-of-life issues for products like these.

In Figure 5.17 the percentages gained and lost under the strict MRE definition is presented for the state-of-the-art recycling, non-CRT scenario (See Chapter 2.4.3, Figure 2.7). The recovery of copper adds the most to the recovered MRE and the recovery of plastics adds the most to the lost MRE.

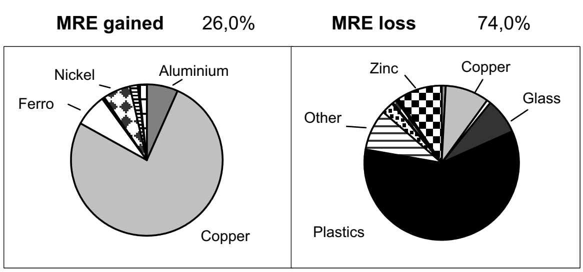


*Figure 5.17 Contribution of materials to the MRE values recovered/lost*

Note that with the strict MRE definition, under state-of-the-art recycling for this cellular phone only 26% weight based recyclability is achieved. The WEEE recyclability targets are clearly not met under this strict definition and leads to the question whether they are realistic because they require plastic recycling, which leads to high costs and almost no environmental improvement as will be shown with Section 5.5.5, Figure 5.22 later on. In Chapter 7, a more elaborated discussion on the efficiency of the strategies prescribed with the WEEE Directive is presented.

In Figure 5.18, the gained and lost QWERTY values are described. The precious metals again contribute the most to the lost and gained values.

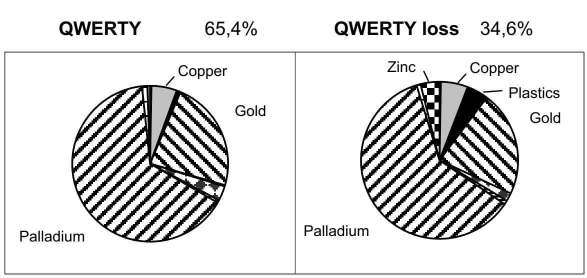


*Figure 5.18 Contribution of materials to the QWERTY values recovered/lost*

In Table 5.12, the environmental impacts per end-of-life stage are presented. The environmental impacts for collection, shredding and separation and sorting/ handling are relatively small compared to the recovered values (negative values) at the copper smelter. Table 5.12 is also dominated by the precious metals, which are recovered at the copper smelter.

| End-of-life stage | Environmental impact (mPts) |
|---|---|
| Transport and collection | 0,18 |
| Shredding and separation | 0,09 |
| Incineration, energy recovery | 0,06 |
| Landfill controlled | 0,00 |
| Copper smelter | -150,58 |
| Aluminium smelter | -0,63 |
| Ferro smelter | -0,06 |
| **Total** | **-150,94** |

*Table 5.12 Environmental impacts per stage for the cellular phone*

Besides the state-of-art recycling scenario as displayed in Table 5.12, also the environmental behavior of the product within other scenarios can be displayed. In Figure 5.19 the environmental performance of the cellular phone within all end-of-life scenarios (the product as a whole goes into one scenario) are shown.

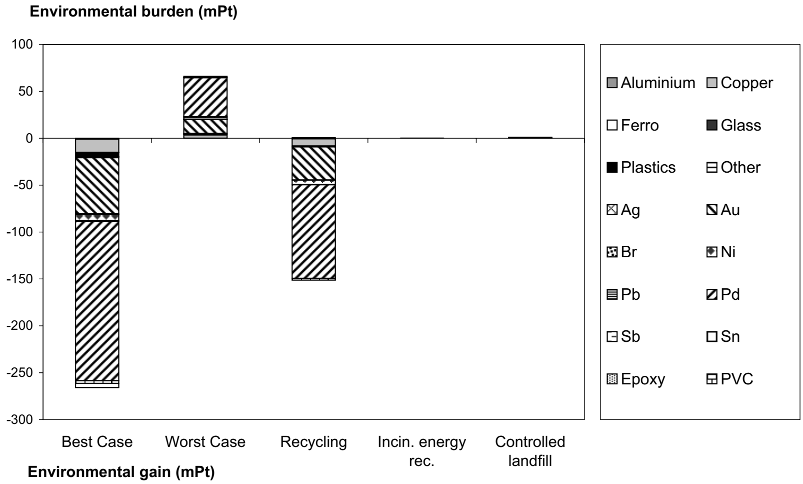


*Figure 5.19 Environmental scenarios cellular phone*

Also in this figure, the contribution of the different materials is incorporated. The 'recycling' bar is the state-of-the-art recycling scenario. Also here, an important conclusion is that although state-of-the-art recycling is applied, the environmental recovery is far from the 'best-case' scenario mainly due to the precious metals not recovered due to dilution to the 'wrong fractions' and due to energy needed at the copper smelter for refining.

### 5.5.3 Costs and revenues

In Table 5.13 the costs per end-of-life stage are presented. This shows an exemption on 'regular' treatment of disposed products: instead of costs, a revenue of € 0,74 is created per product (which is as high as € 8,87 per kg!). The revenues at the copper smelter are contributing the most to this value. In Section 5.6.5 more precious metal dominated products will be investigated in order to check whether this yield is normal for products like this or whether such high concentrations are an exemption.

| End-of-life stage | Integral costs | Costs | Revenues |
|---|---|---|---|
| Transport and collection | € 0,010 | € 0,010 | € 0,000 |
| Shredding and separation | € 0,012 | € 0,012 | € 0,000 |
| Sorting and handling | € 0,006 | € 0,006 | € 0,000 |
| Incineration, energy recovery | € 0,004 | € 0,004 | € 0,000 |
| Landfill controlled | € 0,000 | € 0,000 | € 0,000 |
| Copper smelter | -€ 0,771 | € 0,100 | -€ 0,871 |
| Aluminium smelter | € 0,000 | € 0,002 | -€ 0,002 |
| Ferro smelter | € 0,000 | € 0,000 | € 0,000 |
| **Total** | **-€ 0,739** | **€ 0,134** | **-€ 0,873** |

*Table 5.13 Integral costs per end-of-life stage*

Figure 5.20 again shows the economic equivalent of Figure 5.19. Besides the state-of-art recycling scenario as displayed with the third bar also the economic behavior of the product within other scenarios can be displayed. An important conclusion from this graph is that the only significant contribution to the end-of-life scenarios is the recovery of the precious metals.

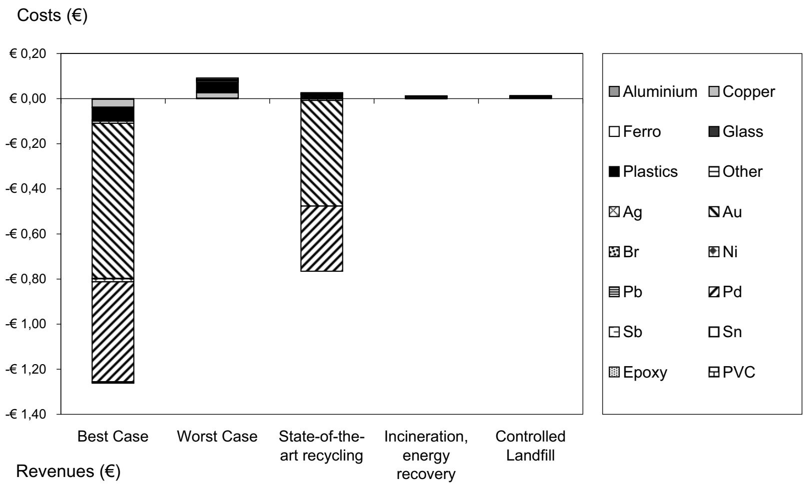


*Figure 5.20 Cost scenarios*

**5.5.4 Eco-efficiency within the Dutch take-back system**
In this section the economic and environmental data are again brought together in the eco-efficiency graphs of Figure 5.21. With this graph, the effect of increasing collection rates is visualised. Consumers are often discarding products like this through the waste bin. As a result the 'leakage' of products is substantially higher compared to larger products like TVs.

The first arrow in Figure 5.21, from 0% collection towards 20% collection (and 62% incineration and 18% landfill) results in much higher environmental gains and higher revenues for the performance of this example within the take-back system as a whole. If it would be possible to collect 100% of the discarded products, than a significant increase in environmental gain is realised against higher costs (first arrow plus second arrow). The total revenues for the system are then increasing from € 0,14 to € 0,74 per cellular phone, the environmental gain from 30 mPts (20% collection) towards 151 mPts per cellular phone for 100% collection, which is a relatively high value compared for only 83,3 grams of product weight.

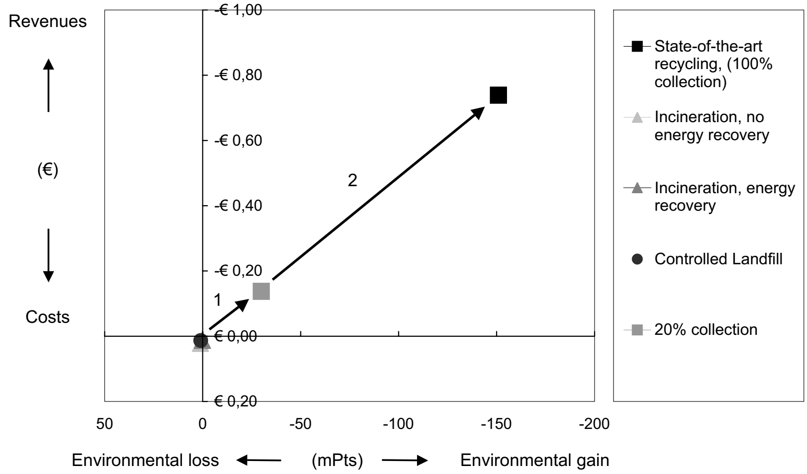


*Figure 5.21 Eco-efficiency of all relevant end-of-life options*

**5.5.5 Eco-efficiency of plastic recycling versus separate collection and treatment**
In this section two alternatives are discussed for the treatment of cellular phones are discussed. The first one is disassembly of plastic housings in order to reach higher weight based recyclability percentages. The second option is separate collection and treatment of cellular phones. In this option the aim is to collect cellular phones separately with adjusted shredding and separation settings.
The results of the first option are displayed with the third arrow in Figure 5.22. In the case of this cellular phone, the disassembly time is determined at 60 s. The weight of the disassembled plastics (back and front cover) is 20 g. The result is an increase in

weight-based recyclability from 26% to 45%. However, despite the plastic recycling effort, the increase in environmental gain is negligible (from 151 mPts gained to 152 mPts). Furthermore the costs for this option are relatively high and leading to a major decrease in revenues (from € 0,74 revenue to € 0,14 revenue, 2 mPts/€ invested). Again, this environmental return per euro invested will be further discussed and related to other options in Chapter 7.5.

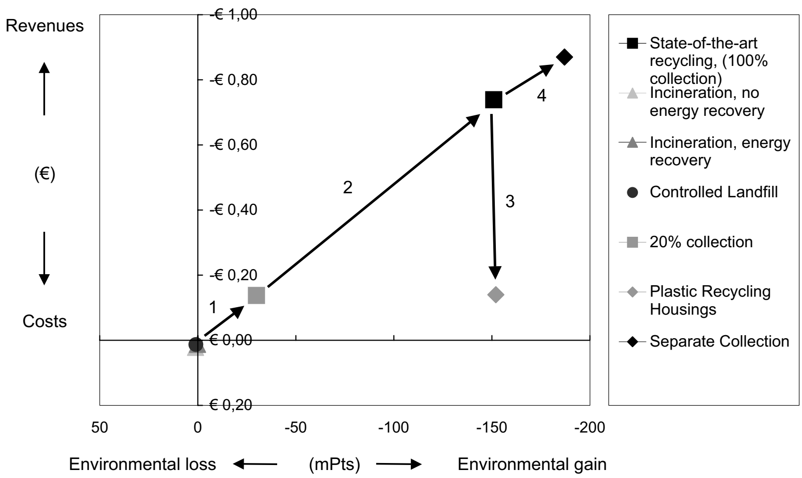


*Figure 5.22 Eco-efficiency of alternative end-of-life options*

The second option of separate collection and treatment (fourth arrow of Figure 5.22) seems to result in a higher eco-efficiency. The result is only valid under the assumptions that a sufficient amount of phones is collected. The adjusted shredding and separation settings present the loss of precious metals to other fractions than the copper fraction (Ansems 2002a). The shredding and separation settings in this case deliver only two fractions: a relatively small and pure ferro fraction and a copper fraction containing almost all other materials. The increase in environmental terms is from (151 mPts to 187 mPts and the revenues increase from € 0,74 to € 0,87). Included are the extra costs for storage, logistics and transport without the 'consumers part'.

Notice that in contrast to the example of the DVD player as discussed in Section 5.3.5, in this case the effort to prevent precious metals to end-up in the wrong fractions pays back. In other words, despite the higher dilution of precious metals in the copper fraction, in this case the proposed change result in a higher eco-efficiency due to the high precious metal concentrations in the product. In Section 5.7 will be elaborated on the role of the precious metal content to these results. The influence of the assumptions made in Section 5.2.3 will be discussed in Section 5.9. In Chapter 7.5, also the relation with current end-of-life policies will be highlighted.

## 5.6 Eco-efficiency results for multiple consumer electronic products

### 5.6.1 Eco-efficiency of (large) consumer electronic products

In this section a wide range of results for many different consumer electronic products are presented. In order to compare the environmental and economic results of the technical improvement options with each other, it is chosen to use Eco-Indicator '99 single scores in millipoints for the environmental results and Euros for the economic results. Besides the example products discussed in the previous sections and in Chapter 3.5 and Chapter 4.5, also the eco-efficiency of other products and product categories can be evaluated. In this section, these eco-efficiency results for many different products will be discussed.

Around 75 different product compositions are derived from (Philips Consumer Electronics 1999a-n; Philips Consumer Electronics 2000a-q; Philips Consumer Electronics 2001a-n; Philips Consumer Electronics 2002a-n). The compositions are estimated from the lists of components from the Ecoscan files and from chemical analysis results of typical PWBs as already discussed in Section 5.2.3. The products in Table 5.14 are modern products and most of them will not be disposed within a few years.

| Product type | # | Year | Comments | Weight |
|---|---|---|---|---|
| LCD Monitors | 3 | 2002 | 15" | 3,5 – 3,8 kg |
| CRT Monitors | 4 | 2002 | 17" (4x), 22" (1x); | 14,2–15,0 kg; 31 kg |
| TVs | 8 | 1999 - 2002 | 20" (1x), 21" (5x), 28" (1x), 32" (1x) | 17 – 55 kg |
| Cellular phones | 5<br>1 | 1999<br>2000 | 5x low-end 1999,<br>1x high-end 2000 | 170 – 190 g<br>83 g |
| DECT phones | 4 | 1999 | | 170 – 190 g |
| Fax/office equipment | 4 | 1999 | Some include scanner or phone | 4,2 – 5,5 kg |
| Audio systems | 7 | 1999 | Including speakers | 17 – 22 kg |
| Portable CD | 5 | 2000 | | 0,4 – 0,6 kg |
| LCD Projectors | 4 | 2000 | Not glass but metal dominated | 5,0 – 8,9 kg |
| CD recorder | 5 | 1999 | Not plastic but metal dominated | 4,1 – 6,5 kg |
| VCR | 4<br>5 | 1999<br>2000 | | 4,1 – 4,8 kg<br>2,1 – 4,7 kg |
| DVD | 15<br>3 | 2001<br>2002 | | 2,1 – 3,8 kg<br>2,0 – 2,6 kg |
| DVDR | 7 | 2002 | Big differences in stage of development products | 2,6 – 6,6 kg |

*Table 5.14 Products investigated with QWERTY/EE*

In Figure 5.23 the QWERTY/EE results are summarised in one graph. Despite the relatively low amount of products per type per year, clear groups of similar products are formed. The economic and environmental performance of the larger products appears in this graph. One exemption in the graphs are the cellular phones, which have a relatively high yield per product and high environmental recovery values till € 4,00 and 1000 mPts per product treated. Other categories are LCD-projectors ranging from

400 to 700 mPts recovered environmental value and in between € 1 and € 4 per product; LCD Monitors (€ 4 to € 6, 200 mPts to 400 mPts); CRT Monitors (around € 7,50, 500 mPts for 17" and around € 10, 1700 mPts for a 22"); Audio systems (from € 5 to € 8, 1000 mPts to 1500 mPts) and TVs (around € 8, -500 mPts for 21" TVs till € 15, 1500 mPts). In Chapter 7.5 also the effect of collection rates in the environmental returns per amount of money invested under the 'quotient approach' will be discussed.

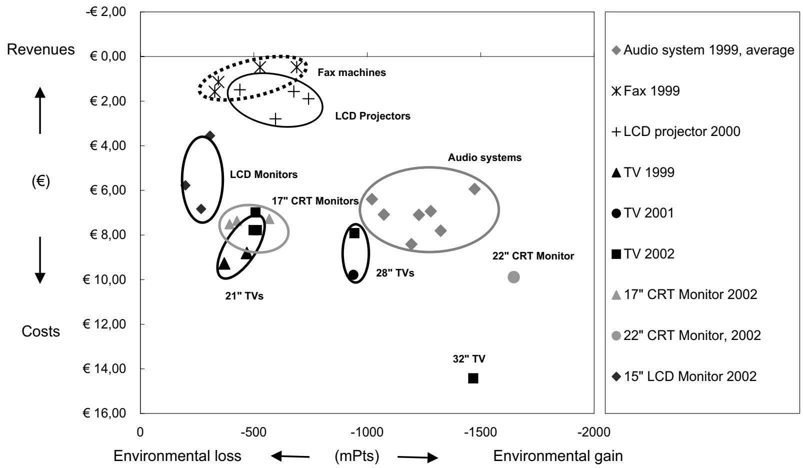


*Figure 5.23 Eco-efficiency of state-of-the-art recycling of various (large) products*

Many small products fall in the area of 0 till 500 mPts and € 0 to € 2 per product. In Figure 5.24 in the next section this area is displayed.

### 5.6.2 Eco-efficiency of (small) consumer electronic products

In this section the relatively small products from Table 5.14 are displayed in the eco-efficiency graph of Figure 5.24. The axes have another scale in this case. In the previous Figure 5.23, the axis were from € 5 revenues to € 15 costs and from 0 to 2000 mPts recovered environmental value. However in Figure 5.24, the (smaller) products with lower values displayed are in the range of € 1,50 costs and € 1,00 revenues and from 0 to 700 mPts.

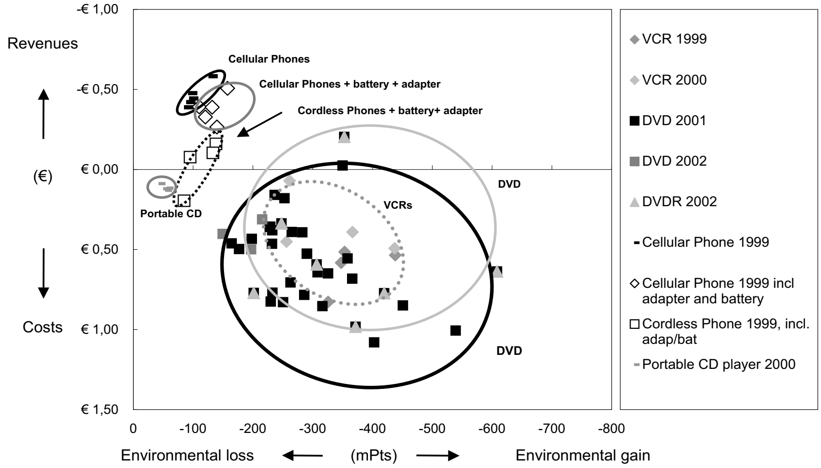


*Figure 5.24 Eco-efficiency of state-of-the-art recycling of various (smaller) products*

In this Figure 5.24, the other product types appear. Again a group of low-end cellular phones is appearing with a positive economic value of around € 0,40 per piece and a also a group of cordless phones appears around a € 0,10 of revenues per piece. Also the portable CD products form a distinct group around € 0,10 costs per piece and 50 mPts recovered environmental value. The DVD players are in the € 0,25 till € 0,75 per piece and 150 to 300 mPts region. The VCRs appear to have similar end-of-life costs compared to the DVD players, but also higher environmental recovery values (from 250 mPts to 450 mPts per piece). The DVD recorders from 2002 do not have a high correlation, due to the large difference in product architecture and degree of development. The same counts for the fax machines (see Table 5.14). These are not very similar due to different functionalities while sometimes a scanner or telephone is built in.

### 5.6.3 Product types with 'high' eco-efficiencies per kg

In order to filter the effect of product weight and size on the eco-efficiency graphs, the same graphs can be determined for the environmental and economic impacts per kg of product. In this way more insight in the costs per kg for the various product types and categories is obtained. In Figure 5.25, the eco-efficiency of products with a relatively high impact per kg are displayed. The precious metal containing products appear in the environmental gain – economic revenues part on the upper right part of the graph.

In this graph also the effect of taking into account the batteries and adapters of phones are included in comparison with the phones as such. Both the economic value as the environmental value per kg is still relatively high in comparison to the cellular phones only. The LCD monitors appear in this graph with relatively high costs for end-of-life treatment. This is caused by the relative high disassembly times for the LCD screens compared to the product weight and environmental value recovered.

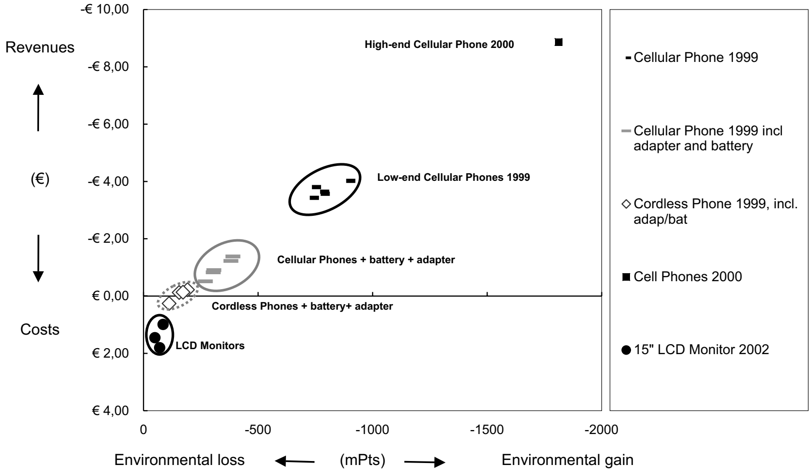


*Figure 5.25 Product types with 'high' eco-efficiencies per kg in end-of-life*

### 5.6.4 Product types with 'low' eco-efficiencies per kg

In Figure 5.26, the same 'zoom in' on the other product categories is carried out. The range of € 0 to € 0,50 costs per kg and 0 to 120 mPts recovered environmental value per kg is displayed.

Also in this graph clear groups are visible. TVs and CRT-monitors are on the down-left side of the graph with integral costs of around € 0,30 to € 0,40 and 30 mPts per kg. More to the right are the plastic dominated products (€ 0,40 and 60 mPts per kg) and more above the metal dominated products. The DVD players form a group around € 0,25 costs and 60 mPts per kg. The VCRs appear to have slightly higher environmental value recovered in comparison to the DVD players. Also the portable CD players and LCD projectors form clear groups in this graph. The 2002 DVD Recorders are scattered in this picture, due to the fact that there are major differences in degree of development of these products amongst the various brands in this graph. Also the fax machines don't have a high correlation due to the difference in products functionality as discussed before.

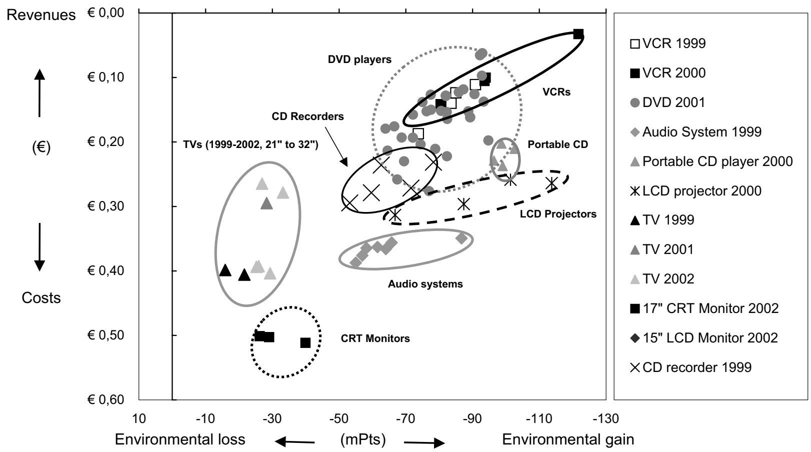


*Figure 5.26 Product types with 'low' eco-efficiencies per kg in end-of-life*

The main conclusion from the last four Figures 5.23 to 5.26 is that due to product characteristics, clear groups representing costs- environmental impact combinations are formed. With these groups, it is possible to estimate end-of-life performance of various products on forehand under the described state-of-the-art recycling configuration. Also the performance of products in other end-of-life scenarios can be determined in a similar way as well as trends over time for the various products when enough data points over more years are available. However, till now only the 'vector approach' as discussed in Chapter 4.2 is applied. In Chapter 7, all fourth quadrant result from this chapter will be ranked on their environmental return per investment and discussed in relation to aligning policy strategies to these results.

In the next Section 5.7, the trends in changes in end-of-life processing already presented for the four example products, will be discussed for a broader range of products in order to estimate the influence of other product compositions on the eco-efficiency directions.

## 5.7 Trends per product category

### 5.7.1 Eco-efficiency directions for plastic dominated products

The first product category to be evaluated is that of plastic dominated products. From Table 5.14, the audio systems, the portable CD players and the fax machines are used as examples for the plastic dominated category. The products chosen have a large variety in product weight. The audio systems (7 pieces) are from the year 1999 and weigh around 20 kg; the fax machines (4 pieces) are from the year 1999 and weigh around 5 kg; the portable CD players (4 pieces) from the year 2000 weigh around 0,5 kg (Philips Consumer Electronics 1999g,k; Philips Consumer Electronics 2000b). The portable CD players have very similar product compositions. The fax machines however, are very different. In two of them, also a scanner and phone is included. The audio systems have also rather different product compositions, especially in PWB weight and sophistication. The consequences of the product differences are also visible in Figure 5.27. The two faxes on the right have more features. The same counts for the spread in the audio system group. The portable CD-players are very close together (also if Figure 5.27 would be enlarged, see also Figure 5.26). In Figure 5.27, the 'state-of-the-art recycling' performance without plastic recycling of the three groups of products is displayed in the eco-efficiency graph.

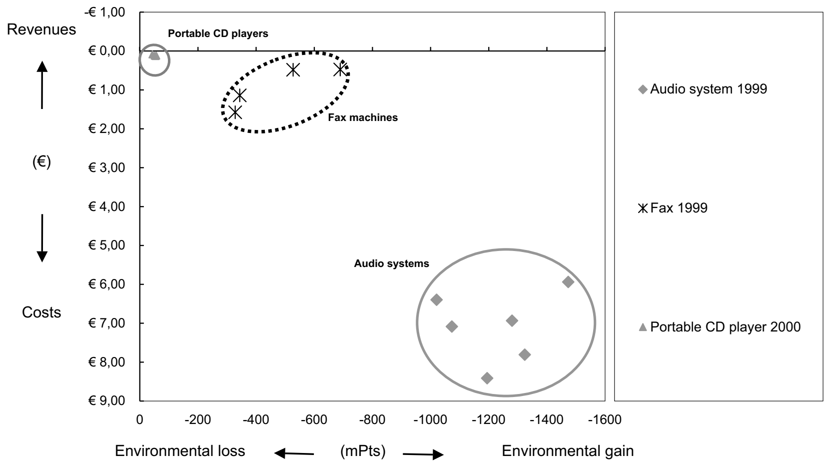


*Figure 5.27 Eco-efficiency of plastic dominated products*

A key question for the plastic dominated is what the relation is between the weight of the plastic housings of the above products and the eco-efficiency of the corresponding improvement avenue: plastic recycling. Furthermore, the plastic recycling results of the example product of Chapter 4.5 can be checked for more plastic dominated products with different weights and compositions. A 'best case scenario' is assumed for the plastic recycling of housings of the three product types. This means plastic recycling is realised under economies of scale and under the assumptions that the plastic housings can be gathered without any 'contaminations', which is not the case for the many of the products in Figure 5.27. The portable CD-player and the audio systems have many of the 'contaminations', like metal insert, stickers, different plastic types connected to the housings like buttons, etc. Despite these aspects, it is assumed that the plastic housings are collected as such without contaminations under the following average disassembly times: 120 seconds for the portable CD-players (many small screws) and around 200 seconds for the faxes and audio systems (Philips Consumer Electronics 1999g,k; Philips Consumer Electronics 2000b). It is further assumed that no flame-retardants are present, The weight of the plastic housings recycled are on average: 130 g for the portable CD players (ranging from 80 to 160 g); 1,3 kg for the fax machines (ranging from 1,0 to 1,9 kg) and 4,1 kg for the audio systems (front- and back-covers ranging from 2,3 to 5,1 kg).

The results for the plastic recycling scenarios are visualised in the eco-efficiency graph of Figure 5.28. In this graph the economic and environmental performance is displayed per kg of product in order to exclude the big differences in weight between the plastic dominated products.

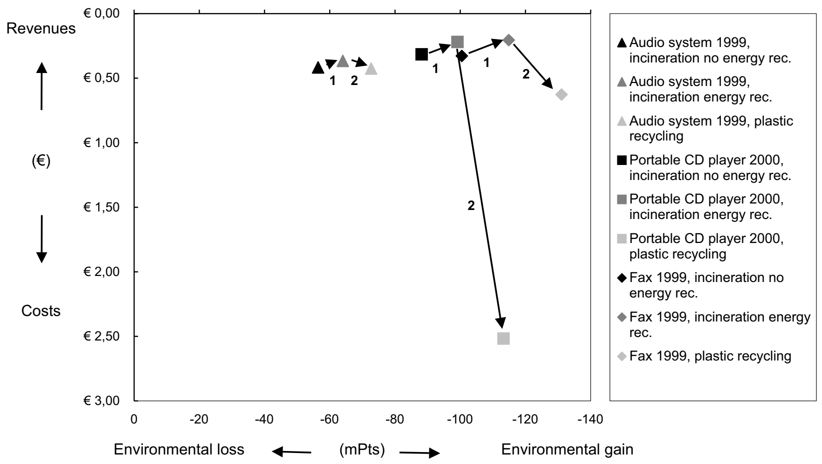


*Figure 5.28 Eco-efficiency per kg of plastic recycling different plastic dominated products*

1. Large plastic housings: The first group op points (on the left) in this Figure 5.28 are the scenarios for the audio systems. The first arrow represents the change in environmental and economic performance of incineration without energy recovery towards incineration including energy recovery of the residue fraction (including most of the plastics within the products). The third point is the difference between incineration with energy recovery and the exclusion of the plastic housings of this operation by applying plastic recycling. This change is visualised with the second arrow. The two arrows on the left show that for the large housings some environmental improvement is realised against small extra costs per kg (there is a move to the right). In this example the disassembly costs are taken into account for the plastic recycling. For most of the CRT or LCD containing, disassembly is required to remove the picture tubes and are the plastic housings acquired separately at zero costs, allocated on the glass content. To be more precisely: plastic recycling of large encasings including disassembly costs, under best case conditions leads to an environmental gain of 150 mPts/€ invested. (From 56 mPts, € 0,37 per kg; 1227 mPts, € 7,10 per product to 64 mPts, € 0,43 per kg; 1447 mPts, € 8,57 per product). Plastic recycling without taking into account disassembly costs, leads in almost all cases to 'vectors' in the first quadrant of Figure 4.4 and thus a positive eco-efficiency.
2. Medium sized plastic housings: The right group of three points in Figure 5.28 are the scenarios for the fax machines. The first arrow again represents the change in environmental and economic performance of incineration without energy recovery towards incineration including energy recovery of all plastics. The second arrow represents the difference between incineration with energy recovery of all plastics and the plastic recycling of the housings. The two arrows together on the right

show that for the medium sized housings environmental improvement is realised against relatively higher costs per kg compared to the audio systems. This means that plastic recycling of medium sized encasings (1,3 kg) under best case conditions leads to an environmental gain of 40 mPts/€ invested (an increase from 115 mPts/kg to 131 mPts/kg and from € 0,21 to € 0,63 per kg).

3. Small plastic housings: The middle group of three points in Figure 5.28 are the scenarios for the portable CD players. The second arrow represents the difference between incineration with energy recovery of all plastics and the plastic recycling of the housings. The two arrows together on the right show that for the small plastic housings only minor environmental improvement is realised against high costs per kg. This means that plastic recycling of small encasings (0,13 kg) under best case conditions leads to an environmental gain per amount of money invested of 6 mPts/€ invested (an increase from 99 mPts/kg to 113 mPts/kg and from € 0,22 to € 2,52 per kg ).

Comparing the plastic recycling of the fax machines with the Soundmachine example (Philips Consumer Electronics 2001e) of Chapter 4.5 (both have medium sized housings shows similar results. The increase in environmental performance is comparable, the costs increase for the fax machine is higher than that of the Soundmachine, this is mainly due to the difference in disassembly time. The required disassembly time for the Soundmachine is around 120 seconds against 200 seconds for the fax. In Chapter 6, more detail will be provided on improving design of consumer electronics in order to make plastic recycling less costly and thus more eco-efficient. In Chapter 7.6.2 results for the various plastic recycling scenarios will be placed in perspective.

### 5.7.2 Eco-efficiency directions for metal dominated products

The second product category to be evaluated is that of the metal dominated products. From Table 5.14, the LCD projectors, the CD recorders, the VCRs, DVD players and DVD recorders are used (Philips Consumer Electronics 1999e,f; Philips Consumer Electronics 2000i,n,q; Philips Consumer Electronics 2001k,l,n; Philips Consumer Electronics 2002b,c). Although the differences in functionality are very small within the individual product groups, there are main differences in weight per products: The LCD projectors are from 2000 and weigh in between 5,0 kg and 8,9 kg (4 pieces). The VCRs are from the year 1999 (4 pieces) and 2000 (5 pieces) and weigh in between 2,1 kg and 4,8 kg. The DVD players are from 2001 (15 pieces) and 2002 (3 pieces) and are in the range of 2,0 to 3,8 kg. The last group are the DVD recorders from 2002 (7 pieces), in this case the difference in product composition and degree of product development is large, which results in differences in weight of 2,6 kg towards 6,6 kg. The differences in material content are relatively large: The plastic content in the CD recorder and VCRs is much higher than in the DVD, DVDR and LCD projectors. The amount of high-integrated PWBs is the highest for the DVDR and LCD projectors resulting in higher precious metal contents. The effect of this and the relation with the technical improvement option of dedicated shredding and separation is discussed after the eco-efficiency results of all metal dominated products under investigation.

Figure 5.29 reflects the differences between products in terms of product compositions and weight. However, also in this case clear groups are formed for the various product types. The large sample of DVD players where the product differences are relatively small also results in a small area of comparable environmental and economic performance for state-of-the-art recycling. The same counts for the VCRs which are more the right (higher environmental recovery) and who are also around € 0,60 integral costs. The CD recorders form a group position lower at around € 1,50 integral costs per product. The spread in eco-efficiency results is higher for the LCD projectors and the DVD recorders who both have the largest differences in weight.

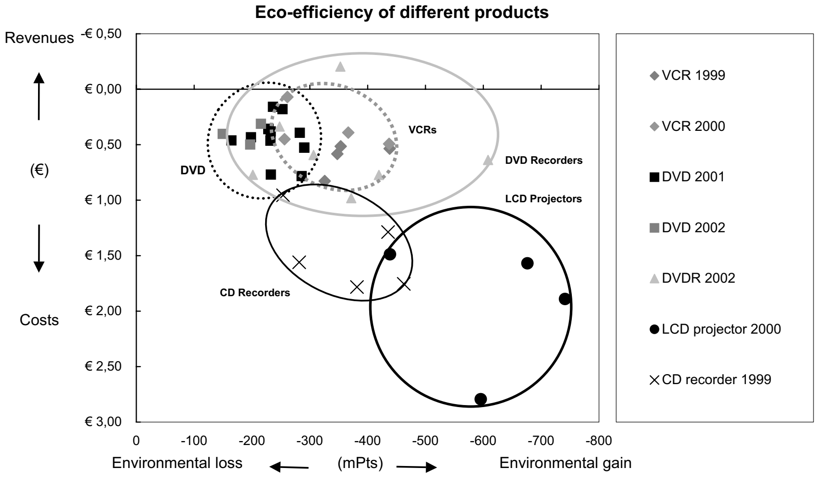


*Figure 5.29 Eco-efficiency of metal dominated products*

A key question for the metal dominated products is whether dedicated shredding and separation of these products would lead to increased eco-efficiency performance. See also the discussion in Section 5.3.5 on this. The improvement option is based on applying dedicated settings for shredding and separation in order to get more PWB materials in the copper fraction. Due to the lower plastic content of metal dominated products no plastic fraction or residue fraction is obtained, only an aluminium, ferro and copper fraction. Only some larger plastic pieces are separated with handpicking. The resulting more 'contaminated' copper fraction should lead to higher amounts of materials recovered without to much dilution of the same most valuable materials. In Seection 5.3.5 for the example DVD player a 'negative' eco-efficiency direction occurred in this situation. In this section it is checked whether the same effect also appears for other DVD players and other metal dominated products. Therefore, like in the previous Section 5.7.1, the eco-efficiency of this technical improvement option is determined in relation to the original state-of-the-art recycling scenario.

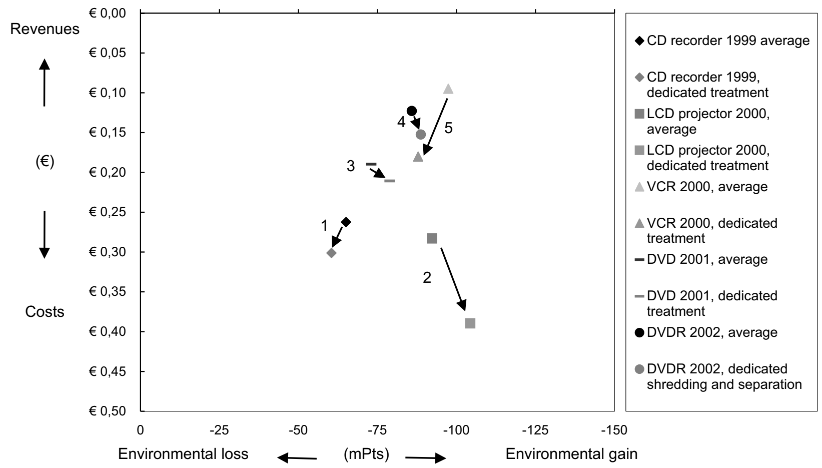


*Figure 5.30 Eco-efficiency per kg of dedicated shredding and separation of metal dominated products*

The results for the dedicated shredding and separation scenarios on all products mentioned above are displayed in the eco-efficiency graph of Figure 5.30. In this graph the economic and environmental performance is displayed per kg of product in order to exclude the big differences in weight:

1. The first two points (first arrow) represent the average result for the CD recorders. The same effect compared to the example DVD player of Section 5.3 occurs. The dedicated shredding and separation doesn't result in higher environmental recoveries and less costs, but to the opposite effect. Also in this case, by sending more plastics and other environmentally relevant materials to the copper smelter with a relatively bad flue gas cleaning, it results in lower environmental gains, whereas in the original scenario more plastics are incinerated in a MSW incineration plant with a more extended and more modern flue gas cleaning system and energy recovery. The net effect is relatively small (only 5 mPts less environmental gain and € 0,04 extra costs per kg) although more valuable metals are recovered in this scenario.
2. The second group of two points visualise the change of state-of-the-art recycling towards dedicated shredding and separation for the LCD projectors. In this case, the metal and precious metal content is relatively higher and the plastic content is lower compared to the previous VCR example. For the LCD projector, the resulting eco-efficiency direction is presented with the second arrow. There is a cost increase from € 0,28 to € 0,39 per kg, but in this case some environmental improvement is realised as well (around 140 mPts/€). The reasons are that the costs are increasing due to the same reasons as for the CD recorders, but the environmental effect of recovering more valuable materials is higher than the changing impacts of incineration of plastics in a copper smelter.
3. The third two points in Figure 5.30 are representing the DVD players. In this case however, there is a small environmental improvement of 6 mPts/kg against a small cost increase of € 0,02 (300 mPts/€). However, the arrow in Figure 5.30 is

relatively small. Due to the low plastic content in comparison with the CD recorder. The effect of increased recovery is more or less in balance with the lower revenues due to dilution of valuable materials.

4. The same counts for the DVD recorders. Although in case the increase in integral costs is higher due to the higher precious metal and ferro content: The environmental gain is increased with only 3 mPts/kg against increased costs of € 0,03 (around 100 mPts/€). The direction is quite similar, but the vector is much smaller compared to the LCD projectors.
5. The fifth set of points is displaying the results for the VCRs. Like the CD recorders also a relatively high plastic content is present in this case. This also leads to the same 'negative' eco-efficiency direction as derived before for the CD recorders: 9 mPts/kg less environmental recovery and € 0,09/ kg higher costs.

From the results above it is concluded that the improvements in environmental terms are not very large compared to the effects measured for plastic recycling of large housings in the previous Section 5.7.1. The integral state-of-the-art recycling costs per kg are much lower for the metal dominated products. The improvement percentages presented are in most cases relatively large due to the already low integral costs of treatment. The results show a few negative eco-efficiency directions for the dedicated shredding and separation of the VCRs and CD recorders. Small positive effects on the environmental performance is realised for the DVD players, the DVD recorders and the LCD projectors. But, in all cases a 'fourth quadrant' result is appearing. In general it is concluded that sorting metal dominated products from the regular browngoods stream including dedicated shredding and separation settings doesn't lead to higher eco-efficiencies. However, for some products with relatively low plastic contents and high precious metal contents, a significant environmental return on investment can be realised. In Chapter 7.5 this will also be discussed in more detail. In Chapter 6, more detail will be provided on improving design of consumer electronics in order to find other improvement avenues for metal dominated products in general and for the example DVD player in particular.

### 5.7.3 Eco-efficiency directions for glass dominated products

The third product category to be evaluated is that of the glass dominated products. From Table 5.14, the LCD monitors, the TVs and CRT monitors are taken as examples (Philips Consumer Electronics 1999m; Philips Consumer Electronics 2000e; Philips Consumer Electronics 2001g; Philips Consumer Electronics 2002e,f,g,h,k,m). The differences in product compositions are relatively small for the CRT and LCD monitors. The differences in the TV sets are larger. The screen sizes and functionality varies from 20-inch mainstream TVs to 32-inch high-end TVs. The disassembly times are included in all scenarios and are known from the Philips Consumer Electronics Environmental Benchmark reports. The corresponding costs are included also for the default state-of-the-art recycling scenario, while also without plastic recycling the CRTs must be disassembled. While not enough product compositions are known to form groups of products with different screen sizes and production years, the following groups are formed representing these different production years and sizes:

| Product | Number | Year | Screen size | Weight (kg) |
|---|---|---|---|---|
| LCD Monitors | 3 | 2002 | 15" | 3,5 - 3,8 kg |
| CRT Monitors | 3 | 2002 | 17" | 14,2-15,0 kg |
| TVs 1999 | 2 | 1999 | 21" (2x) | 22 kg |
| TVs 2001 | 1 | 2001 | 28" (1x) | 33 kg |
| TVs 2002 | 5 | 2002 | 20" (1x), 21"(3x), 32" (1x) | 17 – 55 kg |

*Table 5.15 Groups of glass dominated products investigated*

The differences between products in terms of product compositions and weight are already presented in Figure 5.23. From this graph it is already obvious that the LCD monitors form a different group compared to the CRT containing products. In fact, the LCD monitors are not appearing in the 'glass dominated area' of Figure 5.23, nor in the 'metal dominated area' or 'plastic dominated area' but in between.

A key question for the glass-dominated products is what the results of plastic and CRT glass recycling are in relation to the state-of-the-art recycling scenario. Both options are assumed to be 'best case scenarios' and earlier discussed in Section 5.4.1. With the four groups of products described in Table 5.15, the results of Section 5.4.4 and 5.4.5 are checked. The calculations for both the increased CRT glass and plastic recycling are presented in Figure 5.31. The LCD monitors are excluded from this comparison due to their different characteristics, but will be discussed later when a comparison between the LCD and CRT monitors is made.

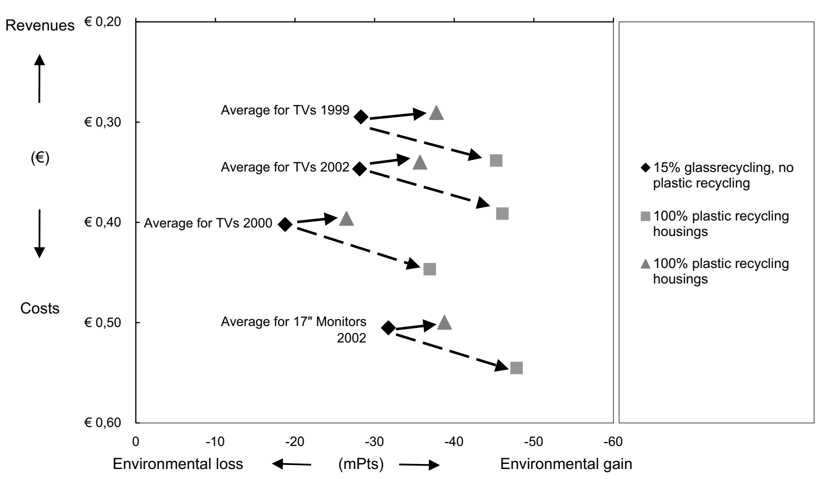


*Figure 5.31 Eco-efficiency per kg of glass and plastic recycling of CRT containing products*

In Figure 5.31, a clear result is generated. The plastic recycling of large housings which are already disassembled (no extra costs accounted to the plastics for disassembly), leads in all cases to an environmental improvement of around 8 mPts/kg and to a small decrease in integral costs per kg. The increased CRT glass recycling leads in all cases to a relatively larger environmental improvement of around 14 mPts/kg compared to the plastic recycling scenario against a cost increase of € 0,08. Although the results per kg are relatively small, they appear for all products under consideration and they are in line with the results of the example 17-inch CRT-monitor. It should be noted that the environmental and economic results are significant for the large products, like the 55 kg 32-inch TV which represents 1500 mPts and € 14,40 per product for state-of-the-art recycling towards 1900 Pts and € 14,02 for the plastic recycling scenario and 2500 Pts, € 16,93 for the CRT glass recycling scenario (400 mPts/€ invested).

The results presented are valid for 'best case' plastic recycling and CRT glass recycling with allocating the disassembly costs to the CRT glass-recycling scenario. In practice however, plastic recycling is often not possible due to the presence of flame-retardants, present in speakers or buttons etc. In Chapter 6, these issues will be further discussed for the example 17-inch CRT-monitor in order to align the above results with the technical characteristics of the plastic housings. Also other improvement avenues for glass-dominated products in general will be presented and evaluated.

Finally, the comparison of applying plastic and CRT glass recycling for LCD monitors and CRT monitors is made. In Figure 5.32 the results for both groups are presented for average products as a whole. Due to lower glass content, Figure 5.32 shows almost no differences in costs for the increased CRT glass recycling option for the LCD monitors (from 69 mPts/kg towards 70 mPts kg and € 0,01 extra costs). The plastic recycling scenario leads to higher environmental gain (from 69 mPts/kg to 85 mPts/kg and cost neutrality). Also here, it is assumed that disassembly of LCD and plastic housings is obligatory for all scenarios. These disassembly costs are relatively high, 650 seconds on average, which is already € 6,50 per product! The effect of the potential toxicity for the LCD fluids is not taken into account here, but is the underlying reason for the obligatory disassembly and corresponding costs.

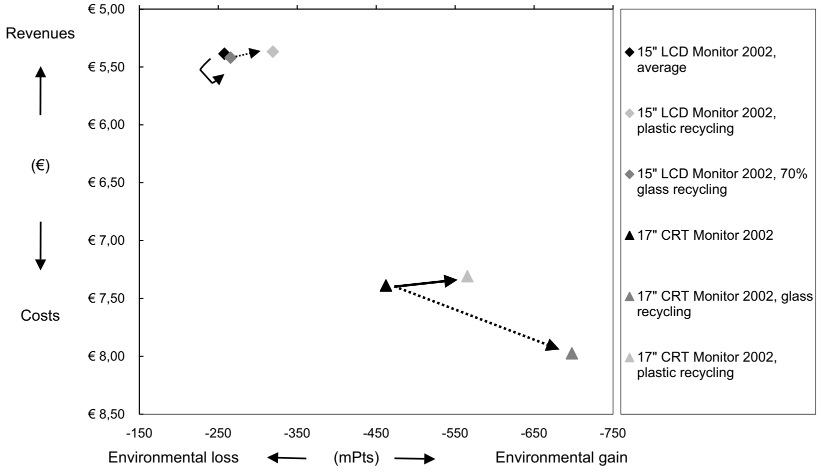


*Figure 5.32 Plastic and CRT glass recycling of a CRT versus a LCD monitor*

### 5.7.4 Eco-efficiency directions for precious metal dominated products

In this section the last product category to be evaluated is that of the precious metal dominated products. For this category two groups of products are evaluated. The cordless DECT phones and the cellular phones will be discussed. Also the relevance of the batteries and adapter will be discussed. Furthermore the results of Section 5.5 where a high-end 2000 cellular phone is used as an example are checked for other precious metal dominated products. From Table 5.14, the Cordless DECT phones from 1999 (Philips Consumer Electronics 1999a) and the cellular phones from 1999 (Philips Consumer Electronics 1999d) are used. Chemical analysis of all PWBs of all phones individually is available while the precious metal content can be very different for phones with the same age and functionality. For the cellular phones the precious metal contents are in between 320 ppm and 385 ppm for gold and in between 187 and 222 ppm for palladium. This is much lower compared to the 500 ppm gold and 800 ppm palladium for the example cellular phone presented in Section 5.5. The precious metal content of the cordless phones varies even more: from 8 ppm to 183 ppm for gold and from 23 ppm to 135 ppm for palladium. The effect of the variation in precious metal content is clearly visible in Figure 5.33.

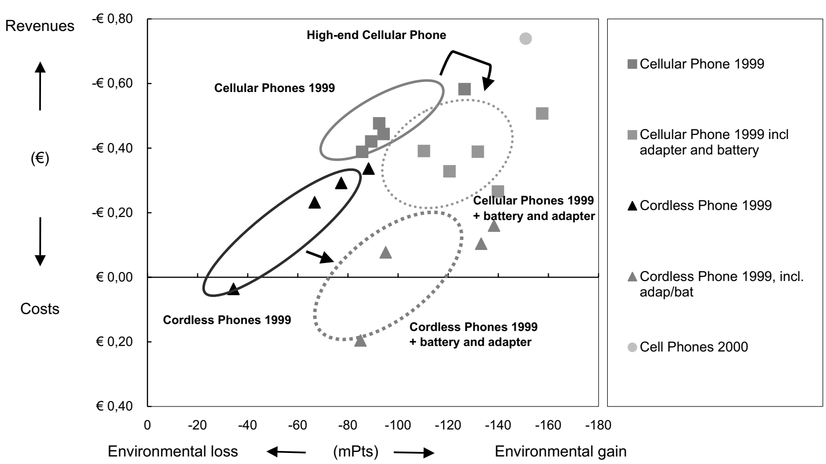


*Figure 5.33 Eco-efficiency of precious metal dominated products*

Figure 5.33 displays the eco-efficiency of all phones under investigation for state-of-the-art recycling, which means recycling of the products as a part of the regular browngoods stream. The effect of the changes in precious metal content is clearly visible. A narrow band of products is formed, which shows that for both the cellular phones and cordless phones (without batteries and power-adapters) the higher precious metal contents lead to an obvious relation between environmental and economic recoveries. It is also shown that the inclusion of the (separate!) recycling of adapters and batteries leads to a significant shift in environmental recoveries and on average slightly lower revenues. It is also obvious that the low-end cellular phones from 1999 (average weight 180 g) result in lower environmental and economic recoveries per product in comparison with the original example of the year 2000 high-end cellular phone (which only weighs 83 g). The revenues for the average low-end 1999 cellular phone is € 3,69 per kg in comparison with the € 8,87 per kg for the more modern high-end cellular phone. From this the question rises whether the technical improvement options of plastic recycling and separate collection and treatment of precious metal dominated products as calculated in Section 5.5. are also valid for lower precious metal concentrations. Therefore the cellular phone of Section 5.5 is compared with the average cellular phone from 1999 and with the average cordless phone. The differences is weight are not as high as in the examples for the other product categories and therefore the results of the separate collection and shredding and separation settings and the plastic recycling scenarios (as earlier discussed in Section 5.5) are presented in Figure 5.34.

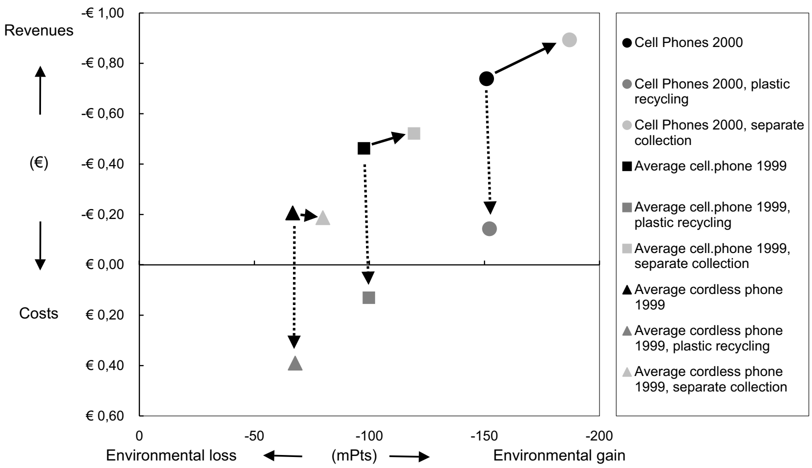


*Figure 5.34 Eco-efficiency per kg of precious metal dominated products*

This graph shows similar trends for all product types. The plastic recycling leads in all cases to almost no extra environmental gain but relatively high extra costs. The separate collection and treatment scenario leads in all cases to an increased environmental performance. But for the products with lower precious metal contents (the cordless phones) it leads to slightly increasing integral costs. This is due to the much higher logistic costs, which were included. In the cellular phone cases, also an increase in economic performance is realised. As discussed earlier, the increase in revenues for products with a relatively high precious metal content is quite substantial (from € 8,87 to € 10,72 per kg for the high 2000 phones and from € 3,69 to € 4,17 per kg for the 1999 low-end cellular phones). The 'fourth quadrant' result for the DECT phones will be discussed and related to other results as well in Chapter 7.5.

Again it should be noted that the underlying assumptions have a significant influence on the results. For the plastic recycling scenario one of the main assumptions is an optimised product design to make plastic recycling technically possible. This will be discussed into more detail in the next Chapter 6. For the separate collection and treatment scenario it means that economies of scale must be realised. In simple words: enough precious metal dominated products must be collected (batches of a few tons) to make it attractive to treat them separately and to make it efficient to be shipped to a copper smelter.

## 5.8 Discussion

### 5.8.1 EDIP'96 and metal dominated products

In order to check the results generated with the Eco-Indicator '99 method, the eco-efficiency results for the example products are also calculated for the EDIP'96 method as a completely different LCA method. In Figure 5.35, the same graph is created compared to Figure 5.8. In this graph, the average MSW disposal point, the state-of-the-art recycling scenario and the dedicated shredding and separation scenario are shown. When comparing both figures, it is clear that exactly the same trend occurs. This remarkable when taking into account that a completely different LCA approach lies behind both graphs.

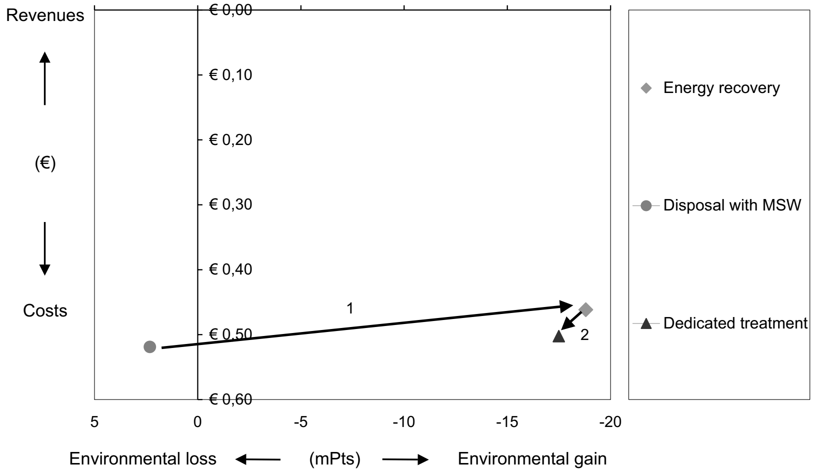


*Figure 5.35 Eco-efficiency of dedicated treatment of a DVD player (EDIP'96)*

One of the reasons for the high correlation is that in general the consequences of all processing steps involved are almost equal. Despite the fact that some materials are valued differently, the role of the various processes involved remains similar. This effect was previously discovered and presented in Chapter 3.6.4, Figure 3.19.

### 5.8.2 EDIP'96 and plastic dominated products

Already in Chapter 3, it was shown that plastic recycling is valued differently for the EDIP'96 method while resource depletion of fossil fuels is not accounted for in this method. When Figure 5.36 is compared with the similar Figure 4.10, this becomes obvious. In Figure 5.36, the effect of increasing collection rates is similar to the effect in Figure 4.10. However, plastic recycling (third arrow) turns out to fall in the third, negative eco-efficiency quadrant compared to the fourth quadrant result of Figure 4.10. However, the comparison between energy recovery in this case from the plastic containing residue fraction in relation to the state-of-the-art recycling scenario (first arrow) is similar to the effect displayed in Figure 4.10 (but for that graph the distance between the two incineration scenarios are displayed for the whole product, in Figure 5.36 it is displayed for the residue fraction only).

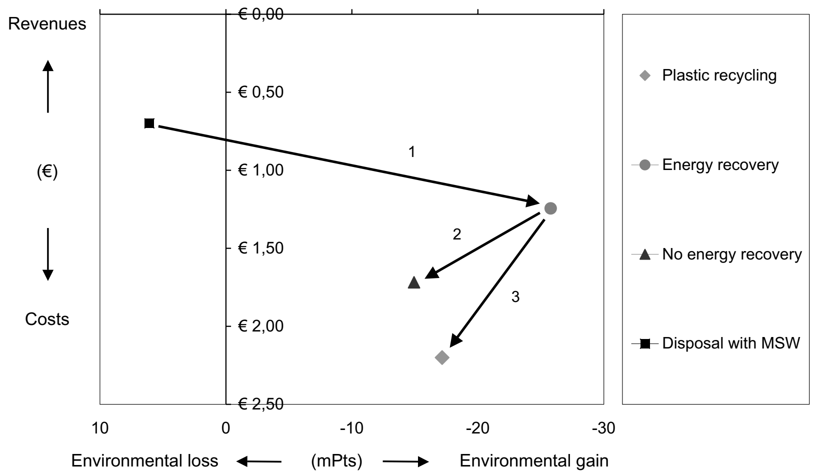


*Figure 5.36 Eco-efficiency of a plastic dominated product (EDIP'96)*

### 5.8.3 EDIP'96 and glass dominated products

In Figure 5.37, the comparison is made with the eco-efficiency results for the 17-inch monitor under the Eco-Indicator '99, as displayed in Figure 5.15. Both graphs show very similar results for the scenarios: increase of collection rates and CRT glass recycling and very different results for the plastic recycling.

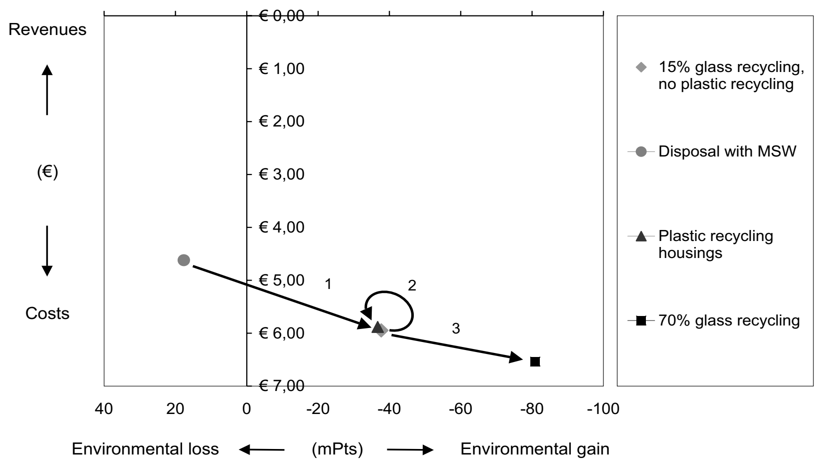


*Figure 5.37 Eco-efficiency of a glass dominated products (EDIP'96)*

Again it is clear that under the EDIP method all scenarios work out in a similar way compared to the Eco-Indicator '99 method, except for plastic recycling due the lack of resource depletion factors for plastics. This leads to almost no 'bonus' for preventing new primary material extraction for these plastics and as a result to a lower evaluation of plastic recycling.

### 5.8.4 EDIP'96 and precious metal dominated products

The last comparison to make regarding the sensitivity of the results with respect to the chosen environmental assessment method is for the precious metal dominated products. In this case Figure 5.22 is compared to Figure 5.38, which shows the same scenarios under the EDIP method. The resemblance is remarkable. In Figure 5.22 already a relatively small contribution to the environmental axis is given for the plastic recycling. This leads to exactly the same trends in eco-efficiency for both environmental assessment methods. The evaluation on the horizontal axis for the scenario of increasing collection rates and separate collection is very similar. The plastic recycling including disassembly leads in both cases to a negligible environmental improvement.

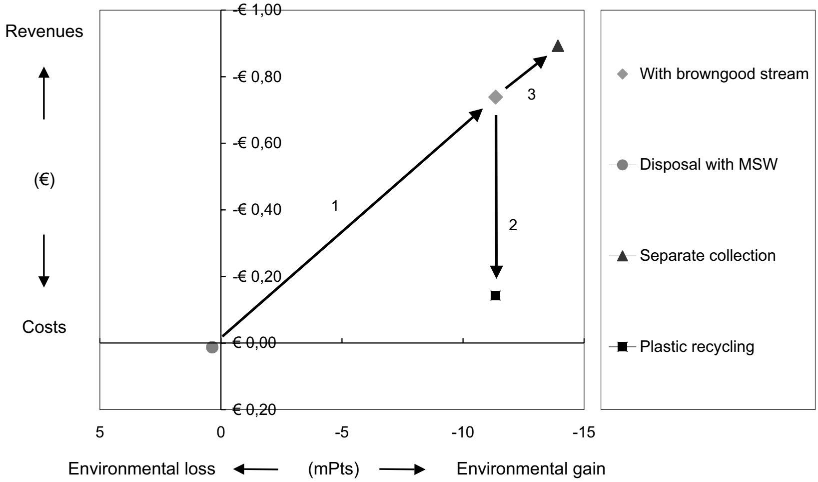


*Figure 5.38 Eco-efficiency of a precious metal dominated product (EDIP'96)*

### 5.8.6 Discussion: Sensitivity and uncertainty in environmental parameters

The main uncertainty factors are already discussed in Chapter 3. Other important parameters having influence on the environmental results are:

1. Number of product compositions known. The calculations and estimates of product compositions based on the Philips Consumer Electronics Environmental Benchmarks are very time consuming. Therefore, 'only 75' different products were assessed. On top of these 75, a substantial amount of products was excluded while the component lists and weighing of those components were incomplete. Despite this limitation, the amount of products assessed is sufficient to derive the

results and trends in environmental performance as visualised in the graphs of Section 5.6 and 5.7.
2. Emissions and energy consumption at metal smelters. This will further discussed in more detail in Chapter 8.
3. Precious metal contents. Further research on this matter is recommended for more modern precious metal dominated products than the 1999 examples described in this chapter. This requires chemical analysis of for instance more modern cellular phones and other small and highly miniaturised products.

### 5.8.6 Discussion: Sensitivity and uncertainty in economic parameters

The sensitivity of the results due to uncertainty in the economic parameters is already discussed in Chapter 4.8. Additional main parameters having influence on the economic results of this Chapter 5 are:

1. Number of product compositions known. The number of products is sufficient to derive the results and trends in economic performance as visualised in the Figure of Section 5.6 and 5.7.
2. Economies of scale. This plays an important role for CRT glass recycling and especially for the plastic recycling scenarios. Costs for plastic recycling can be significantly higher when applied on relatively small streams.
3. Disassembly times. There is a large variety in disassembly times measured. In the cases of plastic recycling of small and medium sized housings, which are comparable in terms of functionality. This has the highest contribution to the relatively high cost increases. In Chapter 6, this issue will be further discussed regarding options to decrease disassembly times.
4. Technical constraints. Many of the plastic recycling cases are jeopardised by the presence of flame-retardants, other plastic types, stickers, buttons etc. In Chapter 6, improvement options on this issue will be presented.
5. Transport and logistic costs. In the case of separate collection and treatment of the precious metal dominated products this aspect is highly uncertain. Further research on the 'logistic aspects' is recommended.
6. Precious metal contents. Especially for the precious metal dominated products, the precious metal contents can vary significantly. Further research on this matter for more modern products with a high degree of miniaturisation is recommended.

## 5.9 Conclusions

### 5.9.1 Results: Ranking of the highest improvements

The highest environmental and economic improvements of technical changes above state-of-the-art recycling are listed in Table 5.16. The highest environmental improvements per product are realised for the CRT glass recycling of CRT containing appliances. The highest environmental improvements per kg of product are realised in the separate collection scenarios of both cellular phones and cordless phones. The highest economic improvements are realised for the plastic recycling of large housings (under a range of assumptions, see Section 5.2.3). High revenues per kg are only realised for the separate collection scenarios of the phones.

| Nr. | Highest environmental gain/ product | mPts | € |
|---|---|---|---|
| 1 | TV 2001 70% glass recycling | -564 | € 1,45 |
| 2 | TV 2002 70% glass recycling | -503 | € 1,25 |
| 3 | 22" CRT Monitor, 2002, glass recycling 70% | -462 | € 1,17 |
| 4 | TV 1999 70% glass recycling | -409 | € 1,00 |
| 5 | TV 2001 plastic recycling | -314 | -€ 0,14 |
| **Nr.** | **Highest environmental gain/ kg** | **mPts/kg** | **€/kg** |
| 1 | Cell Phones 2000, separate collection | -432 | -€ 1,85 |
| 2 | Cellular Phone 1999, separate collection | -174 | -€ 0,48 |
| 3 | Cordless Phone 1999, separate collection | -80 | € 0,07 |
| 4 | TV 1999 70% glass recycling | -18 | € 0,04 |
| 5 | Portable audio, 2001, plastic recycling | -18 | € 0,24 |
| **Nr.** | **Highest economic revenue/ product** | **€** | **mPts** |
| 1 | 22" CRT Monitor, 2002 plastic recycling | -€ 0,28 | -208 |
| 2 | TV 2002 plastic recycling | -€ 0,20 | -213 |
| 3 | Cell Phones 2000, separate collection | -€ 0,15 | -36 |
| 4 | TV 2001 plastic recycling | -€ 0,14 | -314 |
| 5 | TV 1999 plastic recycling | -€ 0,14 | -174 |
| **Nr.** | **Highest economic revenue/ kg** | **€/kg** | **mPts/kg** |
| 1 | Cell Phones 2000, separate collection | -€ 1,85 | -432 |
| 2 | Cellular Phone 1999, separate collection | -€ 0,48 | -174 |
| 3 | 22" CRT Monitor, 2002 plastic recycling | -€ 0,01 | -7 |
| 4 | TV 2002 plastic recycling | -€ 0,01 | -8 |

*Table 5.16 Ranking highest environmental and economic improvements*

### 5.9.2 Results: Ranking of lowest improvements

The lowest environmental and economic improvements of technical changes above state-of-the-art recycling are listed in Table 5.17. The lowest environmental improvements per product are realised for the dedicated shredding and separation settings for metal dominated products with still a relatively high plastic content: the VCRs and CD recorders. In fact for these two groups of products, a relatively small, but obvious negative eco-efficiency direction is realised. The lowest economic improvements or highest integral costs are realised for plastic recycling of medium sized housings (again under a range of assumptions, see Section 5.2.3). The highest costs per kg are appearing for the plastic recycling of small housings. It is obvious that the extra costs are in proportion compared to the environmental gain realised.

| Nr. | Lowest environmental gain/ product | mPts | € |
|---|---|---|---|
| 1 | VCR 2000, dedicated treatment | 30 | € 0,27 |
| 2 | CD recorder 1999, dedicated treatment | 27 | € 0,22 |
| **Nr.** | **Lowest economic revenue/ product** | **€** | **mPts** |
| 1 | Fax 1999, plastic recycling | € 1,76 | -70 |
| 2 | Audio system 1999, plastic recycling | € 1,48 | -220 |
| 3 | TV 2001 70% glass recycling | € 1,45 | -564 |
| 4 | TV 2002 70% glass recycling | € 1,25 | -503 |
| 5 | Portable CD player 2000, plastic recycling | € 1,18 | -7 |
| **Nr.** | **Lowest economic revenue/ kg** | **€/kg** | **mPts/kg** |
| 1 | Cell Phones 2000, plastic recycling | € 7,15 | -15 |
| 2 | Cellular Phone 1999, plastic recycling | € 4,85 | -16 |
| 3 | Cordless Phone 1999, plastic recycling | € 3,47 | -6 |
| 4 | Portable CD player 2000, plastic recycling | € 2,30 | -14 |
| 5 | Fax 1999, plastic recycling | € 0,42 | -16 |

*Table 5.17 Ranking lowest environmental and economic improvements*

### 5.9.3 Conclusions: Eco-efficiency performance of all options

The results of all technical improvement scenarios are summarised in Figure 5.39. In this graph, the changes from state-of-the-art recycling to the scenario under consideration are visualised. The graph visualises the results presented in the Tables 5.16 and 5.17.

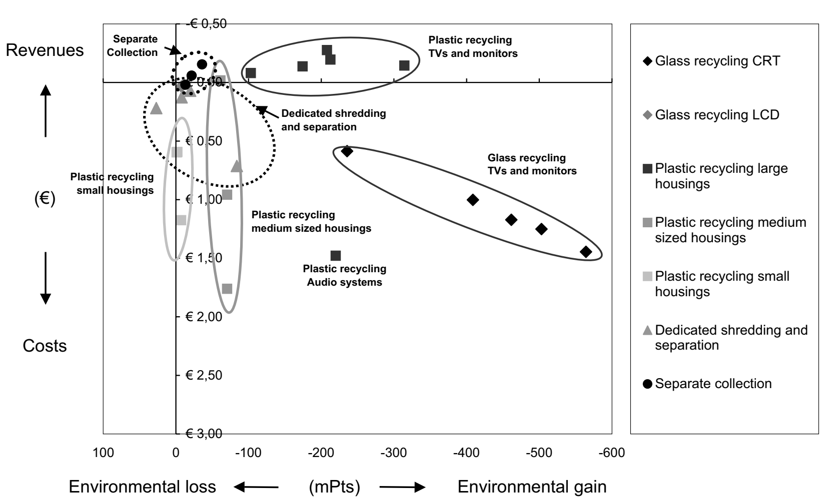


*Figure 5.39 Summary eco-efficiency directions of technical improvements*

In Chapter 7, a more precise and extensive discussion will be presented in the various eco-efficiency directions calculated in this thesis. This includes the ranking of the fourth quadrant results and the alignment with current and alternative policy strategies in order to enhance the eco-efficiency performance of the end-of-life chain.

### 5.9.4 Conclusions: QWERTY/EE methodology

The QWERTY/EE methodology is proved to be very useful in evaluating the environmental and economic performance of products in end-of-life processing and in determining the most promising technical improvement options. With the example products also the relevance for economy and environment is shown for all relevant end-of-life scenarios possible. With the QWERTY/EE methodology the following aspects can be addressed in a quantitative way:

1. Monitoring of the environmental and economic performance of single products and product groups within certain take-back systems.
2. The determination of priorities regarding different materials and multiple end-of-life options (as a total set of end-of-life scenario's).
3. Monitoring of the eco-efficiency of take-back systems as a whole. This will be further discussed in detail in Chapter 7.
4. The quantification of the contribution of different actors and stakeholders. This will also be discussed in Chapter 7.

It is demonstrated that with the QWERTY/EE concept it is possible to determine the performance of various products under a range of technical improvement options in current and to determine the direction and size of the eco-efficiency 'vector'. Apart from this product perspective, the relation with changing waste policies and legislation will be discussed in more detail in Chapter 7.
In some cases the assumptions underneath the QWERTY/EE calculations are very important, for instance for the plastic recycling scenarios. In the next Chapter 6, the relation between the results from this chapter and the optimisation of design for end-of-life is discussed. Chapter 7 the focus is on system operation, legislation and logistics as well as on the roles and consequences of individual stakeholders. But the main target of Chapter 7 will be the discussion on a drastic revising of current policy strategies based in the results calculated in this chapter for many different products and scenarios.

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PHILIPS CONSUMER ELECTRONICS 2001a, Environmental Benchmark of Cellular Phones (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-G01-5051-038, Eindhoven, The Netherlands, March 2001

PHILIPS CONSUMER ELECTRONICS 2001b, Environmental Benchmark LCD Monitors (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-G01-5051-035, Eindhoven, The Netherlands, August 2001

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PHILIPS CONSUMER ELECTRONICS 2001d, Environmental Benchmark Audio Systems (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental

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PHILIPS CONSUMER ELECTRONICS 2001e, Environmental Benchmark Portable Audio (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-G01-5051-158, Eindhoven, The Netherlands, September 2001

PHILIPS CONSUMER ELECTRONICS 2001f, Environmental Benchmark Portable Audio (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-G01-5051-159, Eindhoven, The Netherlands, October 2001

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PHILIPS CONSUMER ELECTRONICS 2001h, Environmental Validation of Flat TV 2.3 Environmental Assessment), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-G01-5051-141, Eindhoven, The Netherlands, November 2001

PHILIPS CONSUMER ELECTRONICS 2001i, Environmental Benchmark Audio Sets (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C01-5051-001, Eindhoven, The Netherlands, December 2001

PHILIPS CONSUMER ELECTRONICS 2001j, Environmental Benchmark TVCR (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-G01-5051-177, Eindhoven, The Netherlands, November 2001

PHILIPS CONSUMER ELECTRONICS 2001k, Environmental Benchmark DVD players (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C01-5051-002, Eindhoven, The Netherlands, December 2001

PHILIPS CONSUMER ELECTRONICS 2001l, Environmental Benchmark DVDs (Green Flagship Selection 2001), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C01-5051-005, Eindhoven, The Netherlands, December 2001

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PHILIPS CONSUMER ELECTRONICS 2002b, Environmental Benchmark DVDR (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-004, Eindhoven, The Netherlands, May 2002

PHILIPS CONSUMER ELECTRONICS 2002c, Quick Scan DVDR, Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-005, Eindhoven, The Netherlands, March 2002

PHILIPS CONSUMER ELECTRONICS 2002d, Environmental Benchmark Audio Sets (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-006, Eindhoven, The Netherlands, March 2002

PHILIPS CONSUMER ELECTRONICS 2002e, Environmental Benchmark (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-, Eindhoven, The Netherlands, 2002

PHILIPS CONSUMER ELECTRONICS 2002f, Environmental Benchmark 15" LCD Monitor (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-007, Eindhoven, The Netherlands, May 2002

PHILIPS CONSUMER ELECTRONICS 2002g, Environmental Benchmark 32" Upmarket TV (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-008, Eindhoven, The Netherlands, May 2002

PHILIPS CONSUMER ELECTRONICS 2002h, Environmental Benchmark 32" High-end TV (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-009, Eindhoven, The Netherlands, May 2002

PHILIPS CONSUMER ELECTRONICS 2002i, Environmental Benchmark 22" CRT Monitor (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051011-, Eindhoven, The Netherlands, September 2002

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PHILIPS CONSUMER ELECTRONICS 2002k, Environmental Validation of Flat TV 2.4, Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-014, Eindhoven, The Netherlands, May 2002

PHILIPS CONSUMER ELECTRONICS 2002l, Environmental Benchmark 17" CRT Monitors (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-015, Eindhoven, The Netherlands, September 2002

PHILIPS CONSUMER ELECTRONICS 2002m, Environmental Benchmark 17" CRT Monitors (Green Flagship Selection 2002), Philips Consumer Electronics, Environmental Competence Centre Document Code AR17-C02-5051-016, Eindhoven, The Netherlands, September 2002

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# *Chapter 6: Design improvement options and alignment*

## 6.1 Summary

In this Chapter 6, the relation and alignment between end-of-life processing and design is discussed. The use of the QWERTY/EE approach in design activities is explained with two screening redesign cases and two detailed redesign cases for the four example products representing the different product types. It will be shown that design plays a limited but not negligible role in improving environmental performance of products in end-of-life. The main improvement options for redesigning products turn out to be enabling of plastic recycling, delivering better fractions in shredding and separation and reducing disassembly time and end-of-life costs. The improvement bandwidth of design is limited due to requirements other than environmental ones, besides the life cycle perspective. Costs, functionality requirements, reliability and safety regulations, marketing constraints, limited development times and supply chain aspects limit the freedom for applying Design for End-of-Life to its full potential. Heavy metals (excluding copper) do not have a high influence or priority, but recovery of precious metals is in some cases highly relevant.

Although the QWERTY/EE approach as such is not primarily developed for design purposes, it will be proven that this methodology for calculating environmental performance of products and end-of-life scenarios is very valuable for determining also the relevance of redesign. The insights where the environmental loss in end-of-life occurs, the contribution of the various processes involved, the information on which materials to prioritise and finally how to evaluate redesigns turns out to be highly valuable. Consequently, it is recommended to incorporate and further develop certain parts of the QWERTY/EE approach for existing Design for End-of-Life tools and for design processes in general. Also the aspect of end-of-life cost predictions on forehand in the design process of products is an important recommendation.

## 6.2 Introduction

### 6.2.3 Backgrounds and objectives

One of the subprojects within the IOP project as mentioned in Chapter 1 is the 'Design for Chemical Content' research of TNO Industrial Technology in cooperation with the TU Delft. This work (Eikelenberg 2003) contains many of the QWERTY evaluations according to the methodology presented in Chapter 3. The results of this work, especially regarding the redesign cases conducted and design rules applied, is summarised in this chapter. However, in contrast to the strict design perspective of (Eikelenberg 2003), the primary focus of this chapter is on the use of the QWERTY methodology within (re)design processes in general and on the quantified determination and evaluation of (re)design priorities in particular. Furthermore this chapter contains the last updates and environmental data on end-of-life processing that were not included in the TNO work. More on this matter is already presented in Chapter 2.7, with the discussion on Life-Cycle Inventories of base metals. The results of the TNO Industrial Technology – TU Delft research will be used to demonstrate the application of QWERTY.

The fifth research question of Chapter 1.2 concerns the role of product design in the end-of-life chain and the resulting improvement potential of design for end-of-life in particular.

Research question 5.

> *What can be the improvement potential of specific design for end-of-life of certain products from an eco-efficiency perspective and what 'design' developments can lead to better alignment with technology and policy?*

In other words, the goal of this chapter is the alignment of design for end-of-life with technology and policy by quantifying and the evaluation of (re)design priorities from an environmental perspective. With this goal it is chosen to primarily apply the environmental perspective. The (re)design activities are aimed at increasing environmental performance of end-of-life treatment. In the use of QWERTY/EE as an evaluation instrument, also the economic performance of redesigned products will be taken into account. The end-of-life costs of the original versus the redesigned products are made explicit in the evaluation. The following aspects will be addressed in this chapter:

1. Design solutions and changes to improve end-of-life performance of the various product categories by decreasing losses in end-of-life treatment.
2. Evaluation and review of the 'design improvement bandwidth'
3. Role of heavy metals in the total Design for End-of-Life approach and specific design solutions.
4. Analysis of the environmental losses due to not preventing primary material extraction, damage to ecosystems and humane toxicity as well as setting design priorities related to this.

### 6.2.2 Position and structure of this chapter

With this chapter the application and alignment area of 'design' with end-of-life treatment will be discussed. The QWERTY/EE approach developed in Chapter 3 and 4 will be applied and linked to the 'design influence' on the environmental and economic performance in end-of-life processing.

In the previous Chapter 5, many technological improvement options were discussed and evaluated. One of the main assumptions and starting points underneath these options was that the products under consideration are suitable for the end-of-life treatment option considered like for instance plastic recycling. This will be clarified in this chapter. In Figure 6.1, the position of this chapter is illustrated.

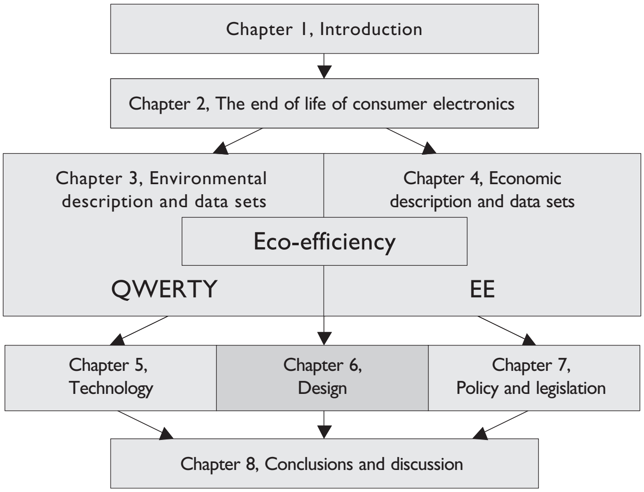



*Figure 6.1 Position of Chapter 6*

In Section 6.3, the application of QWERTY within Design for End-of-Life approaches in general will be discussed. In the Section 6.4 to 6.6 the four example products of Chapter 4 and 5 will be explored from a design perspective. Two of the four examples, the Soundmachine and cellular phone will be used as screening design cases and presented in Section 6.4 and 6.5. These screening cases will not be including evaluation of the redesign options. The other two cases of Section 6.6 and 6.7, the DVD-player and the 17-inch CRT monitor will be very detailed and far-reaching redesign efforts, including detailed QWERTY analysis and evaluation. In Section 6.8 discussion on the results will take place. Finally in Section 6.9, conclusions will be drawn.

### 6.2.3 Assumptions and boundary conditions

Some of the assumptions applicable for Chapter 5, are also relevant for this Chapter and repeated below:

1. State-of-the-art recycling is based on current shredding and separation technologies as earlier presented in Chapter 2.4.
2. End-of-life processing data is representing the Dutch take-back system.
3. Costs for consumers for handing in products are excluded from the integral costs unless stated otherwise.
4. Chemical analysis of the PWBs is performed on the two example products of Section 6.6 and 6.7 as well as a complete list of components and subassemblies

5. The Eco-Indicator '99, Philips Best-Estimate, Hierarchic Perspective, Average Weighting set, with a weighting factor Resource Depletion – Minerals adjusted to 5%, is used as a default environmental assessment model (see Chapter 3.4.2).
6. For all examples, the fractions sent to a subsequent process meet the acceptance criteria applicable for this process, unless stated otherwise.

A few additional assumptions and criteria are relevant for the design part:

7. Redesign activities **may not lead to an increase in the environmental burden over the life cycle**. This means for instance that for material selection, the combined environmental burden over raw material extraction, manufacturing and production and end-of-life may not increase and for the use phase it means that energy consumption may not be increased due to for instance changing component selection.
8. Redesign options and solutions must not lead to exceptional extra costs in the production phase. Extra costs due to design as such, as well as the corresponding redesign options fall out of the scope of this chapter. In this chapter, costs of design and manufacturing of the redesign proposals is not determined quantitatively. One exception to this are the disassembly times.
9. Product lifetime is not altered with the redesign activities. Optimal product lifetime considerations like in (van Nes 2003) are out of the scope of this thesis.
10. Redesign options should not jeopardise reliability of products nor decrease functionality requirements.

In this chapter, the term 'design' must be regarded as incremental product design and not as system design or radical changing functionality. These broader aspects mostly are not specifically end-of-life or environmentally driven, but by changing demands for functionality and by technological developments in general. All redesign options and strategies not fulfilling the above criteria are excluded from the evaluation and priority setting for this incremental design.

## 6.3 QWERTY/EE and Design for End-of-life methodology

### 6.3.1 Design approaches

Many different design approaches and abbreviations exists with respect to the incorporation of end-of-life aspects of products with many different abbreviations: Design for Recycling (DfR), Design for Chemical Content (DfCC), Design for Heavy Metals (DfHM), Design for Disassembly (DfD), Design for Non-Disassembly (DFND), etc. In this thesis however it is chosen to use Design for End-of-Life (DFEOL) as a more comprehensive term for optimising the environmental performance of products in their end-of-life phase (Mathieux 2001, Rose 2001, van Nes 2003).

In this chapter the DfCC procedure of (Eikelenberg 2003) procedure contains special focus on the use of heavy metals and the chemical content in general, is followed for the redesign cases. The procedure is displayed in the next Figure 6.2. The aim of the procedure is to enable from a design perspective where the bottlenecks are in current product design and to generate redesign options.

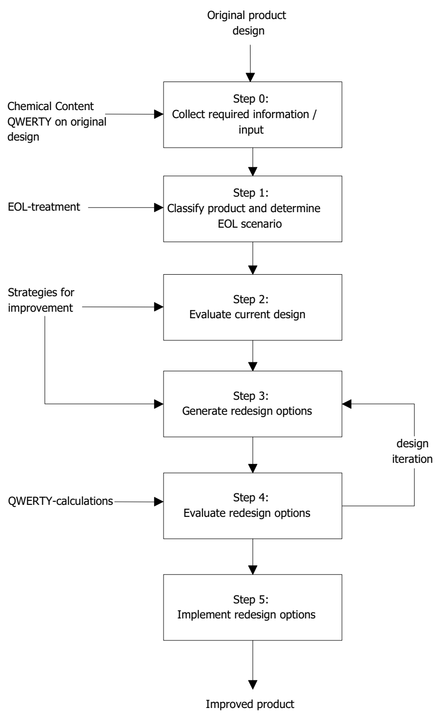



*Figure 6.2 DfCC approach*

The first two steps in the procedure are covered with the information already available in this thesis in the previous chapters. The steps 2 till 5 are indirectly described in Section 6.3.3 and further. The particular role of the QWERTY concept in the above approach is mentioned in Section 6.3.2.

### 6.3.2 QWERTY analysis in redesign activities

In Figure 6.3, the best case, worst and actual state-of-the-art recycling are displayed for the environmental impacts of the DVD player from Chapter 5.5. This graph is presented again to demonstrate what the effects of redesigning a product should be. The following three points are important guidelines for redesigning a product.

1. The aim of design from an environmental perspective is not only to recover maximum environmental value at end-of-life, at the same time also the environmental value connected to the materials within the product in the manufacturing stage should be decreased. This is an important principle, while it should be prevented that recycling percentages, either on a weight basis, or on a QWERTY basis are increased by 'adding more environmental value' into products at the beginning of the life cycle. Such an activity would lead to overall increases of environmental impacts over the life cycle. Therefore the first arrow in Figure 6.3 is directed upwards: The total environmental value of the materials compositions should be decreased.

2. The second arrow represents the second important notice. When a redesigned product is not recycled, the environmental impacts must not increase as well. Therefore, the environmental value connected to the 'worst case scenario' should be decreased as well for instance by avoiding the use of toxic materials.
3. The third arrow shows that a redesign action should lead to minimising the gap between maximum environmental value to be recovered and the actual performance of product in the recycling scenario under consideration.

The result of a successful redesign activity should comply with these three conditions at the same time and not only to one or two of them, in order to prevent higher environmental impacts of products that were redesigned for an environmental point of view. In this respect, Figure 6.3 is crucial for the evaluation of redesign cases.

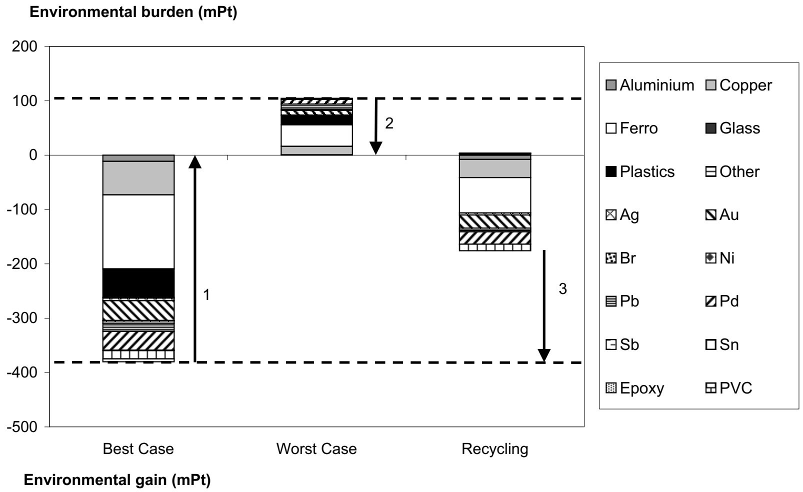
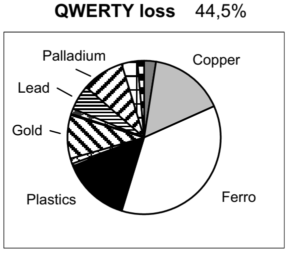



*Figure 6.3 Desired redesign directions*

However, in order to determine priorities for redesigning products, other environmental information is needed like the loss of environmental value between the first and the third bar in Figure 6.3. This is also earlier addressed like in Chapter 5.5, Figure 5.4. In the next Figure 6.4 this graph is presented again.




Contributions:

| | |
|---|---|
| Ferro | 14,7% |
| Plastics | 11,5% |
| Copper | 5,8% |
| Au | 3,1% |
| Pd | 2,9% |
| Pb | 2,5% |
| Zn | 1,1% |
| Sn | 1,0% |
| Aluminium | 0,7% |

*Figure 6.4 Main losses in QWERTY value for the DVD player*

From this Figure 6.4 the main environmental losses between the first bar and the end-of-life scenario of the third bar of Figure 6.3 are obtained. Note that the losses are total losses from the point of discarding of the product allocated on the different materials. This includes the losses of materials to the wrong fractions, emissions, energy consumption of shredding and separation, but also the effects of transport and collection, which were allocated on all materials. The use of a graph like Figure 6.4 is to determine quickly which materials to prioritise at the start of the redesign activity and does not only show the losses in shredding and separation and secondary material processing, but all environmental impacts. The environmental calculations should be used in detail for determining the relevance of every redesign option at the beginning of the redesign activity.

### 6.3.3 Main design strategies

Based on a quick QWERTY analysis, there are three main strategies to apply in order to increase the amount of materials in the right fractions and to reduce emissions of the environmentally relevant substances including heavy metals. The three main strategies relevant in this thesis are derived from (Eikelenberg 2003):

1. Reduce or replace the amount of critical and undesired materials like penalty elements and hazardous substances. This strategy incorporates volume and weight reduction where possible. Furthermore the use of heavy metals should be avoided when components with less toxic substances are available. Also alloys containing toxic or disturbing elements for further processing should be prevented where possible. In Chapter 7.8, with the example of lead-free soldering this will be further discussed.
2. Reallocate materials. With proper reallocation of materials cleaner fractions can be obtained. Based on analysis of problem areas within the product under investigations, in some cases reconfiguring of components of assemblies might be a option.
3. Improve the unlocking properties of parts and components. Both for shredding and separation as for disassembly, the unlocking properties of materials and components play an important role. The changes of materials appearing in the 'wrong' fractions can be decreased by changing product architecture in general and by changing types, sizes or form of the connections between components or assemblies involved.

### 6.3.4 Redesign options

From the main design strategies, generic design options can be derived. A detailed list of these design guidelines is derived from (Eikelenberg 2003, Deckers 1998a,b, van Hemel 1997, Huisman 2000a, Huisman 2002a, Huisman 2003a, Langerak 1997, Mathieux 2001) and displayed in Appendix 5. The list of rules is very generic. In the actual cases of this chapter, they will be applied and evaluated on their relevance and potential for the various example products. From this list some of the most important guidelines are substracted and presented in Table 6.1.

| Nr. | Design Rule |
|---|---|
| 1 | Decrease disassembly times |
| 2 | If use of compatible materials is impossible, make easy to disassemble modules which each consist of compatible materials (disassembly steps quickly uneconomical in case of consumer electronics, but sometimes possible) |
| 3 | Place modules that need to be disassembled in the outer areas of the product and make them easy to disassemble |
| 4 | Replace components by alternatives with higher recycling value or a low amount of penalty elements |
| 5 | Select a switching power supply, use power supplies and motors with improved unlocking performance of the copper winding and iron core |
| 6 | Do not use metal inserts in large plastic parts |
| 7 | Do not attach buttons, windows, doors etc. to the housing or front if they are not made of the same material |
| 8 | Concentrate material groups in easily separable or separate assemblies of the product |
| 9 | Use the same plastic for housing, front and brackets |
| 10 | Do not attach components made of a material mix (e.g. PWB's) to parts made of mono material larger than 50 g. |
| 11 | Heavy metal coatings should not be used |
| 12 | Improve separation characteristics like magnetism, electric conductivity |
| 13 | If you use different plastics for large plastic parts, the difference in specific density should be larger than 0.1 kg/dm3, e.g. PP with ABS |
| 14 | Use magnetic metal fixtures when parts of different plastics (e.g. housing) are connected |
| 15 | If screws are necessary, use bridle screws made out of the same plastic |
| 16 | Use form enclosures rather than screws |
| 17 | Avoid connections between heavy metals and steel or plastic |

*Table 6.1 Most relevant design rules and guidelines*

The generic design rules and guidelines will be applied on a number of screening design cases in the next Section 6.4. In this section examples will be presented on applying the design procedure of Figure 6.2 including the determination of redesign priorities and evaluation with the QWERTY approach as presented in Figure 6.3 and 6.4 as well as the application of design rules like in Table 6.1. The screening cases are applied on one example product for the four product categories. After this section, two detailed redesign cases will be presented on two example products that were already discussed in the previous chapter.

### 6.3.5 Detailed QWERTY analysis and design evaluation

The methodology developed in Chapter 3 and earlier displayed for the Soundmachine example in Chapter 3.5 is applied here on the DVD player. In Figure 6.5 the detailed analysis of the role of different materials in the selected end-of-life scenario is displayed. This graph is both very useful for the step 0 and the step 4 of the DfCC procedure of Figure 6.2. It is a more detailed representation of the difference between the first and the third bar of Figure 6.3.

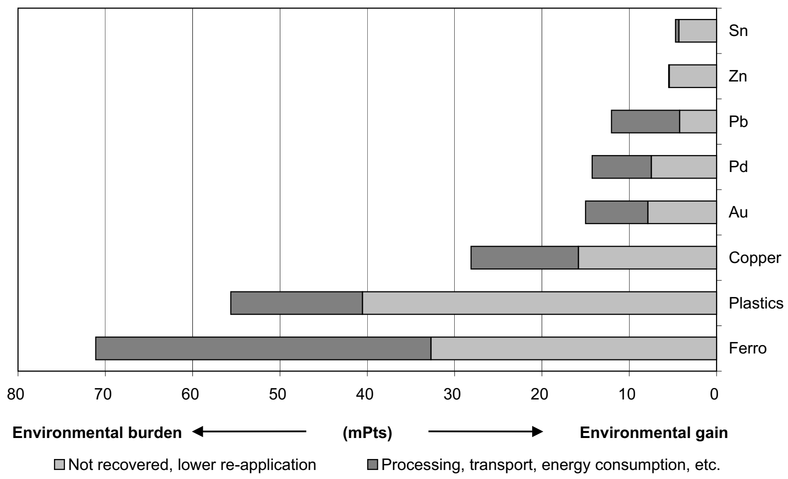



*Figure 6.5 Detailed analysis of losses for the different materials*

In Figure 6.5, environmental impacts are to the left. The left part of the bars show (more or less) inevitable environmental burdening due to processing itself. The right parts of the bars are due to materials not recovered or with a much lower level of re-application, which can be improved by creating better fractions or separation characteristics. This partly falls in the improvement scope of the designer The left part of the bars is displaying the non-recovered environmental value of the corresponding material. This is for some materials including the grade function representing a lower degree of re-application of the material. The aim of Figure 6.5 is twofold. It can be used on forehand in a detailed analysis of the environmental losses connected to the different materials. It can also be used afterwards in evaluation of the redesign effort in verifying whether really a reduction in environmental loss is realised for the materials involved. Figure 6.5 only partly displays this origin of loss of environmental value for the example DVD player.

The emissions of the transport and collection stage are out of the influence area of the designer, except for the size and volume of the products. Thus, besides the losses connected or allocated on the different materials, also insight in the environmental gain and burden per process are necessary in order to derive detailed information on the role of the end-of-life processes and stages involved. In fact, not only the environmental loss as displayed in Figure 6.5, but also the environmental gain due to material recovery is useful information.

In Figure 6.6, this role of the end-of-life processes involved per material is displayed. Environmental gain by recovering environmental value is on the right side in this graph. Figure 6.6 displays the third bar of Figure 6.3 in terms of contributions of processes to the environmental value involved. The aim of the redesign effort is to increase the third arrow in Figure 6.3. Therefore, the following graph is applicable in the evaluation of this direction. Comparing Figure 6.6 for the original design with the redesign should lead to a move in the direction to the right part of Figure 6.6. The graph can also be applied in the first steps of the DfCC approach when not enough knowledge or information is available to select the right design avenues. Figure 6.6 shows that the copper smelter contributes the most to the environmental performance, followed by the ferro smelter and incineration with energy recovery of the plastics. Design should be focused on creating an ideal copper fraction in environmental terms in the first place, thereafter on optimising the performance of the treatment of the ferro smelter and the behaviour of the plastic at incineration.

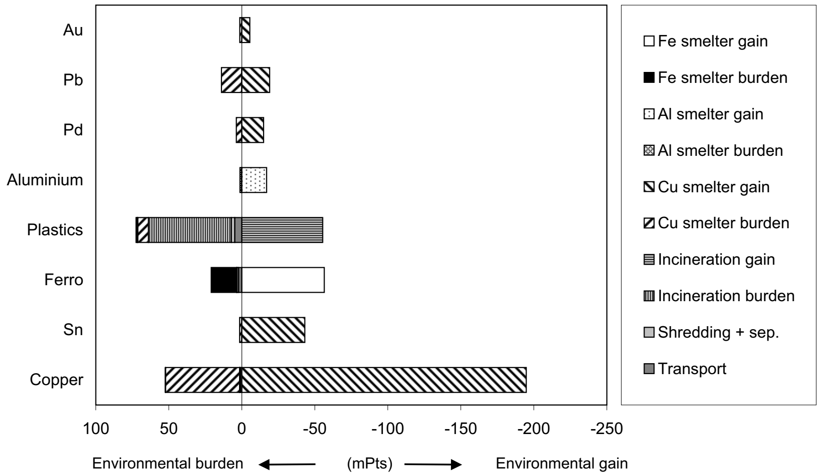



*Figure 6.6 Environmental analysis of the processes contributions DVD player*

## 6.4 Screening redesign case of a plastic dominated product

### 6.4.1 QWERTY analysis

The first screening case is the plastic dominated Soundmachine from Chapter 4.5. For this product the detailed QWERTY analysis and the first steps of Figure 6.2 are conducted. This 'screening' design case in not actually redesigned. Under the state-of-the-art recycling scenario, the following QWERTY loss values are derived as displayed in Figure 6.7. The fraction compositions of this product in state-of-the-art recycling were already discussed in Figure 5.2 of Chapter 5.3. The plastics and copper cause the main losses in end-of-life treatment.

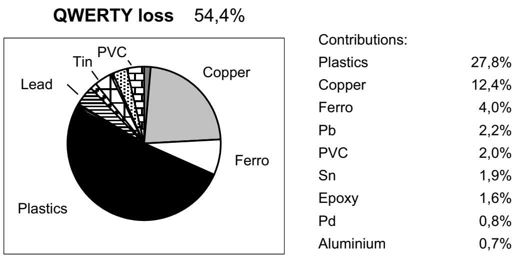



*Figure 6.7 QWERTY losses for the Soundmachine*

The question is however, whether the losses of Figure 6.7 are caused by inevitable environmental burden of processing or by not recovering environmental value of materials. Therefore, the environmental loss caused by the difference between the best case – full recovery of environmental material value and the selected end-of-life scenario is displayed in Figure 6.8.

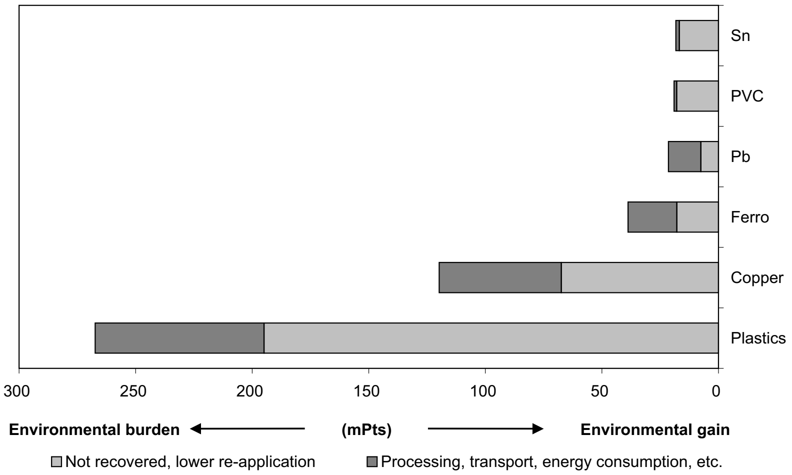



*Figure 6.8 Loss of environmental value for the Soundmachine*

Figure 6.8 shows that the main cause of the QWERTY loss is primarily originating from non-recovering environmental value of copper and plastics and secondly for environmental burden of processing including emissions. The role of the various processes involved, analogue to Figure 6.6, is displayed for the Soundmachine in Figure 6.9. This picture shows the contributions and relevance of the various processes to the third bar of Figure 6.3.

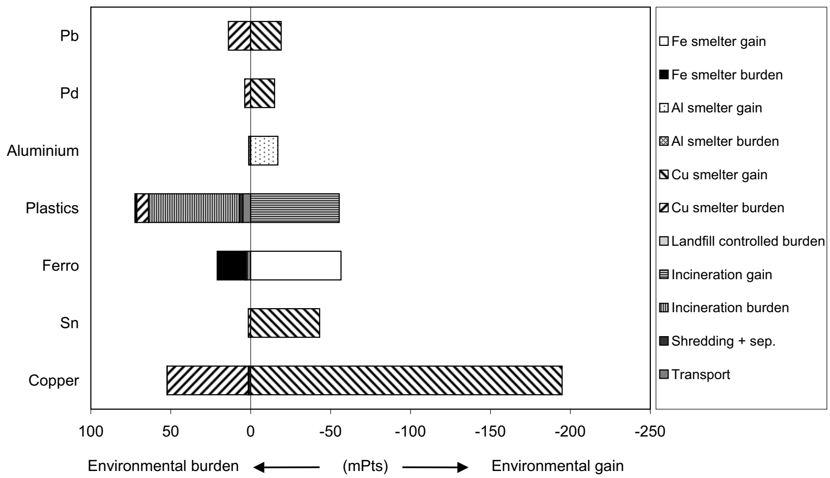



*Figure 6.9 Role of end-of-life processes for the Soundmachine*

Figure 6.9 shows the relative importance of the various end-of-life processes involved. The copper smelter is very important for the recovery of environmental value of copper and tin. The incineration with energy recovery is important for the plastics in the residue fraction. See also Figure 3.9 in Chapter 3.5.5.

### 6.4.2 Redesign priorities and options

From the Figure 6.7 to 6.9, the following two main design avenues for the Soundmachine are derived (Philips 2001e, Eikelenberg 2003, Langerak 1997):

1. Plastics are not recycled while too many impurities, like metals, coatings, stickers and too many types of plastics are used. The specific problems for this product are:
   a. Parts are made of two different plastic
   b. The housings, control panel and logos appear to be metal coated.
   c. All PWBs and other parts are attached to the housings with metal screws.
   d. A very large amount of screws is used (and also many different types), leading to a high disassembly time if plastic recycling would be applied.
   e. In the plastic housing metal speaker covers are fixed.
2. Copper is partly ending-up in the residue fraction due to the fact that all PWBs are attached to the housing and other parts, in shredding and separation some copper – plastic combinations are not appearing in the copper fraction.

In line with Table 6.1, the following design options are derived for this product (Eikelenberg 2003):

1. Use more of the same plastic, where possible and do not attach any other materials to the plastic.
2. Use plastic screws instead of metal screws.
3. Replace metal speaker covers by plastic ones or do not fix the metal covers to the housing (form closure, if housing breaks, covers will be released).

4. Try to fix parts with form closures or snappers instead of screws.

When the above design rules are followed then it is easier to apply plastic recycling of medium sized housings as earlier described in Chapter 5.7 and Figure 5.28 (right group of points representing plastic recycling of medium sized housings). In fact, due to the decrease in disassembly time the eco-efficiency direction would be less 'downwards'. From an environmental perspective the size of the copper and especially the plastic bar of Figure 6.9 would be more to the right (higher environmental gain). In terms of 'alignment' of design and end-of-life processing: the suggested redesign options are leading to increased environmental performance by better separation of materials under current state-of-the-art recycling conditions but also to better eco-efficiency performance when plastic recycling of medium sized housings would become a more common end-of-life processing activity. The eco-efficiency of plastic recycling of medium sized housings is already discussed in Chapter 5.7.1 and will be further placed in perspective regarding other eco-efficiency directions in Chapter 7.5.

### 6.4.3 Material selection and life cycle perspective

With Figure 6.10, the best case recycling scenarios for all three different types of housings are presented for the Soundmachine (the worst case scenarios are not displayed while no major differences occur here). The first bar represents an plastic housing, the second a steel housing, the third a aluminium housing. The graph shows that for the steel and aluminium housings more environmental value is put into the product (the left three bars in the graph). Much of this value can be recovered under state-of-the-art recycling (the second set of three bars on the right). But still, the difference between the material value of production and this value representing 100% collection and treatment is increasing (the first and fourth bar). It is clear that both the selection for steel as aluminium leads to a higher environmental burden in production. The material deformation processes are neglected in this picture. These values are higher for metal housings (bending, cutting, etc.) compared to plastics (extrusion and injection moulding). Nevertheless, it is known that these values are low in comparison to the material extraction value. Due to the fact that collection rates are far from 100% for products like this, in reality much of this environmental material value is not recovered.

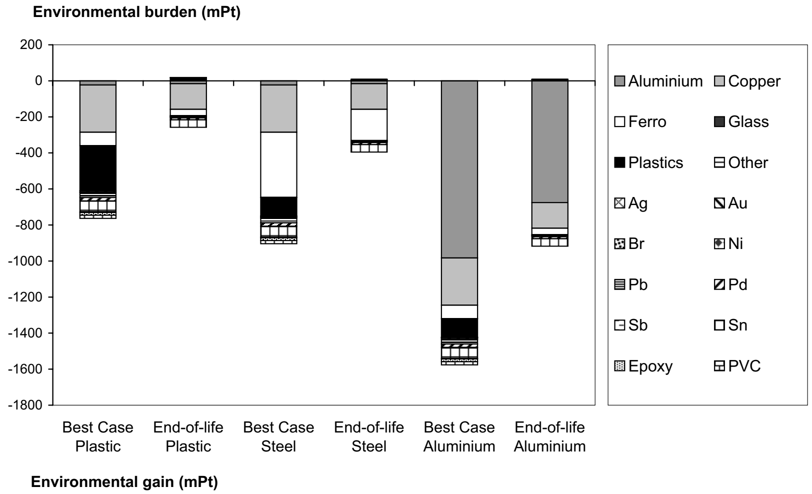



*Figure 6.10 Life-cycle perspective and product design for different Soundmachine housings*

From this it can be concluded that the strategy of replacing plastic housings by steel housings **for instance to increase weight based recyclability**, leads to neglecting of the important life cycle perspective and thus to higher environmental loads. Besides the environmental considerations, also costs considerations turn out negative when plastic housings are replaced by metal housings, which are generally much more expensive. It can be concluded from this example that not only a violation of the important life-cycle perspective takes place but a negative eco-efficient direction as well.

## 6.5 Screening redesign case of a precious metal dominated product

### 6.6 QWERTY analysis

The second screening case is the high-end 2000 cellular phone as earlier discussed in Chapter 5.5. The end-of-life scenario under investigation is the treatment of the cellular phones as a part of the regular browngoods stream and not the separate treatment scenario. The corresponding fraction compositions of this product in state-of-the-art recycling were already discussed in Table 5.11. The battery and adapter were excluded from the QWERTY analysis. Still, they will be shortly mentioned in the design part of Section 6.5.3.

Also for this product, the following QWERTY loss values are derived and displayed in Figure 6.11. The environmental loss in end-of-life treatment is completely dominated by the precious metals.

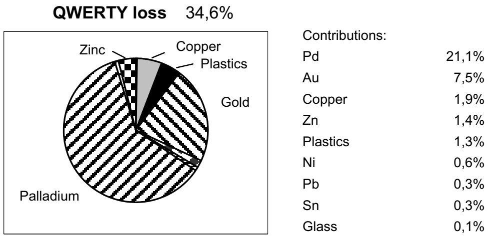



*Figure 6.11 QWERTY losses for the cellular phone*

The question is again, whether the losses connected to the precious metals of Figure 6.11 are caused by inevitable environmental burden of processing and refining, or by not recovering these materials from the right fractions. Therefore, the environmental loss caused by the difference between the best case – full recovery of environmental material value and the selected end-of-life scenario is displayed in Figure 6.12 for the cellular phone.

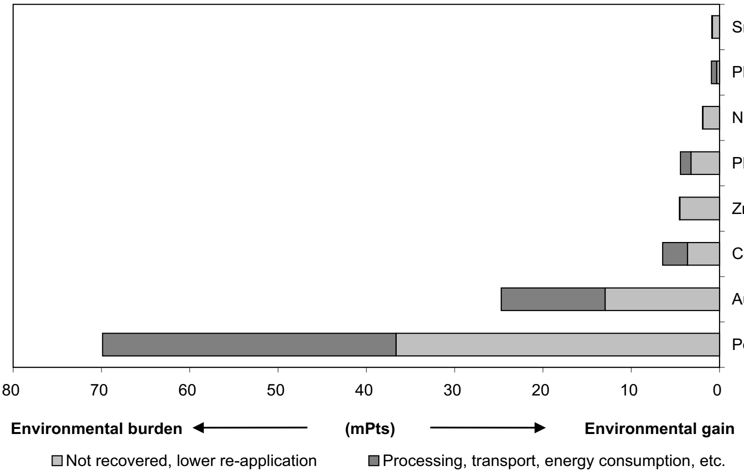



*Figure 6.12 Loss of environmental value for the cellular phone*

Figure 6.12 indicates that the main cause of the QWERTY loss is about equally originating from not recovering environmental value of palladium and gold and from the environmental burden of processing, including emissions and refining of the precious metals at the copper smelter.

The role of the various processes involved, analogue to Figure 6.6, is presented for the cellular phone in Figure 6.13. This picture shows the contributions of the various processes. It demonstrates that only one process is really important for the environmental impacts of treatment of this cellular phone. The copper smelter is the only relevant process for the recovery of environmental value of the precious metals. This leads to the notice that the redesign of the cellular phone should be focused on the fractions going to the copper smelter.

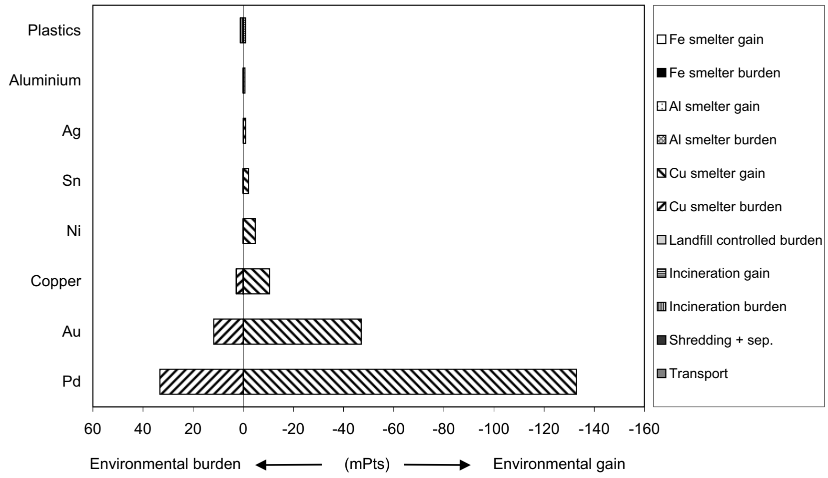



*Figure 6.13 Role of end-of-life processes for the cellular phone*

### 6.5.2 Redesign priorities and options

From the Figure 6.11 to 6.13, the main design avenues for the cellular phone are based on the only relevant priority for in this product: to prevent precious metals to be treated with other fractions than the copper fraction and to optimise the composition of this fraction from an environmental perspective .The single source of the precious metals is the PWB, therefore the following design rules are applicable (Mirec 2002a, Eikelenberg 2003):

1. When the separate collection improvement option in end-of-life processing is applied in the future, then the copper smelter will not accept too much steel in the copper fraction. Consequence is that when the shredding and separation sequence of Figure 2.8 of Chapter 2.4.3 is applied, good separation of the ferro parts must be possible. The subsequent design improvement is: do not attach steel to the PWB, or reduce the amount of steel used to make the fraction directly acceptable for the copper smelter.
2. A similar issue is the presence of aluminium. However is this case, a certain amount of aluminium is appreciated by the copper smelter as a slag former in the metal smelting process itself. However, a structural too high amount, leads to too much slag formation and loss of more valuable materials to the slags. The design improvement in this case is to avoid too much aluminium attached to the PWBs.
3. In case of EMC-shielding, it is recommended to lock metal parts by a form closure instead of screws, so that it will be unlocked when shredded.

Usually, adapters and phones are collected separately as individual products. Therefore, one remark is made regarding the adapters: Use a switching power supply. This will substantially reduce the amount of copper and steel used in the product. The battery of this cellular phone was also excluded from the QWERTY analysis. Batteries are often handed in separately. In case a battery is still present, it must be disassembled, as it is mandatory in the WEEE Directive. As a recommendation, this might give an opportunity to separate other disturbing materials in the same act, thus creating a cleaner fraction directly. If the steel part for instance for EMC shielding, can be separated in the same step, the copper fraction becomes better acceptable and has higher precious metal concentrations.

When the above design rules are followed for the cellular phone then it is made possible to set up a separate system for collecting disposed cellular phones as earlier described in Chapter 5.7.4 and Figure 5.34. This would be applicable on both the high-end cellular phone as the low-end cellular phones in this picture. From an environmental perspective only, the size of the precious metal bars of Figure 6.13 would be more to the right (higher environmental gain).

## 6.6 Detailed redesign case of a glass dominated product

### 6.6.1 QWERTY analysis

The first detailed redesign case is the 17-inch CRT monitor from 2002 as earlier presented in Chapter 5.4. For this example, the complete Design for Chemical Content (DfCC) approach of Figure 6.2 is applied. The end-of-life scenario under investigation is the CRT scenario of Chapter 2.4.3, Figure 2.6. The corresponding fraction compositions of this product in state-of-the-art recycling were already discussed in Table 5.7. In this redesign case, the fraction compositions for this monitor will be evaluated as well in Section 6.6.4. Also for this product, the following QWERTY loss values are derived and displayed in Figure 6.14.

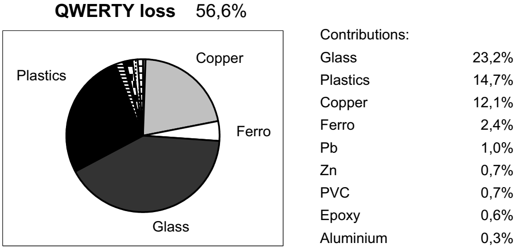



*Figure 6.14 QWERTY losses for the 17-inch CRT monitor*

From Figure 6.14, the main loss in environmental value is mainly related to the glass, the plastics and the copper content. The environmental impact of processing on one hand, an on the other hand the impact of not recovering these materials from the right fractions is visualised in Figure 6.15.

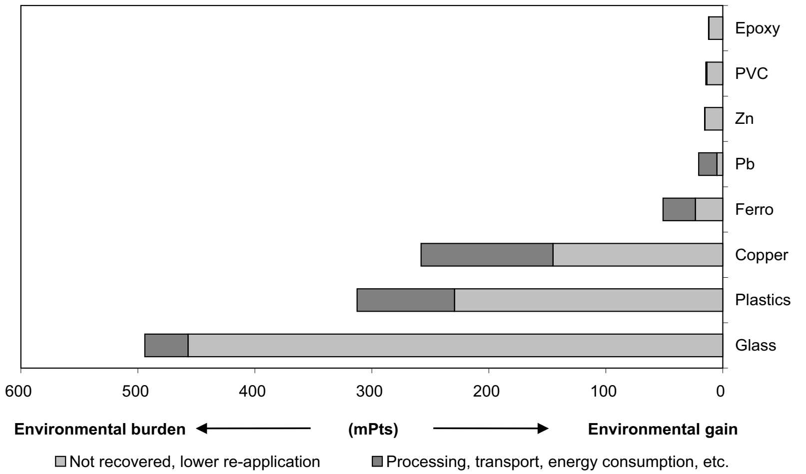



*Figure 6.15 Loss of environmental value for the 17-inch CRT monitor*

Figure 6.15 indicates that the main cause of the QWERTY loss is originating from non-recovering environmental value of glass and plastics. This is obvious, because the state-of-the-art recycling scenario is based on the average amount of CRT glass recycling within the Dutch system (only 15%) and it is also without plastic recycling. The plastic fraction is incinerated with energy recovery. The role of the various processes involved, analogue to Figure 6.6, is presented for the 17-inch CRT monitor in Figure 6.13.

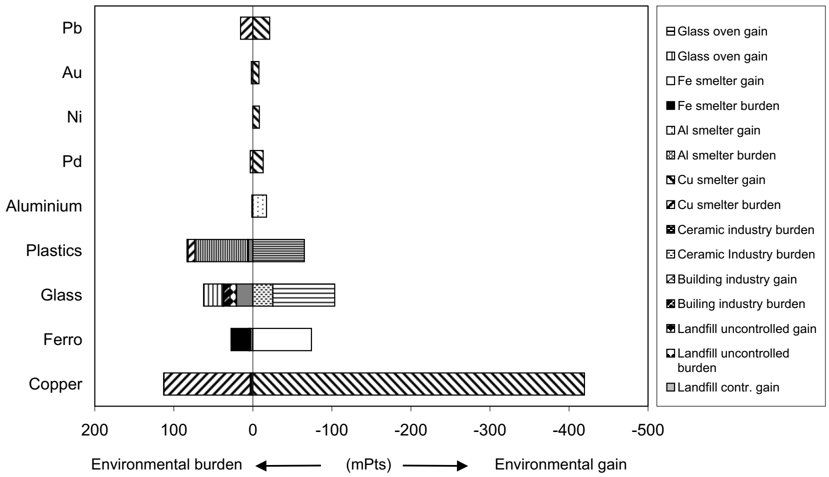



*Figure 6.16 Role of end-of-life processes for the 17-inch CRT monitor*

Due to the contribution of copper, plastics and glass to the environmental loss of this example, respectively the copper smelter, the plastic incineration and the treatment processes for CRT glass (glass furnace, ceramic industry, building industry and landfill) have a significant influence on Figure 6.15.

### 6.6.2 Redesign priorities

From the Figure 6.13 to 6.15, the design priorities and avenues for the 17-inch CRT monitor are derived (Mirec 2002a, Eikelenberg 2003). One important aspect to be discussed on forehand is that CRT glass recycling of CRT-glass is not widely spread. Technically it is possible to recycle screen glass to screen glass and cone glass to cone glass as earlier discussed in Chapter 5.4. The material cycles for CRT glass are not closed due to other reasons than design. Also the rapid growth in sales of flat panels will make it more difficult to deal with a bulk of 'historic glass' towards a probably decreasing demand (Mirec 2002b). Nevertheless, according to Figure 6.15, efforts that make it easier to recycle the glass would improve the eco-efficiency performance as displayed in Chapter 5.4.5.

Besides the QWERTY-analysis also the fraction composition is evaluated based on the preferred and non-preferred materials in end-of-life processing. From Figure 6.13 to 6.15 and this evaluation the following critical components are identified:

1. The front and the back panel of the plastic housing contain flame-retardants due to safety reasons and regulations. Whether the use of flame-retardant is really necessary falls out of the scope of this thesis. Despite this, the separation of the two types of plastic is required for plastic recycling and it also leads to higher costs when recycled.
2. It is important to be able to get a clean CRT glass fraction in glass cleaning processes.
3. A high amount of copper is appearing in the residue fraction and the aluminium fraction. Copper in the residue fraction will be lost. Unlocking properties of copper (and aluminium) parts are general bottlenecks in recycling.
4. In steel recycling, copper is a penalty element and also cannot be recycled. Critical components are motors and transformers.

In addition to the identification of critical parts and components it is very important to make an inventory of connections in the product. Especially connections between materials that need to be directed to different fractions are important. These connections need to break to assure that materials are separated as desired. In current practice however, this often is not the case and particles consisting of several materials appear in the residue fraction or in another fraction. Furthermore, in Chapter 5.4 and 5.7.3 it is showed that disassembly time has a significant influence on the costs of the treatment of glass dominated products. The numbers and types of connections present in the monitor can be found in (Philips 2002l) and (Eikelenberg 2003).

### 6.6.3 Redesign options

For the generation of redesign options the QWERTY priorities, the critical parts and components and the analysis of connections are used. Based on the DfCC approach of Figure 6.2 the following (incremental) redesign options are proposed in (Eikelenberg 2003), specifically for this type of products:.

1. Reduce critical materials or substitute undesired materials with others
   a. Make flame-retardant and non-flame-retardant plastics easy to identify and easy to separate from each other.

   b. Replace the metal strip around CRTs by glass-fibre reinforced plastic, resulting in less change of pollution of the glass fraction.
   c. Use a plug instead of fixed main cord and reuse this cable at recycling.
   d. Replace steel attachments of heat sinks by aluminium.
   e. Reduce the size of the over-dimensioned aluminium heat sinks.
   f. Use plastic screws or form closure to attach PWB to front housing.
2. Reallocate materials or components:
   a. Move monitor control PWB to central PWB instead of fixing it to the plastic housing.
3. Optimise connections
   a. Replace metal brackets of CRT by widgets in plastic housing in order to make disassembly easier and support with icons on the product where to hit.
   b. Create form closures instead of plugs/screws between PWB and steel shield
   c. Form enclosure with back housing to fix the CRT.

The redesign options from above lead to an integrated new design. This redesign will be evaluated in Section 6.6.4. The non-feasible options are excluded from the redesign.

### 6.6.4 Evaluation

The new material composition is used as input for a QWERTY-evaluation. However, the QWERTY-calculation does not take into account the effect of improved connections and reallocation of material in the product to improve separability. The fraction composition of the QWERTY-calculation resulting from the original design is therefore manually adjusted to reflect the improved separability. For each part of which separability will be improved by the redesign the distribution of materials is adjusted. The new fraction compositions then are used as input for calculating the evaluative QWERTY analysis. The adjusted fraction compositions are presented in Table 6.2. This table can be compared with the original table of Chapter 5.4.1, Table 5.7. With this table, for a few metals a better separation is achieved. More of the precious metals are appearing in the copper fraction.

| Fraction | Ferro (g) | Aluminium (g) | Copper (g) | Glass (g) | Plastics (g) | Residu (g) |
|---|---|---|---|---|---|---|
| Aluminium | 0,00 | 40,09 | 8,46 | 0,00 | 0,00 | 0,00 |
| Copper | 6,59 | 44,61 | 729,85 | 0,00 | 0,00 | 111,1 |
| Ferro | 1224 | 0 | 102,74 | 0,00 | 0,00 | 0 |
| Glass | 46,96 | 46,96 | 93,93 | 9158 | 0,00 | 46,96 |
| Plastics | 13,34 | 7,57 | 220,7 | 0,00 | 2193 | 171,8 |
| Ag | 0,000 | 0,000 | 0,163 | 0,000 | 0,000 | 0,000 |
| Au | 0,000 | 0,000 | 0,0098 | 0,000 | 0,000 | 0,0000 |
| Pd | 0,000 | 0,000 | 0,0037 | 0,000 | 0,000 | 0,0000 |
| Other | 0,00 | 1,47 | 122,4 | 123,1 | 58,03 | 80,26 |
| **Fraction Weight** | **1291,0** | **140,7** | **1278,3** | **9280,8** | **2251,2** | **410,2** |
| **Fraction%** | **8,8%** | **1,0%** | **8,7%** | **63,4%** | **15,4%** | **2,8%** |
| Total | | | | | | 14649 |

*Table 6.2 Fraction compositions 17-inch CRT-monitor redesign*

The effect on the total weight and the overall product composition in general is negligible, also because there is no change in amount of environmentally relevant substances. (In the next detailed redesign case, the DVD player this will be different). As a result the change in bandwidth (Figure 6.3) is also negligible. However, the change in fraction compositions should be evaluated, see the third bar of Figure 6.3. This evaluation is done for the Eco-Indicator '99 method and both the default state-of-the-art recycling as the maximum plastic and CRT glass-recycling scenario. The results are presented in Figure 6.17

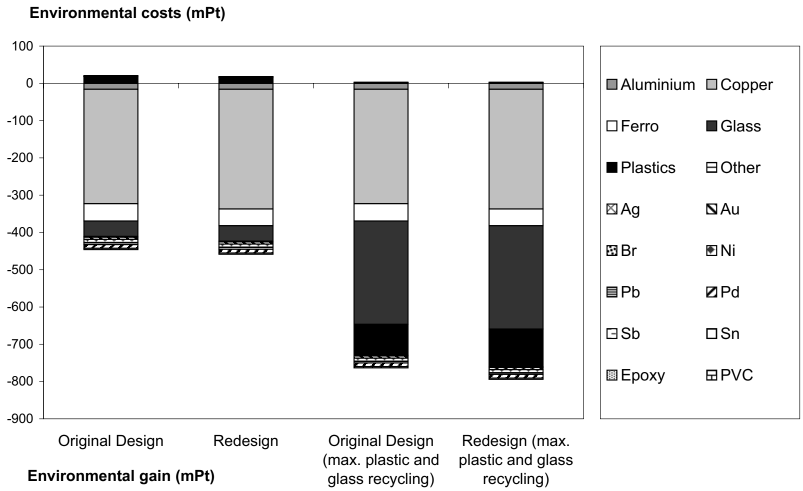



*Figure 6.17 QWERTY Evaluation of the 17-inch CRT monitor redesign (EI'99)*

For the state-of-the-art recycling scenario the increase in recovered environmental value (negative scores) is relatively small for the redesigned product compared to the original design (the first two bars in Figure 6.17). The change in absolute terms is from 425 mPts to 444 mPts (4,3%). The change under the maximum plastic and glass-recycling scenario (see Chapter 5.4 for a description) is also relatively small. This change in absolute terms is from 762 mPts to 796 mPts (4,5%). The reason for this is that the monitor is existing for a relatively long period on the market and is also from a design perspective well developed and therefore an already optimised product.

In order to evaluate the influence of the environmental assessment methods, the same Figure 6.17 is derived for the EDIP'96 method with Figure 6.18.

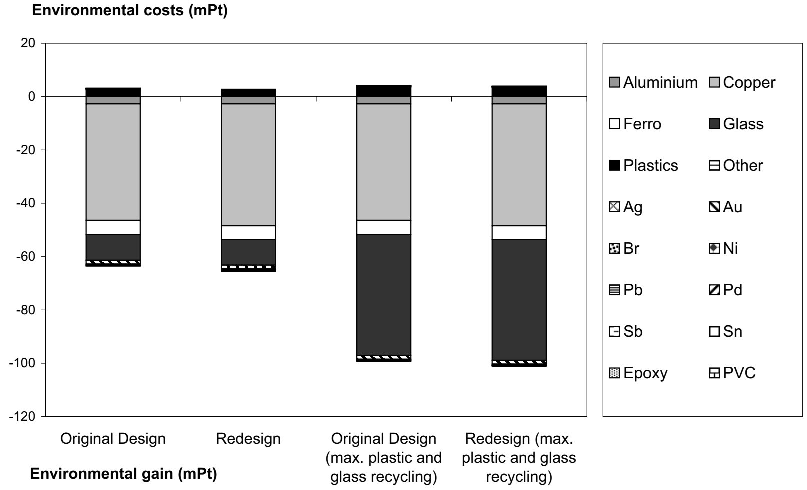



*Figure 6.18 QWERTY Evaluation of the 17-inch CRT monitor redesign (EDIP'96)*

For the state-of-the-art recycling scenario the increase under the EDIP'96 method in recovered environmental value (negative scores) is relatively small for the redesigned product compared to the original design (the first two bars in Figure 6.16). The change in absolute values is from 60,4 Pts to 62,9 mPts (4,1%). This is comparable with the change under the Eco-Indicator '99 method. The change under the maximum plastic and glass-recycling scenario is also relatively small. This change in absolute terms is from 93 Pts to 97,4 mPts (2,3%). This change is smaller than the change under the Eco-Indicator '99 method and is understandable due to the fact that the Eco-Indicator '99 method assigns relatively higher values to the plastics, which is visible from comparing Figure 6.16 and 6.17.

### 6.6.5 Redesign conclusions and discussion 17-inch CRT monitor.

The environmental improvements due to redesign are relatively small. The main reason for this is the fact that the monitor is already a highly optimised product. Since estimations of new fraction compositions have been done conservatively, the influence could be slightly larger. The current calculation sequences of the QWERTY method are not specifically developed for this designer perspective. To be able to evaluate this more accurately, the calculation method needs to take into account the effect of connections between parts of different materials.

An important result also regarding the eco-efficiency approach is the following: The disassembly time of a redesigned 17-inch CRT monitor would be reduced from around 285 seconds to 185 seconds. When the decreased end-of-life costs due to higher recycling are taken into account, the following estimate for end-of-life costs is made.

| Product | End-of-life scenario | End-of-life costs |
|---|---|---|
| Original design | State-of-the-art recycling | € 5,95 |
| Original design | Idem, incl. max glass/plastic recycling | € 6,47 |
| Redesign | State-of-the-art recycling | € 4,86 |
| Redesign | Idem, incl. max glass/plastic recycling | € 5,37 |

*Table 6.3 Change in end-of-life costs for the redesign*

Table 6.3 shows a significant decrease in end-of-life costs for the redesign. These results are only presented in absolute values while they cannot directly be evaluated with the QWERTY/EE concept in the 2D graphs, while the production stage is involved as well. However, it is clear that a small environmental improvement and a significant economic improvement is realised leading to a 'first quadrant' eco-efficiency vector (see Figure 4.4).

## 6.7 Detailed redesign case of a metal dominated product

### 6.7.1 QWERTY analysis

In Figure 6.3 to 6.6, already the QWERTY analysis is made for this DVD player from 2001. The corresponding fraction compositions of this product in state-of-the-art recycling were displayed in Table 5.2 from Chapter 5.3.1. The main conclusions from these graphs are:

1. From Figure 6.4 can be concluded that the main losses are related to the ferro and plastics content.
2. From Figure 6.5 can be concluded that the main environmental losses related to the ferro content are caused by end-of-life processing and not from non-recovery of materials.
3. From Figure 6.6 can be concluded that both the copper as the ferro smelter are the most important processes for treatment this product.

### 6.7.2 Redesign priorities

The design priorities and avenues for the DVD player are derived from (Mirec 2002a, Eikelenberg 2003). Also the fraction compositions of Table 5.2 are evaluated based on preferred and non-preferred materials in the relevant fractions. From this evaluation the following main redesign priorities are identified:

1. Aluminium is used in heat sinks on the PWB. As a result, amounts of both steel and copper are lost to the aluminium fraction. The heat sinks are required for cooling. Probably, the heat loss on the PWB will be reduced in the future, resulting in a lower requirement for cooling.
2. Many connections between different materials are occurring. Connections between steel housing, PWB and plastic parts should be avoided or optimised for shredding and separation.

### 6.7.3 Redesign options

For the generation of redesign options the QWERTY priorities, the critical parts and components and the analysis of connections are used. Based on the DfCC approach of 6.3.3 the following redesign options are proposed.

1. Reduce the volume of materials and substitute undesired materials with others.
   a. Lower the height of inner/bottom panels. Making more ribs can reduce the aluminium cooling rib. The PWB size is the limiting factor in the height. (This is in fact not a Design for End-of-Life rule but a general ecodesign strategy).
   b. Remove the buttons, resulting in a reduction of PWB and plastics. All functions are accessible by the Remote Control.
   c. Remove display to (universal) Remote Control.
   d. Use tray car-insert for CD instead of current CD-unit.
   e. Do not select nickel-containing capacitors (alternatives for Ni-Pd capacitors are based on Sn).
   f. Holes in the PWB must be enlarged, since plastic screws are normally bigger. Around the screws, no components are placed.
2. Reallocate materials or components.
   a. Reallocation of copper clamps on PWB instead of on the steel housing.
   b. Reallocate the plug projection in the housing to prevent clasping during the shredder process.
   c. Enhance the distance between the copper and aluminium components on the PWB where cooling requirements are interfering.
3. Optimise connections.
   a. Use plastic screws between PWB and back panel and between PWB and front panel.
   b. Use snap fasteners for the front panel – PWB connection.
   c. Use a form closure to connect PWB to side panel.
   d. Apply a layer construction for the bottom plate – PWB – CD-unit.

The selected redesign options lead to an integrated new design. This redesign will be evaluated in Section 6.7.4.

### 6.7.4 Evaluation

The new material composition resulting from the redesign is used as input for a QWERTY evaluation. The fraction composition of the QWERTY-calculation resulting from the original design is manually adjusted to reflect the improved separability. For each part of which separability will be improved by the redesign the distribution of materials is adjusted. The altered fraction compositions are presented in Table 6.4. This table can be compared with the original table of Chapter 5.3.1, Table 5.2.

| Fraction | Ferro (g) | Aluminium (g) | Copper (g) | Residu (g) |
|---|---|---|---|---|
| Aluminium | 0,014 | 11,4 | 2,08 | 0,32 |
| Copper | 0,57 | 4,9 | 82 | 9,62 |
| Ferro | 1499 | 15,7 | 20,9 | 32,2 |
| Plastics | 3,92 | 1,97 | 103 | 286 |
| Ag | 0,00 | 0,00 | 0,259 | 0,020 |
| Au | 0,00 | 0,00 | 0,036 | 0,004 |
| Pd | 0,00 | 0,00 | 0,008 | 0,001 |
| Other | 0,206 | 0,571 | 75,5 | 20,6 |
| **Fraction Weight** | **1504,0** | **34,5** | **283,9** | **349,1** |
| **Fraction%** | **69,3%** | **1,6%** | **13,1%** | **16,1%** |
| **Total** | | | | **2171,5** |

*Table 6.4 Fraction compositions DVD player redesign*

The effect on the weight and the product composition in general is not negligible in this case. There is a significant change realised. Thus also the effect on the bandwidth is incorporated in the evaluation. The change in all three bars of Figure 6.3 is evaluated. This evaluation is based on the default Eco-Indicator '99 method and checked on consistency with the EDIP'96 method. The results are presented in Figure 6.19.

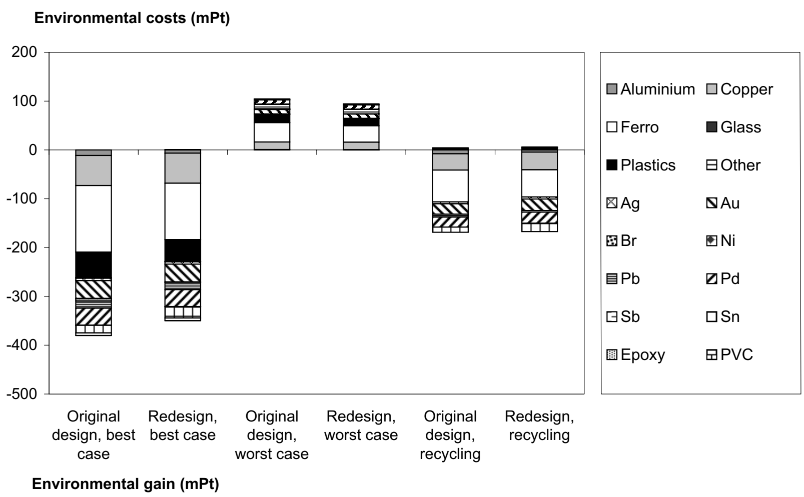



*Figure 6.19 QWERTY Evaluation of the DVD player redesign (EI'99)*

For the state-of-the-art recycling scenario there is a decrease in recovered environmental value compared to the original design (the third set of two bars in Figure 6.19). With this example the importance of Figure 6.3 with the three design strategies appears. The decrease is due to the fact that less material value is 'put into the redesigned product'. The change in absolute values is from 164 mPts to 161 mPts (2% less recovery). The first two bars are a good indication for the reduction in manufacturing load of the product, excluding the environmental value of material deformation and shaping activities like for example extrusion and injection moulding of plastics or bending and cutting for steel. From (Philips Consumer Electronics 2002l) and from checking the relevant values in (Philips Consumer Electronics 2002n) it is known that the difference in environmental value for material operation activities is negligible compared to the material extraction value.

The reduction in bandwidth is from 485 mPts to 443 mPts (8,6%) and is much higher compared to the decrease in absolute environmental values of the considered recycling scenario. This leads to the interesting and contradictive conclusion that a good 'Design for End-of-Life' effort can lead to a lower end-of-life performance of a product in the state-of-the-art recycling scenario. In fact the intended Design for End-of-Life has become a 'Design for Material Application' for this case. For the above example, also the weight based recyclability targets would drop in value for the redesigned products. The redesigned product is less compliant with the WEEE recyclability targets compared to the old product!
In order to evaluate the influence of the above environmental assessment methods on the results, the same Figure 6.20 is calculated for the EDIP'96 method.

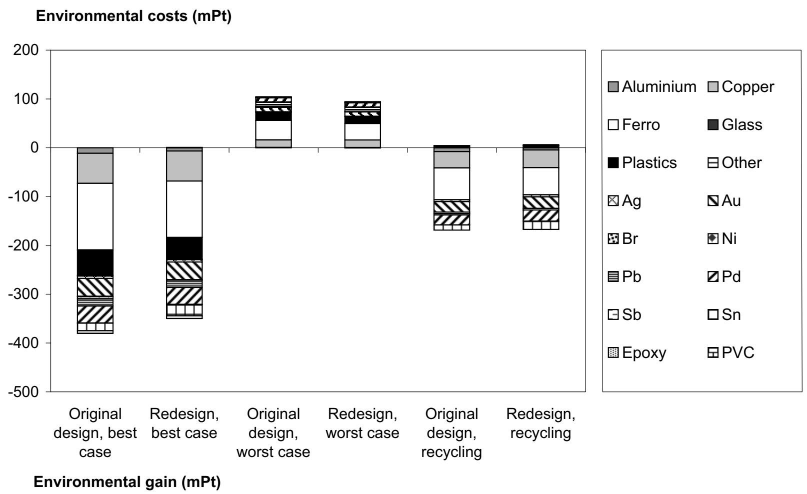



*Figure 6.20 QWERTY Evaluation of the DVD player monitor redesign (EDIP'96)*

Despite the fact that some materials are valued differently when Figure 6.19 and 6.20 are compared, exactly the same trend appears under the EDIP'96 method, supporting the consistency of the redesign results.

### 6.7.5 Redesign conclusions and discussion DVD player

The environmental improvements due to the redesign are much higher than for the 17-inch CRT monitor case. The main reason is probably that the DVD player is a relative new product compared to the monitor. Since estimations of the new fraction compositions have been done conservatively, the influence could also be larger case. Not only the environmental bandwidth is significantly decreased, according to the calculation of end-of-life costs of Table 6.5 (a negative sign means a revenue, a positive sign costs for end-of-life treatment).

| Scenario | End-of-life costs original | End-of-life costs redesign |
|---|---|---|
| Best-case material value | - € 1,80 | - € 1,61 |
| Worst-case material value | € 2,80 | € 2,36 |
| State-of-the-art recycling value | € 0,46 | € 0,33 |

*Table 6.5 End-of-life costs for the redesigned DVD player*

Also in this case a significant decrease in end-of-life costs is obtained. Table 6.5 shows a significant decrease in the end-of-life costs for the redesign as well as a much lower material value put into the product in the manufacturing stage. These results are only presented in absolute values while they cannot directly be evaluated with the QWERTY/EE concept in the 2D graphs, while also the production stage should be considered. However, also in this case, both an environmental improvement and a significant economic improvement is realised leading to the desired 'first quadrant' eco-efficiency vector (see Figure 4.4).

## 6.8 Conclusions and discussion

### 6.8.1 Conclusions: redesign results

The two screening redesign cases and in particular the two detailed redesign cases of this chapter show a limited role of incremental Design for End-of-Life with regard to the improvement of end-of-life performance. The conclusions for the four examples are summarised below:

1. The screening case of the plastic dominated Soundmachine shows that the main improvement areas are increasing the possibility of plastic recycling of the housings and decreasing the disassembly time for this operation. Without these improvements plastic recycling of medium sized housing like these will be even more expensive or even impossible. As will be discussed in the next chapter, the eco-efficiency results for plastic recycling of medium sized housings remains questionable.
2. The screening design case of cellular phone shows the domination of the precious metals. All design efforts should be focused on optimisation of their appearance in the copper fraction. If separate collection of cellular phones would be a common logistic and collection operation, then a few design aspects have to be addressed in order to make this stream acceptable for secondary processing.
3. The environmental improvements of the detailed and, as far as feasible, redesign of the 17-inch CRT monitor are relatively small. The main reason for this is the fact that the monitor is already a highly optimised product. Applying only the feasible redesign options leads not to a change in the best-case – worst-case environmental bandwidth of the product (Figure 6.3). The environmental improvement is around

4% for both environmental assessment methods used. However from a cost perspective, the disassembly time and the end-of-life costs in general for treatment can be reduced significantly, which leads to a positive eco-efficiency.
4. The detailed redesign of the DVD player leads to a small lowered recovery of environmental value. However, the reduction in environmental 'bandwidth' is in absolute values much higher compared to the CRT monitor case for both environmental assessment methods. The remarkable conclusion here is that a successful 'Design for End-of-Life' effort leads to a lower net performance of the product in end-of-life.

The main conclusion of the detailed and incremental redesign efforts of the DVD player and the 17-inch CRT monitor is that the improvement bandwidth of design is limited within given boundaries. Heavy metals (excluding copper) do not a have a high influence or priority in the overall environmental performance in the four cases discussed.

### 6.8.2 The limited improvement bandwidth of Design for End-of-Life

One of the main reasons of the limited environmental improvement with the redesign cases is that the Design for End-of-Life activities are bound to all kinds of restrictions. These restrictions are categorised in environmental restrictions and 'practical' or managerial restrictions. The environmental restrictions are extensively discussed in Section 6.3. The managerial restrictions regarding the design effort for end-of-life purposes are summarised below:

1. Cost aspects are determining. Design solutions that cost more have little chance to be implemented.
2. Functionality and looks: Design changes that affect the looks or functionality in a negative way in the eyes of the designers or marketing department will not be accepted. Often length and depth of products are fixed for fitting products into one product line.
3. Reliability and safety, legal requirements: For instance the obligation to use flame-retardants in covers of TVs and monitors makes plastic recycling currently technically impossible.
4. Development time. The development cycle of many consumer electronics products is so short that a tailor-made Design for End-of-Life evaluation can't be included in the design process. Therefore, experience on this probably has to be collected in 'pilot projects'.
5. Supply chain aspects. Lasting contracts with certain suppliers can limit the selection of 'end-of-life friendly' modules or components.

Despite the very limited degree a designer has for improving end-of-life aspects from an environmental perspective, the examples show that optimising for end-of-life costs can lead to significant improvements. These costs are not directly visible for the producer at the moment, but on the long term with increasing collection of disposed consumer electronics within take-back system paid by the producers themselves, the will certainly have a indirect influence on cost prices of products. The two main avenues for costs decreases in end-of-life are:

1. Optimisation of fractions in order to maximise recovery of economic value.
2. Decrease disassembly time of products that are to be disassembled within current end-of-life treatment and also of the products that are expected to be disassembled in the future. In Chapter 5.6 and 5.7 it is already proven that disassembly times have a significant contribution to the integral end-of-life costs. Furthermore large difference in disassembly times for similar product types is measured for many and many different products. This lead to the indication that there is a large improvement potential for reducing end-of-life costs in the future. It is recommended to producers to further investigate this.

### 6.8.3 QWERTY methodology and the designers perspective

The QWERTY/EE approach as such is not primarily developed from a design perspective. The calculation sequences are for instance not including the products architecture, assembly and disassembly structures and which components and subassemblies are used in a product. In the detailed redesign cases the changes in design to the material, components and fraction compositions are made manually.

Nevertheless, with this chapter it is proven that the QWERTY methodology for determining environmental performance is very useful in determining redesign strategies. The main 'features' are the calculation of the influence and relevance of the various processes involved and which materials to prioritise. Also the evaluation of the redesign results is very valuable. The implementation of streamlined environmental calculations for various end-of-life scenarios is recommended for the development of design tools like Ecoscan-Dare (Korse-Noordhoek 2001). In such tools, it is not possible or desired to apply a traditional and time consuming LCA with very limited room to compare alternatives very quickly. Due to the comprehensive methodology and the environmental descriptions of all relevant end-of-life options, the QWERTY/EE concept can be incorporated resulting in dynamic and very useful results and information. One last recommendation is to further develop the life-cycle check on the redesign results. In the case of a substantial changing material selection, also the full production values of materials including deformation processes etc., should be incorporated. The Figure 6.3 (left bar) should be extended with the environmental value of deformation and shaping processes for materials.

### 6.8.4 Alignment of design and future end-of-life processing

In Section 6.8.1 the conclusion is presented that the detailed redesign efforts of the DVD player and the 17-inch CRT monitor with regard to the improvement bandwidth of design, is very limited. However, some of the options in Chapter 5 who have relatively higher environmental improvement potential are only possible under alignment of design and this end-of-life processing. Also the relation between design and other end-of-life processing like copper smelter processing is relevant. In Chapter 7.8 the example of lead-free soldering and the consequences for the primary and secondary metal cycles will be discussed in further detail. Also the further alignment of fraction compositions resulting from treatment of electronic products will be highlighted.

Furthermore, for design purposes it also very relevant to have accurate descriptions of the end-of-life scenarios applicable for the product under consideration, including the collection rates or percentages that the product is appearing in a certain scenario.
In the next chapter, the alignment of end-of-life processing and legislation, waste policy and system performance as well as the roles of the various stakeholders involved will take place.

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# *Chapter 7: Policy, legislation and take-back system operation*

## 7.1 Summary

In this chapter the QWERTY/EE approach is used for evaluation of policy strategies in general and as proposed in the WEEE and RoHS Directives in particular. The proposed strategies are related to the possible system improvement options outlined in the previous chapters. The main policy strategies are the use of weight based recyclability targets, the minimum collection rates, the restrictions on the use of certain substances and 'outlet and treatment control' rules. These will be further evaluated and put in perspective in this chapter based on positive and negative eco-efficiency directions. Furthermore, directions to be balanced in terms of environmental gain versus extra costs will be indicated. The eco-efficiency directions are based on QWERTY/EE analysis of certain changes in technology or system operation, like CRT glass recycling, or changing collection infrastructures. From this analysis, the following organisation can be made in options to be promoted, options to be avoided and options where environment and costs need to be balanced (see Figure 4.4 and Chapter 4.2.4 for more details).

The eco-efficiency directions to be encouraged, with lower costs (or higher revenues) and increased environmental performance are:

1. Increase collection rates of precious metal dominated products.
2. Separate collection of precious metal dominated products with relatively high precious metal contents.
3. Increase collection rates metal dominated products with high precious metal and low plastic contents.
4. Plastic recycling large sized housings (>2,5 kg, only under Eco-Indicator '99 taking into account resource depletion fossil fuels) and only when disassembly costs are assigned to the removal of picture tubes.

The eco-efficiency directions to be balanced since they involve higher costs (or lower revenues) and increased environmental performance are: (ranked in order of preference):

1. Increase collection rates of metal dominated products.
2. Separate collection of precious metal dominated products with relatively low precious metal content.

3. Increase CRT glass recycling.
4. Increase collection rates of glass-dominated products.
5. Increase collection rates of small plastic dominated products.
6. Dedicated shredding and separation of metal dominated products with low plastic content.
7. Plastic recycling of medium sized housings.
8. Preventing residue fractions with high plastic contents to be sent to the cement industry.
9. Plastic recycling small sized housings (very low environmental return on investment).

The eco-efficiency directions to be avoided are, higher costs, higher environmental burdens:

1. Incineration without energy recovery of plastic and residue fractions.
2. Dedicated shredding and separation of metal dominated products with a relatively high plastic content.
3. Residue fractions with relatively low plastic contents sent to the cement industry.

The eco-efficiency results derived with the QWERTY/EE method appear to be very consistent and not very sensitive to the choice of the underlying environmental assessment method, except for plastic recycling. This is less preferable under other environmental assessment methods not addressing resource depletion of fossil fuels.

The above eco-efficiency directions lead to the following conclusions regarding the main policy strategies for discarded electronic products:

1. Recyclability targets in the WEEE Directive are in too many cases leading to undesired eco-efficiency directions and in a few cases even to lower environmental performance. The current recyclability targets should be abolished completely and replaced by obligatory treatment and by outlet control rules and regulations to derive a more eco-efficient system performance: The greatest eco-efficient improvement potential for take-back system operation lies in outlet control rules, which are also far easier to monitor. The following rules seem rather stringent, but the integral costs involved are expected to be lower in comparison with recyclability targets:
   a. Glass recycling: minimum percentages for CRT glass recycling and re-application in the ceramic industry as well as a maximum landfill percentage.
   b. Plastic recycling and disassembly could be encouraged for large sized housings (>2,5 kg, not containing flame-retardants), but leads to very low environmental returns on investment for medium sized housings (between 1 and 2,5 kg) and should be avoided for small sized housings (<1 kg).
   c. Aluminium, copper and ferro fractions must be sent to their corresponding metal smelters with modern flue gas cleaning processes.
   d. Incineration without energy recovery should be prohibited. Contaminated residue fractions or fractions with low plastics contents should not be incinerated in cement kilns or other incineration plants without appropriate flue gas cleaning.
2. Collection rates should be split per product category. Especially for metal dominated and precious metal dominated products higher percentages should be pre-

scribed and enforced. Collection rates enhancing measures must be applied with precaution in order to avois high costs for collection and logistics, especially for small products.

3. Recyclers should determine when to apply dedicated treatment of metal dominated products, while in this case environmental and economic optimisation is directed equally. No treatment rules are necessary in this case.
4. A separate collection system for precious metal dominated products with precious metal content above certain concentrations should be prescribed or encouraged.

## 7.2 Introduction

### 7.2.1 The four main policy strategies

Already in Chapter 2, the most important policy strategies to come to eco-efficient implementation of the goals of take-back and recycling were mentioned. Most of these strategies are to some extent covered with the WEEE Directive (Commission of the European Communities 2003b) but are by far not the most effective and efficient ones as will be proven in this chapter. The implementation of the directives in national take-back systems must take place before August 2005 with creating national take-back systems by the EU member states individually. In the directives a high emphasis is given on prescribing weight based recyclability targets (WEEE) and also at restrictions for the use of hazardous substances (RoHS). Besides these two strategies, there are two other strategies, which are also explicitly addressed in the directives. At first, a minimum collection rate of 4 kg per inhabitant per annum is prescribed for all product categories together and therefore not specified for the material compositions of the products collected. Secondly, also some very general rules are mentioned for treatment and export of electronic scrap. This includes treatment rules like obligatory disassembly of PWBs and LCD screens above a certain size described in Annex IIa of the WEEE Directive (Commission of the European Communities 2003b). In Appendix 7, more details are presented regarding this Directive. The treatment rules for disassembly of PWBs are not reflecting current 'best practice' recycling operations as described in Chapter 2.4. Moreover, for many products it would lead to very high disassembly times and corresponding costs. The resulting negative eco-efficiency direction can be avoided by proper shredding and separation settings, leading to similar separation characteristics. Therefore, the obligatory treatment rules for PWBs are not in line with increasing take-back system performance. For the remainder of this chapter, this specific treatment rule is disregarded.

It will be shown that the four main strategies from the current perspective need to be revised in order to come to really eco-efficient take-back systems. These main strategies in the WEEE and RoHS Directives are summarised below:

1. Prescribing recycling targets based on minimum weight based percentages to be achieved with end-of-life processing per product category (Commission of the European Communities 2003b).
2. Prescribing minimum collection targets. In the WEEE Directive, only the following collection targets are described per inhabitant per annum: 4 kg (by December 2006).

3. Restrictions on the use of hazardous substances (RoHS), (Commission of the European Communities 2003a).
4. Outlet control of secondary material streams is only indirectly addressed through existing waste treatment rules in Annex IIa of the WEEE Directive. However, a change of the regulations could be considered, indicating which end-of-life routes are allowed and not allowed for treatment of the various fractions resulting from shredding and separation processes. The avoidance of export of scrap to other countries with old-fashioned secondary processing or no processing could also be considered. This also counts for landfill bans for certain fractions.

### 7.2.2 Objectives

The sixth research question from Chapter 1.2 relates to the role of waste policy and legislation as well as take-back system operation. In this chapter, the evaluation of current legislative strategies and how a more eco-efficient balancing of the four main policy strategies is presented.

Research question 6:

*What are main priorities from an eco-efficiency perspective for policy, legislation and take-back system operation in order to increase end-of-life system performance and to enhance further alignment with technology and design? What are the main strategies to increase eco-efficiency in end-of-life treatment and how should these be prioritised?*

In addition to this research question the following (sub)questions per strategy should be answered:

1. Regarding the prescription of recyclability targets:
   a. Are the weight based recyclability targets the right means to improve end-of-life system performance for an environmental perspective and is this strategy also efficient from an economic perspective?
   b. Are these targets in the right balance with other strategies that can be enacted?
   c. Are the prescribed recycling targets unambiguous? Is this weight-based recyclability objective or for instance subject to interpretation by the individual EU member states?
   d. Can weight-based recyclability accurately be measured and monitored in practice for take-back systems in place?
2. Regarding the prescription of collection rates:
   a. Are collection targets the right means to improve end-of-life system performance from an environmental perspective and is this strategy also efficient from an economic viewpoint?
   b. What are the options for collection rate enhancing measures and the corresponding environmental and economic consequences with respect to the logistic part of take-back systems?
   c. Should collection rates be differentiated and prioritised per individual product category?

3. Regarding restrictions on the use of hazardous substances:
   a. Are the restrictions the right means to improve end-of-life system performance from an environmental perspective and is this strategy also efficient from an economic perspective?
   b. What is the influence of the restrictions with regard to the life-cycle perspective?
   c. Are there macro effects in secondary processing to be expected due to changing product compositions?
4. Regarding outlet and treatment requirements:
   a. Which end-of-life routes are to be preferred and can they be prescribed and which routes are not to be preferred for the various fractions involved?
   b. Are export bans or landfill regulations necessary or appropriate?

### 7.2.3 Position and structure of this chapter

In this chapter, the eco-efficiency approach of Chapter 4 will be applied to evaluate the strategies available in increasing take-back system performance. In Section 7.3 a further discussion on the contents of the WEEE Directive is presented. Whereas in Chapter 5 mainly a technical scope is applied and the **performance of single products** are placed in a central position, in this chapter available policy and legislative strategies are reviewed on the improvement options discussed in Chapter 5. The outcomes for multiple products are related to policy strategies which are the most effective and which are suppressing the least preferable and inefficient options. Special attention is given to the use of the 'recyclability targets' strategy and the comparison with the QWERTY definition of Chapter 3 in Section 7.4. In Section 7.5 the results of the eco-efficiency part of the QWERTY/EE method as worked out for many products in Chapter 5, are further discussed. Furthermore they are ranked in terms of eco-efficiency directions to promote or to avoid. In Section 7.6, the balancing of the eco-efficiency directions with the optional policy strategies will be discussed. Subsequently, an important Section 7.7 on the boundary conditions relevant for the policy strategies will be presented. In Section 7.8, a detailed analysis of the restrictions on hazardous substances strategy is performed, including presentation of the results of a case study on the environmental effects of lead-free soldering versus traditional soldering. In Section 7.9, financial analysis of the contributions and consequences for the main stakeholders involved will be presented. The chapter finishes with discussion and conclusions as well as recommendations on the role of policy and the alignment with the design and technology perspectives as earlier presented in Chapter 5 and 6. In Figure 7.1, the position of this chapter in the structure of this thesis is sketched.

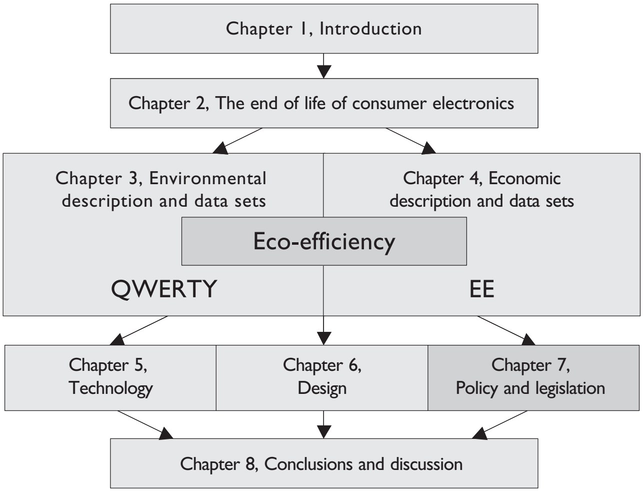


*Figure 7.1 Position of Chapter 7*

### 7.2.4 Assumptions and preconditions

The main assumptions and preconditions relevant for this chapter are repeated below:

1. State-of-the-art recycling is based on current shredding and separation technologies as earlier presented in Chapter 2.4.3. Shredding and separation behavior is based on the distribution tables derived from (Ansems 2002a) and checked by experts from TU Delft Applied Earth Sciences and Mirec (Mirec 2002a).
2. Data is representing the Dutch take-back system.
3. Economies of scale for CRT glass and plastic recycling as well as market matureness for secondary materials leading to representative market prices are assumed to be in place.
4. Costs for consumers for handing in products at a municipality, retailer or other collection point are excluded from the integral costs unless stated otherwise.
5. The state-of-the-art recycling graphs and results are based on treatment of residue fractions in a MSW-incineration plant with energy recovery if not stated otherwise.
6. The Eco-Indicator '99, Philips Best-Estimate, Hierarchic Perspective, Average Weighting set, weighting factor Resource Depletion – Minerals adjusted to 5%, is used as a default environmental assessment model (see Chapter 3.4.2). The main results are checked with the EDIP'96 method as previously introduced in Chapter 2.6.
7. All examples and cases are presented under the assumption that for instance fractions sent to a subsequent processes fall under the acceptance criteria applicable.

## 7.3 Characteristics of the WEEE and RoHS Directives

### 7.3.1 Backgrounds

In 1996 the first starts were made to reduce the amount of hazardous substances in waste and to promote recovery from waste to save resources. From 1998 several draft versions of the WEEE and RoHS Directives were published. In 2002, they passed the Conciliation Committee. In February 2003 they are officially published as EU laws (Commission of the European Communities 2003a,b). The implementation of the WEEE Directive in national take-back systems must take place before August 2005 latest. At that time, producers are obliged to finance collection and treatment for their own products as a consequence of their producer responsibility. Within certain boundaries, each producer is free to fulfil the obligation by joining a collective system or to develop a separate individual system. The Directive also prescribes the necessary information to be given to households: like not to dispose WEEE with MSW, how return and collection systems are operating and where collection points can be found.

### 7.3.2 Restrictions on hazardous substances

The RoHS Directive must be implemented before July 2006. In this directive, the Member States must ensure that no new electronic products are put on the market containing lead, mercury, cadmium, hexavalent chromium, PBBs and PBDEs. A few exceptions like lead oxide in CRT glass and mercury in fluorescent lamps are allowed. For some of these substances maximum allowable concentrations and more extensive descriptions of allowable thresholds are envisaged in the near future. Due to the high potential toxicity values of all the above substances, the restrictions as such are generally regarded as appropriate. However for lead, which is by far the least toxic substance of the list, also other environmental effects due to changing towards lead-free solders appear. The oncoming restrictions already have resulted in a fast change in for instance solder application. The technical development of changing from lead containing solders (Sn60Pb40) towards lead-free soldering (like Sn95Ag3,8Cu0,7) is already in progress for years and is especially in Japan leading to a substantial degree of application in new consumer electronics.

Lead-free solders contain (more) tin, silver and copper that have significant higher resource depletion values than lead. Due to these higher resource depletion values for the alternative materials the question raises whether a violation of the life cycle perspective principle is appearing for lead-free soldering. This specific issue will be discussed in Section 7.8 (Deubzer 2000, Miric 2000, Griese 2000, Turbini 2000).

### 7.3.3 Prescribing recyclability and recovery

The 'recycling' definition used in the WEEE Directive is: 'The reprocessing in a production process of the waste materials for the original purpose or for other purposes, but excluding energy recovery which means the use of combustible waste as a means of generating energy through direct incineration with or without other waste but with recovery of the heat'.

The recovery definition of the WEEE Directive related to the processes described is linked to the 1975 Council Directive on Waste (Commission of the European Communities 1975). The amounts sent to one of the recovery operations described in this Directive are accounted as 'recovered'. Included in the operations are the metal smelters and all operations that use fractions as a way to generate energy. With this definition clearly the cement kiln, incineration with energy recovery and almost all other operations are included except incineration without any energy recovery and landfill options.

The recycling and recovery targets per category are summarised in Table 7.1.

| Product Category | Minimum recycling percentage | Minimum recovery percentage |
|---|---|---|
| Large household | 75% | 80% |
| Small household, tools and toys | 60% | 50% |
| IT equipment | 75% | 65% |
| CRT containing | 75% | 70% |

*Table 7.1 Minimum recycling and recovery percentages in the WEEE Directive*

With the recycling definition it is not clear what is meant with 'waste materials for original purpose'. In Chapter 2 already some possible interpretations of different MRE definitions were given:

1. Material recycling efficiency based on the amount of materials treated by a recycler per total amount collected/ discarded.
2. Material recycling efficiency based on the amount of materials not sent to landfill per total amount of materials collected/ discarded.
3. Material recycling efficiency based on the total amount of materials sent to secondary material processing, which is the weight of the fractions sent to the corresponding processors, e.g. the weight of copper fraction to the copper smelter and the aluminium fraction sent to a aluminium smelter.
4. Material recycling efficiency based on the amount of target materials sent to secondary material processing (the weight of the copper in the copper fraction sent to a copper smelter).
5. Material recycling efficiency including energy recovery based on one of the above definitions including energy recovery: for instance 18% of the combustible waste to be counted as recovered in addition to the amount of materials recovered like in (Ploos van Amstel Milieuconsulting 1997).
6. Material recycling efficiency based on the amounts of materials actually recovered and reapplied in its original form: e.g. the amount of copper and other recoverable materials in the copper fraction multiplied with the average recovery for copper and the other recovered materials at the copper smelter under consideration (this will be further referred to as the strict MRE definition).

Apart from these 6 definitions, other mixed forms between them are imaginable. It seems that the 'recycling definition' as meant in the WEEE Directive comes closest to the third definition, but even then it is still not clear what is meant with 'other purposes'. Is a residue fraction sent to a cement kiln included in one way or another? Is a glass fraction used to replace feldspar in the ceramic industry included or a plastic fraction used in road pavement/ asphalt included or not?

The transposition into national law is left over to the individual Member States. It is feared that different definitions will be used per country. This may lead for instance to unequal positions for recyclers which are in one country allowed to sent glass to a processor with a very low level of reapplication and in another country bound to more strict conditions. This leads distortions in competitions due to differences in costs for secondary treatment. These dissimilar economic positions for different recyclers are in principle not allowed by the EU.

In the Netherlands, the second definition is used till 2002 and reported in the monitoring reports of the NVMP take-back system (De Straat Milieuadviseurs 2002, NVMP 2002a). In all cases, a weight-based definition for recyclability is ineffective regarding the environmental intents of take-back systems. Under the third definition, products will always be accounted as 100% recycled, when collected and treated by a recycler and when the resulting fractions are sent to secondary material processors also addressed as such. When under the definition of secondary processing also the cement kiln, the building industry or other 'low-ranked' processing is included, then a product will very easily be accounted as a 100% recycled. This is obviously in no relation with actual environmental performance.

The most objective definition is the sixth one, addressing only materials really recovered and contributing to closed loops. Besides, the fact that this definition does not address environmental 'reality' it is also just as complicated to handle compared to the QWERTY definition of Chapter 3. The double ensemble issue (see Chapter 2.3.5) must be described and captured in some sort of calculation sequence in order to determine the outcomes for such a weight-based recyclability of single products in complex end-of-life systems. However, still no adequate 'weight based solution' for recyclability can be realised, because the level of re-application cannot be determined on a weight basis. See also Chapter 3.3.4 for this issue.

### 7.3.4 Outlet control and export of scrap

The proposed (unclear) definition and corresponding targets in the WEEE Directive for products in the proposed categories will be very difficult to monitor in practice. Very often, the treatment at recyclers is not performed according to the product categories described in the WEEE Directive but on basis of material compositions of product (streams) of multiple origins. In fact, the environmental and economic values for many products are not determined by the industry association, but by material compositions. Fractions created are often 'enriched' with for instance copper wire for a copper fraction, to derive a minimum and for further processing acceptable copper concentration in the resulting fraction. Only the material content and size of average mixed streams of products can practically be measured on the input side and whether the resulting fractions are sent to an appropriate secondary processor. This indirectly leads to monitoring of outlet channels of recyclers in general instead of monitoring the performance of individual products or even product streams. Whether the recyclability targets strategy is really eco-efficient will be discussed in Section 7.5.

In the WEEE Directive, also the conditions for treatment outside the EU are described. Treatment of waste outside the EU must be proven to take place under equivalent conditions compared to European rules. Further regulations are not presented for instance with regard to the status of secondary material processors. The possible consequences of this will be discussed in Section 7.8 with the example of a modern versus a more old-fashioned smelter. More detailed information, the division of product categories and the definitions used in the WEEE and RoHS Directives can be found in Appendix 7.

## 7.4 Recyclability and recovery targets

### 7.4.1 Introduction

Inevitably, the main policy strategy followed in the WEEE Directive is the use of recyclability targets. In this section, the strategy of prescribing minimum weight based recycling targets is evaluated with respect to the alternative QWERTY definition. Already in Section 7.3.3, it is concluded that:

1. There is no unambiguous weight based recycling definition.
2. Currently, the level of re-application of secondary materials cannot be taken into account in the targets.
3. The targets are leading to different interpretations and resulting definitions per member state.
4. The targets are leading to dissimilar economic positions for recyclers.
5. The targets are leading to monitoring problems. The behavior and compliance of single products within actual take-back system with the prescribe targets cannot (easily) be determined.

In this section, the weight-based definitions are compared with the environmentally based QWERTY definition of Chapter 3 for many examples. In order to allow proper comparison, the 'possible interpretation of the WEEE definition' is replaced with the strict definition already presented in Section 7.3.3 with the definition number 6: Material recycling efficiency is the amounts of materials actually recovered and reapplied in its original form divided by the total product weight.

As a recovery definition, which can also be regarded as the definition number 3 of Section 7.3.3, is chosen: The recovery definition is based on the amount of materials sent to secondary material processing (including the metal smelters, CRT glass and plastic recycling, ceramic industry and excluding cement kiln and building industry).

| Product type | Number | Product Category |
|---|---|---|
| 15" LCD Monitors | 3 | Glass dominated |
| 17" CRT Monitors | 4 | Glass dominated |
| 22" CRT Monitors | 1 | Glass dominated |
| 20" TVs | 1 | Glass dominated |
| 21" TVs | 5 | Glass dominated |
| 28" TVs | 1 | Glass dominated |
| 31" TVs | 1 | Glass dominated |
| Cellular phones (low-end) | 5 | Precious metal dominated |
| Cellular phones (high-end) | 1 | Precious metal dominated |
| DECT phones (cordless) | 4 | Precious metal dominated |
| Fax/ office equipment | 4 | Plastic dominated (high metal content) |
| Audio systems | 7 | Plastic dominated |
| Portable CD players | 5 | Plastic dominated |
| LCD Projectors | 4 | Metal dominated (not glass dominated!) |
| CD recorder | 5 | Metal dominated |
| VCR | 9 | Metal dominated |
| DVD | 18 | Metal dominated |
| DVDR | 7 | Metal dominated |

*Table 7.2 Products considered in this chapter*

The two weight based definitions are compared with the QWERTY definition of Chapter 3 in order to determine whether the definitions show the same results for the directions discussed in the previous section. Subsequently, the optimal eco-efficiency directions are investigated and ranked in Section 7.5. The balancing of the policy strategies in order to acquire optimal and efficient system operation is discussed in Section 7.6. In Table 7.2, all products used in the next sections, are presented again (for more details see also Chapter 5.6, Table 5.14).

### 7.4.2 Products with large sized plastic housings

In Figure 7.2, the results of the three definitions for the Audio systems (Philips Consumer Electronics 1999n) are displayed. In this figure it is shown that the strategy of minimum recyclability targets on a weight basis overvalues the effect of plastic recycling of the large housings in comparison to the QWERTY definition. Under the QWERTY definition, the increase between incineration without energy recovery and with energy recovery is about as large as the difference between plastic recycling and incineration with energy recovery. The effect of energy recovery is not included in the MRE and recovery definitions. The mechanical plastic recycling choice is under all definitions the most favourable. The question remains whether the plastic recycling of these housings is eco-efficient. This will be discussed in Section 7.5.4. However, it is already clear that expensive plastic recycling leads to a significant increase for the weight based definitions, but not for the environmental alternative.

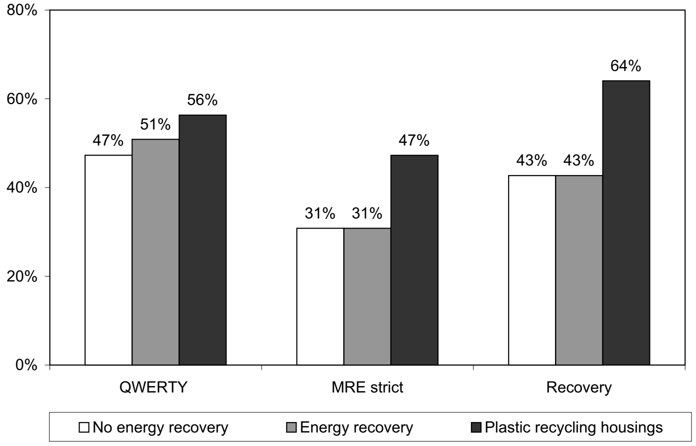


*Figure 7.2 QWERTY versus MRE versus recovery for plastic recycling of Audio Systems*

**7.4.3 Products with medium sized plastic housings**

In Figure 7.3, the results of the calculations for the same definitions are displayed for the fax machines. In this graph it is shown that the strategy of prescribing recyclability on a weight basis again overvalues the effect of plastic recycling in comparison to the QWERTY definition. The graph is almost similar to the previous Figure 7.2.

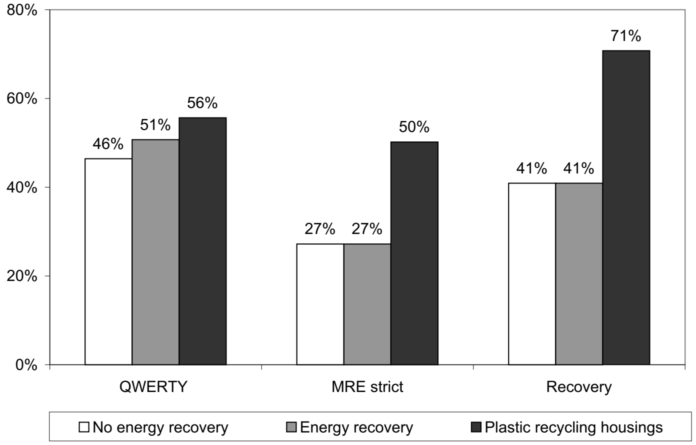


*Figure 7.3 QWERTY versus MRE versus recovery for plastic recycling Fax machines*

Also in this case, under the QWERTY definition, the increase between incineration without energy recovery and with energy recovery is about as large as the difference between plastic recycling and incineration with energy recovery. Still, the plastic recycling choice is under all definitions the most favourable from an environmental perspective. The question remains whether the medium sized plastic recycling of these housings is eco-efficient. This will also be discussed in Section 7.5.4. However, also here, the plastic recycling leads to improved weight based recyclability but does not contribute to this extent to the environmentally based QWERTY scores.

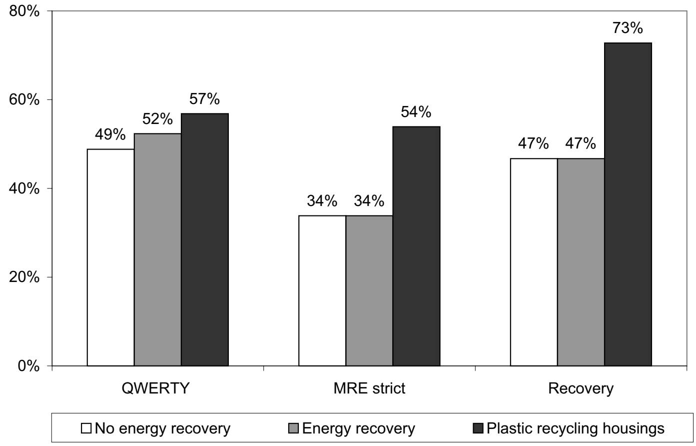


*Figure 7.4 QWERTY versus MRE versus recovery for plastic recycling Portable CD players*

### 7.4.4 Products with small sized plastic housings

In the next graph, displaying the effect of plastic recycling of small sized housings, for the third time a more or less similar graph appears. See Figure 7.4.

The plastic recycling of small sized housings also leads to a better environmental performance. But in order to determine whether this change towards plastic recycling is eco-efficient, the end-of-life costs must be taken into account as well to determine how much environmental improvement is realised against which costs. Figure 7.2 till 7.4 show similar results. However, from an economic and efficiency perspective there are large differences for the various sizes of plastic housings. This will be further discussed in Section 7.6.4. Furthermore, the position of plastic recycling with regard to other eco-efficiency directions will also be considered in more detail.

### 7.4.5 CRT glass recycling

In this section a 21-inch TV is chosen as an example to determine the effect of increasing the CRT glass recycling from 15% current practice to 70% as a technological maximum. The results are displayed in Figure 7.5. The scenarios and underlying assumptions have been previously described in Chapter 5.7.3 and are also shown in Section 7.2.4. An important remark is that only an extended producer responsibility towards the CRT-glass manufactures would lead to increased CRT glass recycling. When applied on a larger scale, also the **decreasing demand and production** for CRTs compared to LCD screens within the European market has to be taken into account. The effect of increased CRT glass recycling is larger than the mechanical plastic recycling of the large housings for all definitions. Note that with applying a less

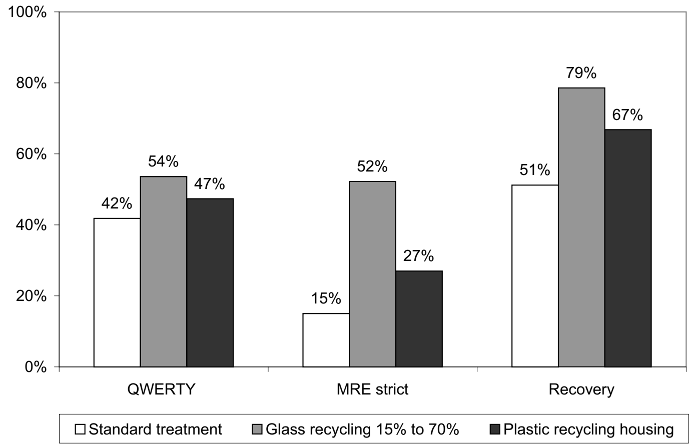


*Figure 7.5 QWERTY versus MRE versus recovery for plastic and CRT glass recycling of 21-inch TVs*

strict definition the effect of downgrading versus CRT glass recycling would be taken into account. Compared to the QWERTY scores, the strict MRE definition also overvalues the CRT glass recycling. However, in this case the difference between the weight based and the QWERTY definition is smaller. Again in this section, the efficiency questions are not answered. This will be done in the Section 7.5.3, with both the calculation of the extra end-of-life costs for plastic recycling and CRT glass recycling for products like this. In Section 7.10.2 more information is presented regarding the boundary conditions of increasing CRT glass recycling.

### 7.4.6 Dedicated shredding and separation

In this section, two different types of metal dominated products will be discussed. The first are the average VCRs sold in 2000. They have a relatively low precious metal content and high plastic content. The second are the average for DVD Recorders sold in 2002 with a relatively high precious metal content and low plastic content. The dedicated shredding and separation settings as presented in Chapter 2.4.3 are applied and the results are compared with the regular shredding and separation settings for these products as part of the regular browngoods stream. The results are introduced in Figure 7.6.

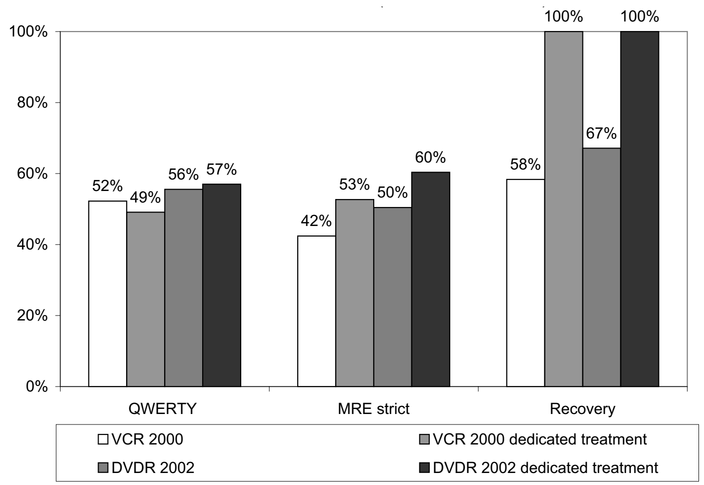


*Figure 7.6 QWERTY versus MRE versus recovery of two metal dominated products*

Figure 7.6 shows very different results for the same operation. From an environmental perspective, the effect of dedicated shredding and separation is negative for the VCR, whereas the MRE shows a higher value. The reason is that no residue fraction is created, which leads to these higher MRE scores. The drop in environmental results is due to much dilution of the precious metals in the copper fraction and from higher emissions at the copper smelter due to more plastics present in the copper fraction. In Chapter 5.7.2 this effect is discussed in more detail.

As a consequence, the recyclability targets do not reflect the underlying negative environmental effects. However, for the DVD Recorders, the result of dedicated shredding and separation is positive both from a MRE as a QWERTY perspective. In this case, the precious metal content is high enough to justify dedicated treatment. This shows that the MRE values are not pointing in the same direction compared to more accurate QWERTY method. Also in this case, the eco-efficiency perspective will be investigated in Chapter 7.5.6. It will be shown there that the environmental recovery and economic optimisation are pointing in the same direction for dedicated treatment.

### 7.4.7 Separate collection

In this section, the comparison is made between separate collection and treatment of cellular phones and plastic recycling of the same housings. In addition to the example of Figure 7.4 also another end-of-life scenario can be compared with the plastic recycling of small plastic housings. The results are visualised in Figure 7.7.

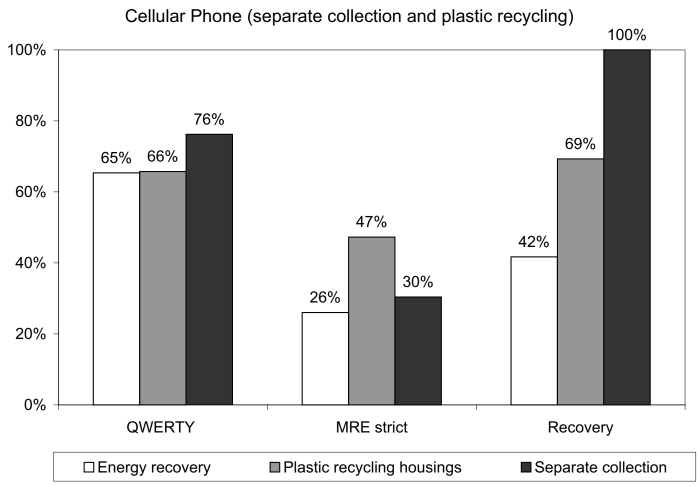


*Figure 7.7 QWERTY versus MRE versus recovery of precious metal dominated products*

Figure 7.7 shows another example of large differences between the environmentally based QWERTY definition and the weight-based MRE and recovery definitions. The separate collection results in higher QWERTY scores compared to the plastic recycling scenario and the treatment together with the regular browngoods stream with energy recovery of the residue fractions. The MRE definition shows the contrary. The precious metals are neglected due to their low weight, but are highly relevant from an environmental and economic perspective. This high contribution of precious metals is earlier presented in Chapter 5.5.2. Plastic recycling is preferred with the MRE definition and the high relevance of the precious metals is completely ignored. When trying to find compliance with the WEEE recyclability targets may lead to a completely wrong focus on the wrong materials, like in (Franz 2002). In Section 7.5.5, these results will be evaluated on their eco-efficiency performance. There it will be demonstrated that with applying separate collection both a significant environmental and economic performance can be realised.

## 7.5 Eco-efficiency directions

### 7.5.1 Introduction

Before discussing the eco-efficiency results of all examples presented in the previous sections, in short the use of the four quadrants of the 2D eco-efficiency graphs is repeated. In Figure 7.8 the eco-efficiency graph of Chapter 4.2, Figure 4.4 is displayed again. The reason for this discussion is, that in order to understand the next sections, the two steps of the eco-efficiency method must be familiar.

At first, four quadrants of the 2D eco-efficiency graph can be distinguished. The graph represents the environmental scores on the X-axis with environmental gain to the right and environmental burden to the left. The Y-axis displays economic revenues (or lower costs) above and (higher) costs below. The graph is intended for determining eco-efficiency **vectors** due to a certain change to the performance of the end-of-life system as a whole. When for example plastic recycling of housings is applied and the resulting vector compared to the original situation without plastic recycling is directed to the first quadrant, a 'positive eco-efficiency' is realised. The opposite counts for the third quadrant. Strategies and directions in such a case should be avoided from both an environmental as an economic standpoint. The first and third quadrant options are clear, the second and fourth quadrant options lead to choices to make.

Secondly, the second quadrant (lower environmental gain, higher revenues) and the fourth quadrant (higher environmental gain, higher costs) need balancing. In both cases, the **quotient** can be calculated and ranked with other options. This shows, besides the size and direction of the eco-efficiency vector how much environmental gain is obtained per amount of money invested (or the opposite). Most of the directions for which the vector approach is applied are fourth quadrant options. In Chapter 5, only one of the end-of-life scenarios selected, leads to the second quadrant effect as will be displayed in Section 7.5.7. When a certain change leading to a vector in the second quadrant is avoided, the result is a fourth quadrant direction and can be treated as such.

For all possible improvement options in the fourth quadrant for end-of-life treatment of consumer electronics in the fourth (and second) quadrant, earlier discussed in Chapter 4 and 5, the absolute millipoints gained versus the extra costs in euros are calculated. These resulting 'mPts per €' can be used to rank the different options available.

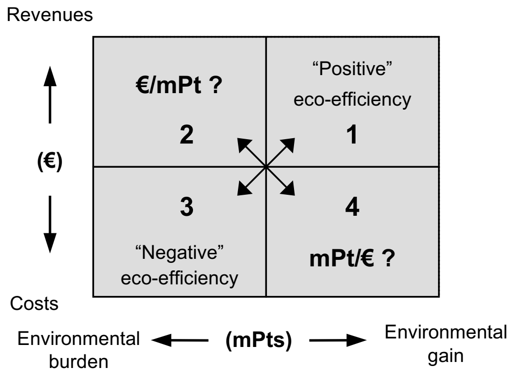


*Figure 7.8 The four eco-efficiency directions*

In order to answer the question which investments or regulations should be prioritised, the main improvement options already discussed in the previous sections are evaluated into more detail in the next sections. The results are used for a comparison with the currently proposed regulations and the four main policy strategies of Section 7.2.2 in general. It will be determined whether these strategies lead to the right directions. The strategies: 'apply weight based recyclability targets', 'increase collection targets' and 'outlet and treatment control rules' are evaluated. The option 'restrictions on hazardous substances' is evaluated separately in Section 7.8.

The following changes and directions earlier presented in Chapter 5 and Section 7.4 are evaluated:

1. The comparison of state-of-the-art recycling versus disposal with MSW streams, which is an evaluation of increasing collection rates for various products. This also leads to conclusions on which products to focus on first in collection. (Section 7.5.2).
2. The effects of increasing CRT glass recycling from 15% to 70% for glass fractions resulting from various products. This is also directly linked to the 'outlet control' strategy. (Section 7.5.3).
3. The effects of increasing mechanical plastic recycling for small, medium and large housings. This can both be enhanced by prescribing recyclability targets as well as with outlet and treatment control regulations (Section 7.5.4).
4. Separate collection of precious metal dominated products. This is directly linked to the prescription of recycling targets and the organisation of take-back systems. (Section 7.5.5).
5. Dedicated shredding and separation of metal dominated products. This is directly related to treatment rules (Section 7.5.6).
6. Energy recovery from residue fractions in MSW incineration compared to the option without energy recovery and the effect of incineration for thermal recovery in a cement kiln. This is also linked to outlet control rules (Section 7.5.7).

In Section 7.2.4, the main assumptions and preconditions are already presented. One important remark is added: The products presented in the next sections are in most cases not single products, but average 'products' representing multiple and comparable products. In Table 7.2, all different products used in the next section, are presented again as average products (for more details see also Chapter 5.6, Table 5.14).

### 7.5.2 Increasing collection rates

In this section the effect of collection versus disposal of products with MSW is discussed. All products presented in Table 7.3, are evaluated. In Table 7.3, all products appearing in the first quadrant (environmental gain and revenue) and fourth quadrant of Figure 7.8 are displayed. In contrast to the graphs in Chapter 5.6 and 5.7, the eco-efficiency is calculated for the change from disposal with MSW towards collection and state-of-the-art treatment. For all (average) products in the upper part of Table 7.2, the environmental gain is higher and the integral costs are less compared to the treatment with MSW. Thus, the result is that increasing collection rates for these products should be promoted from a system performance point of view. Note that of all products investigated, only some of the metal and all precious metal dominated products appear in Table 7.3. The negative sign in the table for the mPts represent environmental gain, the negative sign for the economic result represents an economic revenue. The costs and environmental scores are presented for prevention of disposal with MSW towards state-of-the-art recycling of single products.

| End-of-life treatment versus disposal | | | |
|---|---|---|---|
| **1st quadrant** | **mPt** | **€** | **N.A** |
| VCR 1999 | -374 | -0,25 | |
| DVDR 2002 | -367 | -0,37 | |
| VCR 2000 | -337 | -0,30 | |
| DVD 2001 | -250 | -0,05 | |
| DVD 2002 | -192 | -0,05 | |
| Cell Phones 2000 | -151 | -0,75 | |
| Cellular Phone 1999 | -98 | -0,48 | |
| Cordless Phone 1999 | -67 | -0,23 | |
| **4th quadrant** | **mPt** | **€** | **mPt/€** |
| Fax 1999, average | -479 | 0,15 | -3176 |
| Portable CD player 2000 | -52 | 0,03 | -1610 |
| CD recorder 1999 | -373 | 0,27 | -1374 |
| LCD projector 2000 | -624 | 0,59 | -1063 |
| 28" TV, 2001 | -1003 | 0,99 | -1017 |
| Audio system 1999, energy recovery | -1264 | 1,46 | -868 |
| 21" TV 2002 | -696 | 1,72 | -405 |
| 22" CRT Monitor, 2002 | -1708 | 4,45 | -384 |
| 32" TV 2002 | -1576 | 4,57 | -345 |
| 20" TV 2002 | -543 | 2,53 | -214 |
| Portable audio, 2001, plastic recycling | -316 | 1,50 | -210 |
| 17" CRT Monitor 2002 | -492 | 2,88 | -171 |
| 21"TV 1999 | -449 | 5,48 | -82 |
| 15" LCD Monitor 2002 | -264 | 4,75 | -56 |

*Table 7.3 Products located in the 1st and 4th quadrant, collection and treatment versus disposal*

The second group of products in Table 7.3 is located in the fourth quadrant. From a system performance point of view, investments are necessary to achieve higher environmental gain with collection and treatment compared to disposal with MSW. In Figure 7.9, the environmental scores for these products are presented on the X-axis (with environmental gain to the right) and the products under consideration are displayed on the Y-axis. Note that these products are an average for a group of similar products (See Table 7.2).

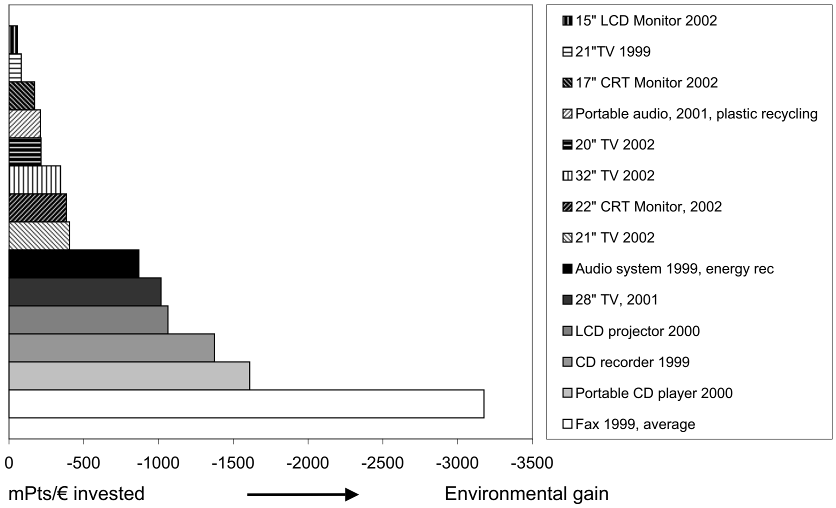


*Figure 7.9 Environmental gain per* **€** *invested for collection and treatment*

Figure 7.9 shows that the metal dominated products have the highest recovery of environmental value under state-of-the-art recycling. The glass and plastic dominated products have the lowest environmental gain in this quadrant per euro invested! In contrast to the ranking of products presented in Chapter 5.9, the above graph is independent of the weight of the product, because the environmental value (in mPts per kg or appliance is divided by the euros invested per kg or appliance). This directly leads to indications on which products to invest first to in terms of collection rate enhancing measures. Combining both Table 7.3 and Figure 7.9 results to the conclusion that enhancing collection rates for precious metal and metal dominated in terms of eco-efficiency should be given priority from a system point of view. Per amount of money invested the highest environmental returns are acquired for metal dominated products, followed by the precious metal dominated and finally by the glass dominated products. The differences between the products for the quotient environmental gain over costs are significant. For the metal dominated products this ranges from 800 – 1600 mPts per euro invested, for almost all glass dominated products this is around 200 – 400 mPts per euro invested. In the next sections there will be elaborated on the ranking of these fourth quadrant options as well as in Figure 4.30 of the conclusions of this chapter.

### 7.5.3 CRT Glass recycling

Already in Chapter 5.7.3, the eco-efficiency of CRT glass recycling is presented in 2D-graphs. All increased glass-recycling options, from 15% average towards 70% on average for the Dutch system, are located in the fourth quadrant of Figure 7.8. For all these cases the environmental gain over the amount of money can be visualised in a similar graph as Figure 7.9. In Figure 7.10, the effects of glass recycling for all different products CRT containing products are displayed. It shows a constant value of around

400 mPts invested for all different products, with screen sizes from 17-inch towards 32-inch and also for both TVs and Monitors. The outcomes clearly show the consistent benefits of an 'outlet' control strategy for glass fractions. Prescribing a minimum amount of glass to be returned to CRT glass furnaces leads to relatively high environmental gains per amount of money invested. In Section 7.6, further discussion will take place on the balancing of the various policy strategies. A few important assumptions are relevant, see Section 7.2.4 and 7.4.5 for this.

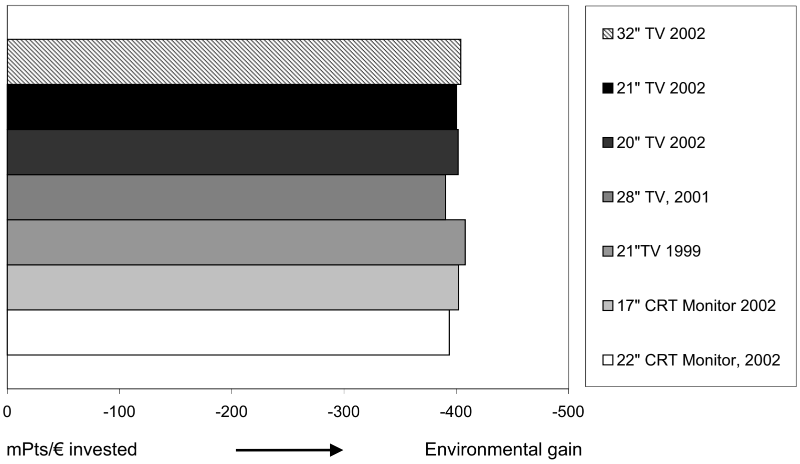


*Figure 7.10 Environmental gain per € invested for increased CRT glass recycling*

### 7.5.4 Plastic recycling

In Chapter 5.7.1 and 5.7.3, the eco-efficiency directions for plastic recycling were already presented. In this section, these results are further discussed. All plastic recycling options for different products within the Dutch state-of-the-art recycling scenario will be discussed, related to their treatment without plastic recycling but including energy recovery from the plastic and residue fractions created. The eco-efficiency options connected to the additional plastic recycling are located in the first quadrant and in the fourth quadrant. The first quadrant results are displayed in Table 7.4. In this table, the largest encasings have the highest environmental gain and economic value recovery under the Eco-Indicator '99 method. Only large encasings from CRT or LCD containing appliances occur appear in this table. This is due to the fact that a comparison is made with a situation of already disassembled housings due to presence of a CRT or LCD screen. Note that an important assumption is that no flame-retardant are present so that plastic recycling is technically possible.

| Plastic recycling | | | |
|---|---|---|---|
| 1 st quadrant | mPt | € | N.A. |
| 32" TV 2002 | -389 | -0,41 | |
| 28" TV, 2001 | -314 | -0,14 | |
| 22" CRT Monitor, 2002 | -208 | -0,28 | |
| 21" TV 2002 | -190 | -0,16 | |
| 21"TV 1999 | -174 | -0,14 | |
| 20" TV 2002 | -104 | -0,09 | |
| 17" CRT Monitor 2002 | -103 | -0,08 | |
| 15" LCD Monitor 2002 | -61 | -0,02 | |
| 4th quadrant | mPt | € | mPt/€ |
| Audio system 1999 | -219,88 | 1,48 | -148,66 |
| Portable audio 2001 | -70,49 | 0,96 | -73,59 |
| Fax 1999, average | -70,49 | 1,76 | -40,02 |
| Portable CD player 2000 | -7,20 | 1,18 | -6,12 |
| Cellular Phone 1999 | -2,11 | 0,59 | -3,57 |
| Cell Phones 2000 | -1,25 | 0,60 | -2,09 |
| Cordless Phone 1999 | -1,08 | 0,60 | -1,82 |

*Table 7.4 Products with a positive eco-efficiency due plastic recycling*

All large, medium and small sized plastic housings, for which disassembly time is required, are located in the fourth quadrant of Figure 7.8 and are shown in Figure 7.11. From this graph, with again higher environmental value recovery to the right, the trend is clear: The smaller the plastic housing, the lower the environmental gain per amount of money invested. The lowest bar (highest environmental gain) of Figure 7.5 is the plastic recycling of a large housing of an audio system. The two bars above are for medium sized housings and for the smallest housings from a portable CD player, from the cordless and cellular phones, the environmental return per euro invested is almost zero.

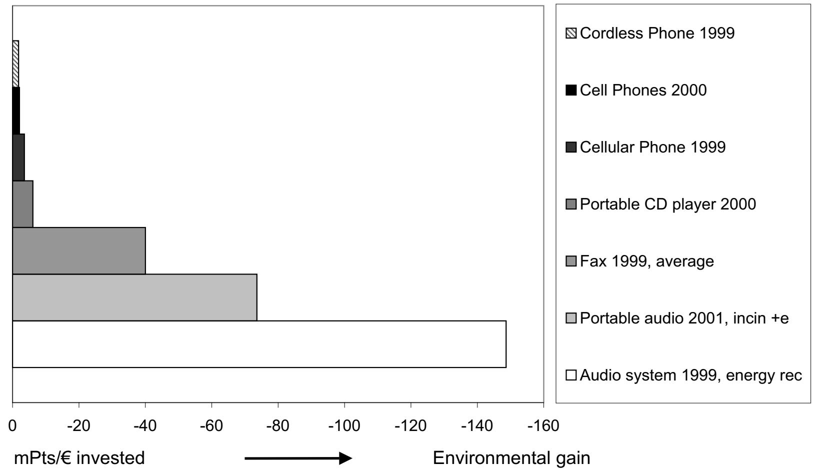


*Figure 7.11 Environmental gain per € invested for plastic recycling housings*

Regarding the policy strategies to prefer, the plastic recycling of large sized housings for which disassembly is required, leads to much higher environmental gains compared to the medium and small housings. Precondition is that no flame-retardants are present. The environmental return per euro invested is relatively low for medium sized housings and almost zero for plastic recycling of small housings. The environmental return on investment for plastic recycling due to prescribing recyclability targets, is compared to for instance CRT glass recycling much lower. Section 7.6.2 will be further elaborated on this issue.

### 7.5.5 Separate collection precious metal dominated products

In Chapter 5.7.4, an alternative option is presented for separate treatment and collection of cellular phones in particular and for precious metal dominated products in general. The results of Chapter 5 are further discussed here regarding the relation between current end-of-life treatment and where policy strategies should focus on. Plastic recycling of these products is already discussed in the previous section. The separate collection and treatment, as introduced in Chapter 2.4, Figure 2.8, is dealt with in this section. The eco-efficiency results connected to the separate collection and treatment is displayed in Table 7.5.

| Separate collection and treatment | mPt | € |
|---|---|---|
| Cell Phones 2000 | -36,04 | -0,15 |
| Cellular Phone 1999 | -21,75 | -0,06 |
| Cordless Phone 1999 | -13,09 | 0,02 |

*Table 7.5 Separate collection and treatment of precious metal dominated products*

This table shows that the cellular phones are located in the first quadrant of Figure 7.8. Compared to regular treatment as part of the browngoods stream, the separate collection, including higher costs for logistics and transport, a higher environmental gain and higher economic value recovery is obtained. The cordless phones with a much lower precious metal content are located in the fourth quadrant for the separate collection. All results are displayed in Table 7.5. Compared to the other strategies, like in the previous section, the separate collection of the cordless phones still leads to an environmental recovery of 690 mPts per euro invested.

Regarding the policy strategies to prefer, the separate collection of cellular phones seems eco-efficient for the cellular phones with relatively high precious metal contents. The results for separate collection are directly related to these precious metal contents of the products. These were 800 ppm for gold and 500 ppm for palladium for the high-end cellular phone. The content for the low-end 1999 cellular phones was 350 ppm gold and 200 ppm palladium, the cordless phone contained on average 125 ppm gold and 100 ppm palladium. This leads to the general conclusion that for products with precious metal contents higher than approximately 250 ppm gold and 150 ppm palladium, separate collection and treatment is always eco-efficient. For values below this the environmental return per amount of money invested in still substantial. See also Figure 5.34 from Chapter 5.7.4 for more details. An important assumption here, was that sufficient numbers of precious metal dominated products could be collected. Sufficient means here that at least batches of a few tons have to be collected to make it acceptable for a copper smelter.

With regard to the policy strategies, it seems that the most important recommendation for precious metal dominated products is that no recyclability targets should be prescribed, but an obligatory separate collection amount. Again, in Section 7.6 will be further elaborated on this issue.

### 7.5.6 Dedicated treatment metal dominated products

In Chapter 5.7.2, an alternative option is presented for the treatment of metal dominated products with sufficient precious metal content and a relatively low plastic content. By sorting these products from the regular browngood stream and with adjusted shredding and separation settings, both an environmental as an economic higher value recovery is to be expected. The adjusted settings are displayed in Figure 2.9 of Chapter 2.4. However, as earlier discussed in Chapter 5.7.2 and Figure 5.30, the result for some products are a negative eco-efficiency direction due to too much dilution of the precious metals in the copper fraction or too less concentrating of valuable materials. In this table, five average products are presented. For two of these average products, the CD recorder and the VCR, the environmental burden and the integral costs increase as well. For these products, the precious metal content is not high enough and the relatively high plastic content causes higher environmental burdens in the metal smelters compared to the MSW incineration of the residue fraction. Extra sorting costs are included for the dedicated treatment (€ 0,14 per kg).

| Dedicated shredding and separation | | | |
|---|---|---|---|
| **3rd quadrant, avoid** | **mPt** | **€** | **N.A.** |
| CD recorder 1999 | 26,93 | 0,22 | |
| VCR 2000 | 29,80 | 0,27 | |
| **4th quadrant** | **mPt** | **€** | **mPt/€** |
| DVD 2001 | -7,92 | 0,13 | -62,47 |
| LCD projector 2000 | -83,88 | 0,71 | -117,68 |
| DVDR 2002 | -19,62 | 0,07 | -278,33 |

*Table 7.6 Dedicated shredding and separation of metal dominated products*

In Table 7.6, three other products have higher environmental gains compared to the standard treatment as part of the browngoods stream. In Figure 7.6, the environmental return per euro invested is displayed. The more modern products with a higher degree of miniaturisation of PWBs have higher environmental value recoveries compared to the more developed and optimised DVD players. It should be noted that the average dedicated treatment for 13 DVD players sold in year 2001 result in a direction in the fourth quadrant of Figure 7.12, whereas the example DVD player (with a lower precious metal content) ends up in the third quadrant. See Figure 5.8 of Chapter 5.3 for this result. This shows that the dedicated shredding and separation settings should not be applied when low precious metal contents are expected. The choice for dedicated shredding and separation seems very sensitive to these actual precious metal contents. When applied, sorting of these products should take place on basis of knowledge which products are expected to have sufficient precious metal concentrations and low plastic contents, based on age, functionality etc.

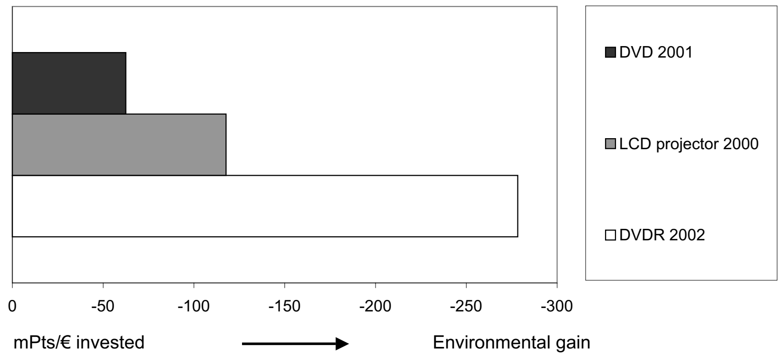


*Figure 7.12 Environmental gain per € invested for dedicated shredding and separation*

In the next section will be elaborated on how to balance policy strategies for metal dominated products. In the conclusions of Section 7.10 all eco-efficiency directions will be compared and ranked.

### 7.5.7 Effects of energy recovery

In this section, the relevance of energy recovery from plastic and residue fraction will be presented. For four different plastic dominated products the difference between incineration with and without energy recovery under state-of-the-art recycling for the Dutch situation is described. The result is presented in Table 7.7.

| Energy recovery versus no energy recovery | mPt | € |
|---|---|---|
| Fax 1999 | -62 | -0,53 |
| Portable CD player 2000 | -6 | -0,05 |
| Audio system 1999 | -146 | -0,97 |
| Portable audio 2001 | -55 | -0,47 |

*Table 7.7 Incineration with versus incineration without energy recovery*

All energy recovery scenarios compared to the without energy recovery scenarios appear in the first quadrant of Figure 7.8 independent of the amount of plastics present in the products. This leads to the conclusion that in general outlet control for plastic and residue fractions should be encouraged and incineration without energy recovery should be forbidden. For the Audio System of Table 7.7, the effects of sending the residue and plastic fractions to various outlets including the cement kiln are visualised. When the incineration with energy recovery as the default state-of-the-art recycling scenario of this plastic dominated product is compared to the incineration without energy recovery is, a clear negative eco-efficiency result is obtained displayed with the first arrow of Figure 7.13.

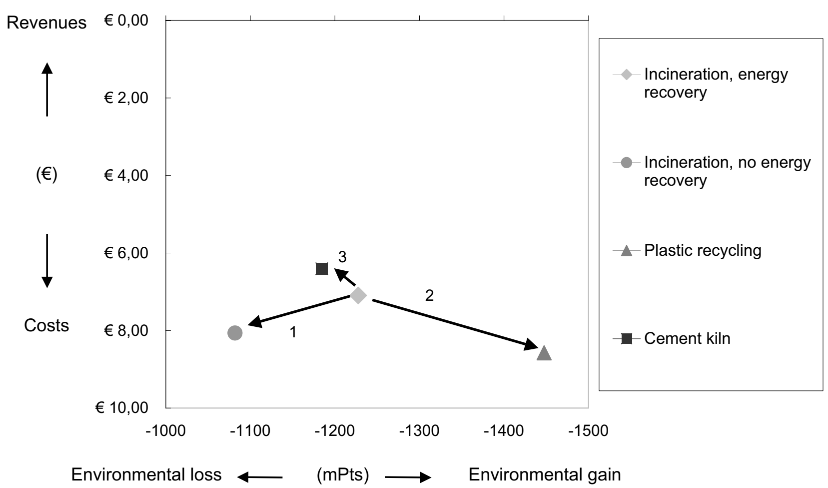


*Figure 7.13 Eco-efficiency directions for treatment of plastic and residue fractions*

The second arrow displays the plastic recycling scenario. Which leads to the change in environmental scores and extra costs as displayed in Table 7.7. The third arrow is the cement kiln scenario to which both the residue and the plastic fractions are sent. This change is points into the direction of the second quadrant (see Figure 7.8). This means less costs and less environmental gain due to the net effect of higher emissions (worse flue gas cleaning) and higher thermal energy recovery (positive). This change in the direction of the second quadrant is comparable with a change in the fourth quadrant while it can also be regarded as the reverse effect of investing in sending fractions to incineration with a MSW stream including energy recovery, instead of a cement kiln. The net effect is a sacrifice of 62 mPts for 1 € gained. To compare: the plastic recycling scenario (in relation to incineration with energy recovery), leads to an environmental gain of 149 mPts/ € invested. This leads to the conclusion that in this case plastic recycling is to be preferred over application in the cement industry of the plastic fraction as a fuel.

For smaller housings the similar effect of treating the contributions to the residue fractions is located in the third quadrant of Figure 7.8 as a negative eco-efficient effect. This is displayed in Table 7.8. The reason is a relative lower plastic content in the 'contribution to the fractions' treated at a cement kiln, originating from smaller products in comparison to the Audio System example.

| Cement kiln versus energy recovery | mPt | € |
|---|---|---|
| Fax 1999 | 12,9 | 0,15 |
| Portable CD player 2000 | 2,2 | 0,01 |
| Audio system 1999 | 43,0 | -0,69 |

*Table 7.8 Treatment of residue fractions in a cement kiln versus energy recovery at MSW*

## 7.6 Balancing policy strategies

### 7.6.1 Collection rates

The eco-efficiency directions and results of the previous options are summarised in this section, sorted according to corresponding policy strategy and ranked.

The general collection rates prescribed in the WEEE Directive should be more focussed on the products with a positive eco-efficiency of collection versus disposal with MSW, as in the first quadrant of Figure 7.8:

1. The increase of collection rates for precious metal dominated products. Regular treatment of precious metal dominated products is already eco-efficient when treated as a part of the regular browngoods stream. The collection rates of these products should be increased as far as possible taking into certain boundary conditions as will be discussed in the next Section 7.7.2.
2. The increase of collection rates for metal dominated products with a relatively high metal and low plastic content (DVD players, DVDR, VCRs). Both the precious metal dominated products and these metal dominated products have compared to disposal as MSW a positive end-of-life value and a higher environmental value recovery.

Other options fall in the fourth quadrant of Figure 7.8. These environmental gains realised should be prioritised according to the financial consequences:

3. The increase of collection rates for other metal dominated products not falling under the category listed above. The environmental return for this are ranging from 800 – 1600 mPts/€ for the comparison with disposal MSW versus collection and treatment.
4. The increase collection rates for glass-dominated products. This option ranges in between 200 mPts/€ and 400 mPts/ € invested.
5. The increase collection rates for glass-dominated products and for small plastic dominated products, the environmental return per euro invested is in between 100 mPts/€ and 300 mPts/€.

Policy and legislation should prioritise on prohibiting disposal of the metal and precious metal dominated products with MSW instead of increasing collection rates of small plastic dominated products. Increasing communication towards consumers and a small return fee might be options, but further research is needed on this. Furthermore, certain boundary conditions are relevant regarding collection rate enhancing measures as will be discussed in Section 7.7.2.

### 7.6.2 Plastic recycling

The recycling targets prescribed in the WEEE Directive should be more targeted to the options with a positive eco-efficiency as in the first quadrant of Figure 7.8:

6. The application of plastic recycling of already disassembled large sized housings (from CRT containing products with screen sizes larger than 17-inch). This is under the assumption that housings containing flame-retardants can be recycled. Prescribing recycling targets using a strict MRE definition must be aligned with the results of Section 7.4.2. Even including this plastic recycling of large housings, only a 42% MRE was realised.

Other options regarding plastic recycling fall in the fourth quadrant of Figure 7.8 (environmental gain and higher costs):

7. The plastic recycling of large sized housings for which disassembly should take place (between 150 mPts/€ and 250 mPts/€ invested). For medium sized housings: the environmental return per euro invested is smaller: in between 50 mPts/€ and 150 mPts/€ invested. This counts for housings with a weight in between 1 kg and 2,5 kgs. In this case the recyclability targets could be replaced by an obligatory (percentage) for dismantling and plastic recycling.
8. The plastic recycling of small sized housings: the environmental return per euro invested is very small: in between 2 mPts/€ and 20 mPts/€. Prescribing recyclability targets has very little effect on the environmental gain for these appliances. The only effective and efficient measures could be outlet control regulations for shredding and separation in order to assure appropiate treatment at recyclers and energy recovery of the plastics (this will be further discussed in Section 7.6.7).

In general it can be concluded that the large focus on increasing plastic recycling should be differentiated as a result of the eco-efficiency calculations of this chapter. A positive eco-efficiency for plastic recycling seems only valid for large encasings already being disassembled due to the presence of a CRT or LCD screen and only when plastic recycling is really technically possible. For medium and especially for small houings the eco-efficiency results are far less efficient with regard to high reyclability targets prescribed for these products.

In Figure 7.14 the mPts per € gained versus the size of the plastic housings is presented. In this graph no CRT or LCD containing appliances are displayed while the disassembly costs were accounted to the CRT glass present in these products. From this graph a good correlation occurs between the integral costs for plastic recycling versus the environmental gain realised per euro invested. A large group of products with housings smaller than 100 grams are in the bottom left corner of Figure 7.14.

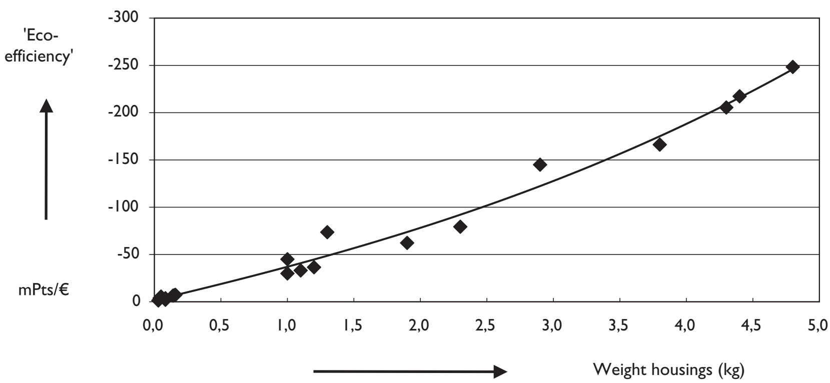


*Figure 7.14 Size of plastic housings versus environmental gain per euro invested*

### 7.6.3 CRT glass recycling

The increase of CRT glass recycling from 15% (current status) towards 70% technological maximum) results in Section 7.5.3 in a direction located in the fourth quadrant. (For all these products the disassembly time required is accounted to the CRT glass recycling).

9. The increase in CRT glass recycling from 15% to 70%. A consistent value of around 400 mPts environmental gain per euro invested for all different products, with screen sizes from 17-inch towards 32-inch is realised. In Section 7.10.2 a further discussion on the issue of increasing CRT glass recycling and the practical consequences for policy strategies, enforcement and monitoring will be presented.

### 7.6.4 Separate collection and treatment

The separate collection and treatment of precious metal dominated products results in positive directions located in the first quadrant of Figure 7.8:

10. Separate collection of precious metal dominated products with precious metal contents above approximately 250 ppm for gold and 150 ppm for palladium should be encouraged. For these products a separate collection system and adjusted shredding and separation would be beneficial from an environmental and economic

perspective. Preconditions are that economies of scale can be realised so that a sufficient number of product can be collected. Enforcement of the present recyclability targets is leading to eco-inefficient end-of-life treatment and should be abolished. For small precious metal dominated products, other strategies are to be envisaged: An obligatory separate collection or sorting of this product out of the regular streams is recommended.

The following directions are located in the fourth quadrant and should be prioritised in terms of amount of money invested versus environmental gain. The options are ranked on their environmental return per euro invested:

11. Separate collection of precious metal dominated product with precious metal contents lower than 250 ppm for gold and 150 ppm for palladium. The environmental return per amount of money is around 700 mPts/€ dependent on the actual concentrations. Also in this the environmental return per money is relatively high, which leads to the same recommendations as for the precious metal dominated products with higher precious metal contents.

### 7.6.5 Dedicated shredding and separation

Some of the dedicated shredding and separation settings (Chapter 2.4.3) for some metal dominated products lead to directions in the fourth quadrant:

12. Dedicated shredding and separation of metal dominated products, only when the plastic content is relatively low and the precious metal content is expected to be relatively high due to the presence of highly miniaturised PWBs (50 mPts – 250 mPts/€).

Under the same settings, some products undergo a change in the third, eco-efficient negative direction:

13. Dedicated shredding and separation of metal dominated products with a high plastic content and a too low precious metal content. (sse also the DVD player example of Chapter 5.3.5 and the relatively old products CD recorder 1999 and VCR 2000 of Section 7.4.6).

The current recyclability targets strategy does not necessarily lead to the most eco-efficient directions for these dedicated shredding and separation settings. The most effective way of treatment is primarily driven by financial considerations. These are consistent with the environmental performance for these products under these settings.

### 7.6.6 Energy recovery options

Energy recovery from plastic and residue fraction are discussed in this section.

14. Residue fractions resulting from plastic dominated products with medium and small sized housings should be incinerated with energy recovery compared to thermal energy recovery and higher emissions at the treatment at a cement kiln. ‘Saving’ these fractions from a cement kiln leads to an environmental improvement of 60 mPts/€ invested. Or in other words, using a cement kiln for these fractions

leads to an environmental worsening of 60 mPts per euro saved compared to energy recovery at incineration with MSW.

A few directions should definitely be avoided. These appear in the third 'negative eco-efficiency' quadrant:

15. Incineration without energy recovery of plastic and residue fractions. In general it can be concluded that also in this case, the weight based recyclability targets cannot lead to the right eco-efficiency direction due to the fact that energy recovery is (still) not unambiguously incorporated in the targets.

All options will be summarised again in Section 7.10.4 till 7.10.6.

## 7.7 Boundary conditions

### 7.7.1 Life-cycle perspective and material selection

As earlier displayed in Chapter 6, it is possible to increase both the QWERTY as MRE recyclability scores for products by putting more environmental (and economic) value into products. The adaptation of weight based recyclability targets may lead to an increase in environmental production values for electronic products. For instance replacing plastic encasings by steel or aluminium encasing leads to higher recyclability scores under most definitions. This effect is displayed in Table 7.9 with the effects of replacing a plastic encasing of a Soundmachine (medium sized housing).

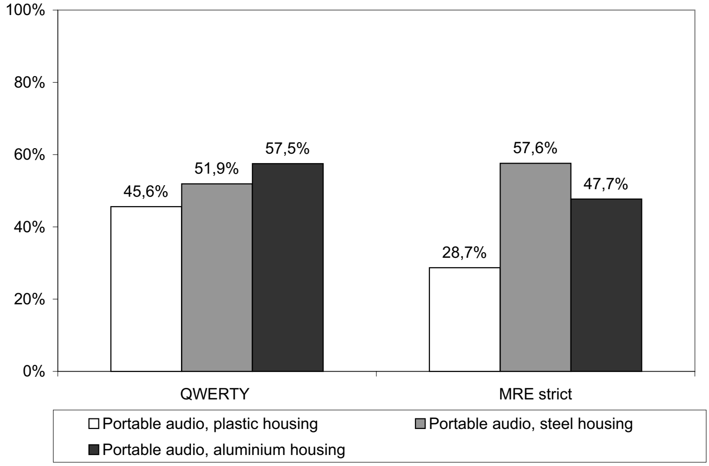


*Figure 7.15 QWERTY versus MRE for different housings of Portable Audio*

Figure 7.15 shows that replacement of plastic housings by steel or aluminium housings results in higher recyclability scores under both the strict MRE and QWERTY definition. If the replacement is specifically done to realise recyclability targets also an environmental improvement in end-of-life is realised. However, as earlier discussed in

Chapter 6.3, with Figure 6.3, the life-cycle perspective should be taken into account. The Figure 6.3 shows that material selection should be applied in such a way that the environmental value put into a product at the production stage is reduced, that the worse case scenario (no recycling) should lead to lower environmental burden and that the absolute recycling scenario or environmental value recovery should be increased.

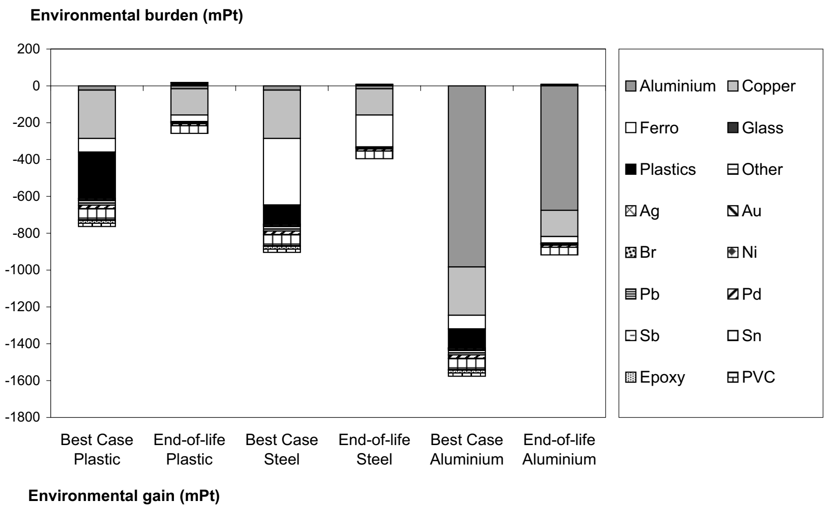


*Figure 7.16 Life-cycle perspective and product design for different Soundmachine housings*

In Figure 7.16, the same graph earlier presented in Chapter 6.4.3 and Figure 6.10 is displayed. With Figure 7.16, the best case and recycling scenarios for all three housings are presented for the Soundmachine (the worst case scenarios are not displayed while no major difference occur here). This graph shows that with the steel and aluminium housings more environmental load is put into the product (the left three bars in the graph). Much of this value is recovered under state-of-the-art recycling, but the difference between the material value of production and this value for 100% collection and treatment is increasing. Due to the fact that collection rates are not 100% for products like this, in reality even more (environmental) material value is lost. On top of that, the environmental effects of shaping and deformation are neglected in this picture. These values are generally higher for metal housings (bending, cutting, etc.) compared to plastics (extrusion and injection moulding). Usually, also less material is lost in case of using plastics compared to using metal housings. Next to the environmental consideration, also costs considerations turn out negative when plastic housings are replaced by metal housings, which are generally much more expensive. It can be concluded from this example that the 'prescribing recyclability targets' strategy leads to **violation** of the important life-cycle perspective.

### 7.7.2 Strategies for enhancing collection rates

In the previous sections, the behavior of single products within the Dutch situation is discussed. With the QWERTY/EE approach it is also possible to determine performance of product-streams or take-back systems as a whole as well as what the effects of collection rates enhancing activities are. Especially the increase in collection rates of precious metal and metal dominated products is suggested to lead to higher eco-efficiencies. However, the effect of measures to take in order to achieve this effect must be taken with some precaution. The reason for this is that costs for logistics and transport are highly sensitive for changes in the collection infrastructure and because these costs can be relatively dominant on the integral costs for end-of-life treatment. This will be illustrated with the example of changing logistics of the Dutch E&EE system.

One way to obtain higher environmental recoveries in practice is to change the national collection infrastructure. Currently, the main collection routes in the Dutch E&EE recycle system are through retailers (8%) and municipalities (90%) via Regional Sorting Stations towards recyclers (NVMP 2002a,b). In order to increase the collection rates, which are currently around 60% for CRT-containing appliances (monitors and TVs) and on average 20% for other small and medium sized electronic products for 2001, a 'pick-up on demand' system can be considered. In such a system both large and small household appliances can be collected at households, separately from MSW. The question is what the effects of extra transport, with waste collection trucks or vans, are on the environmental and economic indicators.

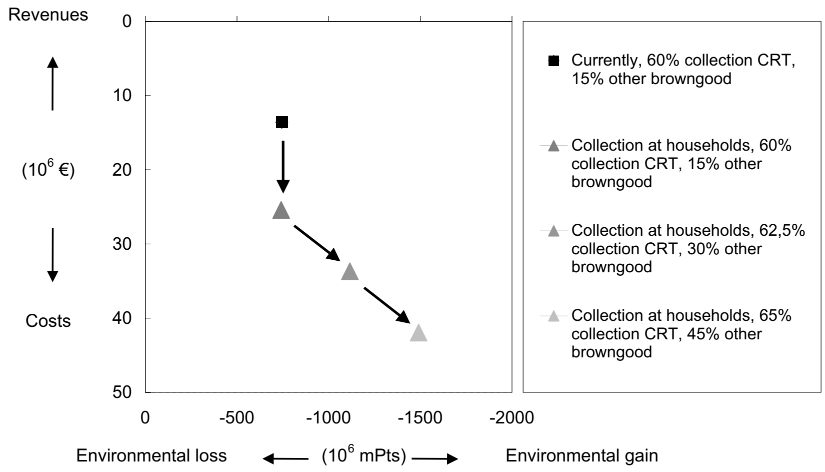


*Figure 7.17 Eco-efficiency of changing collection infrastructure*

In Figure 7.17, the effects on the system as a whole are shown. Three scenarios are visualised starting from no increase in collection rates (60% collection of CRT-containing and 15% other consumer electronics, towards 65% for CRT-containing (assumed to be a collection ceiling due to a large second hand circuit) and 45% for other consumer electronics. The graph shows that, although the increased transportation doesn't seem to have a large effect on the environmental performance, the collection costs are increased with 11,8 million € for the same collection rates (see the first arrow in Figure 7.17).

If under the pick-up system the collection rates would rise, then an environmental improvement of approximately 100% could be realised against an approximately 300% increase in costs, excluding even higher initial investment costs! (The second and third arrow of Figure 7.17 combined). Furthermore, the (not directly visible) decrease in incineration and landfill costs due to higher collection rates were already taken into account. The effect on the costs for producers (see the previous section for this effect), result in increased transportation costs of roughly 30 million € for the highest collection rates. (This very rough result is remarkable compared to the other 'fourth quadrant directions: in this case the environmental gain is only 28 mPts per euro invested, just above the most 'expensive' direction found so far: plastic recycling of small sized appliances).

It can be concluded that from an eco-efficiency perspective the current collection infrastructure seems preferable above 'pick-up on demand' at households and that other ways should be considered to obtain higher returns from consumers into the take-back system. As all assumptions and other aspects can be quite dominant in deriving a picture like Figure 7.17, more research is necessary to determine the more exact effect of Figure 7.16. The example should therefore be considered as an 'eco-efficiency' warning for obtaining higher collection rates without taking into account efficient logistics.

### 7.7.3 Monitoring problems

The consequence of changing policy strategies would probably also lead to a different monitoring approach. While under the use of the recyclability target strategy, it is very difficult to determine precisely whether the prescribed targets are met. The monitoring will automatically move towards counting and measuring streams entering from collection and leaving recyclers towards secondary processes (for example in (De Straat Milieuadviseurs 2002)). This way of monitoring is already prescribed by the WEEE Directive in Article 7.3 of the Directive, but detailed monitoring rules are not yet present and will follow within 18 months after enforcement of the Directive.

From the present work it can be concluded is that monitoring directly is to be aligned with the outlet regulations for fractions created by recyclers. The only new aspect is that secondary processors should be addressed as such for the treatment of individual fractions. This means that metal smelters should be addressed as such and that in particular for fractions with materials that can undergo a lower level of re-application level maximum percentages can be set for the lowest re-application processes. For instance for glass a minimum percentages of x% to replace new CRT glass, y% to the ceramic industry and a maximum of z% to the building industry and a prohibition of landfill could be considered. This is well in line with the eco-efficiency directions proposed in the previous section and can far more easily be monitored. The same counts for a prohibition of incineration without energy recovery of residue fractions.

## 7.8 Restrictions on hazardous substances, the lead-free soldering example

### 7.8.1 Lead-free soldering

In this section the consequences of the implementation of the RoHS Directive will be discussed. The example of lead-free soldering is used to illustrate the consequences from an environmental perspective. The case of lead-free soldering versus traditional soldering will be evaluated from a life-cycle perspective. The phasing out of lead is probably the most disputed restriction in the RoHS Directive. The replacement of lead in solders is intended by replacing traditional SnPb solder 60% Sn, 40% Pb) with lead-free soldering of which SnAgCu (with Sn 95,5%; Cu 0,7%; Ag 3,8%) is the most common alternative. With the cooperation with the TU Delft Applied Earth Sciences department and the work of (Scholte 2002) addressing LCIs on the base metals involved and the subsequent research on the additional finishing materials for lead-free soldering (van den Tweel 2003), an environmental assessment is performed and substantiated with the dynamic base metal production modelling as introduced in Chapter 2.7. The main results of this research are repeated in the next section and special attention is given to the uncertainties in LCA of lead-free soldering versus traditional soldering, the problems with allocation and the main results for the main environmental themes resource depletion, eco-system quality and human health.

### 7.8.2 Main results

The results of the LCA analysis for the comparison of traditional SnPb versus SnAgCu solder are very sensitive to the weighting factors applied. This is due to the relatively high toxicity value for lead in traditional solder resulting in high value for the damage category human health and to a lesser extent to ecosystem quality. On the other hand has the lead-free solder relatively high contribution to resource depletion due to the higher silver content and to a lesser extent also from tin. On top of that, the resource depletion factors used are very uncertain as previously discussed in Chapter 2.7.5, which is leading to very high resource depletion values for the lead-free soldering. In Figure 7.18 are the LCA results presented for the Eco-Indicator '99 method excluding resource depletion. In this graph are three scenarios displayed per solder type. The three bars on the left are representing lead-free soldering including the end-of-life phase of respectively incineration, landfill and state-of-the-art recycling. The three bars on the right are representing traditional PbSn solder including the same end-of-life phase. As a result, for all scenarios the lead-free solder is scoring better when no resource depletion is taken into account.

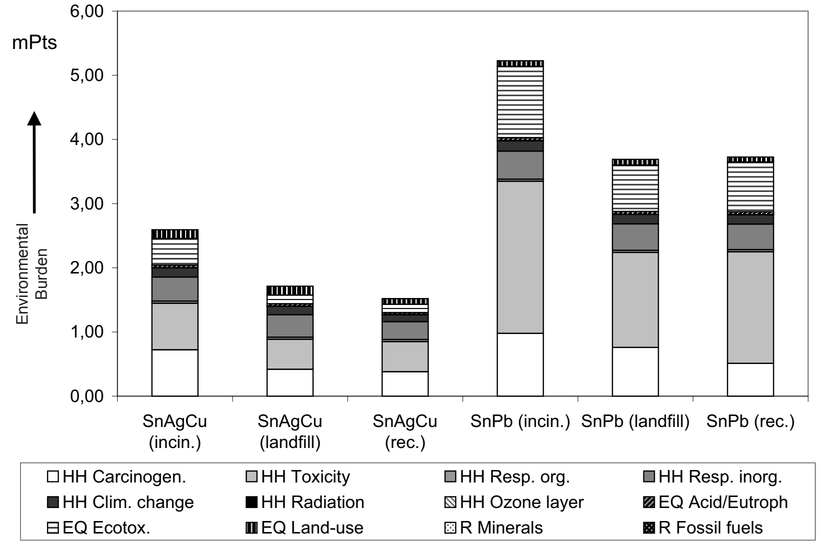


*Figure 7.18 LCA scores for lead-free solder versus traditional solder (no resource depletion)*

The question raises what the effect of taking into account some resource depletion. This is displayed in Figure 7.19 for the default Eco-Indicator '99 method as used in this thesis. In this case the resource depletion-weighting factor is set at 5% of the original value.

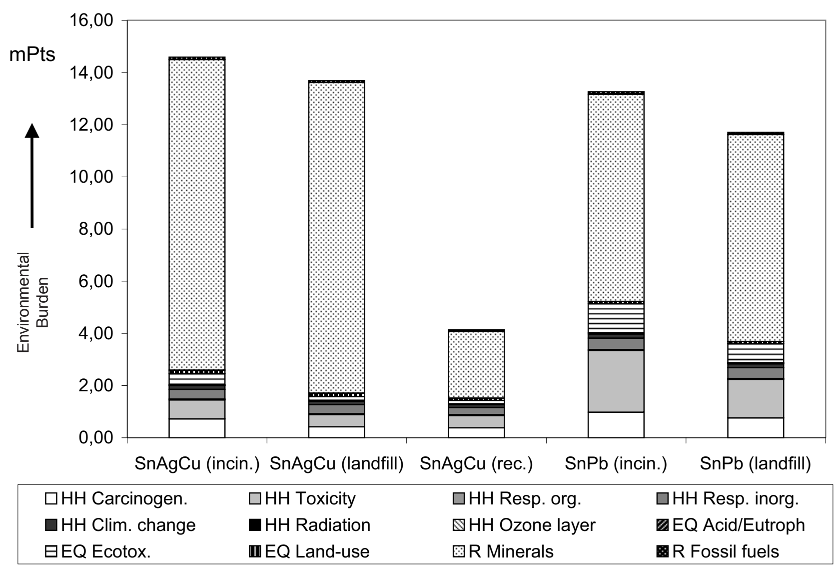


*Figure 7.19 LCA scores for lead-free solder versus traditional solder (5% resource depletion)*

In this case the scenarios for both solders are more or less comparable. The disposal scenarios score worse for the lead-free soldering in relation to the traditional solder, the opposite counts for the recycling scenario. The last LCA comparison is made with the standard weighting factors for resource depletion in Figure 7.20.

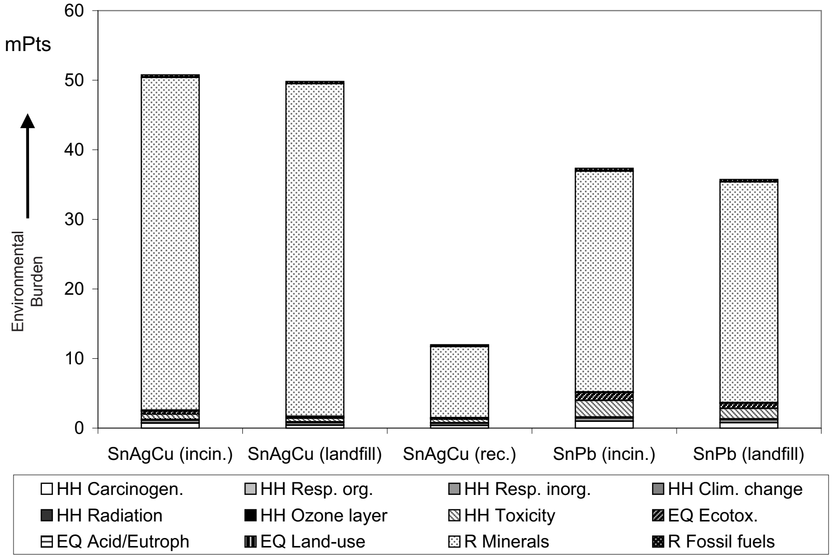


*Figure 7.20 LCA scores for lead-free solder versus traditional solder (100% resource depletion)*

In this case, the lead-free soldering scores the worst for the disposal scenarios and about equal for the recycling scenario. All figures show the relevance of end-of-life treatment to recover material value for both solders in comparison to the disposal scenarios. The strategy of restricting the use of lead reduces the environmental impact over the total life cycle with a factor 2 to 4 when no resource depletion is taken into account; the exact factor is depending on the end-of-life scenario. When a certain weight is assigned to resource depletion, the most common lead-free soldering alternative can score worse from an environmental perspective.

### 7.8.3 The influence of flue gas cleaning in metallurgical processes

From the research of (Scholte 2002) it is also known that the state-of-the-art of the metallurgical processes involved has a large influence on the environmental results. In Figure 4.21is the production of 1 kg lead from both primary as secondary origin displayed. The LCA score (y-axis) is plotted against the flue dust capturing efficiency ranked from 90%(!) to a 100%. This graph shows a major increase in environmental scores when gas-cleaning systems are not state-of-the-art. Many similar results are also found for other metal production routes both from primary or combined primary and secondary origin.

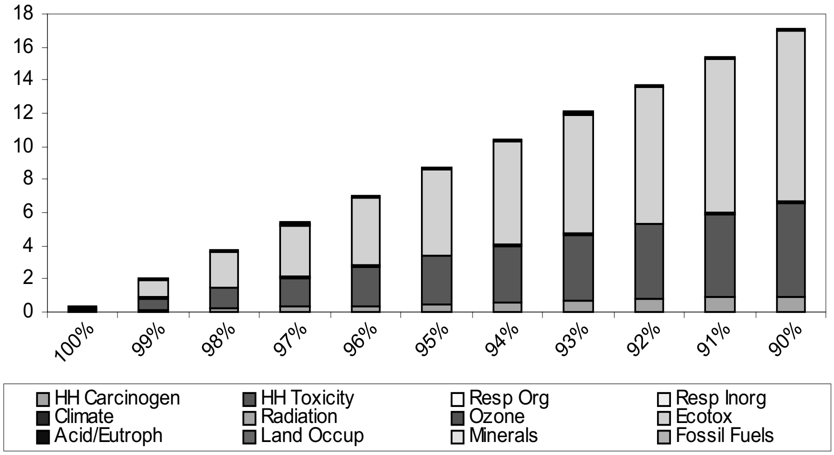


*Figure 7.21 LCA scores for lead production versus flue dust capture efficiency*

A similar effect, also for the lead production example is displayed in Figure 7.22. In this graph the effect of the type of smelting is exhibit for modern smelting techniques versus old smelting techniques. Both modern and old metal smelting in this case for lead is leading to average LCA scores for metal production. This also means that the very unilateral focus on the prevention of the use of lead in electronics is too narrow. Also the relation with global metal production and the awareness of the environmental gain that can be realised on a global scale should be taken into account regarding the restrictions for certain hazardous substances. Furthermore, due to the high interconnectedness of metal production systems, the restrictions applied for lead may very well result in an unchanged production of this metal. Moreover, the metal production systems are not only an environmental burden. They also make it possible to actually close material loops and thus the prevention of new material extraction.

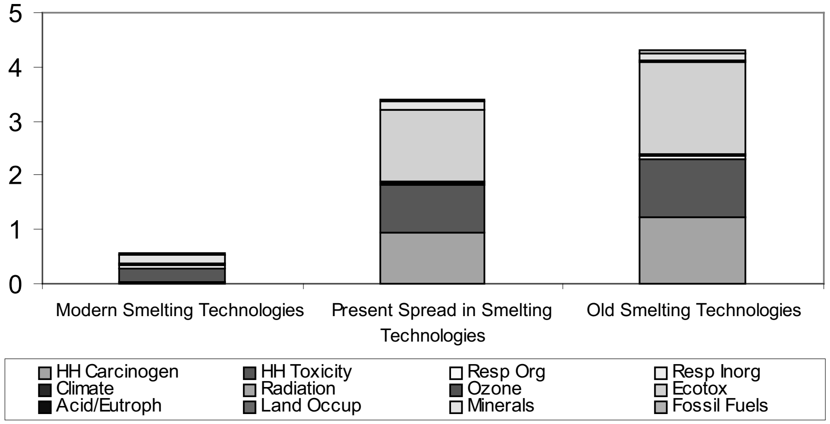


*Figure 7.22 LCA scores for lead production under different smelting techniques*

### 7.8.4 Conclusions

Within the scope of this thesis, no costs calculations were possible for an eco-efficiency comparison of changing towards lead-free soldering. In order to do so, the high transition costs for changing towards lead-free soldering should be taken into account. Besides this it is known that the economic material value as such, does lead to a small increase in the value of lead-free soldered PWBs.

The lead-free soldering example shows that lead-free is not beneficial from all environmental perspectives. It leads to lower toxicity potential but these benefits should be balanced with the additional resource depletion created. In fact, it is a typical example of not taking into account the life-cycle perspective on forehand when creating end-of-life legislation. For more details is referred to (Scholte 2002, Verhoef 2003a,b, Spriensma 2002). For more backgrounds behind the static and dynamic modelling, the problems with allocation due to the high interconnectedness and the uncertainties in determining resource depletion, is referred to Chapter 2.7.

## 7.9 Consequences and contributions per stakeholder

### 7.9.1 Introduction and assumptions

All costs, either directly or indirectly, made for end-of-life treatment, are paid by the consumers. However, it will be shown that there is a major shift in costs from the public domain towards the producers, who sooner or later will incorporate these costs again in the market prices of products.
In the eco-efficiency approach as presented in this thesis, it is not clear what the financial consequences for individual stakeholders can be. In order to determine these consequences graphs can be plotted illustrating the costs to be paid within the Dutch take-back system by the various stakeholders for individual products. Also the relation with expected collection rates can displayed. Before presenting these graphs for producers (who pay for operating the take-back system) and the public domain (who pay for indirect costs of disposal) the following assumptions must be taken into account:

1. Data are representing the Dutch take-back system.
2. Logistic costs of consumers handing in products at retailers/municipalities are excluded.
3. The 2nd hand circuit and exports of products are excluded as well
4. Non-recycled products are collected with MSW: 23% to landfill, 77% to incineration, the base waste disposal fees for these are mentioned in Chapter 4.3.4 and 4.3.5.
5. The indirect costs included are:
    a. Penalties due to unwanted materials (on top of base waste disposal fees, see right part of Chapter 4.3, Equations 4.1 and 4.2).
    b. Revenues of material of energy recovery included (at incineration with energy recovery).
    c. Costs of transport from municipalities towards the Regional Sorting Stations are paid by the municipalities (fall under the government/ consumer line)
6. Costs of achieving higher collection rates (like advertisement, other logistic systems) are neglected.

7. No economy of scale effects occurs in the collection stage due to higher collection rates. Linearity is assumed to be present between costs and collection rates (which in reality is not the case).
8. Plastic recycling of housings is excluded unless stated otherwise.

In the next section, an example is given for four products representing their corresponding product category.

### 7.9.2 Costs versus collection rates of plastic dominated products

Figure 7.23 describes the costs for two groups of stakeholders. On the one hand are the combined costs for consumers and government (the public domain) for the Soundmachine as function of the collection rate for this product. On the other hand are the costs for producers, who pay for the take-back system as a whole through a their collective take-back recycling organisation (NVMP 2002a,b). Besides the logistic costs of municipalities, all other costs and revenues involved are paid by NVMP.

Figure 7.23 shows that the costs for NVMP are relatively faster increasing under increasing collection rates (or change of collecting this product related to end-of-life costs for the same products) compared to the total integral costs for the system. Under higher collection rates the relative shift of costs from the public domain towards producers will be higher. In the end, consumers will always pay for higher costs. Within the Dutch E&EE system, these costs are covered with a visible fee. Whenever this visible fee is abandoned (8 years after enforcement of the WEEE Directive by national law), the extra costs (corresponding with the producer line) must be incorporated in the regular market prices for consumer electronics.

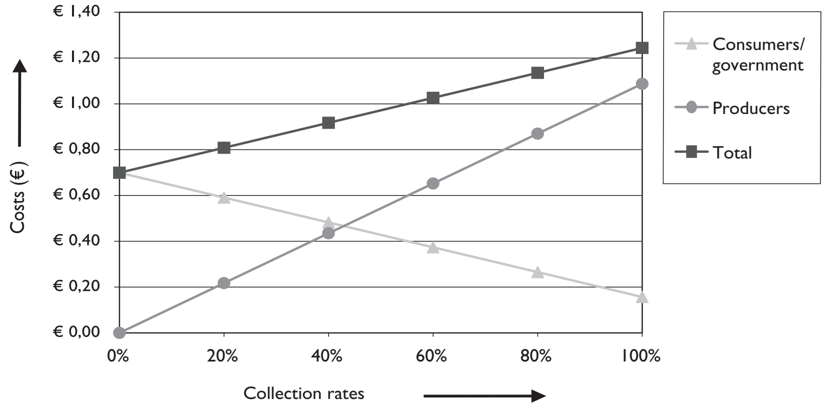


*Figure 7.23 Costs per stakeholder and collection rates for a Soundmachine*

From Section 7.5 the question comes up what the effect of plastic recycling of medium sized housings would be on a graph like Figure 7.23. The answer to this is visualised in Figure 7.24, which is similar to Figure 7.20, but with plastic recycling of housings included (1,3 kg).

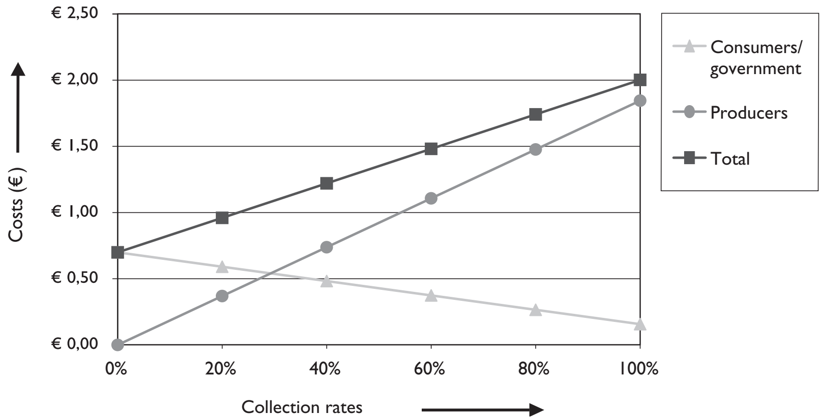


*Figure 7.24 Costs per stakeholder and collection rates for a Soundmachine*

Figure 7.24 shows that for the 'best case' plastic recycling option, much higher costs are placed on NVMP. The state-of-the-art recycling costs for this product within the system increase from € 1,23 to € 2,01 per product (3,9 kg). See Chapter 4.3.7 and 4.5.5 on the settings for plastic recycling.

### 7.9.3 Costs versus collection rates of metal dominated products

In this section the DVD player is discussed regarding the costs for this product and the costs per stakeholder. Figure 7.25 shows that the costs for NVMP are increasing under increasing collection rates compared to a small lowering in costs for the total integral costs in the system for this product. Although for this product under increasing collection rates a shift in costs towards the NVMP is appearing.

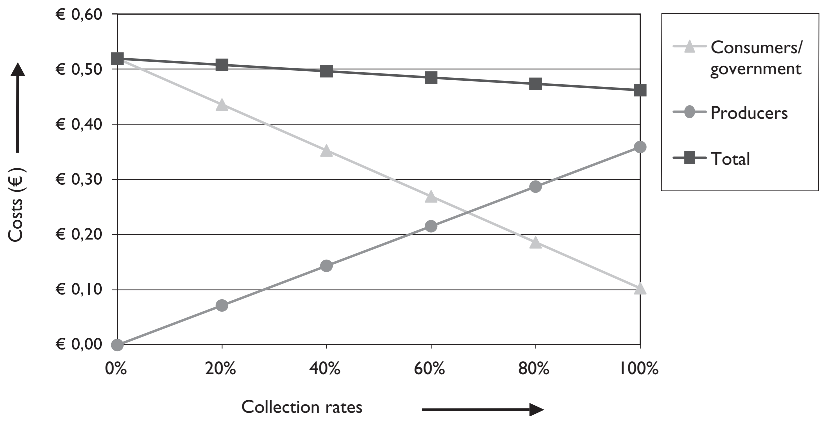


*Figure 7.25 Costs per stakeholder and collection rates for a DVD player*

The avoidance of indirect costs is not directly visible for the consumers. The lowering MSW disposal costs are probably not noticed in respect to the overall costs to be paid for consumers per year for their MSW. Although the small integral cost improvement from a system point view, when the MSW costs in general are not lowered due to (small) reduction in load due treatment of consumer electronics in a separate take-back system, the resulting effect might be an increase in costs for consumers.

### 7.9.4 Costs versus collection rates of glass dominated products

In this section the 17-inch monitor is discussed regarding the integral costs for this product and the costs per stakeholder to be paid individually. Figure 7.26 shows that the costs for producers are increasing under increasing collection rates compared to a small lowering in costs for the total integral costs in the system for this product. Although for this product under increasing collection rates a shift in costs towards the producers is appearing.

In this case, the extra costs are both increasing for both the system as a whole as the producers.

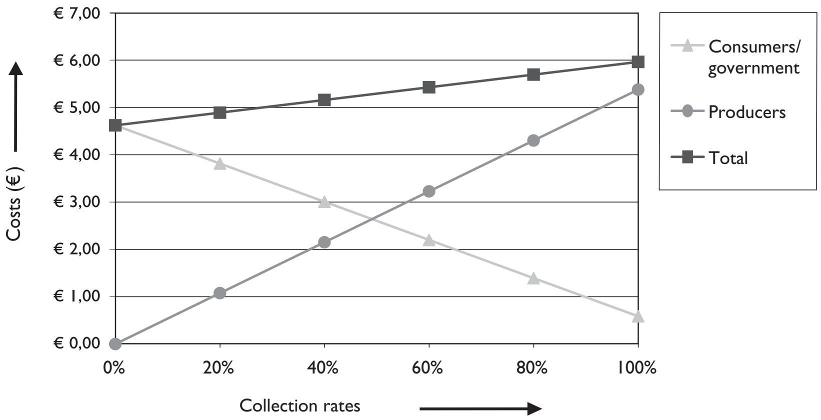


*Figure 7.26 Costs per stakeholder and collection rates for a 17-inch monitor*

### 7.9.5 Costs versus collection rates of precious metal dominated products

In this section the high-end cellular phone from the year 2000 is elaborated on regarding the integral costs for this product and the costs per stakeholder to be paid individually. Figure 7.27 shows that there is an increase in revenues for products like these, both for the system as a whole as for the producers (including the recyclers) under increasing collection rates. Revenues are below in this graph with a negative sign.

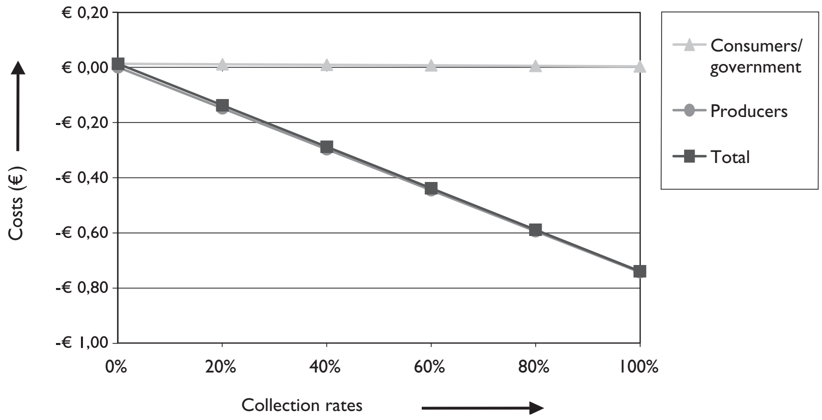


*Figure 7.27 Costs per stakeholder and collection rates for a cellular phone (high end)*

The increase in costs can even be enlarged with applying the separate collection and treatment of precious metal dominated products. This effect is depicted in Figure 7.28.

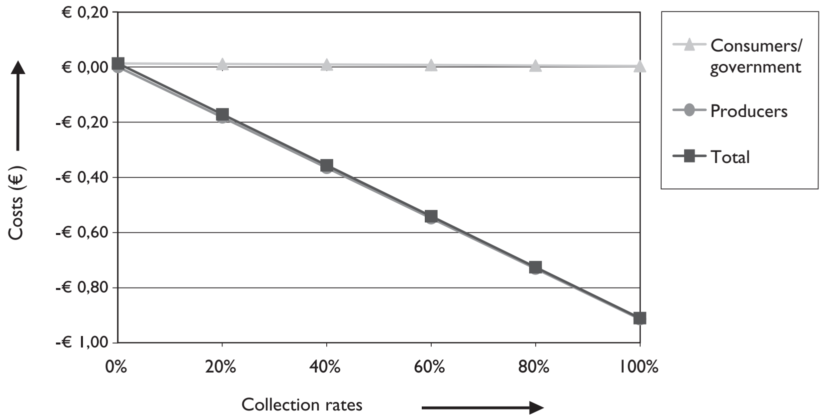


*Figure 7.28 Costs per stakeholder for a cellular phone (high end) under separate collection*

Figure 7.28 shows an maximum extra increase in revenues for the separate collection and treatment of around € 0,20 per appliance at 100% collection. This is including the costs for extra logistics and separate collection.

## 7.10 Conclusions and discussion

### 7.10.1 Alternative policy strategies

The sixth research question from Chapter 1.2 is answered in this chapter:

Research question 6:

*What are main priorities from an eco-efficiency perspective for policy, legislation and take-back system operation in order to increase end-of-life system performance and to enhance further alignment with end-of-life processing and design? What are the main strategies to increase eco-efficiency in end-of-life treatment and how should these balance?*

The main priorities from a policy perspective have been derived with the application of the QWERTY/EE concept. The environmental validation of the newly developed QWERTY approach as an alternative for the weight based recyclability definition has been proven to be very useful. Besides the main 'practical' flaws of weight based recyclability definitions, it is also shown that certain policy directions based on MRE definitions can lead to higher environmental burdens in recycling. Also a ranking of preferred measures, measures to be balanced in terms of environmental gain per money invested and some measures to be avoided are generated. These three categories are mentioned again for the examples evaluated in this thesis in Section 7.10.4 till 7.10.6. Apart from these results it can be concluded that:

For weight based recyclability targets:
1. Weight based recyclability targets do not properly address the important issue of level of re-application of secondary materials.
2. Weight based recyclability targets cannot balance different end-of-life scenarios and options in the right way.
3. Weight based recyclability targets may lead to violation of the life-cycle perspective for instance due to replacing plastic housings by steel or aluminium housings to achieve the targets.
4. Weight based recyclability targets are subjective and leave room for interpretation by individual EU member states
5. Weight based recyclability targets lead to monitoring problems. The behavior and compliance of single products within actual take-back system with the prescribe targets cannot (easily) be determined.
6. Weight based recyclability targets as currently defined in the WEEE Directive may lead to rewarding 'bad' performing recyclers over 'good' performing recyclers.
7. Weight based recyclability targets are not the right means to improve end-of-life system performance and should be replaced with the QWERTY alternative.

For prescription of collection rates:
1. Collection targets should be split per product category: relatively high for metal dominated products and precious metal dominated products,
2. Collection rate enhancing strategies can lead to high in-efficiencies from a costs perspective when the consequences for collection and logistics are overlooked.

For restrictions on the use of hazardous substances:
1. Restrictions on the use of hazardous materials are to be checked from a environmental life-cycle perspective. The case of lead-free soldering shows that decreasing

toxicity potential leads to an increase in resource depletion values. A balancing of multiple environmental themes must be performed **before** proposing Directives.

Outlet and treatment requirements:
1. Outlet control measures are in general more efficient and environmentally effective than prescribing recyclability targets. The current monitoring system in countries with a take-back system in place can better be aligned with this type of regulations.
2. Export bans, landfill bans and prohibition of incineration without energy recovery of plastic and residue fractions should be considered. Treatment of copper fractions in copper smelters without appropriate flue gas cleaning should be avoided.
3. Treatment requirements (for recyclers) are in general not necessary and are already covered by traditional health and safety regulations.

The actual eco-efficiency directions to be encouraged respectively balanced or avoided are presented in Section 7.10.4 till 7.10.6. But first the sensitivity of the results is discussed, as regards the choice of the environmental assessment method as well as practical enforcement and monitoring problems will be discussed.

### 7.10.2 Practical enforcement and monitoring consequences

The practical consequences of the alternative policy strategies proposed are expected to be well manageable. It is expected that by applying 'fraction declarations' for fractions leaving recyclers, combined with lists of acknowledged and well operating secondary processors for the metal fractions, plastic fractions and residue fractions are not leading to large difficulties in enforcement and monitoring (Veerman 2003). An exception is envisaged for the treatment of CRT glass fractions. There is no legislative framework and resulting enforcement for CRT glass producers to treat and use secondary glass fractions, while producer responsibility for the end-use equipment producers is not affecting the few CRT glass producers present in Europe. Extending producer responsibility to the suppliers of CRTs might be the only way to deal with this issue and to realise 'acceptable' market prices for secondary CRT glass. Also the technical and organisational boundaries should be kept in mind. A CRT glass furnace has technical maximum percentages for secondary glass, which are mixed with primary materials. Also the relationship between 'historic glass waste' and the future demand for CRT glass must be taken into account due to the rapid change to LCD screens instead of CRT screens.

### 7.10.3 Results under a different environmental assessment method

The results of the eco-efficiency directions Section 7.5 are to be checked on their sensitivity for different environmental assessment methods. For instance in Chapter 3.6.1 and Chapter 4.6.1, it is shown that the EDIP'96 method does not address resource depletion of fossil fuel depletion. As a result, plastics and plastic recycling are valued lower. So in absolute terms there can be large differences for the valuation of plastics. The question remains to what extent the eco-efficiency directions of Section 7.5 as such are influenced. Besides the examples already presented in Chapter 5.8, in this case an 28-inch TV is chosen to illustrate the result of various end-of-life scenarios. In Figure 7.29 the resulting eco-efficiency directions are depicted.

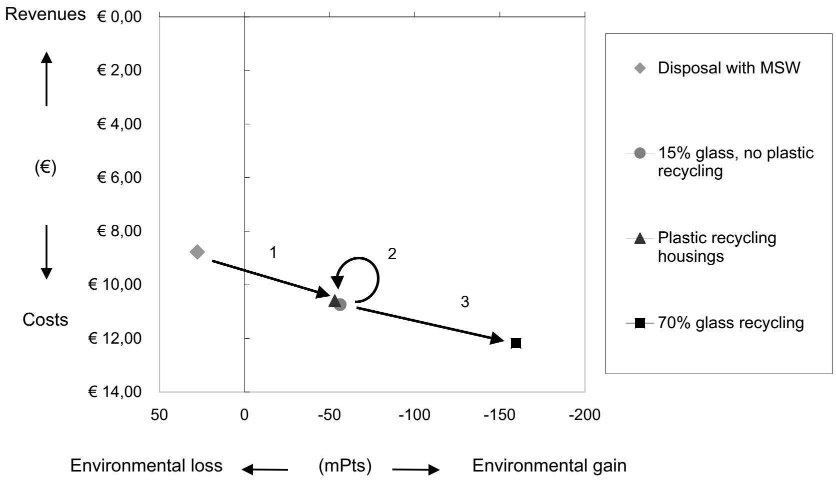


*Figure 7.29 Eco-efficiency directions for a 28-inch TV*

Figure 7.29 shows that prevention of discarding products with the MSW stream, for the TV leads to higher environmental gains and a similar direction in the fourth quadrant (first arrow) compared to the Eco-Indicator '99 method as for instance displayed in Chapter 5.7.3, Figure 5.31. The increase in CRT glass recycling leads to the third arrow. The effect of plastic recycling is negligible as already expected (second arrow). In the next section it is shown, that with disregard of plastic recycling, all other eco-efficiency directions and options under the EDIP'96 method are similar to the Eco-Indicator '99 approach. In fact, apart from the plastic recycling, the diversion in the three categories 'encourage', 'balance' (even the ranking is similar) and 'avoid' remains unchanged. The underlying reason is that (in simple words) the processing is determining the overall performance. This effect was already discovered with the comparison of Figure 3.9 and Figure 3.18 of Chapter 3. In Table 7.10 of Section 7.10.5, the ranking of all options under both environmental assessment methods is calculated and displayed.

### 7.10.4 Eco-efficiency directions to be encouraged

In Table 7.9, all options with a positive eco-efficiency due to a certain change are presented. The last option doesn't appear for the EDIP'96 method. In this case, the resulting direction is in the second quadrant of Figure 7.8, due to the exclusion of fossil fuel depletion from the method.

| Ranking | Strategy |
|---|---|
| 1 | Increase collection rates precious metal dominated products |
| 2 | Separate collection precious metal dominated products with relatively high precious metal content |
| 3 | Increase collection rates metal dominated products with relatively high precious metal and low plastic content |
| 4 | Plastic recycling large sized housings (not in EDIP'96) |

*Table 7.9 First quadrant strategies: Encourage*

The exact preconditions especially applicable for the recycling of large sized housings and separate collection of cellular phones are discussed in Section 7.5. It should be noticed that the disassembly costs for CRT containing appliances are not assigned to the plastic housings. Would this be the case, then also the plastic recycling of large sized housings would fall in the fourth quadrant of Figure 7.8 and be subject to the correlation as as displayed in Figure 7.14.

### 7.10.5 Eco-efficiency directions to be balanced

In Table 7.10, all options to be balanced regarding the environmental gain per euro invested are presented. The ranking of options is displayed for both the Eco-Indicator '99 as the EDIP'96 method The plastic recycling options under the EDIP'96 method are appearing in the third quadrant (higher environmental impacts and higher costs) of Figure 7.8 as discussed before. Note the remarkable resemblance between both rankings. Despite some differences in valuating various materials, the resulting 'fourth quadrant' options (higher environmental gain and higher costs) are put in the same order. The plastic recycling of small sized housings leads to a relatively very low environmental return on investment compared to all other options.

| Ranking | Strategy | EI '99 mPts/€ | EDIP'96 mPts/€ |
|---|---|---|---|
| 1 | Increase collection metal dominated products | > 800 | > 100 |
| 2 | Separate collection precious metal dominated products with relatively low precious metal content | 600-800 | 80-100 |
| 3 | Increase glass recycling 15% to 70% | 380-420 | 65-75 |
| 4 | Increase collection rates glass dominated products | 200-400 | 30-60 |
| 5 | Increase collection rates small plastic dominated products | 100-300 | 15-50 |
| 6 | Dedicated shredding and separation metal dominated products with low plastic content | 50-250 | 8-40 |
| 7 | Plastic recycling medium sized housings | 50-150 | N.A.: 3rd quadrant |
| 8 | Prevention of residue fraction from large plastic housings to cement kiln | 60-80 | 8-12 |
| 9 | Plastic recycling small sized housings | 2-20 | N.A.: 3rd quadrant |

*Table 7.10 Fourth quadrant strategies: Balance*

The exact preconditions especially applicable for the recycling of medium and small sized housings and CRT glass recycling are discussed in Section 7.5. The fourth quadrant options of Table 7.10 are displayed in Figure 7.30 to illustrate the large difference between the various options.

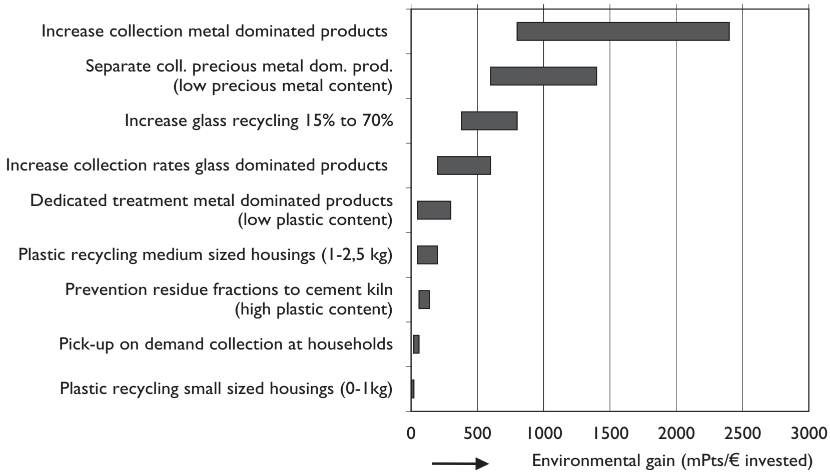


*Figure 7.30 Ranking of 'fourth quadrant' options in environmental gain per money invested*

### 7.10.6 Eco-efficiency directions to be avoided

In Table 7.11, all options to be avoided from both an environmental as an economic perspective are presented. Two of these options are regarding the destination of plastic and residue fractions. Increasing energy recovery is preferable and can be achieved by appropriate outlet control measures. Dedicated shredding and separation of metal dominated products can be left over to the recyclers due to the fact that environmental and economic value recovery are similarly directed.

| | Strategy |
|---|---|
| 1 | Incineration without energy reocvery of plastic and residue fractions |
| 2 | Dedicated shredding and separation of metal dominated products with a relatively high plastic content |
| 3 | Residue fractions from small and medium sized housings to cement kiln |

*Table 7.11 Third quadrant strategies: Avoid*

The exact preconditions especially applicable for the dedicated shredding and separation are previously discussed in Chapter 5.3.5 and Section 7.5.6.

### 7.10.7 Rewarding ecodesign in a collective system

The chosen methodology to evaluate system performance from a product perspective leads to the proposal of a radical change in using policy measures. The methodology developed can be applied on predicting the behaviour of individual products within take-back systems. The calculation of individual performance upfront for use in a rewarding system for collective systems might be very valuable. With regard to the major shortcomings of weight based recyclability scores and due to increasing miniaturisation and application of plastics, this alternative system might be very valuable for monitoring purposes. The QWERTY/EE concept based on actual environmental performance and prediction of end-of-life costs would be more 'honest' in evaluating the performance of single products, recyclers, secondary processors and even systems as a whole. In general: good end-of-life treatment is rewarded.

### 7.10.8 The policy debate on take-back and recycling

The application of the QWERTY/EE approach for stakeholder discussions can bring more detailed environmental information in the ongoing debates. When applied, it can be very useful and is expected to lead to better end-of-life system performance in general, to some extent without even consensus on which environmental assessment model to use or which priorities to assign to the different environmental themes.

Furthermore it can be concluded that the optimisation of fractions sent to the 'right' processors who are closings material loops should get more attention because this determines to a very large extent the system performance. The present use of recyclability targets leads generally speaking to an overemphasis on parts of the end-of-life chain that are in practice of less importance.

Despite the fact that it is expected in general that the proposed changes lead to a higher effectiveness for policy makers and legislators and higher efficiencies and less costs for the system as a whole, the exact consequences are not calculated in this thesis. However, the consequences of the proposals can be calculated when the actual numbers of products affected by the proposed changes are known. An example of this, was presented in Section 7.7.2.

The precise effects of the WEEE Directive towards an implemented and certain steady-state take-back system cannot easily be measured because these systems are not realised yet. Even the Dutch take-back system, in place for a few years now, has fluctuating collection rates per year. Despite all this, the QWERTY/EE concept makes it possible to determine under given collection rates and types of discarded products, what a total system performance would be in terms of environmental and economic performance. Also the consequences of 'WEEE compliance' and the effect of the proposed 'selection of alternative strategies' in this thesis could be determined. Furthermore, a system evaluation should be extended with other product categories like IT equipment, whitegoods, toys and tools etc.

After flexible implementation of the WEEE Directive, an evaluation round is recommended. The QWERTY/EE approach and background data of this thesis would be the appropriate means to perform such an evaluation. With the QWERTY concept both the environmental effectiveness of the regulations and the economic efficiency can be determined and linked to policy strategies that are enhancing eco-efficiency of end-of-life chains.

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# Chapter 8: Conclusions and discussion, recommendations

## 8.1 The central research goal

The core of this thesis was to develop ways and means to provide a quantitative yardstick for assessing recyclability of products in environmental terms. Moreover, a comprehensive eco-efficiency concept has been set-up to determine the performance of certain technical, design and policy changes and enhancing communications among the stakeholders involved in end-of-life treatment. The main research goal of this Ph.D. thesis has been formulated as:

*To determine the performance of discarded consumer electronics in quantitative environmental and economic units and the alignment of treatment, design, policy and legislation and end-of-life system operations in order to improve the eco-efficiency over the end-of-life chain.*

This core goal has been split up in six research questions and corresponding steps:

1. The description of the 'playing field' and the role of all actors or stakeholders and processes involved and the need for a quantitative approach.
2. Development of quantitative environmental descriptions for product recyclability.
3. Development of a quantitative eco-efficiency concept for end-of-life.
4. The application of the eco-efficiency concept to the performance measurement of many individual products in different end-of-life scenarios. This is also including an assessment on the technical improvement potential for these products.
5. The role of product designs on the end-of-life performance and the subsequent improvement potential in particular.
6. The role of public policies and the way these are translated into legislation and take-back system operation as well as the prioritisation of legislative strategies based on the results of the eco-efficiency calculations.

These questions are respectively addressed in the previous Chapters 2-7. This leads to the following conclusions and discussion points per chapter. Specific recommendations for all target audiences follow in Section 8.8.

## 8.2 The need for a quantitative approach

In order to come to a quantitative approach for describing environmental and economic performance of end-of-life treatment, knowledge in the fields of applied ecodesign, waste and secondary processing, metallurgy, waste policy and legislation, (electronic) product design and product characteristics, environmental assessment, return logistics and economics of end-of-life treatment has been integrated, connected and given place in a multidisciplinary approach. From there, the following ingredients are necessary as discussed in Chapter 2:

1. The end-of-life processing chain and the relevance or contribution of certain processes, including the environmental effects at disposal and of secondary material processing
   a. Descriptions of collection and return logistics.
   b. Descriptions of shredding and separation processes and possible settings.
   c. Description of waste processing, e.g. incineration and landfill.
   d. Description of secondary processors, e.g. metal smelters, glass recyclers, etc.
2. Analysis of which environmentally relevant substances are contributing the most to environmental performance.
3. The differences between the various product categories involved.
4. The solution to the double ensemble issue in order to track the performance of individual products over a complex end-of-life chain (products are treated as part of product streams, from there multiple fractions are created with multiple destinations).
5. The choice for and discussion on the use of available quantitative environmental assessment methods. The Eco-Indicator '99 method with an adjusted weighting factor for resource depletion of minerals was chosen as the default method. With this method also human health, ecosystem quality and resource depletion aspects are addressed separately.

As a result, the criteria for the development of two interrelated methodological parts are defined. Firstly an environmental alternative for weight based recyclability and secondly the relation between the described environmental gain and the financial consequences for take-back and recycling are captured in new methodology.

The aim for the development of the quantitative approach for evaluating end-of-life performance of products is related to complex and ongoing discussions between stakeholders involved in end-of-life treatment. This starting point resulted in formulating the lack of a quantitative approach for addressing recyclability of products in environmental terms and the efficiency of end-of-life treatment of these products. It is demonstrated in Chapter 2 and later on in Chapter 4.2.3 that a comprehensive and qualitative environmental and economic assessment of the end-of-life of consumer electronics is rarely found. An important 'gap' exists regarding the quantitative description of end-of-life from a product perspective as a start for broader evaluations. Very often, research on this matter has a very qualitative character based on reviewing systems with general environmental principles. The focus in this thesis, however, is on the behavior of individual products within larger end-of-life treatment systems. This product performance in environmental and economic terms has a central position and is considered regarding a proper alignment of technology improvement options, design strategies and policy.

## 8.3 The QWERTY concept

The QWERTY concept (Quotes for environmentally WEighted RecyclabiliTY) has been developed as an alternative for weight based recyclability and focuses on the determination of environmentally weighted recycling scores and both relative and absolute results. The concept describes the quantitative environmental performance of processing of discarded products in detail. It is very powerful in assessing the effectiveness of end-of-life processing, the consequences of design of products in relation to recyclability issues and the consequences of proposed legislation on take-back and recycling of consumer electronic products.

QWERTY takes into account the 'environmental value' of the treated secondary materials, including the level of re-application and the connected environmental burden of end-of-life treatment. The basic mathematical procedures for calculating QWERTY scores were presented in Chapter 3 as well as the application on a plastic dominated product within various end-of-life scenarios. The double ensemble issue and all other description of end-of-life processing involved have been addressed in environmental calculation schemes within the QWERTY method. Application of the concept shows how well the primary **environmental** goals of take-back and end-of-life treatment, reduction of material depletion, controlling potential toxicity and reducing emissions, are achieved in actual environmental terms. In some cases, the environmental results are not in line with the intended regulations. The example of the plastic dominated product portable audio product, the Soundmachine shows its added value to the alignment of policy and take-back system operation, technology and design in order to increase environmental performance of end-of-life treatment of consumer electronics.

The main characterises of this concept are:

1. The contribution of individual materials and material fractions to the environmental performance of products can be determined.
2. The consequences for individual stakeholders to the overall system performance are described as well as the avenues through which they can increase end-of-life system performance.
3. The consequences of system organisation by visualising the impact in the result of logistics, collective versus individual systems, collection rates, etc.
4. The relation between certain policy or legislative actions and the resulting environmental performance and economic effects
5. It is based on current best available insights in science and LCA on environmental 'accounting' and it enables fast and streamlined assessments, based on precooked environmental and economic data sets to avoid time consuming activities for evaluation of individual products. Therefore data on all relevant processes are included.

With the Soundmachine example it is demonstrated that the QWERTY analysis leads to detailed information on both the role of materials and processes involved in end-of-life treatment. A sensitivity analysis, carried out on the use of single environmental indicators showed that the contribution of the end-of-life processes to the environmental value gained and lost of recycling is very similar, despite the fact that the value connected to the various materials can differ substantially in some cases. This counts especially for the plastics content of products. The discussion showed the influences of uncertainties in some of the most contributing parts to the environmental scores: transport distances, recovery percentages, incineration and landfill settings and energy consumption of shredding and separation. The largest sensitivities lie in the description of leaching at (uncontrolled) landfill sites. However the influence on the result is even in this case limited to a few percent for all different environmental assessment methods integrated in QWERTY.

## 8.4 The eco-efficiency (EE) extension of the QWERTY concept

In Chapter 4, the QWERTY concept is extended with economic descriptions of all processes involved and already described in Chapter 3. The resulting concept is abbreviated as QWERTY/EE. The core of the eco-efficiency approach is the representation of eco-efficiency in 2D graphs for the total system performance. Primarily a **'vector'** approach is chosen. This approach directly shows directions with a positive eco-efficiency (higher environmental gain and revenues) and negative eco-efficiency (the opposite). Improvement options or changes leading to a direction in the first quadrant can be mentioned as positive eco-efficiency and should be promoted. The opposite counts for the third quadrant of Figure 4.4 and Figure 7.8. The fourth quadrant (higher environmental gain and higher costs) and the second quadrant (lower environmental gain and higher revenues) options are to be balanced in terms of environmental gain per amount of money invested. In fact, based on the size and direction of these second and fourth quadrant options, the **'quotient'** approach is applied. The results can be ranked on environmental returns per amount of money invested. This is worked out in detail in Chapter 7 with the discussion on the consequences of different policy strategies.

With this methodology many aspects can be addressed quantitatively. The environmental and economic performance of single products in different end-of-life scenarios, the contribution of individual materials and material fractions can be analysed and optimised:

1. The eco-efficiency performance.
2. The consequences and contributions for single stakeholders.
3. The effect of technical improvement options like plastic recycling.
4. The alignment between the stakeholders involved.

The eco-efficiency of take-back and recycling can be addressed in quantitative values. With the example of the Soundmachine, it is shown that the eco-efficiency concept as a whole is very useful in determining the 'overall performance picture'. Furthermore, the influence of single aspects and issues on this can be determined. For the same example product, the methodological platform was demonstrated regarding the calculation of the influence of technical improvement options, the role of product design and waste policy and legislation.

Sensitivity and uncertainty analysis regarding the economic part has been carried out as well. It could be concluded that the assumptions made, the scope and the boundaries of the economic part of the eco-efficiency calculations are very important. The main discussion items in terms of uncertainty and sensitivity of the results are the use of specific data for the Dutch situation. High uncertainties are present for the collection and transport costs. Especially in the first stages of collection and the contributions of consumers to this, large deviations are possible. The data used in this thesis is mainly based on the 2001 situation for the Netherlands. Other aspects determining the economic data quality are economies of scale and immaturity of secondary glass and plastics markets, the ongoing changes in material substitution and dematerialisation of products, the amounts and concentrations of precious metals, application and changes of new technologies (which are usually functionality driven) like the fast increasing sales of LCD screens instead of CRT screens and finally fluctuations in (secondary) material prices, especially for palladium which has a large influence on economically optimal recycling infrastructures and shredding and separation settings. It is recommended that developments like described above should be followed with the QWERTY/EE method in order to determine how fast and in which direction eco-efficiency performance of end-of-life chains can change.

Generally it can be concluded that addressing costs and revenues in relation to environmental costs and revenues on a quantitative way, is a powerful way for rethinking about the eco-efficiency of the end-of-life of consumer electronic products. Furthermore, better in-sights in the system performance and the demands and constraints of secondary material processors are obtained. Despite the uncertainties in economic data, due to the use of very specific and actual data, a good view on the current performance of the Dutch take-back system is obtained.

## 8.5 Technological improvement options

The QWERTY/EE application on four example products representing plastic dominated, metal dominated, glass dominated and precious metal dominated products resulted in very useful eco-efficiency directions These results were substantiated with a broader analysis on around 75 different products with different characteristics in brand, size and production year. From this the following eco-efficiency directions were derived: The highest environmental improvements per product were realised for the CRT glass recycling of CRT containing appliances. The highest environmental improvements per kg of product are realised in the separate collection scenarios of both cellular phones and cordless phones. The highest economic improvements are realised for the plastic recycling of large housings from CRT or LCD containing appliances for which disassembly was already necessary. High economic revenues per kg product are only realised for the separate collection scenarios of precious metal dominated products.

The lowest environmental improvements per product are realised for the dedicated shredding and separation settings for metal dominated products with still a relatively high plastic content: the VCRs and CD recorders. In fact for these two groups of products even a relatively small, but distinct negative eco-efficiency direction is realised. The lowest economic improvements or highest integral costs are realised for plastic recycling of medium sized housings. The highest costs per kg are appearing for the plastic recycling of small housings. These results clearly indicate that the extra costs are out of proportion in relation to the environmental gain realised in this case.

The QWERTY/EE methodology proved to be very helpful for evaluating the environmental and economic performance of end-of-life processing from a product perspective. For the carrier products also the relevance for economy and environment has been shown for all relevant end-of-life scenarios possible. It has been demonstrated that with the QWERTY/EE concept a more accurate selection and ranking of improvement options within current and future end-of-life processing can be made. This also shows which options shouldn't get priority. In this way it is possible to balance waste policy strategies or legislation as elaborated on in Chapter 7.

The assumptions behind the QWERTY/EE calculations are very important, for instance for the plastic recycling scenarios and the number of product compositions known. In this study, the amount of products assessed is sufficient to derive the results and trends in environmental and eco-efficiency performance as visualised in Chapter 5.6, 5.7 and 7.5. Other aspects of relative high influence on the results are the emissions and energy consumption at metal smelters and how precise precious metal contents of products are known. For disassembly times a large variety is measured leading to significant contributions to total end-of-life costs for several products. In the cases of plastic recycling of small and medium sized housings this has the highest contribution to the costs involved. Many of the plastic recycling cases are jeopardised by the presence of flame-retardants. This makes plastic recycling technically impossible and the scenarios calculated not applicable. Furthermore, it leads to higher treatment costs that cannot be avoided. Also multiple and mixed plastic types or the presence of stickers and buttons can play a negative role. This is besides the already low eco-efficiency of the plastic recycling options as such.

The chosen methodology to evaluate system performance from a product perspective can also be applied on predicting the behaviour of individual products within take-back systems. In principle, this can be used to develop rewarding systems for good performing manufacturers within a collective take-back system.

## 8.6 Design for end-of-life

The two screening redesign cases and in particular the two detailed redesign cases of Chapter 6 showed a limited role of incremental Design for End-of-Life with regard to the improvement of end-of-life performance only. The conclusions from the design case studies are summarised below:

1. The screening case of the plastic dominated Soundmachine shows that the main improvements are increasing the possibility for plastic recycling of the housings and decreasing the disassembly time for this operation. Without these improvements plastic recycling of medium sized housing will be very expensive or even impossible.
2. The screening design case of the cellular phone shows the domination of the precious metals. All design efforts should be focused on optimisation of getting precious metals in the copper fraction. If separate collection of cellular phones would be organised, then applying a few design aspects can make this stream better acceptable for secondary processing.
3. The environmental improvements of the redesign of the 17-inch CRT monitor are relatively small. The main reason for this is the fact that products like these are already highly optimised. The environmental improvement potential is only around 4% under two different environmental assessment methods used. However, from a cost perspective, the disassembly time and the connected end-of-life costs in general can be reduced significantly.
5. The detailed redesign of the DVD player leads to a lower recovery of environmental value. However, the reduction in environmental value put into the product is in absolute values much larger under both environmental assessment methods. The remarkable conclusion here is that a successful 'Design for End-of-Life' effort, which is in fact proper material selection, leads to a lower end-of-life performance in end-of-life. See Chapter 6.7.4, Figure 6.19 for all details.

The main conclusion of the detailed redesign efforts of the 17-inch CRT monitor and the DVD player is that the improvement bandwidth of design is limited. The main reason is that the incremental Design for End-of-Life activities is bound to all kinds of restrictions. These restrictions can be categorised in environmental restrictions and 'practical' or managerial restrictions. The environmental restrictions are due to the life-cycle perspective in particular. A violation of this principle is for example replacing plastic housings with steel or aluminium housings as demonstrated in Figure 6.10. The managerial restrictions are due to all kinds of financial considerations, functionality demands and other design aspects like looks, reliability and safety constraints, development time and supply chain aspects.

Despite the very limited degree of freedom on the short term for improving end-of-life aspects from a design perspective, the examples show that optimising for end-of-life costs can lead to significant improvements. These costs are not directly visible for the producer at the current moment, but on the long term with increasing collection of disposed consumer electronics within take-back system to be paid by the producers themselves, there will certainly appear a indirect influence on cost prices of products.

The two main avenues for costs decrease in end-of-life are optimisation of fractions in order to maximise recovery of economic value and decreasing disassembly times for products expected to be disassembled.

The relation between design and other end-of-life processing like copper smelter processing is relevant. The further alignment of fraction compositions from treatment of electronic products remains a relevant issue in the future also due to increasing miniaturisation and changing product compositions.

## 8.7 Public policies and strategies for electronic waste

The main priorities from a policy perspective are derived with the application of the QWERTY/EE concept and the results presented in Chapter 5. A further elaboration on the eco-efficiency directions related to discarded products resulted in the following division in:

1. Directions to be favoured by policy measures (first quadrant of the 2D eco-efficiency graphs of Figure 4.4 and Figure 7.8: higher environmental gains, lower costs).
2. Directions to be balanced in terms of environmental return per amount of money invested (mainly fourth quadrant options: higher environmental gain and higher costs).
3. Directions to be avoided (third quadrant: lower environmental gain, higher costs).

The eco-efficiency directions to be encouraged are:

1. Increase collection rates of precious metal dominated products and of metal dominated products with relatively high precious metal and low plastic contents.
2. Separate collection precious metal dominated products with relatively high precious metal contents.
3. Plastic recycling of large sized housings when disassembly is already applied for the removal of a CRT or LCD.

The eco-efficiency directions to be balanced in terms of environmental gain versus costs are, in order of preference (see also Figure 8.1):

1. Increase collection rates of other metal dominated products.
2. Separate collection precious metal dominated products with relatively low precious metal content.
3. Increase CRT glass recycling.
4. Increase collection rates glass-dominated products.
5. Increase collection rates plastic dominated products with small and medium sized housings.
6. Dedicated shredding and separation of metal dominated products with low plastic contents.
7. Plastic recycling of medium sized housings.
8. Prevention of residue fraction from large plastic housings to cement kiln.
9. Pick-up on demand collection at households. The environmental return is compared with the above options very small.

10. Plastic recycling small sized housings, environmental return on investment is almost zero.

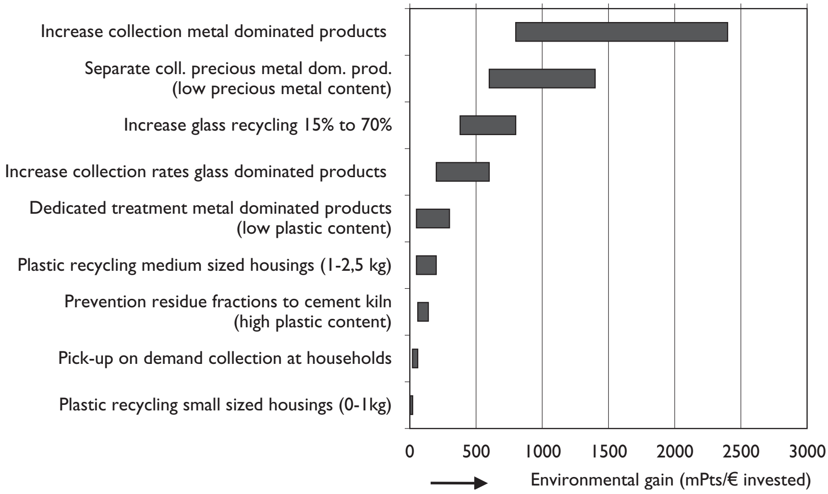


*Figure 8.1 Ranking of 'fourth quadrant' options in environmental gain per money invested*

The eco-efficiency directions to be avoided are:
1. Incineration without energy recovery of plastic and residue fractions.
2. Dedicated shredding and separation of metal dominated products with a relatively high plastic and low precious metal contents.
3. Residue fractions with a relatively low plastic content (from small and medium sized housings) to the cement industry.

The results derived with the QWERTY/EE method appear to be very consistent and not very sensitive to the choice of the underlying environmental assessment method, except for plastic recycling which is less preferable under (all) other environmental assessment methods not addressing resource depletion of fossil fuels.

The above division of eco-efficiency directions leads to the following conclusions regarding the use of policy strategies:
1. Recyclability targets in the WEEE Directive are in some cases leading to very low environmental returns on investments and in a few cases even to lower environmental performance. They should be abolished completely and replaced by obligatory treatment and outlet control rules. Outlet control rules are far easier to monitor (although the following rules seem rather stringent, the integral costs involved are expected to be lower in comparison with recyclability targets). Details are presented in Chapter 7.10.
2. Collection rates should be split per product category. Especially for metal dominated and precious metal dominated products higher percentages should be prescribed. Collection rates enhancing measures must be applied with precaution in order to avoid relatively high costs of collection and logistics, especially for small products.

3. Recyclers should determine when dedicated treatment of metal dominated products is efficient, while in this case environmental and economic optimisation are equivalent. No treatment rules are necessary for these product categories.
4. A separate collection system for precious metal dominated products with precious metal content above certain concentrations should be prescribed or encouraged.

The application of the QWERTY/EE approach in stakeholder debates can be very useful and when followed and implemented it is expected to lead to better end-of-life system performance in general. In most cases consensus on which environmental assessment model to use or which priorities to assign to the different environmental themes is not required while 'all arrows point is the same direction'. However, upfront agreement on which environmental assessment method to start with for evaluation purposes is recommended.

The use of recyclability targets leads to an overemphasis on aspects of the end-of-life chain that are of relatively less importance. Generally speaking, most environmental attention should be given to the relation between recyclers creating the 'right fractions' for the 'right secondary processors' who are closing material loops with these fractions. Also attention should be given to the realisation of economies of scale and efficient collection infrastructures.

The exact policy measures or steps to take, especially for the options displayed with the fourth quadrant need special attention. These can be supported by calculations as made in this thesis. For instance, when an evaluation round is performed, a few years after implementation of the WEEE Directive, the QWERTY/EE methodology, the underlying calculation schemes and the background data presented in this thesis, would be the appropriate means to do this.

## 8.8 Recommendations

### 8.8.1 Recommendations for producers and designers

In this section a few recommendations are given for all stakeholders involved. The recommendations are intended to better align stakeholder debates based on the insights acquired in this thesis.

The first group to be addressed are the producers or manufacturers of electronic equipment. The following remarks are to be made:
1. Use environmental validation of the end-of-life phase of products and use scientific knowledge as presented in this research when negotiating about setting up recycling systems in order to assess the efficiency of proposed measures.
2. More knowledge on product compositions. This sounds trivial, but in many cases, product weight, compositions and characteristics are not known sufficiently. Use or develop streamlined environmental benchmarking and validation as a means to determine the position of products with regard to other concurrents.

3. Determine end-of-life costs upfront: Especially for operation in collective systems, an alternative division of the total costs of take-back system operation instead of a split on market share is possible. Estimates on actual end-of-life costs for products treated can be calculated and can possibly lead to significant cost reduction in negotiations.
4. Take into account the improvement options for products design of Chapter 6, especially the reduction of disassembly times can still be significant and also lead to lower assembly times and a more efficient plastic recycling when required in the future.
5. With the QWERTY/EE approach it is possible to monitor the individual or collective take-back systems that are joined per country. With the insight acquired, performance demands can be better substantiated.

It is proven that the QWERTY/EE methodology for calculation of environmental performance is very useful in determining redesign strategies and evaluation of design choices. The main 'features' are the calculation of the relevance of the various processes involved and which materials to prioritise. Also the evaluation of the redesign results is very valuable. The implementation of streamlined environmental calculations for various end-of-life scenarios is recommended for the further development of design tools. An important recommendation is a further evolvement of a life-cycle perspective check on the redesign results. In the case of substantially changing material selections, also the full production values of materials including deformation processes etc., should be incorporated. In this respect, the Figure 6.3 is highly relevant and can easily be extended with this environmental value of these processing.

### 8.8.2 Recommendations for recyclers and secondary processors

The use of QWERTY/EE can help to evaluate the environmental and economic consequences of technical improvement options like adjusted shredding and separation settings or plastic recycling. Besides minimising costs for end-of-life treatment, also comparisons can be made to assess the eco-efficiency performance of different recyclers. With the proposed calculation schemes and the solution of the double ensemble issue (the description of the behavior of multiple products in products streams, products stream in multiple fraction with multiple destinations, see Chapter 2.3.5), also the average performance of single products within larger end-of-life processing infrastructures can be predicted and communicated towards other parties involved in take-back and recycling. Also eco-efficiency comparisons between concurrent recyclers can be made and communicated. Finally, the importance of closing material loops and the connected environmental burdens and gains can be substantiated with QWERTY/EE and communicated to other stakeholders.

### 8.8.3 Recommendations for policy makers

The main recommendation for policy makers is to revise targets and strategies with respect to actual measurement of environmental gain realised in relation to the financial consequences of the (envisaged) regulations. The QWERTY/EE method is a perfect opportunity for linking policies and legislation to a real eco-efficiency basis . Also the proposed alternative for quantitative determination of the desired level of re-application of secondary materials can assist greatly in ongoing discussions on the matter, also for different waste streams than consumer electronics.

The proposed and far reaching alternatives for weight based recyclability targets, are serving the environmental goals (which are common grounds for all stakeholders) much better. It is clearly proven that the current strategies will lead to far less eco-efficient end-of-life systems for discarded consumer electronics. On top of that, the proposed way to balance policy and strategies is much more practical and is rewarding good and proper recycling activities. It is also more in line with current and future monitoring of take-back systems. Another important recommendation as a summary of the conclusions in Section 8.7 is that waste policies should be much more targeted and prioritised regarding the various product categories and material compositions involved, rather than on basis of the scope of industry associations.

### 8.8.4 Recommendations for (national) take-back system operators

The recommendations for operators of take-back systems are manifold. QWERTY/EE can be used for:

1. Comparison between different take-back systems for different products and in between different countries.
2. Comparison of the eco-efficiency performance of different recyclers contracted.
3. Measuring of the effect of increasing economies of scale.
4. Rewarding of good ecodesign of individual manufacturers in a collective system when the performance of single products is assessed upfront from an eco-efficiency perspective.
5. Further optimisation of the end-of-life chain from an eco-efficiency perspective.
6. The monitoring of system performance can be enhanced and the scope of monitoring can be widened to actual environmental performance instead of only measuring mass streams.
7. Further alignment with policies prescribed within the European situation can be aimed at and the own position in the European playing field can be better understood and substantiated with quantitative means.

Until now, the scope of the QWERTY/EE method is limited to the consumer electronics. This can relatively easy be extended to other product categories like IT equipment, whitegoods, toys and tools etc, in order to come to broader evaluation of take-back system evaluation and to acquire larger economies of scale.

### 8.8.5 Recommendations for scientists and further research

Many underlying research fields can be further explored and connected to the presented approach for environmental validation and eco-efficiency analysis of end-of-life issues. Next to a broadening of the scope towards other electric and electronic products, also completely different product categories can be addressed in a similar way.

Within the category of consumer electronics also an ongoing in-depth analysis is proposed to reduce uncertainties and to gain more insights in the interrelations of the research fields. In this way stakeholder debates on the organisation of future take-back systems can be further supported. From a scientific perspective, this thesis must be regarded as a starting point and a first comprehensive collection of all relevant data in the field of product end-of-life evaluation. The following aspects are regarded to be of particular interest:

1. Better process information and description of material loops in general also for take-back systems other than the Dutch system. Special focus should be given to the emissions at incineration and other thermal processing installation, landfill sites, glass recyclers, cement kiln, building industry and the metal smelters. The copper-smelting routes in particular are found to have major impact on the environmental results. Large differences between modern versus more old-fashioned flue gas cleaning systems at smelters are known. Also further analysis on the optimisation of grade – recovery functions connected to streamlined environmental assessments is regarded as an undiscovered and interesting research area.
2. The QWERTY/EE evaluation of a take-back system can also be performed for other countries. For instance in the US where discussions on creating take-back system for consumer electronics are still taking place, the approach is very useful in order to optimise end-of-life chains from an eco-efficiency perspective and to prevent the mistakes made with the EU Directives.
3. More (accurate) Life Cycle Inventories for the most important materials should be obtained. Connected to this, better methodological descriptions and data must be implemented for improving the characterisation of resource depletion of minerals.
4. The behavior of flame-retardants in end-of-life processing and in particular in incineration or smelting processes must be further investigated. In this thesis all environmental consequences of flame-retardants were connected to the total bromine content of the products under investigation. However, the behavior of flame-retardants and the connected possible dioxin and furan formations steps should be better modelled and investigated. The same counts for the still unclear toxicological effects of liquid crystals present in LCD screens.
5. In this thesis a very practical and successful attempt was made to streamline environmental assessment methods for end-of-life evaluation. In LCA software and related programs, the end-of-life phase is neglected or not properly addressed due to for instance allocation problems. The way of thinking and modelling behind the QWERTY/EE method might be useful for implementation in LCA models and software tools as well.
6. Disassembly analysis and developments in this field may play an important role in improving environmental and in particular economic performance. Further research on this topic not only focused on component reuse or remanufacturing options but also towards material recycling is recommended for a limited number of product types. The extension of the QWERTY/EE approach to evaluate reuse and remanufacturing potentials is an important recommendation and regarded as a next possible step in broadening the scope of this methodology.
7. The graphs in this thesis addressing the loss and contributions of the various processes to this loss, both from an environmental as an economic perspective

should be further worked out in detail in order to determine the inevitable costs and environmental burdening that cannot be managed and the part or improvement bandwidth due to costs or environmental burden that can be minimised or possibly avoided. This counts specifically for graphs like for instance Figure 3.9 and Table 4.8.
8. The results presented in this thesis are based on products sold in between 1998 and 2002. It is recommended to determine the influence of changing product compositions over a much longer period. Also differences between brands could be followed to a larger extent.
9. Incineration with a higher energy recovery than for MSW plants including dedicated and modern flue gas cleaning should be investigated and evaluated. This might be a more eco-efficient improvement for all non-recyclable (mixed) plastics and housings.

### 8.8.6 Recommendation: stimulate multidisciplinary research

With the establishment of the connection between many different and 'fundamental' or traditional research areas to a comprehensive environmental and eco-efficiency approach, a very successful multidisciplinary research has been conducted. Despite all kinds of uncertainties in parameters, data, specific research fields and processes involved, the most important conclusions and results regarding the role and position of technology, design and policy are in almost all cases pointing into the same direction. For sure, the most important aspect making this multidisciplinary approach successful, is the very fruitful cooperation with many people from various backgrounds and their willingness to contribute to this complex type of research and for not 'sticking' to much to their own traditional research fields. The cooperation between the various university groups, companies, recyclers and knowledge institutes involved in this research is by definition an important condition for success.

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# *Appendix 1: Terminology, definitions and abbreviations, materials described*

## Terminology and definitions

*Collection rates* are defined as the percentage of a certain type of products handed and treated in a take-back system versus the total amount of products. Products in stock at consumers are not included in this definition. The not collected products are either exported or treated with MSW.

*Design (for end-of-life)* is defined as the product (re)design in order to improve end-of-life performance in environmental or economic terms.

*Disassembly* is either the manual or automated splitting of products in components or fractions (before an optional shredding step) to increase the value of certain fractions or the (obligatory) removal of contaminants and hazardous materials.

*End-of-life* and the *end-of-life chain* is defined as the part of the life-cycle of a certain product starting with the point of disposal by a customer (this can be a consumer, organisation or business) till the point where materials are re-entering production chains. Remanufacturing and reuse also fall under the end-of-life chain.

*End-of-life routes* are defined as the activity of treating products, products streams, components, assemblies or *fractions* in *secondary material processing* or *final waste processing*

*End-of-life scenarios* are defined as the total set of treatment of certain products, products streams, components, assemblies or *fractions* with *mechanical treatment, disassembly, reuse, remanufacturing, secondary processing* and *final waste processing*

*Final waste processing* is defined as the treatment of products, products streams, components, assemblies or *fractions* by landfill, controlled or uncontrolled, or by incineration of the product with or without energy recovery.

*Fractions* are defined as streams of multiple materials with one or more target materials to be recovered at *secondary processes* or as (residue) streams formed to be treated by *final waste processors*

*Mechanical treatment* is defined as the (sorting and) shredding of (streams of) discarded consumer electronics followed by separation of materials into *fractions* by processes like magnets, Eddy-Current separation or air tables.

*Recycling* is used as a general term for treating (streams of) discarded products in one way or another.

*Material recycling* is referring to the activity to recover by treating streams of discarded consumer electronic products in a central facility either with *mechanical treatment* or *disassembly.*

*Remanufacturing* is defined as the activity where reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned, inspected for possible repair and reuse.

*Reuse* is defined as the second hand trading of products, assemblies or components for use in its original purpose.

*Secondary material processing* is defined as the activity aimed at specific recovery of one or more valuable material, obvious examples are copper smelting, plastic recycling and CRT glass recycling.

*State-of-the-art treatment* is defined as the single *end-of-life scenario* reflecting the current average treatment of browngoods within the Dutch *take-back system*

*Take-back systems* are defined as the total sets of *end-of-life scenarios* of multiple products streams including collection and logistics of these streams and the organisational and financing systems.

## Abbreviations

| | |
|---|---|
| ADSM | Active Disassembly using Smart Materials |
| CML2 | Centrum voor Milieukunde Leiden (LCA method) |
| CRT | Cathode Ray Tube |
| DC | Distribution Centre |
| DfCC | Design for Chemical Content |
| DfD | Design for Disassembly |
| DfHM | Design for Heavy Metals |
| DFND | Design for Non-Disassembly |
| DfR | Design for Recycling |
| EDIP'96 | Environmental Design of Industrial Products (LCA method) |
| EI'95 | Eco-Indicator '95 (LCA method) |
| EI'99 | Eco-Indicator '99 (LCA method) |
| ELDA | End-of-life Design Advisor |
| ELSEIM | Metrics for End-of-life Strategy |
| EPR | Extended Producer Responsibility |
| EPS | Environmental Priority Strategies (LCA method) |
| EQ | Ecosystem Quality (part of Eco-Indicator '99 method) |
| EU | European Union |
| EVCA | External Value Chain Analysis |
| EVR | Eco-costs Value Ratio |
| HH | Human Health (part of Eco-Indicator '99 method) |

| | |
|---|---|
| LCA | Life Cycle Assessment |
| LCD | Liquid Crystal Display |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LME | London Metal Exchange |
| MFA | Mass Flow Analysis |
| MRE | Material Recycling Efficiency |
| MSW | Municipal Solid Waste |
| NGO | Non-Governmental Organisation |
| PBB | Poly-Brominated Biphenyls |
| PBDE | Poly-Brominated Dimethyl Ethers |
| PMRCM | Product Material Recycling Cost Model |
| PWB | Printed Wiring Board |
| QWERTY/EE | Quotes for environmentally WEighted RecyclabiliTY/ Eco-Efficiency |
| RD | Resource Depletion (part of Eco-Indicator '99 method) |
| RoHS | Restriction on the use of Hazardous Substances (EU Directive) |
| RSS | Regional Sorting Station |
| SFA | Substance Flow Analysis |
| TPI | Toxic Potential Indicator |
| UNEP | United Nations Environmental Programme |
| WBSCD | World Business Council for Sustainable Development |
| WEEE | Waste of Electric and Electronic Equipment (EU Directive) |

## Parameters used in QWERTY/EE

| | |
|---|---|
| $EVW_{min,i}$ | the defined minimum environmental impact, maximum recovery of environmental value for the weight of material i; |
| $EV_{subst,i}$ | the environmental substitution value for the extraction of raw material for material i, measured with a relevant environmental impact assessment score; |
| $m_i$ | the weight of material i within the product; |
| $EVW_{min}$ | the total defined minimum environmental impact minimum environmental value for the complete product. |
| $EVW_{max,i}$ | the defined maximum environmental impact/for the weight of material i; |
| $EV_{max\ eol,i}$ | the maximum environmental impact for material i in the end-of-life scenarios under investigation, e.g. the 'worst case scenario (usually or incineration without energy recovery, or uncontrolled landfill). |
| $EV_{pretr,i}$ | the aggregated environmental value for material i undergoing pre-treatment steps (f.i. transport and storage, complete shredding and separation); |
| $EVW_{max}$ | the total defined maximum environmental impact or maximum environmental value for the complete product. |
| $EVW_{actual,i}$ | the defined actual environmental value for the weight of material i for the EOL scenario under consideration; |
| $x_i$ | the percentage of material i undergoing the defined pre-treatment steps; |
| $rec_i$ | the percentage of material i being recovered and substituting its corresponding primary material; |

| | |
|---|---|
| $grade_i$ | the grade in which material i is occurring after recovery (only relevant for recovered material with a different level of re-application compared to the original material); |
| $EV_{eol,ij}$ | the environmental value for material i going into end-of-life route j; |
| $y_{ij}$ | the percentage of material i ending up in end-of-life route j; |
| $EVW_{actual}$ | the defined actual environmental value for the complete product and the EOL scenario under consideration. |
| $QWERTY_i$ | the amount in which material i contributes to the total QWERTY score (in percent); |
| QWERTY | the QWERTY score for the complete product; |
| $QWERTY_{loss,i}$ | the amount in which material i contributes to the total QWERTY loss score (in percent); |
| $QWERTY_{loss}$ | the QWERTY loss score for the complete product. |
| $MRE_i$ | the contribution of the weight of material i to the Material Recycling Efficiency; |
| MRE | the total Material Recycling Efficiency for the whole product weight and the corresponding EOL scenario under consideration. |
| $IC_{inc}$ | the integral costs paid for incineration of the material fraction |
| $IC_{inc,i}$ | the contribution of material i to the integral costs for incineration |
| $m_i$ | the weight of material m in the fraction |
| m | the weight of the fraction |
| $TC_{inc}$ | the general treatment costs for the fraction (set at 250 €/ton, (Fraunhofer 2002a)) |
| $UD_i$ | the threshold for material I for which above a penalty has to be paid |
| $P_i$ | the penalty paid for material i, only if $m_i > UD_i$ |
| $IC_{landfill}$ | the integral costs paid for landfill of the fraction |
| $IC_{landfill,i}$ | the integral costs for material i to the integral costs of landfill |
| $m_i$ | the weight of material i in the fraction |
| m | the weight of the fraction |
| $TC_{landfill}$ | the general treatment costs for the fraction (set at 140 €/ton for controlled landfill and 64 €/ton for uncontrolled landfill, (Fraunhofer 2002a)) |
| $UD_i$ | the threshold for material i |
| $P_i$ | the penalty paid for material i, only if $m_i > UD_i$ |
| $IC_{copper}$ | the integral costs and revenues paid/received from a copper smelter |
| $m_i$ | the weight of material i in the fraction |
| m | weight of the fraction |
| $UD_i$ | the Unit Deduction for material i (above this threshold revenues are received). |
| $LME_i$ | metal prices for material i at the London Metal Exchange (see Section 4.3.8) |
| AF | Adjustment Factor, the percent of the LME price offered by the smelter |
| $RC_i$ | the refining charge to be paid for material i |
| $TC_{copper}$ | the general treatment charge to be paid for fractions delivered at the smelter |
| $IC_{copper, pen}$ | the integral penalty costs paid for the fraction/ lot at the copper smelter |
| $IC_{copper, pen,i}$ | the total penalty for material i to the integral costs of the copper smelter |
| $m_i$ | the weight of material m in the fraction |
| m | the weight of the fraction |
| $UD_i$ | the penalty threshold for material i |
| $P_i$ | the penalty paid for material i, only if $m_i > UD_i$ |
| $IC_{ferro}$ | the integral costs and revenues paid/received from a ferro smelter |
| $m_{ferro}$ | the weight of material i in the fraction |
| m | weight of the fraction |
| $LME_{ferro}$ | metal prices for iron at the London Metal Exchange (see Section 4.3.8) |

| | |
|---|---|
| $TC_{ferro}$ | the general treatment charge to be paid for the fraction delivered at the ferro smelter |
| $IC_{aluminium}$ | the integral costs and revenues paid/received from an aluminium smelter |
| $m_{aluminium}$ | the weight of material i in the fraction |
| m | weight of the fraction |
| $LME_{aluminium}$ | metal prices for iron at the London Metal Exchange (see Section 4.3.8) |
| $TC_{aluminium}$ | the general treatment charge to be paid for the fraction delivered at the aluminium smelter |
| $IC_{min,i}$ | the best case economic value, minimum costs, for the weight of material i; |
| $IC_{subst,i}$ | the maximum economic substitution value for the extraction of raw materials for material i, |
| $m_i$ | the weight of material i within the product/ fraction; |
| $IC_{min}$ | the total defined lower boundary minimum economic value for the complete product or fraction under consideration |

## Material (categories) used in QWERTY/EE

| | |
|---|---|
| ABS | Acryl Butyl Styrene |
| Ag | Silver |
| Al | Aluminium |
| As | Arsenic |
| Au | Gold |
| Be | Beryllium |
| Bi | Bismuth |
| Br | Bromine |
| Cd | Cadmium |
| Ceramics | Ceramics |
| Cl | Chlorine |
| Cr | Chromium |
| Cu | Copper |
| Epoxy | Epoxy |
| Fe | Ferro |
| Glass | Glass |
| Hg | Mercury |
| HIPS | High Impact Polystyrene |
| Liquid Crystals | Liquid Crystals |
| Ni | Nickel |
| Other | f.i. wood and cardboard |
| Pb | Lead |
| Pd | Palladium |
| Plastics | Plastics aggregated, excl. PVC |
| PP | Polypropylene |
| PS | Polystyrene |
| PVC | PVC |
| Sb | Antimony |
| Sn | Tin |
| Zn | Zinc |

# Appendix 2:

# Tables and figures used in this thesis

# *Appendix 3:*

# *The QWERTY/EE calculation scheme*

Schematic description of the QWERTY/EE calculation sequences:

Input

| | | |
|---|---|---|
| Component Compositions<br>**Non Detailed** →<br>Main materials<br>Product Category<br>**Detailed** →<br>All materials | Product Composition<br>**Non Detailed** →<br>Cu/Fe/Al/Plastics/Rest content<br>**Detailed** →<br>(All metals etc) | EOL scenario/ distrib.1<br>**Shredding settings** →<br>CRT containing<br>Non-CRT containing<br>Precious metal dominated<br>Metal dominated<br>→ |
| Fraction Composition<br>**Non Detailed** →<br>Main materials<br>incl subsequent steps<br>**Detailed** →<br>All rel. materials within fractions | Env.asses.model<br>**Aggregated scores**<br>Air EI95<br>Water EI99 HH, EQ, RD<br>Soil EDIP96 no resd.<br>Primary EPS<br>Second. CML2 | Processes/ distrib. 2<br>Landfill and leaching model<br>Incineration model<br>Copper smelter<br>Ferro smelter<br>Aluminium smelter<br>Glass furnace<br>Plastic recycler, etc |
| Economic Data<br>MSW, landfill, incineration, penalties<br>Copper smelter, incl penalties<br>Material prices, LME<br>Glass replacement options<br>Sorting, sampling, storage costs<br>Shredding and separation costs<br>etc. | Logistics<br>**Transport distance**<br>**Costs**<br>Consumer - retailer/ municipality<br>Retailer/ municpality - DC/RSS<br>Consumer - RSS<br>Alternatives: Pick-up on demand | Collection rates<br>**Collection rates**<br>Small appliances default,<br>Medium sized appl. HH, EQ, RD<br>Large appli. |

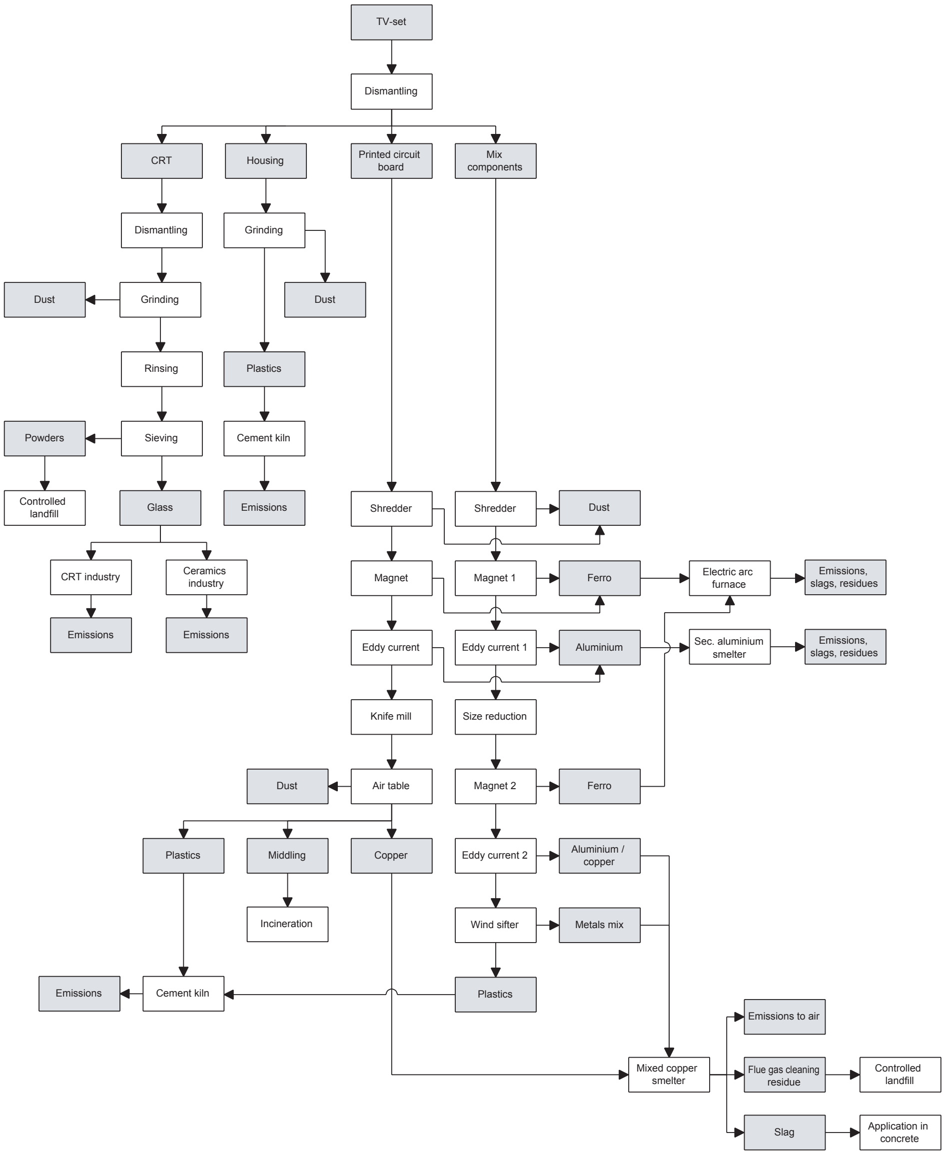
Output

| | | |
|---|---|---|
| Basic Results<br>MRE<br>QWERTY<br>QWERTY loss<br>Cost efficiency<br>Absolute environmental result<br>Absolute economic result | EOL Scenario analyser<br>MRE vs QWERTY<br>Other environmental scenarios<br>Other economic scenarios<br>Costs per stakeholder<br>Environment per stakeholder | Other LCA methods<br>MRE<br>QWERTY<br>QWERTY loss<br>Cost efficiency<br>Absolute environmental result<br>Absolute economic result |
| Eco-efficiencies<br>2D EE graphs<br>Collection rates<br>Multiple scenarios<br>Plastic, glass recycling<br>Separate collection<br>Multiple shredding settings | Multiple results<br>Glass dominated<br>Plastic dominated<br>Metal dominated<br>Precious metal dominated | Contributions of processes<br>Loss due to lower grade/ non rec.<br>Impacts of indiv. processes<br>Life cycle check redesigns |

# Appendix 4:

# Detailed end-of-life processing trees

For CRT containing appliances (Source: Ansems 2002a).



# *Appendix 5:*

# *Generic design for end-of-life rules for consumer electronics*

This table is derived from (Eikelenberg 2003)

| Nr. | Design Rule |
|---|---|
| 1 | Determine key heavy metal parts |
| 2 | Reduce the weight of materials with little value |
| 3 | Determine whether the product has a positive, neutral or negative recycling value |
| 4 | Replace components by alternatives with higher recycling value or a low amount of penalty elements |
| 5 | Determine which End-of-Life scenario is applicable for your product |
| 6 | Increase the number of connections between heavy metals and copper or printed circuit board |
| 7 | Select low heavy metal components |
| 8 | Set up (co-)development projects for low heavy metal components |
| 9 | Develop power supplies and motors with improved unlocking performance of the copper winding and iron core |
| 10 | Select a switching power supply |
| 11 | Avoid specifications which require key heavy metal items |
| 12 | Do not use metal inserts in large plastic parts |
| 13 | Concentrate material groups in easily separable or separate assemblies of the product |
| 14 | Improve separation characteristics like magnetism, electric conductivity |
| 15 | Use magnetic metal fixtures when parts of different plastics (e.g. housing) are connected |
| 16 | If screws are necessary, use bridle screws made out of the same plastic |
| 17 | If you use different plastics for large plastic parts, the difference in specific density should be larger than 0.1 kg/dm3, e.g. PP with ABS |
| 18 | Use different colours for difficult to separate plastics (e.g. black and white, black and red) |
| 19 | Look for specific physical properties that are easy to separate |
| 20 | Do not attach buttons, windows, doors etc. to the housing or front if they are not made of the same material |
| 21 | Use solid wiring instead of threaded wire wherever possible |
| 22 | Use the same plastic for housing, front and brackets |
| 23 | Use form enclosures rather than screws |
| 24 | Make enclosures of parts that have to be unlocked at least 10 mm |
| 25 | Do not attach components made of a material mix (e.g. PCB's) to parts made of mono material larger than 50 g. |
| 26 | If you need connections between heavy metal parts and either steel or plastics, make them large |
| 27 | Avoid connections between heavy metals and steel or plastic |
| 28 | Heavy metal coatings should not be used |
| 29 | No design measures necessary for lead and zinc in common steel shredder material mixes (higher lead content in consumer electronics) |
| 30 | Limit the amount of copper in steel to be recycled |
| 31 | Reduce the volume of waste by reducing the amount of toxic materials |
| 32 | Use material coding (coding only relevant for preparatory disassembly or mechanical disassembly) |
| 33 | Use recyclable materials |
| 34 | Use compatible materials |
| 35 | If use of compatible materials is impossible, make easy to disassemble modules which each consist of compatible materials (disassembly steps quickly uneconomical in case of consumer electronics, but sometimes possible) |
| 36 | Place modules that need to be disassembled in the outer areas of the product and make them easy to disassemble |
| 37 | Select easy to loosen or break fastening techniques (only breaking fasteners is relevant, except for preparatory disassembly) |
| 38 | Code dangerous substances and make them easy to remove |
| 39 | Minimise the number of materials |
| 40 | Design sub-assemblies which can be easily separated into fragments which will have different treatments |
| 41 | Use only materials that can be cleanly separated by low-cost separation techniques |
| 42 | Use materials that can be melted |
| 43 | If using smeltable materials or materials with different separation properties cannot be used, move critical parts to other positions or make them suitable for manual disassembly |
| 44 | Reduce the size and thickness of the parts made of the highest strength materials |
| 45 | Choose materials with low tensile strength and notch impact strength for the largest parts |
| 46 | Make target materials easy to unlock from the non-target materials |
| 47 | Make target materials easy to unlock from other non compatible target materials |

# Appendix 6:

# Detailed redesign solutions DVD player and 17-inch Monitor

This information is obtained from (Eikelenberg 2003)

## Redesign DVD player

### Redesign strategy 1a: Reduce volume of materials

1. Reduce total volume of the casing in all dimensions. Move the CD-unit from the middle to the side in order to create room for the display.
2. Reduce volume by lowering the height and depth of the casing, keeping the same aesthetic. DVD driver is the limiting factor in the height.
3. Lower the amount of aluminium in the inner/bottom panels. Making more ribs can reduce the aluminium cooling rib.
4. Use thinner steel sheet.
5. Reduce size of PCBs. This will also reduce the use of more expensive components.
6. Integration of PCBs.
7. Use double sided PCBs. Less carrier material is required resulting in a higher concentration of valuable materials.
8. Remove the buttons, resulting in reduction of PCB and plastics. All functions are accessible by Remote Control.
9. Remove display to (universal) Remote Control.
10. Use tray car-insert for CD instead of current CD-unit.

### Redesign strategy 1b: Substitute undesired materials with others

1. Replace metal top housing by plastic. Using submerged marks and ribs for extra support (for stacking different components). (Specific functional requirement to use metal? Image? Generally, plastic is used in audio-equipment.)
2. Replace steel bottom by plastics. Using plastic support on the bottom.
3. Do not select Nickel containing capacitors.
4. Replace screw by a sort of cap.
   Holes in the PCB must be enlarged, since plastic screws are normally bigger. Other possibilities are the use of a metal screw with weakening or controlled "memory" plastic materials (materials return to original form). Around the screws, no components can be placed.

### Redesign strategy 2: Reallocate materials or components

1. Move power (supply) PCB from the right to the left (including buttons). Less cabling is required.
2. Redesign motor for easy separation of steel and copper.
3. Reallocate the copper clamp attachment (2x small spring) on PCB instead of steel housing.
4. Reallocate the plug projection in the housing to prevent clasping during the shredder process.

5. Enhance the distance between the copper and aluminium components on the PCB. (Due to the cooling requirement and the functionality of aluminium, reallocation of the copper and aluminium components might not be possible.)

**Redesign strategy 3: Optimise connections**

1. Use plastic screws, which will break easily, between PCB and back panel.
2. Use plastic screws, which will break easily, between PCB and front panel.
3. Use snap fasteners for front panel/PCB connection.
4. Use screws and different form PCB.
5. Form closure to connect PCB to side panel. PCB is released by pushing in the side panel.
6. Layer construction: bottom plate/PCB/CD-unit. Screw is replaced by plastic, which will break more easily.

## Redesign 17-inch monitor

### Redesign strategy 1: Substitute undesired materials with others

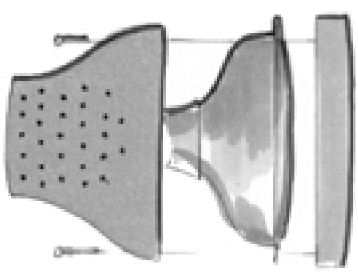
1. Avoid flame-retardant (FR).
2. Make FR and non-FR plastics easy to identify and easy to separate from each other.
3. Replace plastic housing by metal housing (or glass) => create 'Harley Davidson' – look
4. A metal housing could be added to the copper/steel fraction, but the recycling rate would decrease probably.
5. Replace metal strip around CRT by glass-fibre reinforced plastic, resulting in less pollution of glass.
6. Replace monitor by projector. CRT-glass is not required anymore.
7. Use a plug instead of fixed cable and reuse this cable at recycling.
8. Replace monitor control by onscreen display (software) via computer or keyboard.
9. Replace steel attachments of heat sinks by aluminium.
10. Reduce the size of the over-dimensioned aluminium heat sinks (specific functional requirement?).
11. Use plastic screws or form closure to attach PCB to front housing.

### Redesign strategy 2: Reallocate materials or components

1. Move monitor control PCB to central PCB instead of fixing it to the plastic housing.

### Redesign strategy 3: Optimise connections

1. Replace metal brackets of CRT by widgets in plastic housing in order to make disassembly easier and support with icons on the product where to hit.
2. Create form closures instead of plugs/screws between PCB and steel shield base (Pay attention to grounding!).
3. PCB-box at back of CRT: use a spring between PCB and steel box instead of a soldered connection and fix the PCB by a form closures so the PCB will be released when shredded. (Specific functional requirement for the very solid shielding and soldering of the PCB-box at back of CRT?)
4. Form enclosure with back housing to fix the CRT.



5. Use ADSM-materials (intelligent materials).

# *Appendix 7:*

# *The WEEE and RoHS Directives*

Source: (Commission of the European Communities 2003a,b).

## The WEEE Directive

By August 13, 2005: National take-back systems in place.
Categories of electrical and electronic equipment covered by this Directive.

| Product Category | Recycling | Recovery |
|---|---|---|
| 1. Large household appliances | 75% | 80% |
| 2. Small household appliances | 50% | 70% |
| 3. IT and telecommunications equipment | 65% | 75% |
| 4. Consumer equipment | 65% | 75% |
| 5. Lighting equipment | 50% | 70% |
| 6. Electrical and electronic tools | 50% | 70% |
| 7. Toys, leisure and sports equipment | 50% | 70% |
| 8. Medical devices | | |
| 9. Monitoring and control instruments | 50% | 70% |
| 10. Automatic dispensers | 75% | 80% |

The percentages must be achieved by December 31, 2006.

As a minimum the following substances, preparations and components have to be removed from any separately collected WEEE:

1. Batteries,
2. Printed circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimeters,
3. Plastics containing brominated flame retardants,
4. Cathode Ray Tubes,
5. Liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 square centimeters and all those back-lighted with gas discharge lamps,
6. External electric cables,

## The RoHS Directive

Member States shall ensure that, from 1 July 2006, new electrical and electronic equipment put on the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE). National measures restricting or prohibiting the use of these substances in electrical and electronic equipment which were adopted in line with Community legislation before the adoption of this Directive may be maintained until 1 July 2006.

Some exemptions:

5. Lead in glass of cathode ray tubes, electronic components and fluorescent tubes.
6. Lead as an alloying element in steel containing up to 0,35% lead by weight, aluminium containing up to 0,4% lead by weight and as a copper alloy containing up to 4% lead by weight.
7. Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead), lead in solders for servers, storage and storage array systems (exemption granted until 2010), lead in solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunication, lead in electronic ceramic parts (e.g. piezoelectronic devices).
10. Within the procedure referred to in Article 7(2), the Commission shall evaluate the applications for: Deca BDE, mercury in straight fluorescent lamps for special purposes, lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications.

## *Curriculum Vitae*

| | |
|---|---|
| Full name: | Jacob Huisman |
| Place and date of birth: | Dordrecht, May 20, 1973 |
| Civil Status: | Married with Maaike,<br>two great sons named Jonathan (1998) and Job (2000) |

After finishing his Atheneum studies in 1991 at the VSG in Goes, Jaco studied at Eindhoven University of Technology. He finished his Chemical Engineering study in March 1999 with a graduation on Life-Cycle Analysis of different biomass conversion routes at KEMA Arnhem and the Eindhoven University of Technology, Centre for Environmental Technology of the Faculty of Chemical Engineering.

In May 1999 he started his Ph.D. study with Professor Ab Stevels at Delft University of Technology, Faculty of Design, Engineering and Production, Design for Sustainability program. During his Ph.D. he stayed for three days a week at the Philips Consumer Electronics Environmental Competence Centre to perform his research. From August 2001 till November 2001, he stayed at the Fraunhofer IZM – EE Department (Instute für Zuverlässigkeit und Mikrointegration – Environmental Engineering) in Berlin.