The relative importance of uncertainty factors in product end-of-life scenarios

A quantification of future developments in design, economy, technology and policy
The relative importance of uncertainty factors in product end-of-life scenarios

A quantification of future developments in design, economy, technology and policy

Casper Boks
The relative importance of uncertainty factors
in product end-of-life scenarios

A quantification of future developments in
design, economy, technology and policy

Proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft
op gezag van de Rector Magnificus prof. dr. ir. J.T. Fokkema
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op maandag 15 april 2002 om 13.30 uur
door

Casparus Burghardus BOKS

doctorandus in de bedrijfseconometrie,
geboren te Veldhoven
Dit proefschrift is goedgekeurd door de promotor:

Prof. dr. ir. A.L.N. Stevels

Samenstelling van de promotiecommissie:

Prof. dr. ir. A.L.N. Stevels, Technische Universiteit Delft,promotor
Prof. dr. ir. J.C. Brezet, Technische Universiteit Delft
Prof. dr. M.A. Reuter, Technische Universiteit Delft
Prof. dr. T. Tomiyama, Technische Universiteit Delft
Prof. dr. ir. B. Bras, Georgia Institute of Technology, Atlanta, USA
Prof. dr. S. Evans, Cranfield University, Cranfield, UK

The relative importance of uncertainty factors in product end-of-life scenarios
Casper Boks
Thesis Delft University of Technology, Delft, The Netherlands
Design for Sustainability Program publication no. 5
Includes English and Dutch summary


Copyright © 2002 by Casper Boks
Coverdesign & lay-out by Pluuz, Delft
Printed by Druk.Tan Heck, Delft

Distributed by DfS
DfS@io.tudelft.nl
tel. +31 (0)15 2782738
fax +31 (0)15 2782956
Writing a dissertation about a study on 'ringtyp' cancels on pre-1880 perf. 14 Swedish official stamps or about the ancestors of Cornelis Burghardt Kind (Rotterdam, 27-2-1848) to investigate the origin of his middle name in particular, would also have been nice. I am nevertheless very grateful for the opportunity that was handed to me to write a dissertation on uncertainty issues related to the product end-of-life stage.

At the risk of having sinned now against everything that my promotor Ab Stevels ever taught me, like "always put the good news first" and "get to the point as soon as possible" – but that is my prerogative here – I'd like to take this opportunity to put this work into some perspective. To do so I need to divide my target audience, if there ever is one, in two, and address them separately:

For all you fellow colleagues interested in product end-of-life issues: I sincerely hope that you will at least read the last two chapters of this dissertation, for it provides an angle on the product end-of-life stage that has not been presented in literature until now, as far as I am aware of. I have tried to tackle some issues that most if not all research in this area has neglected so far – probably because it is not so straightforward to say sensible things about it. I have tried to fill some of those gaps. This means that the work has become of a rather interdisciplinary nature. Consequently, I have certainly not addressed all the issues in full detail, nor in the methodologically soundest ways, but I hope you will agree that this approach was necessary to be able to bind all the issues together, and to prevent this book from getting even thicker.

For all you nice other people that are considering reading this dissertation out of politeness – don't do it. There are far more interesting things to do in life, and rest assured that I will never test your commitment to what I have done in the last couple of years. Play with your children instead, or go out and have a beer with some friends. It's simply more important. And fun.

Having said that, my gratitude goes out to many people, perhaps not always for actually contributing to this dissertation in terms of content (though Jaco is obviously the Godfather of QWERTY) but always for helping me in some way to cough up the thing. First of all. Ab: Thank you. I guess mostly for letting me do my own thing – though now you've seen what comes of that. . . . I might have taken your requirement of performing independent research a bit to the extreme, but I think most of the time that suited both of us well. But most of all I thank you for agreeing with me that there is way more to life than work – it is this particular opinion we share that makes us work well together, and I will never forget your statement that 'mild forms of unadapted behaviour are greatly appreciated', though I realise that 'mild' is 'a matter of 'absolute and relative' as are so many things. I am grateful as well to Wim Bruens, the manager of the Philips CE
Environmental Competence Centre. Wim, indirectly I have you to thank for many of the opportunities that were granted to me, since you hired me a couple of years ago to bridge the gap between graduation and starting my research, you allowed me to visit the ECC whenever I wanted or needed, and most of all you were convinced that by letting Ab romp around in Delft some good things would come to Eindhoven as well. I hope this dissertation answers some of your questions, and be sure that if you want me to investigate some further particular issues for you – just ask.

Han B., you are now my official boss though you keep on denying it saying you are not allowed to be anyone’s boss – strange since you possess such unique qualities that make you an excellent boss for so many people. Thanks for having me in my new job, and Sacha, thank you for actually making that happen together with Ab. I hope that soon we will finally write that paper together.

I am not going to thank all my colleagues separately here, but djeez .... thanks all you people at DFS for the incredibly pleasant atmosphere and for taking two pitiful orphans on board a couple of years back. Right here I would (almost) like to apologise for all those stamp stories during lunch (and work) – I just can’t help it. Over the years I have made friends at the Philips Environmental Competence Centre in Eindhoven too. Without them this work would have had a lot less figures in it, and since I hope those figures distinguish this dissertation from others in this field, I owe you a big thanks!

Also, I should thank my many friends abroad – Stanford, Berkeley, Brunel, Cranfield, Linköping, KTH, Kalmar, Tokyo, Georgia Tech, FhG IZM & IML come to mind in no particular order for having so much fun and sharing so much support at conferences, and having each other over at our institutes and homes, this was an absolute bonus to the job. Special thanks go out to Jörgen, Carsten, Catherine and Joe for actually accomplishing work together, heck, even publications. Though most of you have by now moved into the lucrative consultancy business I hope we still will be able to meet each other occasionally – on your expenses, obviously. Joe, for you there is free meal on our table in Rotterdam any day.

A word goes also out to the people at Nokia (Ben!). Thanks for sharing data, paying my business class ticket with two times triple frequent flyer credits (off to Italy I went). You almost convinced me to move to Finland but I hear those Helsinki stamp fairs are not that exciting.

Stefano: strange how you have always been with me through the years though you don’t have a clue what my work is about. I hope you never will. You made my private life mix with my work – though some like to keep it separate, for me it was the only way. Thanks.

Family, and Juliette, Ebbe and Marijs especially: my feelings for you are so special that I cannot put them into words here ... you know.

Casper Boks, March 2002
Contents

Summary ........................................ 12

1 Introduction .................................. 14

  1.1 Research questions ....................... 17
  1.2 Positioning of research, terminology, and methodology ........... 17
      1.2.1 Terminology ....................... 18
      1.2.2 Positioning of research and methodology ................. 20
  1.3 Research approach ....................... 24
  1.4 Justification ............................ 27
  1.5 Scope .................................. 30
  1.6 Structure of the dissertation .......... 32

2 The Product End-of-Life Stage .......... 36

  2.1 Product design .......................... 38
  2.2 External factors from a company perspective ................. 43
  2.3 Economical developments ............... 44
      2.3.1 Return characteristics .......... 44
      2.3.2 Economies of scale and return logistics .......... 48
      2.3.3 Market prices for secondary materials .......... 52
      2.3.4 End-of-life processing costs .......... 55
      2.3.5 Labour wages .................... 55
      2.3.6 Fuel prices ...................... 56
  2.4 Legislative developments ............... 57
  2.5 Technological developments .......... 61
      2.5.1 Sorting and handling technologies .... 62
      2.5.2 Disassembly technologies .......... 62
      2.5.3 Shredding and separation (mechanical processing) technologies 65
      2.5.4 Smelting technologies ............ 68
      2.5.5 Incineration and landfill .......... 69
      2.5.6 Disassembly versus shredding and separation .......... 70
      2.5.7 Technology in current end-of-life scenarios .......... 73
  2.6 Environmental developments .......... 78
  2.7 Conclusions ............................ 81

3 Scenario Uncertainty ....................... 82

  3.1 Taking scenario uncertainty into account ................. 83
  3.2 The issue of scenario uncertainty in recent literature ........ 86
  3.3 Uncertainty because of legislative developments ........... 88
3.4 Uncertainty because of technological developments
   3.4.1 Future developments in sorting and handling technology
   3.4.2 Future developments in disassembly technologies
   3.4.3 Future developments in shredding and separation technologies
   3.4.4 Future developments in smelting technologies
   3.4.5 Conclusions on the feasibility of the application of future technologies

3.5 Uncertainty because of economical developments
   3.5.1 Uncertainty because of return characteristics
   3.5.2 Uncertainty because of developments in economies of scale/logistics
   3.5.3 Market prices for secondary materials
   3.5.4 End-of-life processing costs

3.6 Uncertainty because of environmental developments

3.7 Concluding remarks about future developments in end-of-life scenarios

4  End-of-Life Scenario Evaluation

4.1 Existing tools and methodologies for end-of-life scenario evaluation
4.2 Critical evaluation of existing software tools
4.3 Conclusion from review of existing end-of-life evaluation tools

5  The Product Material Recycling Cost Model

5.1 Input and output variables for the PMRCM
5.2 Internal mathematics in the PMRCM
5.3 Evaluation of current (default) end-of-life scenarios
   5.3.1 Metals dominated products
   5.3.2 Plastics dominated products
   5.3.3 Precious metals dominated products.
   5.3.4 CRT containing products
   5.3.5 Synthesis
5.4 Environmentally Weighted Recycling Quotes
5.5 Justification and limitations of the PMRCM
5.6 Conclusions

6  Scenario Analysis

6.1 Structure of this chapter
6.2 Quantified scenarios for technological developments
   6.2.1 Developments in sorting and handling technologies
   6.2.2 Developments in disassembly technologies
   6.2.3 Developments in shredding and separation technologies
6.3 Scenarios for economical developments
   6.3.1 Scenarios for metal prices

1  Introduction

2  Literature Review

3  Methodology

4  End-of-Life Scenario Evaluation

5  The Product Material Recycling Cost Model

6  Scenario Analysis

7  Conclusions
# Table of Contents

6.3.2 Scenarios for secondary plastics prices 167  
6.3.3 Scenarios for end-of-life processing costs 169  
6.4 Scenarios for developments in economies of scale and return logistics 170  
6.5 Quantification of legislative developments 171  
  6.5.1 Rate requirement scenarios (top-down legislative scenarios) 172  
  6.5.2 Natural effect (bottom-up) legislative scenarios 178  
6.6 Quantification of developments in design – analysis of material substitution scenarios 180  
  6.6.1 Metals dominated products 182  
  6.6.2 Plastics dominated products 184  
  6.6.3 Precious metals dominated products 185  
  6.6.4 CRT-based products 188  

7 Overview and Interpretation of Results from the Quantitative Scenario-based Uncertainty Analysis 192  
  7.1 Overview and interpretation of results for metals dominated products 192  
    7.1.1 End-of-life revenues 193  
    7.1.2 Recyclability 194  
  7.2 Overview and interpretation of results for plastics dominated products 194  
    7.2.1 End-of-life revenues 195  
    7.2.2 Recyclability 197  
  7.3 Overview and interpretation of results for precious metals dominated products 197  
    7.3.1 End-of-life revenues 198  
    7.3.2 Recyclability 198  
  7.4 Overview of results for CRT based products 199  
    7.4.1 End-of-life revenues 199  
    7.4.2 Recyclability 201  
  7.5 Comparison of results across product categories 201  
    7.5.1 General observations from the ranking of results 201  
    7.5.2 Observations per type of scenario 203  
    7.5.3 Combining economical and environmental effects 207  

8 Conclusions and Recommendations for the Industry 210  
  8.1 Summary of previous results 210  
  8.2 The ability of companies to influence various developments 213  
  8.3 The relative importance of end-of-life developments 218  
    8.3.1 Priority setting for metals dominated products 219  
    8.3.2 Priority setting for plastics dominated products 219  
    8.3.3 Priority setting for precious metals dominated products 220  
    8.3.4 Priority setting for CRT based products 221  
  8.4 Recommendations for design 222
8.5 Recommendations for technology 223
8.6 Recommendations for policy 223

9 Discussion, Contributions, Future Research 226

9.1 Discussion 226
9.2 Scientific contributions 230
9.3 Practical contributions 231
9.4 Recommendations for future research 232
9.4.1 Methodological framework building for ecodesign related research 233
9.4.2 Economies of scale 233
9.4.3 Brand-specific processing 234
9.4.4 Business implementation of end-of-life knowledge – extension of the system boundaries to include other than end-of-life considerations 235
9.4.5 Design optimisation based on legislative restrictions or restrictions otherwise 235
9.4.6 Design and end-of-life 236
9.4.7 Environmental Value Chain Analysis 237
9.4.8 Plastics markets 237
9.4.9 Elaboration of eco-efficiency concepts related to end-of-life issues 238
9.4.10 Effects of future legislation on end-of-life scenarios 239
9.4.11 Further development of the PMRCM 240
9.4.12 Adaptation of environmentally weighted recyclability scores to fit scenario-based uncertainty analysis 241
9.4.13 Exploitation of multiple benchmark reports across product categories 241

Appendices 244

1 Mathematical model of the Product Material Recycling Cost Model. 246
2 Scenario analysis results in graphs and tables 252
3 A Delphi study on future recycling technology 266
4 More on Active Disassembly 270
5 Environmentally Weighted Recycling Quotes in detail 280

Literature references sorted by author 298

Tables used in this dissertation 314

Figures used in this dissertation 316

Samenvatting 318

Curriculum Vitae 322
Summary

After decades of environmental improvements focusing mainly on manufacturing and waste treatment processes, in the last decade the concept of environmentally conscious product design (or eodesign) has been introduced. Within this discipline, an increasing amount of attention is being paid to the end-of-life stage of consumer electronic products. Although from a life cycle perspective the end-of-life stage contributes relatively little to the overall environmental impact, compared for example to the usage stage, there are ample motives to do research in this area. These motives include understanding the differences in emotion and perception between various stakeholders such as companies, governments, municipalities, consumer organisations and consumer themselves. This is one of the reasons why companies are increasingly starting to be involved with the end-of-life aspects of product design. In the end, the various stimuli for this can be traced back to financial motives, be it because of image or market share improvements, or for example because of avoiding future costs by preparing for take-back legislation.

Research addressing end-of-life issues related to product design has, in the past decade, mainly focused on formulating design guidelines and developing tools to weigh the various relevant aspects of eodesign within company contexts. Although a multitude of predominantly qualitative guidelines has been published, the development of quantitative methods that build upon practical experiences has severely lagged behind. This was caused on the one hand by limited availability of systematically collected useful data, and on the other hand by the confidential nature of data that is available. At the same time a lot of uncertainty remains; limited knowledge is available about how future developments in end-of-life issues will affect product manufacturers in terms of design, technology and strategy.

In this dissertation the most relevant external factors that contribute to this type of uncertainty are lined up. In particular those factors that relate to economical, technological and legal aspects are discussed, both from a current and a future perspective. Using these insights, scenarios have been analysed that represent possible developments in these areas. By means of a calculation module representing a state-of-the-art material recycling process the effects of the various scenarios are compared, using financial end-of-life yields and weight-based recyclability scores as main criteria. Also, scenarios are included that represent alternative material applications in products, obtained from so-called environmental benchmark reports prepared by Philips Consumer Electronics. By comparing results with default end-of-life scenarios and product compositions for four main consumer electronics product categories (metal dominated, plastics dominated, precious metals dominated and CRT based products) various conclusions can be drawn.

It turns out that developments related to fluctuations in the prices and concentrations of precious metals, in particular gold and palladium, result for most product categories in the largest effects on the end-of-life yield. This is in particular the case for miniaturised products with relatively high precious metal contents like cellular phones. For products consisting predominantly of plastics, developments in economies-of-scale will
potentially results in the largest effects. In particular scenarios based on the assumption that economies-of-scale in end-of-life infrastructures will lead to maturing markets for recycled plastics (implying higher prices and improved recovery percentages), result potentially in very favourable results both in terms of financial yields and potentially realised recycling percentages.

Thirdly, scenarios based on developments stimulated by legislation result likewise in significant though overall relatively smaller effects. For products with relatively large amounts of plastics, legislative scenarios assuming forced solutions to meet future recyclability targets (for example by using aluminium housings in television sets) also result in large effects. In such examples however, opposite effects are likely to occur in preceding stages of the life-cycle, and therefore the effects of these scenarios need to be carefully interpreted.

Scenarios that lead to third and fourth order sized effects include scenarios assuming copper price fluctuations, fluctuations in processing costs and legislative or economies of scale scenarios based on less progressive developments. Overall, technology scenarios assuming improvements in the performance of recycling technology show relatively small effects. Lastly, scenarios that are based on alternative material applications have varying effects, and depend in particular on the degree in which substitution between magnetic fractions and (non-recoverable) plastics are analysed.

The recommendations and priorities given in this dissertation are concerned with product design, technology and strategy. With respect to product design it is stressed that plastics play a major role in relation to the end-of-life stage. Regarding the application of plastics various considerations need to be addressed, most of which bear reference to other life cycle stages as well as traditional business criteria like money and quality. Considering technology, the importance of electronics design is stressed. Also, it is made clear that from an economical perspective investments in (recycling) technology will result in relatively small improvements when compared to other investments. As for strategy, it is recommended that so-called value chain principles be considered when developing end-of-life strategies; these include horizontal and vertical chain integration with other stakeholders in the chain, such as suppliers, branch organisations and competitors. This way, the preconditions are created for favourable economies of scale, for example by brand specific processing. Also, some influence may be exerted this way on the process of legislation development.

At the end of this dissertation a relatively large amount of suggestions for further research in this area is done. This is a direct consequence of extending system boundaries in comparison with prior research in this increasingly interdisciplinary area. A number of topics will simply have to be researched further in order to be able to draw less speculative scenarios. On the other hand, it is also suggested that from a life cycle perspective it may be wise to devote a relatively larger percentage of available research capacity to other (ecodesign) disciplines. Examples are the reduction of (the environmental effects of) energy use and the optimisation of logistics processes, and both also in relation to product design improvements.
I. Introduction

In the past decade, original equipment manufacturers (OEMs) have increasingly addressed environmental concerns and started to incorporate these into their product design process. The reasons for this increased focus are manifold, are no doubt a consequence of an increased concern with the future of our planet, but in the short run, and in current business contexts, these concerns are most likely part of a strategy avenue that makes business sense. Here, traditional business interests are at stake like company image, product quality and performance and cost reduction. And for the environmental issue, which is still surrounded with a lot of vagueness, substantiated and unsubstantiated opinions and emotions, a particular additional interest is risk reduction. By refraining from focusing on environmental issues, a company will risk non-compliance with legislation or losing market share to certain consumer segments – both a (financial) risk. By refraining from being pro-active in environmental issues, potentially profitable business opportunities such as improving manufacturing processes, launching new products and finding new market shares will be ignored – with the risk of (financial) underperformance. These are a few of the reasons why environmental issues have gained the interest of companies and continue to do so.

With the environmental issue having become no more and no less than one of the many business interests in today’s consumer electronics industry, it has grown from an issue addressed by environmentalist only to a part of ordinary business with all the rules that come with that.

For a company, there is a vast amount of ways to take environmental matters into account, and areas to focus on. One of those areas, which will be the focus of this dissertation, relates to the stage in the life-cycle of the product where it is discarded and potentially recycled, in this dissertation referred to as the product’s end-of-life stage (see section 1.2 for explanations of the main terminology in this dissertation). In order to develop successful products that cause a minimum of negative effects in their end-of-life stage, but also still fulfil traditional financial and quality requirements, companies face the task to match three cornerstones of successful end-of-life management as depicted in Figure 1.

In order to set the right design priorities, a company needs knowledge. Knowledge is needed on a great number of issues, and one of those issues is what actually will happen with their products during the end-of-life stage, and how this should be viewed in a total life-cycle perspective, both from an environmental and an economical viewpoint. This often depends on the available technology and related infrastructures. How are products collected and where do they end up? Will, or should a product be reused, disassembled, shredded, incinerated or dumped to landfill? Is this different for different products and product categories, and if so, why? How can the end-of-life of products be taken into
account if it will occur only years or perhaps even decades after the product is designed? Is it worth while in the first place to be occupied with this kind of issues? There are many questions, and there are not so many answers, yet. So, end-of-life scenario evaluation is in order to come up with the right strategy. It will be shown though that evaluation of end-of-life scenarios is a mere starting point, and that further comparison of scenario evaluations is necessary to assist in making strategic choices.

The range of possibilities to process products at the end-of-life, together with many influences that can be identified, gives rise to a large number of potential scenarios to be analysed before design priorities can be set. All these scenarios have a different effect on product design and manufacturing, financial and organizational decisions, but also on for example marketing and company image. In fact, the majority of company processes can be affected in some way or another by the decisions that are made regarding the end-of-life stage of the products a company manufactures.

Another important reason to address the issue of product end-of-life is the current and anticipated legal situation for producer responsibility and product take-back. International and regional differences regarding this matter complicate the issue. In several Western European countries (Austria, Belgium, Denmark, Germany, Italy, The Netherlands, Norway, Sweden, Switzerland) legislation addressing the take-back and treatment of Waste of Electrical and Electronic Equipment (WEEE) is being discussed, under preparation or has already been enacted. In at least four more countries initial negotiations with industry have started. Also, on a European Union level a discussion has been ongoing for several years about how take-back systems could be implemented. Since the summer of 1998, the European Union has released no less than four drafts for a new EU directive covering the whole range of waste from electrical and electronic equipment. In its current status, this directive\(^1\) states for example product specific recycling targets, which will form the basis for a number of legislative scenarios in this dissertation.

Demands such as these can have a great impact on the way OEMs do business, and on how they will do business in the future\(^2\). In the worst case, it could completely change their manufacturing processes but also affect for example supplier and consumer rela-

tions. Therefore, until the issue of legislation concerning the take-back and treatment of WEEE is totally crystallized out, it will surround OEMs with a lot of uncertainty and vagueness. But, on the other hand, it is evident for them that they should react to this issue to avoid future compliance problems. They should even consider playing a proactive role, in order to collect the potential benefits of such an approach. Many OEMs are already proactive in this field, but almost without exception they all still have to deal with a great number of uncertainties regarding the end-of-life stage of their products. This is for example illustrated by the fact that companies like Hewlett-Packard, IBM and Electrolux are supporting brand-specific take-back and treatment infrastructures because they hope, or expect to reap the benefits of doing so, based on the assumption that separate treatment of their own environmentally conscious designs will yield higher benefits than combined processing with other, perhaps less sophisticated brands. But the producers of these latter brands may assess the current developments as threats rather than opportunities and have their own reasons for this, for example because they expect that economies of scale will be unfavourable for brand specific processing. This means that companies are making different decisions because they have to base them on incomplete information, or rather on different interpretations and explanations of the same reality.

Apart from political insecurities as outlined above, OEMs are also confronted with technological developments that are hard to assess. The technology to process products in the end-of-life phase has seen rapid developments in the past decade. New disassembly techniques for component separation are researched, as are a range of technologies for material separation. Some of these will be successfully implemented in the recycling industry, others will not. Companies that now decide to design for these new technologies might be the first to benefit from them, but at the same time they run a risk doing so.

Another uncertainty factor is related to market factors. Traditionally, the recycling business is mainly driven by economic incentives – products are recycled if there are some monetary gains expected from that. These gains depend to a high degree on market prices realized for the material fractions that remain after processing end-of-life products. For some of these materials, like palladium, found in considerable concentrations in especially miniaturised electronics products, market prices have been fluctuating greatly, resulting in uncertain monetary yields from the recycling process.

Add to these uncertainties the "normal" uncertainties a company faces in daily business life and the often unclear cause and effect relations between the uncertainty factors mentioned, it is evident that companies face a task to reduce the amount of uncertainty they are facing in order to assess the value of their end-of-life products and to be able to respond to new producer responsibility and take-back legislation.

This dissertation aims to address these uncertainties, to clarify their impending consequences for companies, and to present directions how to deal with them successfully.

These aims have been translated in three research questions, which are presented in the next section.

1.1 Research questions

The research questions posed in this dissertation are a reflection of the issues that are currently alive with companies that manufacture consumer electronic goods and that are faced with a lack of perspective on the magnitude of effects that various end-of-life related developments in legislation, technology, economy and environmental issues will bring to them and to end-of-life infrastructures as a whole. The research questions are:

• What are, in relative terms, for a consumer electronics OEM the most important factors and developments associated with the end-of-life stage of consumer electronics? In particular, what are the main uncertainty factors that are outside the control of these companies?

This question is asked assuming that as a first step, a company will have to understand these factors and developments in order to reduce their uncertainty and the associated impact thereof on end-of-life scenarios.

• How can these factors be quantified according to indicators relevant to businesses?

This question is asked assuming that such quantification will facilitate the assessment of the relative importance of the various developments, and that this may lead to a reduction of their associated uncertainty by careful examination of existing knowledge, and by using insights in the way future end-of-life scenarios might develop.

• What developments associated with the end-of-life stage of consumer electronics have the largest impacts on the economical and environmental performance of discarded products during the end-of-life?

• Furthermore, can a prioritisation of focal areas be identified to facilitate the generation of business opportunities that may arise from changing end-of-life infrastructures?

These questions are asked assuming that companies will benefit from the timely identification of relevant developments and the reduction of associated uncertainty.

1.2 Positioning of research, terminology, and methodology

This dissertation refrains from a discussion on the nature of scientific research, and the role of disciplines such as design science, technology assessment, qualitative and quantitative research therein. It also refrains from a discussion on the exact nature of the research presented in it, be it normative or descriptive, or conceptual, theoretical or empirical. This dissertation is of such an applied nature that further elaborations on the
aforementioned issues, for example relating to work by Fawcett\textsuperscript{3} and Punch\textsuperscript{4}, are believed to be unnecessary. Though these choices offend perhaps against scientific rules set by some, it is believed, and shown, that meaningful results can be derived without addressing these issues at length. Besides, for a discussion on how these typologies could have been integrated in the current research work it is referred to Furuhøjelm\textsuperscript{5}, where the difficulties concerned with 'properly' addressing these issues in a body of research such as this one are set out.

What is needed though is some framework in which the terminology used becomes more meaningful, to facilitate the understanding of the chosen approaches and the way results are derived. What is needed as well is some framework to position the current research in order to understand what type of issues are dealt with for the first time, and to understand the scientific contribution of this dissertation. This section deals with these frameworks.

\textbf{1.2.1 Terminology}

The key topic in this dissertation is the assessment of end-of-life scenarios. Before this term is placed in a wider context, first the term itself is explained.

An end-of-life infrastructure is defined as a structure that encompasses all physical and non-physical elements necessary for the collection, processing and postprocessing of end-of-life consumer electronics, such as a collection depots, recycling companies, outlet channels and an appropriate logistics network.

An end-of-life route is defined as one possibility for a product, product category or material stream to advance through an existing end-of-life infrastructure, from collection to postprocessing.

An end-of-life scenario is defined as one particular setting of the parameters that define a product that has reached its end-of-life, the end-of-life infrastructure it advances through, as well as the end-of-life route it takes.

Product end-of-life evaluation is the process of evaluating scenarios that are likely to happen once they will be disposed of at the end of its useful life. This evaluation process can be done from either a financial or an environmental point of view, but is preferably done using both perspectives in order to come up with useful conclusions. Established methods to do so appear however to be extremely low in numbers.

\textsuperscript{3} Fawcett, J. The Relationship of Theory and Research. F.A. Davis Company, Philadelphia, 1992
The end-of-life stage of a product is a part of the product life cycle. In literature, numerous definitions of the life cycle of a product can be found, but all definitions are some-how based on the simplified form given in Figure 2.

![Figure 2: The product life cycle](image)

Raw materials extraction refers to the extraction of ores and other natural resources from the earth. During material processing these ores are processed or refined into materials that can be used for the production of product components and subassemblies. In the manufacturing stage these are assembled into a product that will be put on the market. After acquisition by the user, in the use stage the product is used for its designed purpose. In this stage, consumer electronics generally cause their main environmental impact because of the energy they need to function. After the product loses its functionality for whatever reason, it is discarded and enters the end-of-life stage, in which several possibilities exist for further treatment. Regarding this end-of-life stage of the life cycle, there is a similar variety in identifying and naming the different phases. The subdivision of the end-of-life stage used in this dissertation is displayed in Figure 3.

![Figure 3: The product end-of-life cycle](image)

- **Collection** encompasses how discarded products are collected, either from private households or institutional users. It includes the transport to the (pre-)processing facilities.
- **Sorting and handling** at the recycling facility means all sorting and handling of the streams of discarded products into categories that will undergo the same end-of-life process.
- **End-of-life processing** includes all manual or (partially) automated disassembly, shredding and separation, and material recycling of the sorted streams of discarded products at the respective facilities.

---


Post-processing refers to the activities carried out to handle any fractions that result or remain after the processing stage, for example the selling of material fractions to smelting plants, selling of parts and components for re-use as well as incineration or landfill.

In literature, the financial implications of a product end-of-life scenario are traditionally often referred to 'end-of-life costs'. However, this naming is misleading, since these implications can have a positive as well as a negative sign. Therefore, throughout this dissertation the following definitions are applied:

- The financial implications of a product end-of-life scenario are referred to as an end-of-life yield. Yields can be either positive or negative.
- In case of positive end-of-life yields these are defined as end-of-life revenues;
- In case of negative end-of-life yields these are defined as end-of-life costs.

1.2.2 Positioning of research and methodology

Research that includes the incorporation of environmental issues into product design and all related areas of business is commonly placed under the denominator "Design for Environment" (DFE). As this dissertation also addresses many of such 'issues', the research presented here can be regarded as a part of DFE as well. However, since Design for Environment is a very broad concept, it is necessary to closer examine where the topics addressed in this dissertation can be positioned.

Design for Environment (DFE) is defined as the systematic consideration of design performance with respect to environmental objectives over the full product and process life cycle. DFE takes place early in a product's design phase to ensure that the environmental consequences of a product's life cycle are taken into account before any manufacturing decisions are committed.

In literature, DFE is generally referred to as a collective noun for various design approaches such as Design for Disassembly, Design for Reuse, Design for Recycling, Design for Remanufacturing. Sometimes (aspects of) Design for Assembly, Design for Reliability, Design for Quality are also considered as part of Design for Environment (see for example Billatos9). Van Hemel and Keldmann10 state that Design for Environment is often not distinguished in industry from Design for Disassembly or Design for Recycling, implying a focus on end-of-life issues only, without considering the full life cycle. An illustrative example of this is found in Sarkis11. In Sarkis' framework,

---

the component Design for Environment is made up of design methodologies that address end-of-life issues only – in his framework it should therefore more appropriately have been called Design for End-of-Life. But at least here Design for Environment is described as one of several Environmentally Conscious Business Practices (ECBP), such as Life Cycle Analysis, Total Quality Environmental Management, Green Supply Chain Management and ISO 14000 EMS requirements. Indeed DFE should be considered as only one of many ways for a company to address environmental issues. In this respect, Mørup\textsuperscript{12} makes an essential distinction between two types of DFX approaches:

- Approaches that will benefit a certain life-cycle phase only (life-phase approach)
- Approaches that will benefit all life-cycle phases (virtue approach)

The latter category allows indeed for placing Design for Environment next to more (also less design-focused) traditional approaches focusing on costs, quality, efficiency, flexibility, et cetera, whereas the first category refers to the more narrow approach of explaining DFE as an umbrella approach for the various (often end-of-life focused) design approaches mentioned earlier.

**End-of-life**

The distinctions made above may reveal a methodological problem. Research devoted to end-of-life issues by themselves would require a life-phase approach, but how then to put this research in a proper business context? After all, product end-of-life scenarios and the uncertainty associated therewith pose a number of managerial problems and insecurities as explained in the introductory words of this chapter. Such problems refer for example to a lack of knowledge and understanding where investment and design priorities should be focused, especially in relation with other business priorities. It will be shown in this dissertation that to arrive at a prioritisation of focal areas, end-of-life issues should be addressed from many perspectives, including technological, economical and political issues. In literature, the scientific categorisation of research that deals specifically with the above issues, i.e. describing end-of-life issues in a sophisticated, methodologically sound way in a broad business context, is minimal. Figure 4 is useful to explain what may be the reason behind this.

![Figure 4: Lack of methodological description of end-of-life issues in a business context](image)

First of all, only limited sophisticated attention for end-of-life issues in methodological descriptions of Design for Environment can be observed. Although end-of-life has

---

always been part of Design for Environment, so far the inclusion of end-of-life issues usually does not go beyond giving qualitative design guidelines. In the dissertation by van Hemel\textsuperscript{13} for example – that could be regarded as a standard book on the exploration of what Ecodesign is – a large overview is given that includes a range of DFE strategies and principles. Although many could be regarded as relevant in end-of-life contexts, the description of strategies or principles like ‘optimisation of end-of-life system’ are confined to a number of rules of thumb, and performance measures are based on mainly qualitative principles. Evidently, the issue here is that a sophisticated description of end-of-life issues, quantitatively addressing various developments in a dynamic context, usually goes beyond the aim of methodology descriptions in a wider DFE context.

Secondly, a lack can be observed of methodological research to position Design for Environment as a part of existing managerial concepts and business practices. Rather, it is often described separately without positioning it within a business context, taking into account all usual business aspects. Moreover, existing methodological frameworks fail to address quantitative research, which makes them less relevant for this dissertation. A reason for this is that research focusing on end-of-life issues has traditionally been very design and technology focused, a statement, which can be substantiated by the pointing out the lack of literature studying simultaneously the process for identifi-
cation, solving, prioritisation and implementation of environmental issues in business contexts. Only in the last two or three years, the focus is (slowly) shifting towards the incorporation of economical and managerial aspects as well, see for example the work by Krikke\textsuperscript{14} discussed briefly below. A similar statement is made by Johnson and Wang\textsuperscript{15}. The aim of this dissertation is partly to be an exponent of this movement.

A successful integration of traditional business aspects into end-of-life focused research should build on multidisciplinary research areas as for example design, engineering and marketing. When this is done, such research can become an extension of existing business concepts like Quality Management or Supply Chain Management, and include disciplines from Design for Environment, Life Cycle Analysis as well as Green Supply Chain Management for example. If this is done, concepts like Integral Chain Management (ICM) can be introduced. ICM is chosen by Krikke as a basis for the determination of recovery strategies and reverse logistic network design. It can be regarded as an extension of the traditional product system or supply chain, starting at raw materials extraction and ending at the consumer. ICM also includes the end-of-life stage of the product life cycle, with the aim to close the cycle of material flows in the supply chain, thereby limiting emission and residual waste. According to Krikke, one of the managerial problems encountered when ICM is implemented, is the problem of how to deal with end-


of-life products that companies are required to take back. The aspect of ICM that deals with this issue is called Product Recovery Management (PRM).

Product Recovery Management is defined as the management of all used and discarded products, components and materials for which a manufacturing company is legally, contractually or otherwise held responsible. According to Krikke, it regards technology, marketing, information, organization, finance and reverse logistics aspects. Although the relevance of the multiple disciplines has been acknowledged, until now no (comprehensive) analysis results are published that take all of them into account. Rather, the current state of research in Design for Environment is, as stated before in this section, an amalgamation of disciplines, where each research project addresses a selection of relevant disciplines but never all of them; a systems approach is lacking. However, plausible explanations for this can be brought forward.

- Relevant disciplines include those that are traditionally not often combined, such as design and logistics, environmental sciences and finance, or engineering and marketing. This means that research that takes place in a traditional design environment tends to ignore (return) logistics issues (or at least assume them to be constant), and for example that research taking place in a traditional economical setting tends to ignore environmental issues. This is also the reason why publications so far have seen little overlap between the various different components and subcomponents of environmentally conscious business practices such as defined by for example Sarkis.
- Bringing together data from all relevant disciplines not only takes the knowledge to do so, but is also likely to require too much time and effort to justify. Moreover, data is likely to be scattered over a large number of stakeholders, not only on an external level (manufacturing companies, recycling companies, transport components, governments, academia), but also on an internal level (finance departments, engineering departments, marketing and design departments, but also across different sites located in different countries). From this point of view, regarding some influences as constant and focusing on the matters that can be addressed practically may prove the only way to get work accomplished.

The extension of DFE with multiple disciplines as is done in Product Recovery Management, as discussed above, will surely benefit the analysis of how to deal with end-of-life issues in a business context. By this, the collective noun DFE can also include design methodologies that address other stages of the product's life cycle, such as Design for Energy Reduction and Design for Life Time Extension. Still, various disciplines are not included. Research means like technology assessment, quantitative scenario analysis, but also chain and stakeholder issues have not been addressed in any methodological framework as yet. In this dissertation, the inclusion of such aspects and methods are explored to enable the proper addressing of the research questions posed in section 1.1. Therefore, a structured approach will be presented in the next section in which these elements are taken on board. This way, a number of external uncertainty factors are addressed that so far other research projects have assumed constant or

given, or that they have not addressed at all. In particular, future developments with respect to technology, legislation and economical factors are assessed in this dissertation. Rather than being a full grown methodology, this approach is a means for systematically reaching the goals set out for this particular dissertation. With that, it builds for example on the way research was carried out by Furuhjelm. In other research contexts, some elements will still be applicable and useful while others will not. Future research for methodology building to address DFE issues is briefly addressed in section 9.4.1. However, a warning is in order here (see also the propositions that accompany this dissertation): methodologically justified research is useful for describing problems in industry focused research, but may slow down finding solutions for them.

1.3 Research approach

The structured approach, which is followed throughout this dissertation, encompasses the following steps:

Step 1: A description of all relevant factors that have an effect on end-of-life scenarios of consumer electronics

With respect to the first research question an analysis is presented of all main factors that affect product end-of-life scenarios from economical, technological, legislative and environmental perspectives. Also, a description is given of current product end-of-life routes that will function as a default scenario against which alternative scenarios will be compared.

Step 2: An analysis of (possible) uncertainties associated with these factors

Next, it is investigated in what way the factors identified in step 1 yield uncertainty, given a time frame no longer than one product generation. This investigation process is done using literature review and information obtained from specialists in the field, both from the manufacturing and recycling industry. The uncertainties investigated contain both 'obvious' developments, such as fluctuating prices for secondary materials, as well as relatively unclear developments such as the implementation of more sophisticated recycled processes and the uncertainties associated with future economies of scales of collection and processing.

Step 3: Quantification of uncertainties

In this step, the uncertainties identified in step 2 are quantified, where possible, in order to be able to determine the impact of these uncertainties compared to each other. The quantification of uncertainties is done based on the analysis carried out in the first two steps, literature reviews and a number of surveying techniques. This leads to the result that insights are obtained on how the different uncertainty factors are likely to develop in future scenarios. In a first instance, this is done on a ceteris paribus basis, meaning that for every individual uncertainty factors it is determined
how it might affect, in quantitative terms, end-of-life scenarios. This is necessary to be able to calculate the consequences of every theoretically possible future scenario. However, it is also examined how uncertainty factors are in some way or another correlated with each other, in order to be able to draw up scenarios that are actually likely to happen in future practice.

**Step 4: Deduction of quantified uncertainties into model parameters**

To facilitate the process of calculating the economical implications of changing uncertainty factors, a cost calculation tool named Product Material Recycling Cost Model (PMRCM) is used to support and facilitate weighing the different implications of uncertainties as they followed from the analysis. The choice for this method is based on an evaluation of methods for end-of-life evaluation, as will be explained in Chapter 4. To be able to weigh the effects of the various uncertainties, changes in the variables of the model are derived from the quantified uncertainties. For example, envisaged technology improvements are for this purpose 'translated' into reduced processing costs and higher recovery percentages and grades.

**Step 5: Analysis of effects**

With the PMRCM, the quantified uncertainties, translated into different values that model parameters can take, are analysed. This scenario analysis enables quantification of effects that result from uncertainty factors developing in different ways.

**Step 6: Ranking and prioritisation of effects**

Finally, in step 6 the results of the scenario analysis in step 5 are presented by ranking them according to their relative impact. This way it is made visible what developments have a potentially larger effect on the performance of products in the end-of-life stage than other developments. Thus, a prioritisation can be made, and recommendations are derived for where the focal areas for OEM attention should be directed, in relation to design, technology and strategy, as well to the overall organisation of relevant issues. Recommendations are given with respect to the way companies should continue to monitor developments affecting the end-of-life scenarios of the products they are currently designing.

In short, the process followed in this dissertation is one of description, evaluation and prediction of end-of-life scenarios, followed by a prioritisation of end-of-life issues a company should focus on. As for the three aforementioned cornerstones technology, design and strategy, Figure 5 shows where they are most applicable in this process.

As for technology, this aspect is present explicitly in the end-of-life description stage. It encompasses end-of-life evaluation as well, and in the end-of-life prediction stage future applications of technology are discussed. In the end-of-life prioritisation stage the technology aspect is less apparent since technology issues are generally observed to be external factors as will be discussed in Chapter 2. Design on the other hand, being one
of the principle tools for companies to influence end-of-life scenarios, is most apparent in the prioritisation stage, but it also is applicable in the prediction stage where future designs can be tested and analysed in order to predict their environmental and economical scores during the end-of-life stage. Strategy, being the third cornerstone, encompasses all stages of this dissertation.

Life Cycle perspective

Many of the approaches referred to in this section focus on one particular stage of the life-cycle only – one or some aspects of the end-of-life stage are addressed without putting these in a broader context. On the one hand this may be necessary as a first step, to gain enough in-depth understanding of the underlying issues, but it also poses a danger. If the full life cycle perspective is not kept, faulty or incomplete conclusions are easily drawn. Where appropriate in this dissertation, annotations will be made discussing the risks involved of losing life-cycle perspective. This is especially relevant in Chapters 8 and 9, where conclusions and recommendations of the underlying research are presented.

Levels of ecodesign

The evaluation of end-of-life scenarios and the derivation of design priorities from that is a research activity that can be positioned in a useful framework referred to as the levels of ecodesign. Stevels and Cramer\textsuperscript{17} define these levels as:

- Level 1: Step-by-step environmental improvement of existing products
- Level 2: Radical design based on existing concepts
- Level 3: Green function innovations and product alternatives, for instance by application of a different physical principle or by replacement of products by services
- Level 4: Green system innovation, design for the fully sustainable society.

The work presented in this dissertation should be positioned at levels 1 and 2, or rather be regarded as research to support these levels. Taking end-of-life considerations into

account is still a relatively new part of the (in itself also relatively new) eco-design concept. This means that still, in many companies, many simple improvements and solutions can be found for improving product performance in the end-of-life stage. However, this dissertation also regards future developments in the end-of-life field, such as technological improvements, that together with an intelligent end-of-life scenario evaluation process can lead to more radical product redesign – which would take the research towards level 2. Only when regarding extreme, long-term technological developments – which is done only sparsely in this work – level 3 improvements can be envisaged. Rather, it will be shown in this dissertation that improvements of this type are not to be expected from activities directly related to products, but from managing the complete value chain, for example through horizontal and vertical cooperation with and through branch organisations, consumer organisations, governmental bodies et cetera (see for example section 8.6).

1.4 Justification

To provide a justification for this dissertation a brief overview of research carried out in ecodesign-related research is in place. The distinction, but especially the correlation between design, technology and strategy related aspects, as made before in this chapter, is particularly helpful here.

Environmentally conscious design did not really exist until a decade ago, except in some niche areas. At that time, the end-of-pipe era was about to come to an end. Technology had been focusing on solutions to clean up waste rather than to prevent it. From a technology perspective, the recycling of electronic equipment was driven by metals recycling only, since both the technology was available to do so, and the economic incentives were there, in contrast to the situation for plastics recycling for which technology was yet unavailable and economics nor legislation provided incentives. From a strategy perspective, companies were dealing with environmental issues through checklists for hazardous substances, and some dispersed initiatives to explore environmentally conscious design projects started in companies like Sony, IBM, Apple, AT&T and Philips. At the same time, also the academic world started to take initiatives. In the United States, the first publications specifically discussing the evaluation of the end-of-life stage of products were from Carnegie-Mellon University and Stanford University. In Europe, initiatives were taken at the TU Berlin and other German universities. These initiatives resulted a few years later, now 4 to 6 years ago, in a large number of Design for X approaches, of which Design for Disassembly was the area which received the most attention. This was probably instigated by the fact that the university departments exploring this new research area where mechanical engineering, traditionally involved with assembly research – disassembly research must have seen like a logical step to venture into economically conscious design (and manufacturing) research. So the technological perspective was on disassembly, trials and pilot projects were initiated, sometimes but not always in cooperation with recycling companies. Companies made selective use of the outcomes of these initiatives, and experimented with tool prototypes that were based on those early ideas. In their strategy, if any, estimates and mainly qualita-
tive argumentations prevailed. In the past years, the field of end-of-life focused research has matured further. From a design perspective, it has been realised that the life cycle perspective was of the utmost importance to place research outcomes in the proper perspective. Control of potential toxicity has been adopted as one of the most important issues to address in design, but also in technology development. Technology research was also extended to include shredding and separation technologies rather than just disassembly. Disassembly research itself has started to assess the possibilities of (selective) automated disassembly. In company strategies, the benefits of product benchmarking for generating design options have been understood, which also enabled more quantitative back up of analysis results – which are being used in tools that are based on real life data, in contrast to a decade ago where such data had not yet been collected. Still, this research area is still young, and literature on successful business implementations of end-of-life considerations put in the proper life-cycle perspective is still scarce.

In the past decade a vast amount of literature has focused on topics relating product design and environmental issues. In these publications, the end-of-life stage of the product’s life cycle has received an increasing amount of attention. From the historical perspective sketched above, it can be understood that the bulk of publications has focused on design issues without much focus on financial or strategic implications. Also, often research has remained very generic, and has failed to address specific or tailor made applications and solutions. In short, the business aspect has been neglected, and of the corner stones design, technology and strategy, the strategy factor has remained unaddressed – a direct consequence of ignoring financial and strategic implications. Without a proper economical or financial analysis environmental design solutions are considerably less likely to be implemented, due to lack of management commitment. This is often a result of not properly addressing (environmental) value chain issues, but can be a cause as well. This is further explained in the initial sections of Chapter 2. Also for the regular financial accounting operations it is necessary to have an applicable method for estimating the financial consequences of a product’s end-of-life stage at the company’s disposal, especially in the light of upcoming legislation.

It is sometimes said that the end-of-life stage of the life-cycle poses an insignificant environmental problem, in comparison to other life-cycle stages such as the manufacturing (including raw material use) stage and the usage stage. An analysis of data presented in several dozens of environmental benchmark analyses carried out at the Environmental Competence Centre of Philips Consumer Electronics in Eindhoven (The Netherlands) revealed the results as depicted in Figure 6. The average environmental impact of a sample of 90 consumer electronics during the disposal stage is on average 2.2%. If the environmental impact of the packaging of the product is included in the total environmental impact, this figures drops to 2.1%.

Average Life Cycle Environmental Impact
(Average of 90 consumer electronics products)

2.2%
37.6%
60.2%

- Manufacturing
- Usage
- Disposal

Figure 6: Average life-cycle environmental impact per life-cycle stage for consumer electronics

Since, the standard deviation is low, only 1.1%, indeed the statement that in general, life-cycle assessment analyses show that the environmental impact of consumer electronics products during the end-of-life stage is only very small, is justified. This could however lead to the wrong conclusions that end-of-life considerations are unimportant in product design. Listed below are several arguments that support the latter remark:

**End-of-life is not solely emissions based:**
The Life Cycle Assessment (LCA) methods that are generally used to assess environmental impacts are essentially based on emissions into the environment. However, part of the (potential) environmental effects during the end-of-life stage are not related to any emissions.

**Space restrictions:**
Especially in densely populated countries like The Netherlands there are severe restrictions on the available landfill space for disposed products. Landfill use as such - being a less preferred option for the use of space - is not taken into account in LCA calculations.

**Embedded potential toxicity:**
Situations occur, for example in landfilling, where emissions into the environment will only occur after several years. This process is called leaching. Usually, this cannot properly be taken into account in current LCA calculations.

**Room for improvement:**
The argument that 2% is just a small percentage does not withstand the fact that 2% improvement can mean a lot to a company. Let's assume that the 2% environmental burden during end-of-life translate to 2% of life cycle costs. Though ecologically 2% can be a marginal improvement, a financial 2% reduction in life cycle cost can be a very significant improvement, especially in industries such as the consumer electronics industry where profit margins are very small and continue to be under pressure.

**Compliance with future legislation:**
In an increasing number of countries proposals have been made to make sure producers will take responsibility for their products during the end-of-life stage (see for example section 2.4).
Reducing financial uncertainty:
Especially in the current situation in which legislation is up and coming, or already enacted, the end-of-life stage of a company’s products causes a great deal of uncertainty, not in the least on a financial level. Future liabilities may put a severe strain on a company when knowledge concerning the end-of-life stage is not available to a satisfactory degree.

Improving company image:
It is a general notion that nowadays a considerable amount of the potential buyers of a company’s product have environmental concerns, and are willing to discriminate between companies by choosing environmentally conscious products. Issues concerning the end-of-life stage of products are an important part of the customer’s concerns, because it is something that touches the experience of the customer more closely than for example environmental issues related to the manufacturing and transportation stages of the life cycle.

Source for creativity:
Addressing end-of-life issues is likely to have indirect positive effects on other aspects of product design and manufacturing. Several examples have shown that when designers take end-of-life issues (for example disassembly) into account, this will also have a positive effect on other stages of the life cycles such as assembly. For instance, by doing an environmental redesign of a computer monitor it was shown that a significant reduction in manufacturing costs was possible.\textsuperscript{19,20,21}

1.5 Scope

In this dissertation the choice was made to assess end-of-life scenarios themselves from a broad perspective, including many different aspects related to economy, technology, legislation, strategy, etc. Moreover, since both current and future aspects of end-of-life scenarios are addressed, a clear demarcation had to be made with respect to scope of the dissertation and focal points to be addressed in order to keep things manageable. The main limitation in scope and/or applicability in this dissertation is the focus on what is generally referred to as brown goods. This product category refers to products such as TVs, VCRs, audio equipment and the like. For practical reasons, the analyses in this dissertation are usually carried out for four product categories spanning the brown goods category. These product categories are metals dominated products, plastics dominated products, precious metals dominated products and CRT-based products. The word ‘dominated’ in this sense refers to both the weight percentages of the constituent materials,


as well as to the environmental effects of these materials (the dominating material category being the determining factor for the environmental profile of the product).

An additional justification for this limitation in scope is the notion that the incentives for recycling of various product categories differ. In Table 1 it is shown that for ICT equipment and professional equipment (like medical equipment) economical incentives exist to recycle these products. This is due to the size and/or high content of valuable materials in these products. For white and brown goods, this is much less so.

<table>
<thead>
<tr>
<th>Product category</th>
<th>Incentives for recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>White and brown goods</td>
<td>Legislation</td>
</tr>
<tr>
<td>Information and communication technology (ICT) equipment</td>
<td>Market protection</td>
</tr>
<tr>
<td></td>
<td>Legislation</td>
</tr>
<tr>
<td>Professional products</td>
<td>Market protection</td>
</tr>
</tbody>
</table>

Table 1: Incentives for recycling

In the context of this dissertation strategies including reuse and/or remanufacturing of (any parts of a) product are not acknowledged as being part of end-of-life scenarios. These strategies still focus on the product characteristics, as they were initially intended and are therefore, according to the definition given previously, not part of the end-of-life phase. Besides, reuse and remanufacturing are generally not considered as a feasible option for electronics products when these products are discarded at the end of their (first) life. In Pöpper et al. the issue of reuse of electronics parts from electronic products is investigated and it is stated that the lack of guaranteed quality properties prevent a broad utilization of used printed circuit boards or components as spare parts or in the production of new electronic products. It is also stated that as long as there is no way to guarantee quality properties of “second-hand” parts, reuse of parts and/or components originating from brown goods will only happen in niches of the electronics industry such as the toy industry in Asia. In such niches the requirements for reused parts or components are low, and is therefore not hindered by the long technology developments cycles and long use time of consumer electronics.

From a geographical point of view, this dissertation will focus on the application of the theory and models within global companies acting in Europe.

From a temporal point of view, this dissertation has a time horizon of about 25 years, meaning it focuses on the end-of-life scenarios of products that will be designed and sold

---

within the next few years, and will be used for up to 20 years before they are discarded.

From an economical point of view, this dissertation assumes the underlying economic situation in Europe ceteris paribus. Any influence that, for example, a major economic recession might have on environmental and economic preferences in a society is therefore disregarded. Notable exceptions from this are possible price changes in market prices for primary and secondary materials that might occur for whatever reason, and the development of legislation applying to product categories within the scope of this dissertation. Such legislation can be regarded as an aspect of the socio-economic situation as well, but is regarded in dissertation as an important variable in end-of-life scenario modelling, subject to uncertainty.

Another self-imposed restriction that applies to this dissertation is the fact that focus will be on external developments as cause for uncertainties related to the end-of-life stage. In Chapter 2 it is recognised that in particular factors related to the Environmental Value Chain may distort, amplify or soften the effects of external developments. For example, contracts with suppliers may hamper the application of (environmentally) preferred materials or components offered by alternative suppliers, personal interests that exist with managers may intensify or weaken attention paid to particular external developments, the (change) in the financial position of a company may amplify the effects of legislation that company is confronted with. It is recognized that many of such factors related to the company itself do significantly contribute to uncertainty regarding the end-of-life stage, or rather the interpretation of the consequences of such uncertainty. However, these are clearly of a different nature compared to the external factors themselves which care easier to generalise. The only internal factor that is focused on in more detail in this dissertation relates to product characteristics themselves. To avoid duplication of explanation regarding the choice of internal and external influences to focus on, it is referred to the beginning of Chapter 2 for a more elaborate discussion on this topic and for an introduction to Environmental Value Chain Analysis as an approach to map internal rather than external influences.

1.6 Structure of the dissertation

In Figure 7 the structure of this dissertation is shown. In Chapter 2, a wide range of external factors influencing end-of-life scenarios are discussed. This is done from a company's perspective. Succeeding a discussion on product characteristics and how they influence choices to be made regarding the end-of-life stage, a discussion on external factors is presented. There is a focus on technological factors, and also economical and environmental factors as well as legislative issues are discussed elaborately. It is also explained how return logistics and related concepts such as economies of scale and the ensemble issue are of considerable importance. An overview will be given of current reverse logistics and recycling processes, and how these are influenced by for example legislative ordinances.
In Chapter 3, the factors discussed in Chapter 2 are taken to a next level. Here, for all individual factors it will be explained where and how uncertainties related to these actors can or will cause difficulties in evaluating future end-of-life scenarios. The assessment of the uncertainties related to future disassembly and end-of-life processing technology is partly done by discussing the results of a Delphi study that was carried out to investigate the specialists' view of future developments in end-of-life scenarios.

Other research has focused on end-of-life scenarios, and how these can be evaluated. Several approaches are reported on in Chapter 4, where the evaluation of existing tools and methodologies is not only used to develop a framework positioning all relevant approaches, but also leads to the identification of a gap in current end-of-life evaluation tools. This gap refers to the lack of a tool that is able to assess both financial and environmental consequences of end-of-life scenarios without having to resort to large amounts of input related to product geometry, but still allows for extensive end-of-life scenario analysis. In Chapter 5 a new approach to evaluate end-of-life scenarios is presented, namely the Product Material Recycling Cost Model (PMRCM). The evaluation in this new approach is done based on both economical and environmental considerations, and it is discussed how the combining of these considerations can in theory be a powerful tool to evaluate end-of-life scenarios.

Next, in Chapter 6 the matter of scenario uncertainty is dealt with using the PMRCM introduced in Chapter 5. For all relevant developments identified in Chapters 2 and 3, scenarios are drawn which reflect the quantified effects (in terms of economical and environmental performance) of positive and/or negative directions of these developments, with various progressive to conservative magnitudes of effects. From these exercises, further conclusions are drawn in Chapter 7, per product category and for all product categories combined, about what factors are most likely to cause major changes in the end-of-life stage of products yet to be designed and manufactured.
In Chapter 8 these results are elaborated on in order to assess the implication for consumer electronics manufacturing business. From the results, priorities are derived for focal areas for attention. Chapter 9 concludes this dissertation, where the initial research questions are (re-)evaluated and a look is taken over the time horizon that was initially set. Also, a number of areas for future research are identified related to product end-of-life issues.

As the structure of this dissertation consists of quite a number of cross-referenced sections, and since the analyses in most sections are often based on results from previous discussions, Table 2 provides an overview of how the different sections are linked. The basis is formed by the external factors discussed in Chapter 2. For all relevant factors, in Chapter 3 it is explained how these factors cause uncertainty in end-of-life scenarios, and in Chapter 6 it is discussed how these uncertainties can be quantified for the purpose of evaluating them with the PMRCM.

<table>
<thead>
<tr>
<th>External factors</th>
<th>Discussion of relevance for end-of-life scenarios</th>
<th>Discussion of uncertainty issues having impact on future end-of-life scenarios</th>
<th>Quantification of uncertainties facilitating PMRCM calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economy</td>
<td>2.3</td>
<td>3.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Legislation</td>
<td>2.4</td>
<td>3.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Technology</td>
<td>2.5</td>
<td>3.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Environment</td>
<td>2.6</td>
<td>3.6</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Table 2: A guide to cross-referenced sections in this dissertation

Five appendices have been added to this dissertation. In Appendix 1 the mathematical details of the Product Material Recycling Cost Model are included, as this model is the basis of most calculations done in this dissertation. In Appendix 2 the results derived in this dissertation are graphically represented. Appendix 3, 4, and 5 are included to provide more detail on a number of topics that have been researched in the course of preparing this dissertation, but they are not vital to understand the main body of this dissertation.
The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios
2. The Product End-of-Life Stage

As defined in Chapter 1, the end-of-life stage of a product is composed of a number of stages – from the last user via collection and sorting and handling to end-of-life processing, often followed by post-processing. While passing through each of the stages, numerous influences affect the product and its environment. These influences can for example be of a physical (for example use or technology related) or non-physical nature (for example legislative or economical related). In order to provide a starting platform for this dissertation, these and a variety of other natures will be discussed in this chapter.

In the first chapter it has been pointed out why describing, evaluating and even predicting end-of-life scenarios should be important to a company. To be able to do this, it is important to understand many of the influences, and to have a general idea how issues in the product’s end-of-life stage are interrelated. Only then, companies will be able to control the influences that can be controlled by them, and to understand the influences that cannot be controlled. As a result, activities can be organised that describe, evaluate and predict end-of-life scenarios, and in general support prioritisation and a proactive attitude towards end-of-life issues and their associated uncertainty.

Before that stage is reached, description of end-of-life scenarios is, as said, a prerequisite, and is therefore the first non-introductory chapter of this dissertation. Description of end-of-life scenarios will enable evaluation, prediction and prioritisation as done in Chapter 4 and onwards. It should be noted again that the focus of this dissertation is on consumer electronic products (not including white goods and IT equipment).

For the purpose of this chapter, it is important to distinguish between two types of influences that affect end-of-life scenarios, namely:

- Influences that ‘happen’ from within the company – in this dissertation designated as internal factors;
- Influences that ‘happen’ outside a company and which are therefore designated as external factors.

![Diagram](Diagram.png)

*Figure 8: Factors influencing product end-of-life scenarios*

The distinction between ‘happening’ inside and outside a company is a bit crude. The distinction becomes blurred when factors are taken into account that for example occur inside a company but are uncontrollable (especially by design departments), or when they occur outside a company but are manageable by a company. Keeping in mind
Figure 1 of this dissertation and including the three cornerstones design, technology and strategy into the distinction facilitates greatly a more accurate way of defining this distinction. In Table 3 it is clarified in what way, or to what degree the cornerstones can be used to influence internal and external factors.

<table>
<thead>
<tr>
<th>Internal factors</th>
<th>External factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Design influences are designated as external factors. Companies do not have the possibility to exert a significant influence on these factors through design parameters.</td>
</tr>
<tr>
<td>Technology</td>
<td>Technology influences with technology aspects are designated as external factors. Companies do not have a major influence on them. For situations other than stated for internal factors, this is usually the case. For example, increasing digitalisation and miniaturisation are autonomous developments to a company.</td>
</tr>
<tr>
<td>Strategy</td>
<td>Factors designated as internal can be influenced by company policies, i.e., actions taken by a company can alter occurring situations into the company's advantage.</td>
</tr>
<tr>
<td></td>
<td>Factors designated as external cannot be significantly influenced by company policies, because they are outside the company's control.</td>
</tr>
</tbody>
</table>

Table 3: Influence of cornerstones on internal and external factors

In Rose\textsuperscript{24} it is explained that, while a number of product characteristics are under the control of a company and can therefore be designated as internal factors and possibly used to predict end-of-life strategies, these do in a significant number of cases not suffice for accurate predictions. It is argued that this causes a gap between predicted and actual end-of-life scenarios. In Rose's work, this gap is explained by the very existence of the influences that are outside the control of the designer, influences that are here designated as external factors. A methodology called the Environmental Value Chain (see also Stevels and Ishii\textsuperscript{25}) is then introduced as a framework for positioning these influences and understanding their effect on end-of-life scenarios. Taking already a step forward towards end-of-life scenario evaluations, Environmental Value Chain Analysis in its current form however does not yet give sufficient directions how to quantity these influences.


outside influences and can therefore be regarded as a tool to describe and understand the aforementioned gap, but not necessarily to close it.

In a way, the remainder of this dissertation can be regarded as a continuation of where Environmental Value Chain Analysis in its present status stops, at least as far as external influences and developments are concerned. This is done by a careful consideration of those external influences, by describing them, analysing their potential to yield uncertainty, and last by quantifying them enabling end-of-life scenario analysis in a way as will be suggested in later chapters of this dissertation. This way not only the uncertainty caused by external factors on current scenarios can be dealt with, but also the uncertainty associated with future scenarios can be assessed.

In the subsequent sections all issues relevant to the product end-of-life stage are discussed. This is done from both a current perspective (to analyse how the product end-of-life stage works) and a future perspective (to be able to anticipate on future developments). In subsection 2.1 and 2.2 both internal and external factors will be discussed, with the majority of attention given to the discussion of external factors as explained previously in section 1.5.

2.1 Product design

Only a limited number of issues related to the end-of-life of a product can be controlled by companies – an issue that will be addressed in more detail in section 8.2. The most important one however is product design – through responsible, environmentally conscious design OEMs can provide the opportunity for their products to be processed in an economically and environmentally preferred way in the end-of-life. How product design affects the end-of-life stage is explained further on in this chapter. Apart from product design, other internal factors can be identified that can have an influence on how this process is organised. Although the bulk of available literature that focuses on environmental management systems does not address the end-of-life stage separately, a good example of work linking company internal factors with a successful implementation of green business is the introduction of the Environmental Value Chain concept. Ishii and Stevels discuss the way companies can be proactive in linking economy and ecology considerations into a successful business strategy, in particular by anticipating non-technical and intangible factors. In this work, the end-of-life stage is not mentioned as such, but it contributes to the understanding how company internal factors can ‘make or break’ environmentally responsible business. Some of the elements to be understood in environmental value chain analysis include strategy management, product management, corporate finance, marketing and company culture. Because the focus of this dissertation is on uncertainty factors external to a company, these elements that all affect the way end-of-life matters are dealt with in a company are not addressed in detail. In section 9.4.7 however, it is briefly discussed how future research in this area may benefit the successful implementation of end-of-life considerations into product design and everyday business.
As for product design, a wide range of product characteristics that have an influence on end-of-life scenarios will be discussed in this section. In principle, they can be divided in two groups:

- Those characteristics that can be influenced during product design and that are not limited by physical boundaries.
- Those characteristics that can only be determined after use of the product.

As for the second group, these characteristics include for example wear and filthiness of the product, which are essentially a consequence of consumer behaviour. Since companies have only few opportunities to influence this behaviour and its consequences for these product characteristics, this second group of product characteristics is classified under the influencing factor “return characteristics”, that is discussed under external characteristics in section 2.2. The characteristics listed in this section all apply to the first class of characteristics. The fact that they can be determined and influenced during product design makes it possible to designate them as internal factors rather than external factors.

In order to obtain an overview of all relevant product characteristics, Rose, Masui et al.\(^{26,27}\) give a useful though not exhaustive list of influencing factors that will be used as a starting point. For each factor the application in relation to the end-of-life of consumer electronics is discussed.

- **Materials**
  This can be regarded as the most important product characteristic that influences almost everything that has to do with the end-of-life stage of a product’s life cycle. For end-of-life evaluation purposes, a useful division of materials can be made as is done below. The different materials are found in consumer electronics products in varying compositions. In Chapter 5, default product material compositions have been established for use in scenario analysis. From these default compositions it can be understood that consumer electronic products can be divided in different product categories that each have their own characteristics as regards their material composition.

- **Ferrous metals** – mainly iron and steel. From an end-of-life perspective, the most important property of ferrous metals is magnetism; with a simple magnetic separation process, ferrous metals can easily be separated from other material fractions. In a life-cycle perspective, it is important to know that ferrous metals have a relatively high impact during production compared to most plastics, but a relatively low impact compared to non-ferrous metals. In electronics products, ferrous metals are used for encasings (for example VCRs), construction parts, and for fasteners such as screws, and in coils.


• **Non-ferrous metals** — mainly copper and aluminium. From an end-of-life perspective, copper and aluminium are important materials. Both of them, but especially copper, are widely used in electronics products. Copper is mainly found in wiring, because of its conductive properties, and on printed circuit boards. Aluminium is used for housing and supporting parts and can be found in wiring. An important application is also in cooling plates around electronics fractions. Because of the relatively high concentrations of aluminium and especially copper in electronics products related to their relatively high market value, copper and aluminium content is an important characteristic for determining the end-of-life value of products. From a life cycle point of view, the environmental impact of copper and aluminium is about 5 times higher than that of ferrous metals.

• **Precious metals** — mainly gold, silver and palladium. These precious metals are used on printed circuit boards and in printed circuit board components such as relays, switch elements, sensors and plug-connections. Because of their economic value, components with high concentrations of precious metals often provide the driver for material recycling of these components and/or for the product they are contained in. In a life-cycle perspective, the environmental impact of the production of precious metals is among the highest of all materials.

• **Plastics** - a wide range of plastics is used in the manufacturing of consumer electronic goods, although a number of resins can be distinguished that are most frequently used from a volume perspective: ABS, PC/ABS, PC, PVC and HIPS. The main application of plastics (from a weight perspective) is in housings of plastics dominated products, such as audio equipment, and in electronic parts and wiring. Plastics are also used in laminates that are the main construction material for printed circuit boards. If plastics are not contaminated with additives such as flame retardants, or contaminated by surface treatments such as paints, lacquers, coatings or stickers, in theory (when available in large enough quantities, and provided reliable markets for secondary plastics exist) they can be recycled for use in secondary applications. However, many of the plastics used in consumer electronics have undergone various surface treatments for technical or style reasons. In general, these plastics are not eligible for recycling. This can be due to their relatively small volumes, but the main reason is because of limited secondary applications due to the fact that these plastics do not meet the necessary specifications for those applications.

• **Glass** is mainly used in tubes for television sets and computer monitors. In a colour tube (CRT = Cathode Ray Tube), usually three different types of glass are contained — screen glass, cone glass and neck glass. The fact that only neck and cone glass are compatible prohibits simultaneous recycling, which makes that the recycling of CRTs is a difficult process (see section 2.5.7 for more details). CRT recycling technology however has become more sophisticated in recent years though, and applications for secondary glass are on the increase. The main problem remains the uncertain composition of recycled glass from CRTs. Whereas CRT manufacturers do have confidence in the properties of raw materials used in traditional glass manufacturing, the risks involved with the difficult determination of the exact composition of recycled glass from CRT may seriously damage the production process28.
• **Weight and size**

The heavier a product and the more material it contains, generally the more financially attractive material recycling becomes, and the possibility that a product will actually be recycled rather than incinerated, increases. Furthermore, the size of a product has a particularly big influence on the return logistics. Products that fit into a garbage bin are often thrown away that way. It then costs a great deal of expense and effort to have them recovered. Medium-sized products that are too big for a garbage bin can be transported by the consumer herself or himself. Apart from collection depots, these products often end up in attics or cellars. Large products that are difficult to transport are often taken back by the retailer upon the delivery and installation of a new product.

• **Wear-out life**

The period of time from initial product purchase until the moment that the product can no longer perform its original functions and will not be repaired. For the products under consideration in this dissertation, a Dutch survey⁴⁹ found the following average wear-out lifes:

- VCR: 5.3 years
- Washer: 9.1 years
- TV set: 7.3 years
- Refrigerator: 10.1 years
- Vacuum cleaner: 9.3 years

Other sources such as the Appareltour⁵⁰ project show that in practice the age of discarded electronic products on arrival at the collection point or the recycling facility is considerably higher. This confirms the hypothesis that households leave their old products “on the attic” for a long period of time (up to ten years) before turning them in to a municipal collection system. This also raises the question if the determination of age and quantities of end-of-life products in collection trials should not be corrected for the fact that a considerable number of households will turn in their end-of-life products only when motivated to do so, for example by an advertising campaign supporting a collection trial. In any respect, the wear-out life of a product and the age of a product when it enters the return logistics infrastructure are two terms, which are sometimes used synonymously, but in practice have different meanings.

• **Design cycle**

The design cycle is defined as the period of time from product purchase between successive generations of a product. Another definition is the frequency that a design team redesigns the product or designs a new product that makes the origi-

---

nal product obsolete. In certain cases, the design cycle can be an important pointer for the preferred end-of-life route option. This is especially true in the case of remanufacturing; products that have long design cycles (e.g., office equipment like copiers or faxes) generally contain components that can be used across product generations which make these products more eligible for remanufacturing than products with short design cycles (e.g., mobile phones). Design cycles are often determined by fashion. Consumer electronics are not only bought for delivery of functionality, they are in many cases also fashion statements. This makes that in many cases the reason they are discarded is because of the fact that they have become outmoded, rather than because they have broken down. This is why the design cycle is often correlated to the technology cycle and replacement life.

- **Technology cycle and replacement life**
  The technology cycle is defined as the period of time that a product will be on the leading edge of technology before new technology makes the original product obsolete or less desirable. For consumer electronics, product generations featuring new functionalities and new design aspects often follow each other after only few years. This leads to a situation where products are replaced even though they still can excellently fulfil their original function but where the price of new products does not prevent customers from buying new products. In this case the replacement life, defined as the period of time before users feel the need to purchase a new product based on increased functionality, is shorter than the wear-out life. In such cases, design strategies that include increasing modularity can in theory extend the time before a product will be discarded by the consumer, which in some cases can be environmentally preferred.

- **Functional complexity, number of materials/parts/modules**
  This refers to both the degree of complexity of parts themselves and the degree of complexity due to connections and interactions between different parts. Complex products in general contain more valuable parts, especially when miniaturization contributes to the degree of complexity. Miniaturization generally comes with an increase in the use of materials (in particular precious metals) that are environmentally potentially toxic as well as economically very interesting to recover. However, complexity of products will in certain cases also mean that relatively more effort is needed to recover materials, due to additional disassembly operations or repeated material processing steps needed to obtain pure enough material fractions for post-processing.

Rombouts\(^{31}\) uses a different distinction of product characteristics in order to predict environmental product profiles that include end-of-life impact. In particular, energy consumption is used as an important indicator for environmental impact of a product. However, from an end-of-life perspective energy consumption is considered less important, although parts that convert or store energy contain in general significant amounts

of copper. Since different material categories as such have already been distinguished in this list of relevant product characteristics, energy consumption is not listed separately. However, it should be noted that energy consumption can be indirectly be a relevant indicator for environmental and economical scores during the end-of-life stage.

2.2 External factors from a company perspective

The previous section presented a short overview of factors that influence the product's end-of-life stage, but that are generally under a reasonable degree of control by a company. The focus in this section is on the factors that are in principle outside the control of a company, depicted in Figure 9. For the purpose of this dissertation, these factors are categorised in four main types of developments, namely economical, technological, legislative and environmental developments.

![Figure 9: External factors influencing the product's end-of-life stage](image)

External factors affect companies via different stakeholders, which is briefly explained here. **Technological developments** such as the development of recycling technology take place at research institutes and recycling companies themselves. Such developments become relevant to a company once these recycling companies become part of a regional or national end-of-life infrastructure such as the one existing in the Netherlands. Business transactions with recycling companies such as signing contracts to recycle end-of-life appliances take place directly or indirectly depending on the organisation of collection and processing. Technological developments that are related to the design and manufacturing processes and that may effect the end-of-life stage, such as the presence of environmentally preferred material or component alternatives, manifest themselves through for example component and subassembly suppliers. **Legislative developments** with respect to the end-of-life stage are imposed by regional, national or international government bodies, which are in turn elected by society. **Economical developments** affect OEMs through suppliers and recyclers (such as costs for transport and processing, and for example the fluctuation of material prices) and politics; developments in economies of scale and return characteristics affect OEMs through the way municipal or national collection and processing infra-
structures have been set up, and can also be stimulated by legislative developments. **Environmental developments** affect OEMs through for example consumer markets (via changing perceptions about environmental issues and demands for environmentally sound products) and research institutes (through increasing knowledge about environmental issues and changing priorities for environmental impact reduction).

From the factors discussed in this section, factors like the development of (recycling) technology, the development of economical parameters like market prices for recycled materials and the presence of competition are obviously outside the influence of a company – unless a company is a monopolist in a relevant area or a heavy investor in recycling technology. For other factors, such as return characteristics and geography, which are here classified as external factors a closer examination is required to determine which aspects can or cannot be influenced by a company. In the subsequent subsections the factors are discussed.

Other external factors that do have an external influence include the presence of business competition, and for example emotions with the different stakeholders in the end-of-life stage. These factors are not separately discussed for various reasons. The main reason is that the influence of these factors is believed to manifest itself already through the various other external factors. For example, the presence or non-presence of competition could lead to changes in the size of a company, its strategy, and eventually in the (design of the) products it manufactures. Emotions within the company itself can have similar effects. Emotions with the consumers could manifest themselves through legislative and environmental developments. When such developments are discussed in the subsequent sections, it is done irrespective of the developments that cause them. Another reason is that these factors do not let themselves easily to be assessed and especially not quantified, and since quantification of internal and external factors leading to uncertainty in future end-of-life scenarios is one of the main objectives of this dissertation (see for example Chapter 6 on scenario analysis) they are left outside the scope of this research.

### 2.3 Economical developments

In this section developments are discussed that affect the end-of-life stage of consumer electronics and that can be headed under economical developments. The topics that are subsequently addressed are return characteristics of products (section 2.3.1), economies of scale and return logistics (section 2.3.2) and market prices for secondary materials (section 2.3.3).

#### 2.3.1 Return characteristics

In this section, the issue of what is called return characteristics is discussed. These return characteristics refer to a number of characteristics of the WEEE volumes that are processed through a return logistics infrastructure. In the current context, the most relevant characteristics include the size of the waste streams and the variety of prod-
ucts contained in the waste stream (homogeneity of a batch). The size of waste streams is important for the discussion on economies of scale (see section 2.3.2), whereas the homogeneity of a batch, and especially across batches leads to the important topic of the ensemble issue. Both topics are discussed further on in this section.

As explained in section 2.1, a number of product characteristics are classified as external factors since these product characteristics only manifest themselves after the use stage of the product life. This as opposed to other product characteristics, which can be determined (and therefore influenced) already during product design and are therefore classified under that heading in section 2.1.

With respect to return characteristics, it is important to make the following distinction:

- Return characteristics that can only be determined for batches of products. In this category, the composition of volumes of WEEE ending up at recycling plants will be discussed shortly (referred to as the "ensemble issue").
- Return characteristics that can be determined for individual products (called external influences in Seliger et al.\textsuperscript{32}, p. 6). In this category, the filthiness of products ending up at recycling plants is relevant. The level of filthiness refers to the amount of dust, dirt and even worse junk that can be found in and between end-of-life appliances, hindering for example disassembly and/or shredding and separation. This is correlated with usage characteristics such as lifetime, location of use, the presence of added or removed functionality or style aspects (for example for modular products) and level of service during lifetime. It is here where the impact of the usage stage comes forward as an influence on end-of-life scenarios.

The presence of return characteristics for individual products makes it difficult to define the return characteristics of a product. The main issue here is whether to observe a product individually or to observe streams of products. One could argue that the return characteristics of a product are defined by

- The actual moment in time when a product is taken back
- The actual place where a product is taken back

However, from an analysis point of view these data are not particularly useful. When evaluating end-of-life scenarios it is much more relevant to observe product waste streams rather than individual products, as will also be argued in the discussion about disassembly versus shredding and separation (section 2.5.6). Main reason for this is that the driver for what happens to a stream of end-of-life products is its material content rather than the individual characteristics of the products in the stream. For this reason, it is much more relevant to speak of return characteristics of a "group" of products. Still, this poses a problem, since it is not yet clear which "group" or stream of products to speak of. In this context, two 'waste' streams are defined, each of them has products clustered in a different way. These streams are the following:

- Streams before end-of-life processing are streams of products, clustered according to

product type or category. These streams occur primarily between OEM and retailers.

- Streams after end-of-life processing are streams of materials or components, or shredded products rather than whole products. The mix of these streams depends mainly on the outlet channel specifications, see section 2.5.6 for more detail on this.

Figure 10: Ensemble issue

The problems with the transgression from product type dominated WEEE streams to material type dominated WEEE streams is here referred to as the "ensemble issue". This issue manifests itself in the actual end-of-life processing rather than during the return logistics process and is therefore regarded as a "return characteristic" rather than a return logistics issue.

The ensemble issue refers to the way streams of WEEE are mixed. In general, WEEE can be divided\(^3\) in at least four product categories: metals dominated products, plastics dominated products, precious metals dominated products and products with glass such as CRTs. Depending on the outlets and the specifications required for concentrations of materials, mixing WEEE into separate batches or streams entering the recycling process is in many cases a relatively delicate matter. The important issue here is the concentration of metals, especially copper and precious metals as these materials yield the highest revenues. For example, copper smelters will generally accept a batch of printed circuit boards (or batches with other parts having relatively high concentrations of copper, like deflection units or wiring) if the perceived concentration of copper is 20% or higher. From a recycler's perspective, it may therefore prove worthwhile to mix a batch of products or product parts that has a copper concentration higher than 20% with a batch of products or product parts that have a copper concentration less than 20% — to end up with a batch that has a copper concentration exactly or slightly over

---

\(^3\) Chiado, J.D. and Boks, C.B. "A Feasibility Study on Active Disassembly using Smart Materials — A Comparison with Conventional End-of-Life Strategies", in the proceedings of the 6th International Seminar on Life Cycle Engineering, Kingston, Canada, June 1999
20%. This to be able to receive the same price for a batch of WEEE while also selling a stream that on its own would yield a considerably lower price. However, such measures can also prove to be counterproductive, depending on the precious metals content of the different fractions; precious metals are paid for when the concentration is above a threshold value. In this case mixing with a batch in which the precious metals content is low may result in losing the precious metals value present in the first batch. These examples clarify the statement that the revenues for recyclers are not (exclusively) in applying the best technology. Rather, the revenues are in knowing how to mix different product and material streams and in knowing the specifications of the different outlet channels in order to optimally tune processing to achieve the highest revenues.

The ensemble issue is also recognized in the application of advanced disassembly techniques. In Knoth et al.\textsuperscript{34} it is stated that sorting of relevant products into product groups or 'disassembly families' that require nearly the same disassembly operations is a key factor in envisaged automated disassembly processes.

Assessing the value of material streams.

In order to assess the concentration of certain valuable or hazardous materials in a large batch of WEEE, recycling companies use an analysis process that will yield these concentrations by a step-wise reduction of the material to be analysed. For example Mirec, the main Dutch recycling company located in Eindhoven, uses the volume reduction process as depicted in Figure 11.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure11.png}
\caption{Sample taking process to assess material content.}
\end{figure}

This figure shows how from a full batch of a certain product or material stream a representative sample can be taken. By analysis of this sample, the material of the full batch can be determined. The reduction steps in Figure 11 show that a 250 kilogram sample is brought to a particle size of 8 millimeters maximum. From this batch, a 50 kg sample is taken for further particle size reduction. After several steps a sample is obtained of 500 grams with a particle size of 0.1 millimeters maximum, which is then used for analysis of the material composition; the remaining sample is split into two sub-samples, one for determining concentrations of volatile elements, and one for determining concentrations of non-volatile elements.

As stated previously, it is more and more realised that the mixing of batches of WEEE might be of higher importance than the way they are processed. Outside recycling

companies, little research is done on optimal mixing of volumes of WEEE. This is probably due to the fact that virtually all data required (especially the outlet specifications) are of a proprietary nature, which is fully understandable since especially the understanding and the knowledge of the outlets can provide the main competitive advantage for recycling companies.

In section 3 it will be further discussed in what way the uncertainty associated with the composition of volumes of WEEE ending up at recycling facilities can be dealt with.

2.3.2 Economies of scale and return logistics

This section deals with economies of scale in end-of-life scenarios and with return logistics, and will be built up as follows: first a description will be given of how collection of WEEE is or can be organised. The current situation in the Netherlands is described, and experiences from other countries will be discussed as well. Secondly, the presence or non-presence of economies-of-scale in return logistics processes and end-of-life scenarios as a whole will be discussed. At the end of this section also geography as a potentially influencing factor on end-of-life scenarios will be discussed in short.

Return logistics – organisation of collection

Return logistics refer to a present infrastructure that facilitates the collection of discarded WEEE from the last users and the transportation of these volumes to either a recycling facility where they will be further processed, or to an incineration plant or landfill site. According to Mulder et al\textsuperscript{35} prerequisites for successful return logistics systems are:

- **High collection rates/volumes**: Mulder et al state that high collection rates are desirable because they allow for more control of a larger part of the WEEE, thus minimising environmental impacts. Two factors are especially influential when it comes to achieving high collection rates: (1) Convenience for the public, (2) Perception and awareness with the public. Therefore it is important to understand the factors that affect the behaviour of the consumer when discarding and returning products. Apart from convenience, awareness of available option and familiarity with the system, the size of the product is also mentioned as an important factor. Furthermore, Mulder states that experiments have shown that municipality collection systems show the highest return rates and are also the cheapest way to collect WEEE.

- **Cost effectiveness**: According to Mulder, the public is less likely to accept collection systems as the cost for these will increase, especially since the consumer will pay for separate collection anyway, no matter what collection system is chosen in the end.

- **Shared responsibility**: Involving all relevant actors in the collection system and sharing the responsibility for making it a success will potentially increase its effectiveness, provided that the actors would only be given responsibility for the steps in the system they are able to influence or control.

• **Subsequent processing:** The fourth success criterion mentioned by Mulder is the way that collection systems affect the subsequent recycling and recovery processes and their associated costs. If the state of returned WEEE differs across brands in a way that a number of producers would benefit from separate processing of their own brands, this could in theory undermine the success of a collective collection system.

In the section below an overview is given of how the WEEE collection process is organised in different parts of the world. Parts of this survey have previously been published in Nagel et al. ²

In The Netherlands, trials have shown that when people are offered the choice, the most popular way of returning products is the 'milieustraat', a municipal depot where people can hand in their products. The 'Apparatour' project ³⁰ showed that about 140 appliances were handed in at such 'streets' per 1000 inhabitants per year. According to the Apparatour project, this is also the cheapest way of organising WEEE collection. Second best is a weekly pick up system at the retailer, where people have returned an old for a new product. In all municipalities where this route existed, about 30% of all collected products were collected this way. Other routes, such as letting the retailer bring the appliances themselves to a depot, or curbside pick up showed less efficiency.

In November 1998, in the Netherlands an agreement was reached between the producers (represented by the VLEHAN and the FIAR, the branch organisations for white and brown goods that have organised themselves through the NVMP – the Dutch association that administers the Dutch end-of-life infrastructure for white and brown goods) and the NVRD (the Dutch organised public works services) about the collection infrastructure for white and brown goods. As a follow-up, a structure was implemented based on regional stations (called ROS – “Regionaal Overslag Stations or regional storage stations). At these stations, that should be no further away than 20 kilometres for all citizens, both household and retailers can leave used equipment at no charge. In the next step, all equipment handed in at the ROS stations is transferred to the producers, that will reimburse the ROS stations for costs made via the disposal levies paid by the customers (see also section 2.4).

The collection rates achieved through this system are presented in Figure 12³⁶. This figure represents the collection rates up to August 2000, in percentages of the amount of estimated yearly discarded products. From this figure it can be learnt that the collection of cooling and freezing appliances develops very favourably, more end-of-life appliances are collected compared to the theoretically discarded amount. For TVs, the collected amounts almost exactly correspond with the theoretically discarded volumes. For the other categories however, far less discarded product are collected in comparison with what is (or should be) theoretically discarded.

In Germany, a number of systems are available for collection of WEEE. Private persons can discard their WEEE through using a recycling yard ("Recycling Hof") or curbside pick-up services ("Sperrmüllabfuhr"). Most of the systems are managed and organised by municipal waste-management companies. For the municipal systems the financial situation depends on each specific municipality. In some cases no extra charge is in place. Instead the financing is taken care of through local waste-management taxes. In other cases an extra charge is to be paid when bringing the end-of-life product to the recycling-yards or when receiving the service of curbside pick-up. For small goods, in some parts of Germany separate collection systems are available, for example through specially marked plastic bags or depot-containers\textsuperscript{37,38}. Some categories of WEEE, mainly white goods or big brown goods like TV sets, are possible to return to the retailers when purchasing a new product. For white goods these systems are organised by manufacturers contracting third party recyclers to take care of their used equipment. A limited number of manufacturers run their own systems. For example, the German Telekom collects about 25,000 phone sets per day, both in their retail outlets and by their staff, when installing new phones.

In Sweden, collection systems for electronic products are available covering almost all Sweden. The responsibility is in the hands of the municipalities that provide the possibility for private persons of discarding their end-of-life electronics and white goods in special containers at the land-fill sites or at special collection centres where also paper, plastics and other products and material are separately disposed of. Only limited services for curbside pick-up is available for consumer electronics. Volumes of WEEE are transported to the recycling facility the municipality in question has signed a contract with (generally the closest one). In anticipation of further WEEE take-back legislation (see section 2.4), in addition to existing facilities, around a thousand additional collection points are to be set up, e.g. at petrol stations and multi-storey car parks.


\textsuperscript{38} Gallenkemper et al. Wissenschaftliche Begleitung des Pilotprojektes der Interseroh AG zur Erfassung von Elektroaltgeräten. Köl., Interseroh, 1997 (in German)
In the USA, some municipalities, cities or counties provide curbside pick-up of major home appliances. Several cities have recycling centers that collect refrigerators, air conditioners, freezers and some televisions. For both of these types of programs there are no additional fees collected by the municipal waste management company. Other cities have programs that encourage users to drop off their used appliances and electronic equipment and other consumers can pick up these products at no cost.

In Japan, until recently, each municipality had its own policy on taking care of end-of-life appliances. Tokyo and Kyoto send collection personnel to the user’s homes on their request, and charge a fee when removing the retired appliances. The fee varies depending mainly on the size – US$ 15 for a bulky refrigerator, US$ 2 for small appliances such as VCRs. Yokohama, Osaka and Nagoya collect the retired appliances that are to be placed by the former users in specified locations on specified dates. As it remains unknown who left which appliance at the location, this method does not require payment for leaving the retired appliance. However, it is expected that with the new take-back legislation enacted in Japan (see paragraph 2.4) the above policies may change drastically.

Economies of scale

In the context of this dissertation the presence of economies of scale is defined as the availability of large enough volumes of WEEE in a certain geographical region to make collection, transport and processing worthwhile activities. This may apply to either ecological efficiency or economical efficiency. Economies of scale in return logistics and end-of-life processing is an important issue. Several reasons exist for this:

• Without the availability of large enough volumes of WEEE, collection and transport costs might be too high to justify economical investment. Also, the environmental impact associated with for instance transport of WEEE (fuel and material use) can not be justified ecologically if it is not balanced by environmental benefits from recycling enough volumes of WEEE.

• Without the availability of large enough volumes of WEEE there will be no satisfactory return on economical investment of setting up recycling facilities.

• Without the availability of large enough volumes of WEEE the capacity of end-of-life processing lines or technologies used might not be used fully which could lead to economical disadvantages (processing costs per kilogram processed might be too high, prices obtained from selling secondary materials might be lower if selling smaller quantities at once), but also to environmental disadvantages (environmental impact per kilogram of processed will be higher). For instance: on a laboratory scale good results can be achieved in separating certain waste streams, whereas in every day recycling practice the same separation process would result in costs out of proportion due to the fact that too little mass of the applicable waste stream is available.

All the above mentioned reasons make that the absence or presence of economies of scale can be the main determining factor in the ability to set up a return logistics and recycling infrastructure if not already so required by legislation. Examples where the lack of economies of scale is hampering the set-up of such infrastructures can be found in for example the USA. In Europe, Sweden is a good example where logistics costs will be considerably higher in some less densely populated areas, due to the lack of favourable economies of scale. It is striking, that related research is very cautious where mentioning the (importance of the) economies of scale issue is concerned.

In section 3.5 the uncertainty associated with (lack of) economies of scale is further discussed.

**Geography**

Geography as a factor of relevance for end-of-life scenarios mainly manifests itself related to return logistics. The main geographical factor is the location of recycling facilities, as this has consequences for all aspects of the return logistics process discussed in section 2.3 including return characteristics and especially economies of scale. The (re)location of recycling facilities in a way that transport distances between WEEE collection points and recycling facilities will increase will in principle have a number of effects. Economies of scale will improve, as larger volumes of WEEE will become available per recycling facility. As explained in section 2.3 this has a number of positive effects related to processing capacity and return on investment. Also, the ensemble issue can be dealt with in a more satisfactory way when larger volumes of WEEE become available. In short, the effects of geographical changes have a direct influence on most issues discussed previously in section 2.3.

**2.3.3 Market prices for secondary materials**

Currently, the recycling of consumer electronics is not fully driven by market forces. The main reason for this is that only a limited number of product categories yield enough monetary benefits for manufacturers and recycling companies during the end-of-life stage to ensure at least cost neutral processing. Looking forward in this dissertation, in Chapter 5.3 it can be learned that only for miniaturised precious metals dominated products such as mobile phones, a positive financial outcome can be expected because of the relatively high amount of valuable precious metals contained in these products. For other product categories, the yield that remains is usually negative after costs for overhead, logistics and other costs are included. This is why parties (companies, municipalities, in the end the customer) offering end-of-life products of these categories to recyclers have to pay a fee rather then receive a price for them.

However, some market forces are important in the recycling process. Especially the market prices obtained for secondary materials influence the recycling process to a great extent. For components containing materials that will yield good prices, they form an incentive for recycling companies to separate these. Fluctuations in secondary material prices might lead to changed focuses in the disassembly process, or changing target
materials in a shredding and separation process – which in turn might lead to the use of alternative end-of-life processes. For these reasons, in this section, market prices obtained by recycling companies for secondary materials will provide the main topic of discussion in this section.

Other economical factors that have an influence on end-of-life scenarios include labour wages for various tasks related to end-of-life processing, operational costs for material separation processes, but also for example fuel prices related to return logistics processes.

The discussion of market prices for secondary materials focuses on two material categories, namely metals and plastics. In Western Europe, market prices obtained for secondary metal fractions depend greatly on the prices set at the London Metal Exchange (LME) – a stock exchange-like institution for metals. It is the world's premier non-ferrous metals market and according to there own statement, can therefore 'provide reference prices for the worldwide pricing of activities relating to non-ferrous metals'\(^{40}\) which is also recognized by specialists' publications\(^{41}\).

The determination of which materials are relevant for analysis with respect to end-of-life scenarios of consumer electronics is done based on experiences with recycling companies. Of all materials found in WEEE, the materials that yield the highest prices per unit of weight on the LME are precious metals, specifically gold, silver and palladium. Although found in low concentrations in most consumer electronics products, their market price is very high which makes parts with even limited concentrations of precious metals candidates for separation in order to retrieve the valuable materials they contain. Another important material to consider is copper. Although the market price for copper is considerably lower than for precious metals, the copper concentrations found in WEEE are often high enough (and locally concentrated enough) to economically justify the separation of these parts to enable retrieving the copper via smelting processes. The last metal important enough to consider retrieval for is aluminium. Disassembly of aluminium or aluminium containing parts in order to separate them for aluminium smelting is therefore often an economically justified activity. In Table 4, an overview is given of current market prices for relevant materials found in consumer electronics products, as set on the LME.

\(^{40}\) [http://www.lme.co.uk/about_lme/roles.html](http://www.lme.co.uk/about_lme/roles.html) (checked July 2000)

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield price per kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>€ 10000</td>
</tr>
<tr>
<td>Silver</td>
<td>€ 175</td>
</tr>
<tr>
<td>Palladium</td>
<td>€ 15000</td>
</tr>
<tr>
<td>Copper</td>
<td>€ 2</td>
</tr>
<tr>
<td>Aluminium</td>
<td>€ 1.50</td>
</tr>
</tbody>
</table>

Table 4: Market prices for materials found in consumer electronics (Nov. 2000)

As indicated before, plastics are present in consumer electronics in large numbers and variety, especially when the number of additives is taken into account. It is this very variety that prevents large-scale plastics recycling, for two main reasons. First of all, plastics that do contain additives can usually not or only at high costs be recycled – the specifications for applying recycled plastics in new products are such that even the smallest amount of additives can frustrate the entire recycling process. This makes it difficult to obtain large enough volumes of recyclates with constant specifications (and even if this would be feasible, the perception of recyclate performance with (designers in) companies would probably need some time to change). The second reason is that the supply of recycled plastics is usually in too small or too fluctuating amounts that application on an industrial scale is prevented. For these reasons, plastics from consumer electronics are usually not recycled, and current market prices cannot be given. However, for the purpose of end-of-life scenario analysis, in Chapter 5 and further on different prices for plastics fractions are used, to reflect a potentially maturing plastics recycling industry and market.

As for other metals (e.g. platinum, zinc, tin, lead, nickel), both information from recyclers such as Mirec in Eindhoven (The Netherlands) and additional material content analyses indicate that these are either present in WEEE in too low concentrations, or that market prices are too low to sell these separately in a profitable way – but usually both. The issue of which metals should be taken into account in an end-of-life scenario evaluation methodology is further elaborated on in section 3.5.3.

In many end-of-life yield calculation applications, the calculation of costs and revenues for material fractions is straightforward: these are usually given per unit of weight. However, there are also market groups in which a stepwise cost calculation is common to use. An important example is the smelting industry. The prices paid for batches of components/products that are offered to smelters depend on the concentration of target elements, usually copper and precious metals. This relation between concentration and price is usually not linear, as depicted in Figure 13. The discontinuities are caused by the presence of penalty elements.

In section 3.5 it will be discussed in what way the fluctuation of market prices for secondary materials cause uncertainty in future end-of-life scenarios. In the remaining subsections of this section, brief attention will be paid to other economical factors.
2.3.4 End-of-life processing costs

The benefits of in particular shredding and separation processes (which are explained in more detail in section 2.5.3) are in the form of prices obtained for retrieved material fractions, as explained above. However, for recycling firms costs are also associated with having these processes in operation. In this dissertation, the factors determining the level of processing costs will not be further investigated as these depend on factors such as the price of energy, capital investments, overhead costs, and depreciation – factors that are not of a specific end-of-life nature. What is interesting though is to investigate the way processing costs per tonne of processed WEEE depend on the capacity use of a certain process. In a standard shredding and separation process as described in section 2.5.3, processing costs at full capacity are € 0.17 per kilogram. However, when for instance a sudden decrease in the amount of WEEE to process will lead to a less than normal capacity use, the actual processing costs per kilogram of WEEE might increase, since the total operating costs of the process will not change significantly. Paradoxically, in such a case a recycler might lower the price of processing WEEE in the hope he will attract more volumes to process. It is therefore important to note that in the scenario analysis further on in this dissertation, processing costs refer to the costs incurred by the recycling company, and do not refer to the price a party had to pay to the recycler to have WEEE processed. Moreover, processing costs depend, at least in theory, on previously discussed factors like economies of scale and the ensemble issue (see section 2.3) and need therefore be analysed simultaneously, as will be done in the relevant sections of Chapter 3 and 6.

2.3.5 Labour wages

The influence of labour wages in end-of-life scenarios is mainly found in the manual labour for disassembly processes. The level of labour wages, together with the prices obtained for secondary components and materials, are the main determining factor for the economically justifiable disassembly depth.

Using the figures from Table 4, an overview\textsuperscript{42} can be given for the amounts of material that should be retrieved in a disassembly process to work on at least a cost neutral basis, see Table 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount of material in grams that needs to be separated to achieve cost-neutral disassembly</th>
<th>Material</th>
<th>Amount of material in grams that needs to be separated to achieve cost-neutral disassembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>0.055</td>
<td>PE</td>
<td>250</td>
</tr>
<tr>
<td>Palladium</td>
<td>0.035</td>
<td>PC, PM</td>
<td>350</td>
</tr>
<tr>
<td>Silver</td>
<td>3.1</td>
<td>ABS</td>
<td>800</td>
</tr>
<tr>
<td>Copper</td>
<td>300</td>
<td>PS</td>
<td>1000</td>
</tr>
<tr>
<td>Aluminium</td>
<td>700</td>
<td>PVC</td>
<td>4000</td>
</tr>
<tr>
<td>Iron</td>
<td>50000</td>
<td>Glass</td>
<td>6000</td>
</tr>
</tbody>
</table>

Table 5: Grams of material that need to be separated to work on a cost neutral basis

The figures in Table 5 are based on the so-called full industrial rate. In Western Europe this industrial rate is approximately US$ 0.50 per minute (including wages, overheads, housing). As can be seen, such rates imply considerable restrictions on the amount of material that can be retained from disassembly. If the work is carried out within the framework of subsidised job-creation schemes or outside Western Europe, then the limits are naturally based on a lower material weight.

Other work that is indirectly necessary for end-of-life scenarios to happen includes obviously the professional activities of the management and supporting staff of recycling companies. These are considered overhead costs and will not be further analysed. However, in this respect it is relevant to mention that hours spent on analysing material contents of material fractions, like explained in section 2.3, will depend on the size of the company (whether it can afford its own laboratory for material analysis), the volumes and types of WEEE processed, and the diversity of outlet channels, their specifications and the rate these are changing.

2.3.6 Fuel prices

The cost of transport of WEEE itself is not a focal point in this dissertation. The main reason for this is that no evidence can be found in literature (or from practical experience for that matter) that it is considered a determining factor for the way end-of-life scenarios are laid out; generally transport costs per kilogram are relatively low in comparison with handling and processing costs. In practice, a return logistics infrastructure is designed and prescribed based on other considerations, and the necessary transport is assumed to be a given factor. Still, in theory, the cost of transport itself, which is greatly determined by fuel prices, but also by labour wages and by (depreciation of) investments in capital goods such as trucks, does have an influence on the evaluation of end-of-life scenarios. Rising fuel prices, as a consequence of economical developments, could for example make transport more expensive, and therefore the required economies of scale could increase, leading to a number of consequences discussed previously in section 2.3. In extremis, this could mean that for some product categories, or in some countries or regions, the decision to set up an end-of-life infrastructure could be negatively influenced.
2.4 Legislative developments

Historically, legislation has been of major influence in the field of eodesign, and especially where it concerns the end-of-life stage. It can even be seen as one of the main driving forces for taking end-of-life considerations into account. Nowadays, (impending) legislation is still for most companies a (if not the) main reason to be involved with end-of-life issues.

The first attempt to enforce legislation applying to the product’s end-of-life stage (from here referred to as WEEE legislation) was made in Germany in 1991, when the first draft of an ‘Electronic Scrap Ordinance’ was published, covering the whole range of WEEE. In the next sections, an overview is given of initiatives that have been taken since. A similar overview is given in Furuhjelm.

**Germany:** Since the draft ordinance of 1991, intense discussion between all involved stakeholders has taken place. In 1998 negotiations between the Ministries of Environment and Economics and an industry initiative led to a consensus on the ‘IT Ordinance’, restricting it to IT products only. The regulations are based on the ‘shared responsibility approach’, with municipalities being responsible for collection and the manufacturers/importers taking care of the recycling itself. Its enaction is still pending, and, due to a change of government after the 1998 general elections, is not likely in a near future.

**The Netherlands:** As a consequence of the new Dutch legislation on producer responsibility and product take-back, VLEHAN and FIAR (branch organisations for suppliers of white and brown goods) have initiated a collection system for discarded white and brown goods as of January 1, 1999. The collection system is based on several waste collection streams, stemming from municipals as well as from shops (‘old for new’). A co-operation of manufacturers and importers will take care of all collected appliances, which will be recycled to the greatest possible extent. The system is financed by a fund under joint supervision of participants and the authorities. Its main financial input is the disposal levy, paid as a surcharge by customers when buying a new product. Mandatory from January 1, 1999 for big and, April 1, 2000 for smaller appliances, these vary from 1 to 18 Euro, as listed in Table 6.

---

48 Ontwerpbesluit verwijdering wit- en bruinoord, concept. Staatscourant 5.8, 24.03.1998 (in Dutch)
In the system, the costs for collection are covered by the authorities.

<table>
<thead>
<tr>
<th>Product category</th>
<th>Disposal levy</th>
<th>Product category</th>
<th>Disposal levy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling and freezing appliances</td>
<td>18 Euros</td>
<td>TVs</td>
<td>11 Euros</td>
</tr>
<tr>
<td>Large white goods</td>
<td>9 Euros</td>
<td>Most audio/video equipment</td>
<td>0 Euros</td>
</tr>
<tr>
<td>Medium white goods</td>
<td>7 Euros</td>
<td>Small domestic appliances</td>
<td>1 Euro</td>
</tr>
</tbody>
</table>

Table 6: Disposal levies for WEEE in the Netherlands

Since its implementation, the Dutch infrastructure for collection and recycling of WEEE has been a success. Based on expected collection volumes (where based on sales figures of about 15 years ago), by the Spring of 2000, virtually all refrigerators were collected. Of the TV sets, about 80% was collected. The other large white goods need additional attention however, since for these products only 50% was collected. As far as ICT equipment such as computers and phones were concerned, four times the expected amount was recycled, namely 3000 tons\(^49\). For the smaller products such as audio equipment, only small amounts were collected.

In the Dutch system the collection and recycling of 'orphan' WEEE – products from brands or importers that have gone out of business or have disappeared – has received special attention, especially for ICT equipment. Here, the participating ICT companies stand surety for the associated costs, a financial responsibility unparalleled by any industry in Europe.

**Denmark:** After lengthy and heated debate over who should bear the cost of WEEE recovery, Denmark has adopted regulations under which municipalities are to collect WEEE separately by December 1\(^{45}\), 1999. A key aim is to ensure proper treatment for heavy metals and to divert them from landfills and incineration plants, as well as to increase reuse and recycling of WEEE\(^{50}\). Consumers will pay for collection and recovery by way of higher disposal fees paid to municipalities, while businesses will pay directly for the service. Producers and importers may request permission to take back their products at their own cost, but must ensure the equipment is treated according to legislation. Consumers may also return used products to retailers willing to receive them. The regulations leave it up to the municipalities to decide whether they want to establish their own treatment facilities or contract with private waste management companies or with other communities. Since the amount of WEEE generated in Denmark is too small to make recovery operations profitable, a large share of such operations is expected to be carried out abroad.

**Sweden:** In 1997 the parliament has enacted legislation that came into force on July 1st, 2001, stating that all waste from electrical and electronic equipment (WEEE) in


\(^{50}\) South, S.G., Stewardship and Product Takeback: Electrical and Electronic Equipment. RCO 20th Annual Conference and Trade Show, Ottawa, October 1999.
Sweden is to be recovered. At recycling plants, all electronic waste must be pretreated by trained personnel\textsuperscript{51}. Like in Denmark and the Netherlands, Sweden has been proactive and enacted national legislation before European legislation comes into force. The Swedish system has many similarities in comparison with the Dutch system, including the possibility for customers to hand in old products for free. A difference with the Dutch system is that around 200 large companies will cover most of the costs, whereas in the Netherlands this is done with a visible fee, as explained above. In the future, producers will also be obliged to accept camera equipment, games and toys, household appliances, telephones, and medical and laboratory equipment. Local authorities will remain to be responsible for old refrigerators and freezers, and are also required to accept WEEE not handed in to the producer.

**European Union:** Regardless of these individual developments, the European Commission's Directorate-General XI has released four drafts so far of a new EU Directive covering the whole range of waste from electrical and electronic equipment. This directive among other things requires producers and importers to organise and finance collection and recycling of products that are put on the market, either collectively or individually. Also, product-specific recycling targets are set up of 70–90% by weight of separately collected appliances. The directive is not expected to become in effect earlier than 2005 due to necessary implementation in national legislation. More details about this proposed directive are discussed in section 3.3. A separate law on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) aims to foster eco-design and to almost completely prohibit the use of halogenated flame retardants and heavy metals such as lead, hexavalent chromium, cadmium and mercury (by January 1, 2008).

**Other individual EU member states:** In several other EU member states initiatives for implementing national legislation on the take-back of WEEE are also commencing. In Spain, an industry-led scheme is being finalized covering both collection and recycling. The scheme as proposed, although organized by industry, will be carried out by local authorities, and will involve a fee for consumers\textsuperscript{52}.

**Switzerland:** Switzerland's take-back ordinance for WEEE, which took effect in July 1998, requires consumers to return used products\textsuperscript{50}. Retailers, manufacturers, and importers are obliged to take back the equipment free of charge and treat it in an environmental responsible manner. The take-back requirement applies to all products regardless of date of purchase. In the Swiss system, manufacturers have to take back only their own brands, however, while retailers have to accept any type of product they sell. The government has not set specific requirements for recovery or disposal, leaving it up to business to make arrangements 'according to state-of-the-art technology'. Financing issues are also left to the market.

\textsuperscript{51} Swedish EPA (2000): Producer Responsibility for Electrical and Electronic Products Ordinance

Norway: Norway also implemented an electronics take-back scheme that is reported to work well\textsuperscript{52}. Norway's take-back regulation for WEEE took effect on 1 July 1999, making producers and importers responsible for the collection, transport, and environmentally safe treatment of a wide range of products\textsuperscript{50}. The regulation allows them to levy a surcharge on new product prices to finance collection and treatment but also obliges them to take back equipment sold before the introduction of the surcharge. Retailers and municipalities have an obligation to accept waste equipment from consumers.

Hungary: Hungary expects to implement a Waste Management Law in 2001, in order to harmonize its laws with the EU because of Hungary's intention to join the EU\textsuperscript{53}. The law will entail the implementation of a system that forces the producers to pay the recycling costs of their products. This will be organised by means of a central environmental fund that ensures the financial background of end-of-life management from the collection process to the recycling process\textsuperscript{54}.

USA: The US has not yet proposed any product take-back legislation. And so far no state has required electronics manufacturers or retailers to accept end-of-life equipment from consumers. However, some states including North Carolina, Wisconsin, Minnesota and California have showed initiatives towards product take back schemes. It is unlikely however that any state legislature on producer responsibility for product take back will be enacted into law in the near future. Over 30 of the states prohibit the placement of appliances into the landfill, which encourages end-of-life organizations to recycle or reuse the end-of-life appliances\textsuperscript{39}.

Japan: In Japan, the "Home Appliance Recycling Law" has come into effect in April 2001. It requires producers to take-back and recycle electronic home appliances. In this law, customers have to pay a recycling fee when they return products to retailers at the end-of-life. The products collected are sent to manufacturers or related recyclers for disposal. Manufacturers and retailers will bear the responsibility for setting up the system within three years. Appliances included in this new law are televisions, refrigerators, washing machines and air conditioners during the first step. These four product categories represent 80% in weight of all home electric appliances sold in Japan. The council has decided to hold off on including of computers and microwaves in abeyance. Computers may be considered in 5-10 years. Some private organizations plan to implement voluntary product take-back schemes of computers.

As for another Asian country, Taiwan has enacted electronic waste take-back legislation as of March 1, 1998\textsuperscript{55}. This entails\textsuperscript{50} that Taiwan has been requiring take-back of


\textsuperscript{35} Corbet Consulting, September Newsletter, 1997

60
end-of-life computers, refrigerators, air conditioners, washing machines, and television sets. The legislation applies to products sold both before and after its entry into force. Retailers must accept used electronics from consumers. Fees levied on manufacturers and importers on the basis of units sold or imported finance the collection and recycling process. Producers have announced that they intend to absorb the fee burden instead of passing it along to buyers of new equipment. A 30% recovery target was set, meaning that the volume of used equipment collected annually should be at least 30% of the volume of new equipment sold. Though there is no target recycling rate, by law all collected units must be sent to a recycling facility.

2.5 Technological developments

For the end-of-life processing of WEEE, a number of technologies are relevant to discuss. Five kinds of technologies are distinguished, as listed below. Following the elaboration on the technologies themselves in this section, at the end of this section it will be investigated which technologies are used for relevant product categories according to current end-of-life scenarios in the Netherlands.

It should be noted that the aim of this section is not to present relevant technologies in great detail. Several publications have done this already in an outstanding way (for example Nijkerk56). The main focus is on presenting an introduction for the identification of uncertainties associated with them as will be done in Chapter 3.

• **Sorting and handling technologies** – these refer to the way product streams are sorted and divided into useful batches of WEEE upon arrival at a recycling facility. Currently, this is usually done based upon experience. Vehicles like forklifts and manual labour support this process.

• **Disassembly technologies** – these refer to technologies, which are used to separate components from the main product and from other components. Disassembly technologies are usually manual operations, although in recent years much research has been devoted to automated technologies using robots, and even more sophisticated technologies like active and cryogenic disassembly.

• **Shredding technologies** – these refer to processes that are used for shredding products or parts of products that remain after disassembly into smaller particles. Shredding is a necessary step before separation technologies can be used.

• **Separation technologies** – these refer to processes that are used to separate a particle mix consisting of various materials into fractions of (almost) the same material. Separation technologies include separation on basis of for example density, conductivity, colour, and weight.

• **Smelting technologies** – these refer to technologies that are used to obtain as pure as possible material from material fractions that result from shredding and/or separation processes. Smelting is for example used to obtain secondary copper and precious metals.

• **Incineration and landfilling** – these refer to burning and dumping of WEEE, or of any remaining fractions that may be left after the use of previous processing steps. In recent years, both have become high-tech businesses, using advanced technology to prevent harmful emissions into the environment.

A number of paragraphs in this section are derived from Stevels and Boks and van Houwelingen. The description of the technologies (especially the sophisticated topic of smelting technologies) is kept short to avoid standard text book-like elaboration. For more detailed descriptions is referred to the mentioned literature.

### 2.5.1 Sorting and handling technologies

Before products from WEEE streams enter the end-of-life processes in a recycling facility, they are usually sorted according to a variety of specifications. These specifications are mainly based on material content. The sorting of the WEEE streams is done based on experience and knowledge about the subsequent processing steps. The associated in-site transportation of batches of WEEE across the area of the recycling facility is done using manual labour assisted by heavy utility vehicles like forklifts, and in some cases conveyor belts.

### 2.5.2 Disassembly technologies

Disassembly, or dismantling, is the most common way in recycling practice to separate components from the main body of the product. Full, partial or selective disassembly is the preferred technology to use in cases where shredding and separation is an inappropriate technology because of the process characteristics. Whereas shredding and separation can be regarded as a destructive technology, disassembly can be regarded as a non-destructive technology, enabling complete recovery (and possibly reuse) of product components.

In principle, disassembly is done for two reasons – although both reasons are because of economical reasons; the first to obtain financial benefits, the second one to avoid financial deficits.

• To obtain components that, in a separated state, have a higher value than when contained within the product. This is for example the case when a component has a high value because of its copper content. In the case where the copper content of a component is higher than a certain threshold value, it is economically justified to separate the component because otherwise the value of the components will get lost in the rest of the product. Generally, disassembly enables to isolate material fractions that are more pure.

• To isolate hazardous substances in order to avoid contamination of other material fractions which may lead to too great an influence on the environmental results or on the financial return. Some components containing hazardous substances can only be disposed of at high(er) fees. In a separated state, these fees apply to the component only, in a non-separated state, these higher fees may apply to the complete product.

---

Therefore, partial and selective disassembly of WEEE is usually carried out in such a way as to remove those components inappropriate for material recycling. In this context, the hazardous components are usually pre-disassembled for separate treatment.

In current disassembly practice, separation of plastics parts aimed at high-application recycling is usually only done with the disassembly of housings of larger electronics goods such as television sets, provided these housings are not contaminated with (halogenated) flame retardants, additives or surface treatments like paints or lacquering. Generally, separation of plastics usually proves only worth while in case large volumes of mono-material plastics can be separated.

In most cases, disassembly is done by hand (referred to as manual disassembly) and is therefore costly. In Western Europe the total industrial rate is approximately € 0.50 per minute (including wages, overheads, housing) although other studies\textsuperscript{58} have been using rates as low as € 0.14 per minute, these might not include overhead costs. Western European labour rates imply considerable restrictions on the amount of material that can be retained from disassembly, as previously explained in section 2.3. As recycling practice is often carried out in an industrial context, disassembly needs to be an economically justifiable activity. For a company it is economically attractive to disassemble products when the disassembly costs of such operations are offset by the increase in end-of-life revenues (or the decreases of end-of-life costs). These end-of-life cost or revenues are determined by the revenues of the recycling of materials or the reuse of parts minus the costs made for the removal of the remaining parts. That is why it is important to be able to determine which disassembly operations are at least cost neutral to perform. Therefore most recycling companies establish so-called standard disassembly times, so that the probable disassembly time of a product can be determined. These standard disassembly times should relate not only to the dismantling activity itself but also to so-called secondary activities such as preparing the product for disassembly, gathering the tools needed for the job in hand, turning or moving the product, removing materials, breaks, etc. In Table 7 a number of standard disassembly times are given. For more information on theoretical and practical determination of disassembly times is referred to Boks et al.\textsuperscript{59}


<table>
<thead>
<tr>
<th>Disassembly operation</th>
<th>Time required</th>
<th>Disassembly operation</th>
<th>Time required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw (instantly accessible)</td>
<td>6.5 sec</td>
<td>Nut/bolt combination</td>
<td>11.5 sec</td>
</tr>
<tr>
<td>Screw (obstructed access)</td>
<td>10.5 sec</td>
<td>Welded joint (per point)</td>
<td>7.5 sec</td>
</tr>
<tr>
<td>Click (instantly accessible)</td>
<td>3.5 sec</td>
<td>Welded joint (per surface)</td>
<td>18.5 sec</td>
</tr>
<tr>
<td>Click (obstructed access)</td>
<td>7.5 sec</td>
<td>Slide</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>Glued joint</td>
<td>12.0 sec</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Examples of average standard disassembly times

Because of the restrictions that manual disassembly pose on an economically justifiable disassembly process, since the beginning of the nineties a number of research projects have focused on automating the disassembly process. Some state (e.g. Knoth et al.\textsuperscript{34}) that disassembly automation is absolutely necessary worldwide because of the dramatically increasing amount of WEEE. However, no figures are given to support this statement. Still, automation of disassembly processes has attracted enough attention to deserve some further elaboration on the subject, especially where the future (economic) feasibility is concerned (see also section 3.4.2).

In theory, automation will improve the disassembly process in a number of ways:

- Replacing manual disassembly labour by automated systems (robots – hence also the term robotized disassembly) will make the disassembly process cheaper because it greatly reduces the need for expensive manual labour.
- The use of automated processes will enable a more precise separation of parts since it improves accuracy of the operations needed for disassembly. In this respect, an increase in the number of non-destructively disassembled parts can be envisaged.
- The use of automated processes will enable the disassembly of a wider range of products than can be economically disassembled using a manual process. This might be true for several reasons:
  - Because of a cheaper process, an automated process enables the disassembly of products that are too small, or contain too few valuable parts to justify the more expensive manual disassembly process for;
  - Automated process can perform disassembly operations that are hazardous or undesired because of other reasons for manual labour work.
  - The use of automated disassembly will lead to better defined material fractions, for example in the case of CRT-containing products\textsuperscript{30}.

In current recycling practice however, the use of automated disassembly processes is far from common. However, reports have been published on automated disassembly tests on a laboratory scale. From these pilot projects, the main conclusion is indicated in Knoth\textsuperscript{34} where it is stated that currently only some pilot projects have been realized. These are in the form of fully automated single purpose solutions, and for only one distinct type of product. In this publication, an application is researched in which product families rather than single product types can be processed. To support the development of automated disassembly processes, research has been carried out in the past decade on topics like disassembly sequence generation\textsuperscript{60,61}, disassembly process planning\textsuperscript{62,63,64}.
and virtual disassembly analysis. It is outside the scope of this dissertation to discuss these research projects, because these research areas deal specifically with the question how to disassemble from a technical point of view. This is the same reason why the research area of disassembly plant lay-out planning is not further discussed here, but some of the mentioned publications by in particular Zussman and Gadh can be regarded as the state of the art in this area of research. In section 3.4.2 it will be discussed how envisaged future developments in the application of automated disassembly processes will affect future end-of-life scenarios.

2.5.3 Shredding and separation (mechanical processing) technologies

Material not detached in the disassembly process usually ends up in a combined form on so-called mechanical processing lines. This processing consists in actual fact of two steps: shredding and subsequently, separation.

Shredding is essential to break down the different sorts of material and achieve a reduction in volume, and to obtain a homogeneously sized input stream suitable for separation processes. Shredding occurs in hammer mills, cutting mills or other shredder-grinder combinations, or by means of cryogenic milling. The shredder or hammer mills used for WEEE generally produce particle sizes between 10 and 100 mm.

The next step, the mechanical process aiming at physical separation of the shredded WEEE scrap to concentrate distinct material types from the main material stream, makes

\]
\]
\]
\]
\]
\]
\]
\]
\]
\]
use of the differences in physical properties including particle size and shape, density, electrical conductivity and magnetic properties\textsuperscript{70}, provided that the materials are first separated (liberated) by a shredding process. The use of different properties has lead to the development of a number of separation technologies, which will be discussed below in short. The combination of these processes is also referred to as bulk recycling\textsuperscript{71,72}.

As there is (still) no universal sequence of mechanical recycling processes, most recycling plants are in one way or another specific to one or a small number of product categories. An example of a typical WEEE recycling process is shown in Figure 14. In this process, separation is achieved in several different separation stages. First, ferrous metals can be separated by magnetic separation. After magnetic separation, often an additional separation process is necessary because for shredded motors, coils or transformers, complete separation cannot be achieved using magnetic separation only. This is due to the fact that copper parts remain attached to iron parts in the shredding process.

Subsequently, non-ferrous materials are separated by means of eddy-current processes. Eddy current processes separate materials, which have different conductive properties using an alternating magnetic field. These processes are particularly suited for separation of non-ferrous metals like aluminium, copper, lead and zinc. In current recycling practice however, the focus of eddy current separation processes is almost exclusively on aluminium.

A variety of other separation methods are then used to separate other fractions. These can be copper-content materials, mixed plastics and precious metals. Dry mechanical separation techniques are wind sifting (used for separation of non-ferrous metals and plastics), gas cyclone separation, vibration methods, fluid beds and sieves (air-based or other). The advantage of these techniques, above wet mechanical separation techniques, like hydro-cyclone separation, flotation and sink/flow separation, is that there is then no problem of wastewater (although dust can also be problematic).

Plastics separation is, compared to ferrous and non-ferrous metals separation, a problematic process. Due to the wide variety of plastics, without or without contaminations (in the form of additives and/or surface treatments), and the fact that the applied technological process often depends on the specific separation goals, plastics recycling can still not be regarded as a common integral part of regular WEEE recycling processes. Though many successes have been achieved on a laboratory scale, for example at the Delft University of Technology department of Raw Materials Technology, wide industrial application of plastics separation processes (other than the disassembly of housings, see the previous section) is not yet present, although several examples exists in cases where


both supply and demand of input and output fractions are present. In these cases, the most commonly used methods for separating plastics are based on density properties.

Although, as stated above, there is not a universal shredding and separation process, however, for the shredding of WEEE that aims mainly at the recovery of metals typically two types of shredders or shredding and separation combinations are relevant to mention:

- **Coarse shredders** are shredders that use hammer crushers that have in-built separators like magnetic separators, air classifiers and sieves, and to which eddy current separators are applied for the recovery of non-ferrous metals. The recovery percentage of non-ferrous metals is here largely determined by the suction capacity of the air classifier.

- **Medium and fine shredders** are shredders use multiple size reduction steps in order to obtain fractions that are of a significantly more homogeneous and smaller particle size. These shredders are mainly used for smaller WEEE and especially for fractions that have a high content of non-ferrous metals (10%-20%).

![Diagram](image)

*Figure 14: An example of a processing line for miniaturisation and separation of consumer electronics*

Of product parts containing ferrous materials, 95% of the magnetic material can be made suitable for high quality recycling by means of magnetic separation processes. High quality recycling of other plastic parts can be achieved when the material consists of more than 95% of thermoplastics of one kind. When this 95% consists of two materi-

---

rials, the part can be recycled with low quality. Parts, which contain less than 95% of thermoplastics, can be considered for other separation techniques. Of these parts 60% of the precious metals can be separated and recycled with high quality. Currently, 80% of the aluminium and 90% of the ferrous can be recycled with low quality. Other plastic parts and the rest fraction can be considered for incineration and landfill.

When a choice between incineration and landfill has to be made, the caloric value has to be considered. High caloric value materials produce net energy during incineration and therefore this is preferable to landfill. Metals produce 0 MJ/kg while plastics produce 40 MJ/kg. Therefore the best solution for plastic parts, if they cannot be recycled, is incineration. When the caloric value is higher than approximately 8 MJ, incineration is preferred.

If the product is not stripped of its toxic parts, the entire product has to be treated as chemical waste and will be charged accordingly. It will therefore end up in higher waste incineration tariffs. Separation of parts will be attractive when the costs of dismantling and processing of toxic parts minus the economic value of the remaining non-toxic materials are lower than the costs of processing the entire product.

Only a very small portion of end-of-life related literature has focused on shredding and separation as an end-of-life strategy. In 1996, Coulter et al.74 acknowledge this already in an automotive context, stating that the, at that time current recycling guidelines concentrate mostly on manual disassembly, and that many fail to note that there is much larger variety of recycling and separation guidelines to be considered. This observation can also be made in an electronics context. Whereas most literature (certainly prior to 1999) and especially design oriented literature, solely focuses on disassembly oriented strategies, Weißmantel41 was one of the first to discuss shredding and separation processes in a specific relation to products or product design issues. For more information on separation techniques is referred to for example, Nijkerk56, Arola et al75, Zhang and Forssberg20, van Houwelingen76 and Ram et al77.

2.5.4 Smelting technologies

The metallurgic processes used for reclamation of material fractions from WEEE are both extensive and complex, and the processes used depend greatly on the requirements for the secondary materials. Especially for copper, a large variety of applications

exists, in a range of different degrees of purity. Depending on the requirements for the secondary copper and the specifications of the copper-containing WEEE fractions, pure copper will have to be added to the recycling process to some extent. In general, the higher the copper concentration in WEEE fractions, the more and the better alternatives exist, and higher the price will be that can be obtained from copper smelters. That is why for recycling companies it is usually beneficial to achieve high copper concentrations by means of disassembly and shredding and separation processes.

2.5.5 Incineration and landfill

Residual materials from disassembly or material recycling processes, for which no other (useful) application is available, or which contain potentially toxic substances, are usually incinerated. Two incineration processes are relevant to discuss in the current context:

- Incineration with energy recovery. This is also referred to as quaternary recycling and thermal recycling). This process involves the incineration of non-reusable materials by using energy generation technology and good flue gas purification.
- Incineration of non-reusable materials without energy generation technology but with flue gas purification.

The incineration of materials is generally lower on the list of environmental priorities than product, component and material reuse. One major exception is the destruction of environmental pollutants during incineration (i.e. the destruction of flame retardants).

Incineration is usually not complete and a residual product is left behind (slag). Metal can sometimes be recovered from this slag. How this residual slag is to be treated in an ecologically responsible manner, is one of the most important cost factors for determining the incineration rate to be charged. This applies to an even greater extent for the purification of flue gases released during incineration, especially aggressive chloride and bromide-based gases. Combined with organic residues these compounds can be the basis for dioxin production. This, thanks to the technological improvements and more careful processing in modern incinerators, is now more nearly under control and flue gases nowadays meet the extremely strict standards that have been set. Obviously, the highest rates are charged for those waste categories that demand the most intensive flue gas purification processes. In Table 8 additional waste charges for various substances are given, as provided by the Dutch incineration plant AVR.
<table>
<thead>
<tr>
<th>Presence of chemical element</th>
<th>Additional fee in € per 1000 kg</th>
<th>Maximum presence if higher, prices are to be negotiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>If more than 1%, for every additional 1% 15</td>
<td>20%</td>
</tr>
<tr>
<td>Sulphur</td>
<td>If more than 1%, for every additional 1% 40</td>
<td>10%</td>
</tr>
<tr>
<td>Bromine, Fluorine, Iodine</td>
<td>If more than 1%, for every additional 1% 45</td>
<td>5%</td>
</tr>
<tr>
<td>Sodium, Potassium, Lithium</td>
<td>If more than 1%, for every additional 1% 50</td>
<td>10%</td>
</tr>
<tr>
<td>Mercury</td>
<td>If more than 5 ppm, for every additional 5 ppm 20</td>
<td>1.00 ppm</td>
</tr>
<tr>
<td>PCBs, dioxins</td>
<td>If more than 50 ppm, for every additional 50 ppm 75</td>
<td>500 ppm</td>
</tr>
<tr>
<td>Metals Group 1</td>
<td>If more than 1%, for every additional 1% 20</td>
<td>20%</td>
</tr>
<tr>
<td>(Cr, Co, Cu, Pb, Mn, Mo, Ni, V, W, Zn)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metals Group 2</td>
<td>If more than 1%, for every additional 1% 40</td>
<td>20%</td>
</tr>
<tr>
<td>(Sb, As, Be, Cd, P, Se, organic Si, Ti, Sn, Ag)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Additional waste charges for various substances

As for landfill, only the deposit of residual material in a controlled fashion as solid waste at a landfill site is discussed as it is the only permitted landfill option in most cases. Although (in the Netherlands) special landfill sites exist for difficult to process waste fractions, eventually landfill will (have to) be replaced with incineration\(^77\).

2.5.6 Disassembly versus shredding and separation

Not regarding reuse, theoretically disassembly of end-of-life appliances serves the goal of reclamation of valuable and hazardous substances best (Figure 15). By dismantling end-of-life appliances, environmentally relevant fractions can best be isolated and appropriately treated thereafter.

Recyclers face however the fact that manual disassembly is very costly, and that more cost effective automated disassembly processes are not to be expected in the near future\(^78,79\). Therefore, from a total systems perspective, and without heavy subsidizing, disassembly is often not a feasible option. In particular this applies to competitive, non-subsidized recycling markets. Because of these facts, in several Western European countries nowadays approximately half (on a weight basis) of all discarded electronic appliances are shredded and subsequently separated into various material streams. This has lead to the approach that the determination of end-of-life scenarios requires primarily


1. Prevent discarding
2. Reuse of the product as a whole
3. Reuse of subassemblies and components
4. Material recycling
   - in original application
   - in lower grade application
   - back to feedstock plastics
5. Energy reuse (use as fuel)
6. Incineration (with energy recovery)
7. (Controlled) disposal as waste

Figure 15: Hierarchy of end-of-life destinations

a perspective based on the output of the recycling process rather than on the input of the process. It has been pointed out in Ram\textsuperscript{77} et al. that for shredding and separation, end-of-life processing is about material streams and about separating or joining them, rather than about individual products.

Also, Zhang and Forssberg\textsuperscript{70} acknowledge shredding and separation as both an economically and ecologically sound solution for treating waste from electronic products, although they foresee several problems. One of the problems mentioned is the unlocking or liberation of copper from WEEE products. Whereas aluminium can usually easily be separated from WEEE scrap, copper is often used in such a sophisticated way in electronic products, that copper parts can be attached to various plastics, ceramics, ferrous metals and precious metals that separation of copper from WEEE is relatively complex. The use of high-speed granulators has in such cases proved to be beneficial.

In Haberland et al.\textsuperscript{80}, an article from 1997, the remark is made that disassembly as a recycling technique is superior to the wide spread shredding and sorting technology. In the same article, it is concluded that eventually disassembly represents the best method to achieve a cycle-economy. It can be assumed that with this bold statement they mean disassembly is preferred over shredding and separation as a recycling technology from an ecological perspective, as they also state that the low degree of disassembly is "the problem today".

Wolf et al.\textsuperscript{81} argue that an impact analysis on a scenario that addresses only a single process option like complete disassembly or complete incineration is not sensible. Rather, a mix of recycling and disposal should be defined depending on the product. In the same vein, Furuhjelm et al.\textsuperscript{82} also discuss disassembly and shredding and separation


as two options for recycling. They state that regarding both technologies as excluding each other is not realistic. They should be regarded as complimentary, where initial disassembly should be regarded as a step preceding shredding and separation. Although this remark is valid in some cases, especially where CRT-containing products are involved, calculations in section 5.3 and further show that shredding and separation is the preferred scenario for many product categories, especially for low value brown goods.

Outlet specifications determine choice of recycling process

The way end-of-life appliances are processed in recycling companies is often a direct result of the specifications of these outlets. This is true for both disassembly and mechanical processing. Recycling companies will have to judge the outgoing fractions by a number of outlet specifications such as scrap dealer specifications (Fe, Al, Cu, precious metals smelting), plastics recycler specifications and incineration specifications, depending on the outlet. A few examples include:

- Depending on the available outlets and their specifications, disassembled Printed Wiring Boards (PWBs) are separated in one, two or three categories (IC-rich, modern, and old), which could affect the sorting process considerably.
- Copper smelters usually demand a >20% copper concentration in material fractions that are sold to them by recyclers. This affects both the disassembly process (e.g., copper wiring separation) and the shredding and separation process (e.g., the choice of degree of size reduction to obtain preferred unlocking characteristics). It also affects the way (batches of) material fractions are mixed after processing (see also the ensemble issue discussed in section 2.3).
- Separation of certain specific plastics fractions is only (economically) justifiable in case a market exists for secondary plastics, which in turn depends on economies of scale and the specifications for secondary plastics applications. An example of this is the separation of large mono-material housings of television sets that are disassembled anyway because of the removal of the CRT. These plastic parts are only worth while to separately process further if large enough quantities exist to ensure a solid basis for re-application.

These examples show that the way products are processed in their end-of-life phase strongly depends on what options exist for recyclers to dispose of the resulting fractions. This is not a constant factor: different outlets have different specifications for these fractions, and both vary over time. For a recycler, this means that, apart from the fluctuations in supply of end-of-life appliances, also the demand from the secondary materials processing market varies. These mechanisms make that the recycling strategy for processing WEEE equipment is essentially determined by the outlet specifications that are set at the end of the end-of-life stage.

In a global context, the factors described above lead to big differences in end-of-life costs. Differences in economies of scale and recycling capabilities lead not only to differences in logistics costs but also to different preferred processing techniques. Outlet channels and specifications differ also, which leads to the conclusion that it will be problematic to realize similar recycling efficiency targets in the different countries at similar costs.
2.5.7 Technology in current end-of-life scenarios

In section 1.1, where some of the terminology used in this dissertation was introduced, already a broad overview was given of what an end-of-life scenario is, and of what stages it is composed. The aim of this section is to describe current end-of-life scenarios using all factors discussed in the previous two sections. Distinction will be made across a number of product categories, as was done in Table 9.

At this stage, associated costs and environmental impacts of current end-of-life scenarios will not be given, as this depends on the evaluation method to be used. Existing methods for evaluating end-of-life scenarios will be presented in Chapter 4, and in Chapter 5 the new approaches will be presented that will be used to evaluate all end-of-life scenarios discussed in this dissertation, including current scenarios.

The results presented in this section are mainly applicable to the Netherlands, as this country can be regarded as one of the leading countries in the world as far as having the successful implementation of an end-of-life infrastructure is concerned.

As earlier addressed in section 2.4, in the Netherlands, authorities and industry have agreed about end-of-life strategies to be followed and recycling ratios to be realized. The agreement has resulted in the end-of-life processing scenarios for the brown goods category as given in Table 9.

<table>
<thead>
<tr>
<th>Product category</th>
<th>Example</th>
<th>Main end-of-life processing strategy</th>
<th>Recycling percentage being realised, on a weight basis</th>
<th>Recycling percentage as proposed by European Union</th>
</tr>
</thead>
<tbody>
<tr>
<td>Products containing picture tubes</td>
<td>TVs, monitors</td>
<td>Disassembly</td>
<td>ca. 68% (old products)</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ca. 75% (new products)</td>
<td></td>
</tr>
<tr>
<td>Metal dominated products</td>
<td>Video recorders</td>
<td>Shredding and separation</td>
<td>ca. 53% (VCR)</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ca. 70% (miniset)</td>
<td></td>
</tr>
<tr>
<td>Plastic dominated products</td>
<td>Audio products</td>
<td>Shredding and separation</td>
<td>ca. 30%</td>
<td>70%</td>
</tr>
<tr>
<td>Precious metal dominated products</td>
<td>Portable phones</td>
<td>Shredding and separation</td>
<td>ca. 9% (cellular phones)</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ca. 67% (car stereo)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ca. 32% (walkman)</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Main end-of-life processing strategies for brown goods category.
Table 9 shows that both for products containing picture tubes and for products without picture tubes reasonable recycling percentages can be scored. This is particularly apparent because the products above refer to products, which are on average 15 years old and originating from the pre-ecodesign period. The table also indicates that, in the Netherlands, with shredding and separation as main processing strategy relatively good results can be scored. Apparently, the technology and the outlets in place fit the purpose of recycling. However, this relatively good score is partly reached by the composition of the waste stream; metal dominated products form the largest group, whereas plastic dominated products are relatively scarce. The recycling percentages obtained in the pilot project Apparetour and in the current take back programmes are still substantially lower than those proposed in the Draft Ordinance on electronic waste of the European Union, as can be seen in the rightmost column in Table 9.

In the subsequent sections current end-of-life scenarios for the four product categories are physically described. Related costs and estimations of the associated environmental impact will be given for a number of products. The examples are partly derived from a research project called “Design for non-Disassembly”, carried out in a co-operation between Philips Consumer Electronics and TNO Industry. The findings of this research project have been presented in several publications\(^\text{77,83}\). Since the finalizing and evaluation of this project, additional product analyses and benchmarks have been carried out as follow-up. Also, experiences based on graduation projects carried out at Delft University of Technology have been included. Most of these projects were partly carried out at Philips Consumer Electronics.

**Products containing picture tubes**

This product category basically consists of television sets and CRT-based computer monitors. The presence of the picture tubes makes that for the determination of the processing scenario almost all other product characteristics are irrelevant. Current separation technology is not equipped to handle satisfactorily the recycling of glass from picture tubes, which accounts for approximately 50% of the total product weight. This makes the presence of the CRT the decisive factor for determining the preferred end-of-life scenario, which is disassembly.

In the current end-of-life scenario, first the picture tube and some additional parts are separated from the rest of the product by manual disassembly. This is done to enable the tube to be processed further, and therefore they are cleaned by removing the deflection unit, the electron tube, stickers, rubber parts, glues and metal bands. For a typical TV set and monitor from 1996, a representative disassembly oriented end-of-life scenario entails the separation of parts as shown in Table 10.

\(^{83}\) Deckers, J.M.H., Ram, A.A.P. and Kalisvaart, S, Recyclability of High Volume Electronics - Design for Non Disassembly, Philips Centre for Manufacturing Technology, CTR598-98-0011
<table>
<thead>
<tr>
<th>Component</th>
<th>Avg. weight % TV</th>
<th>Avg. weight % monitor</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>16</td>
<td>12</td>
<td>Incineration, or recycling if no flame retardants are present</td>
</tr>
<tr>
<td>CRT</td>
<td>62.5</td>
<td>38.5</td>
<td>CRT recycling</td>
</tr>
<tr>
<td>Electronics</td>
<td>8</td>
<td>12</td>
<td>Cu smelter</td>
</tr>
<tr>
<td>Ferrous parts (e.g., speakers, EMC shielding)</td>
<td>5.5</td>
<td>17</td>
<td>Fe smelter</td>
</tr>
<tr>
<td>Deflection unit</td>
<td>2.5</td>
<td>3.5</td>
<td>Mech. processing</td>
</tr>
<tr>
<td>Other Cu parts (e.g., degaussing coil)</td>
<td>0.5</td>
<td>1.5</td>
<td>Cu smelter</td>
</tr>
<tr>
<td>Other Al parts (e.g., earth corset, degaussing coil)</td>
<td>0.3</td>
<td>0.5</td>
<td>Al smelter</td>
</tr>
<tr>
<td>Mains cord</td>
<td>0.2</td>
<td></td>
<td>Cable processing</td>
</tr>
<tr>
<td>Electron gun</td>
<td>0.5</td>
<td></td>
<td>Mech. processing</td>
</tr>
<tr>
<td>Rest fraction</td>
<td>4.5</td>
<td>15</td>
<td>Incineration</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Disassembly scenario for CRT based products, including outlets for different parts

After the disassembly process the following situation exists:

- Recycling of the CRTs is possible, but there is only a limited capacity for the current CRT glass industry to use post consumer CRT glass in production. The processing of tubes entails shredding and pulverising of the tube, after which the glass is sieved. If necessary, this process is repeated until a homogenous mass is obtained which can be sold as a secondary material to either the TV glass industry or the ceramic industry. However, melting glass from picture tubes with the aim of reapplication in new picture tubes requires sophisticated technology, since the specifications (especially the purity requirements) for tube glass are extremely high. Therefore, end-of-life picture tubes need to be dismantled and cleaned to a high degree, but even then there is a limited application for secondary glass. Only with a high-level separation in cone-, screen, and neck glass the recycling of used CRT glass will be successful. Small amount of recycled CRT glass can be added to virgin glass for the production of cone glass for new CRTs. In 1996, Philips conducted preliminary tests have been successful of using up to 10% of recycled glass (referred to as ECORAM – ECOlogical Raw Material) into new CRTs. Main problem with this application was the lack of flexibility – it was difficult to guarantee a continuous and large enough stream of recycled CRTs necessary for production. Several years later, improvements were made in both the composition of ECORAM, the specifications for cone glass and the logistic process. This has lead to the application of up to 20% ECORAM in cone glass production, a result that was previously regarded as very optimistic. Still, on a large industrial scale, a continuous application of more than 10% ECORAM is not possible because of insufficient as well as fluctuating capacities in the supply chain. The application of screen glass in new TV screens is currently regarded as not feasible,

but in the (near) future this reapplication might become feasible as well.

- The electronics fraction is processed via a shredding and separation process as described previously in this chapter. Ferrous metals and aluminium from the electronics fraction are sold to iron and aluminium smelters respectively. If the remaining copper/mixed plastics fraction meets the copper smelter specifications, which it generally does, it is sold to them.

- Granulating and reusing the plastic housings in the original application is not done, mainly because the granulate does not meet the specifications for the materials currently used for cover parts. In particular, the granulate contains flame retardants which are in general not longer used for cover parts. Mixing the granulate with virgin material to meet the specifications for reuse in the original application, or using it for less demanding applications is theoretically possible but unlikely to happen, mainly because of lack of financial incentives to do so. This is a result from the immaturity of secondary plastics markets. This issue is discussed further in Chapters 6 and 8 since assuming maturing secondary plastics markets will have a significant effect on the economics of end-of-life processing.

- The other fractions are sold or disposed of as indicated in Table 10.

**Metal dominated products**

Products from this category generally have metal housings. Magnetic parts make up over 60% of the total product weight. Video recorders are almost always in this category, but also audio equipment such as mini sets has often metal housings. These products further exhibit few plastic parts, typically less than 20% of the total weight of the product.

Depending on the exact disassembly scenario and the size of the product itself, disassembly times for this product category are between 1.5 and 4.5 minutes. Usually, further processing and selling of the separated parts does not outweigh the cost for the disassembly process (as will be proven in section 5.3), even if the products are designed substantially more disassembly friendly.\(^{85}\)

The considerations given above make that metal dominated products are an excellent candidate for mechanical processing and are therefore processed that way. Although the weight of the products from this category are dominated by ferrous metals, the low prices obtained for ferrous metals for detailed figures on these prices) make that the results of the shredding and separation scenario are for a large part determined by the copper and precious metal content of the PWBs in the products.

**Plastics dominated products**

In plastics dominated products, plastics are particularly used for the outside cover. Examples are faxes and audio products such as sound machines. In these cases, more

---

\(^{85}\) Langerak, M. *The waste of audio products: are there alternatives or is it a dead end?* Graduation report. Delft University of Technology, Faculty of Industrial Design Engineering, 1997.
than half of the product weight consists of plastics, while the total weight of the magnetic materials can still add up to as much as 40%. The precious metals content is generally moderate or low since these products in general appear to include a relatively low weight of electronics. Since generally no valuable components are to be retrieved either, disassembly is usually too expensive for products from this category. Therefore, plastic dominated products are usually also mechanically processed. Like for the metal dominated category, the results of the shredding and separation scenario are again determined to a great extent by the material composition of the PWBs in the products. On average it can be assumed\textsuperscript{83} that for products in this category the PWB composition is similar to that of products from the metals dominated products category. The differences in costs result from the higher weight percentage of plastics here. Disposing of the remaining fraction is therefore more expensive.

In section 5.3 it will be shown that because of the high plastics content in this product category, the recycling efficiency is considerably lower than in the metals dominated product category. Of course, the recycling efficiency could theoretically be improved by additional disassembly, but that would take end-of-life costs out of proportion.

**Precious metal dominated products**

Since precious metals are mainly found on PWBs, the weight of products in this category consists for a relatively high percentage of electronics (20% up to more than 40% for cellular phones). Products falling in this category are therefore mainly portables or miniaturized products such as walkmans and cellular phones. Also car stereo equipment falls in this category. The cover materials for these products can either be plastics (for example walkmans) or metals (car stereo).

It will be shown in section 5.3 that the conventional weight-based material recycling efficiency in this product category is relatively low. Because of the focus on precious metals, the rest of the materials in the product are more or less "sacrificed". The weight of these materials contributes therefore in a negative way to the material recycling efficient score.

Apart from the high associated costs making it unattractive, disassembly of miniaturized products is hardly of any use. The recovery of materials from disassembled components can only be done on a very small scale due to the size of the products and the fact that most parts are contaminated in one way or another due to the product configuration. This experience is confirmed in an ECTEL report on the end-of-life management of cellular phones\textsuperscript{86}.

In another study\textsuperscript{82}, disassembly and shredding and separation were compared as options for recycling of a TRX, a transceiver unit for a radio base station. From the results of this analysis the conclusion was drawn that the preferable end-of-life treatment for this product, considering both ecological and economical parameters, was shredding in a shred-

\textsuperscript{86} ECTEL Cellular Phone Working Group, End-of-life management of cellular phones: An industry perspective and response, 1997.
der for electronical equipment, and subsequent materials recovery. Disassembly was found to add no additional value. Also, the energy use necessary for disassembly was found to be five times higher than the amount necessary for shredding and separation.

Regarding this issue, an article by the large Spanish electronics recycler Indumetal Recycling S.A. describes a specific recycling process for cellular phones\(^{87}\) said to be 'environmentally friendly'. It entails the separation of button cells and batteries, and apparently the LCD screens were mechanically separated after the shredding process. Any further disassembly was found to be economically prohibited, a result that agrees with the statements made above. In the Indumetal process, metals are recovered through well-known separation techniques. Plastics from cellular phones were in this case also separated, though suggestions for design improvements regarding plastics and rubbers are made to allow for easier separation.

### 2.6 Environmental developments

Last (but not least) in this list of external influences, the 'environment' is discussed. Although the environment as an influencing factor is omnipresent and acts and reacts in countless ways to all societal phenomena, it is chosen here to discuss a number of environmentally related issues that have a particular influence on end-of-life scenarios and the ways to evaluate them.

In essence, products that have reached their end-of-life are processed for two reasons. There may be economical incentives to do so, in case materials or components can be resold at a price higher than the cost of reclaiming these materials or components. There are often also ecological incentives to do so, in order to prevent hazardous materials to end up in the environment. These ecological incentives are often translated in economical incentives through either legislation (by becoming costs for non-compliance) or consumer demands. In the latter case companies may face losing market share if a significant portion of its consumers demand a certain environmental responsibility from companies. Consideration like these lead to a discussion on what is actually regarded as environmentally responsible behaviour related to the consumer electronics industry.

In this respect, Stevels\(^{88}\) distinguishes different types of 'green':

- Scientific green
- Government green
- Company green
- Customer green

In the subsequent subsections these different types of green are discussed.

---


\(^{88}\) Course mateiral Delft University of Technology
Scientific green

In science, Life Cycle Assessment (LCA) is regarded as 'the most objective' way to determine the environmental impact of products, processes and systems. LCA seeks to examine the complete environmental profile throughout the full life cycle and includes for example electricity generation, infrastructure and other factors which cannot directly be influenced by the designer or industry. In 1993, the SETAC (Society of Environmental Toxicology and Chemistry) issued what would become the basis of LCA methodology\(^9\). So far, LCA scores are usually solely based on emissions and can therefore, as argued in section 1.4, not accurately described the product end-of-life stage, since here (potential) environmental impact is not solely emissions based.

LCA basically consists of two parts: the construction of databases with impact scores for individual materials, processes and scenarios, and the application of a method that uses these impact scores to calculate aggregated scores for whole products or systems. The latter part in particular can be done only using subjective motivations, since various environmental impacts (such as damage to human health and to ecosystems) have to be weighed.

The 'LCA community' has been putting great efforts into constructing databases with reliable environmental impact information. However, disagreement on how to attribute environmental impacts to emissions in an accurate, well quantified way continues to maintain the absence of a standard LCA method that is beyond discussion. The differences in subjectively interpreting various environmental effects is the main reason for this, and causes differences across various methods, and even across generation of the same method. Still, a number of tools using a variety of databases and metrics have gathered substantial support and are widely used across the world, including for example Ecoscan\(^{90}\), Simapro\(^{91}\), and GaBi\(^{92}\). It seems that, although uncertainties associated with the choice of the proper method do exists, the main uncertainties are associated with the regular updates of environmental impact databases. Although the result for an overall environmental score does not necessarily depend on the method used\(^{93}\), for analysis of selected life cycles or product parts only, significant differences can occur easily.


\(^{91}\) http://www.ecoscan.nl


Therefore an objective interpretation of such results can be difficult especially in an end-of-life context.

**Government green**

Government green is discussed as a separate type of ‘greenness’ since the priorities that are attributed to different environmental problems do not always necessarily reflect the same order as they would have been if based solely on scientific arguments. This is mainly due to the inclusion of a wider variety of environmental issues into the decision process than is done by LCA – again, many of these additional issues are not emissions based. They also include issues that citizens (the voting public) regard as important for maintaining or improving quality of life or which are associated with emotions that perhaps cannot be substantiated by (LCA-based) scientific back-up, such as reduction of landfill sites, recycling issues and phasing out of (perceived) hazardous materials such as PVC.

**Customer green**

Stevels\(^{94}\) distinguishes seven archetypes for environmental consumer orientation. In Table 11 these archetypes are given with the average percentages for each archetype as found in Northern Europe.

<table>
<thead>
<tr>
<th>Archetypes</th>
<th>Average percentage in Northern Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmentally Engaged</td>
<td>15%</td>
</tr>
<tr>
<td>Environmental Optimists</td>
<td>15%</td>
</tr>
<tr>
<td>Disoriented Consumers</td>
<td>13%</td>
</tr>
<tr>
<td>Environment too Complicated</td>
<td>15%</td>
</tr>
<tr>
<td>Environmental Pessimists</td>
<td>15%</td>
</tr>
<tr>
<td>Growth Optimists</td>
<td>10%</td>
</tr>
<tr>
<td>Enjoy Life</td>
<td>17%</td>
</tr>
</tbody>
</table>

*Table 11: Seven archetypes of environmental consumer orientation\(^{94}\)*

As it is certain that for each archetype different perceptions of green and therefore different behaviour is to be expected, it is uncertain how the percentages of archetypes will be distributed in the future and how this will affect behavior in terms of buying and returning (ecodesigned) products.

In addition to the distinction that Stevels makes, an additional level of distinction is relevant, depending on the intended audience. For every type of green, different audiences can be identified. In this respect, Dutilh\(^{95}\) makes a distinction between four intended


\(^{95}\) Dutilh, C. Life Cycle Assessment (LCA), Information booklet issued by the Netherlands Ministry of Housing, Planning and Environment, November 2001.)
audiences for LCA studies (which in Stevels' distinction would be considered as scientific green), namely businesses, consumers, public authorities and students. All distinguished intended audiences are different in their need for detail and accuracy of supplied information. Similar distinctions for intended audiences can be made for the other types of green as well. So, the way that results of environmental studies in general should be communicated is not only a matter of interpretation, but also of envisaged use. Back to the context of this dissertation, in section 4.3, it will be further discussed how intended audiences determine the development of tools for end-of-life evaluation.

2.7 Conclusions

In this chapter an overview has been given of factors that have an effect on the end-of-life stage of consumer electronics, in particular to those factors that are external to a company and for which limited ways exist to control them. In particular, focal attention was given to external factors of a technological, legislative and economical nature. Also, it has been explained which product characteristics have an effect on the end-of-life stage, and that additional influencing factors exist that are less tangible, because they express developments within a company as addressed by the Environmental Value Chain theory. With this chapter, step 1 of the research methodology introduced in section 1.1 has been taken, but the first research question

‘What are for a consumer electronics OEM the most important factors and developments associated with the end-of-life stage of consumer electronics?’

still has only partly been answered. In order to determine what the most important factors are, the remaining steps have also to be taken. Step 2, to be taken in the next chapter, deals with the investigation of where the factors discussed in this chapter lead to uncertainty for the consumer electronics manufacturer, thus answering the second part of the first research question

‘In particular, what are the main uncertainty factors that are outside the control of these companies?’
3. Scenario Uncertainty

In Chapter 2, current end-of-life infrastructures and routes for consumer electronic products have been discussed, including various influencing factors such as legislative, technological and market developments. Because of these developments, the results of environmental and/or economical assessments of end-of-life scenarios are very likely to change when one or more of the influencing factors, such as those discussed in the previous chapter, changes. In the remainder of this dissertation, the term 'scenario uncertainty' is used to express the fact that (for companies) the absolute and relative effects of the various developments in end-of-life on relevant performance indicators are not easily known or determined upfront, which could lead to missing information for successful policymaking with respect to environmental issues. So, rather than formal definitions of uncertainty such as absolute, approximation or systematic uncertainty, in this dissertation the term uncertainty is used as a qualitative expression of lack of information.

In Chapter 3, it is investigated in what way these factors are likely to, or expected to, behave and change in the future. It will be assessed whether this will have a significant effect on end-of-life scenarios and on the performance indicators that are used to assess these scenarios. It will be discussed how to incorporate uncertainty about changing influencing factors (from here on referred to as scenario uncertainty) into end-of-life scenario evaluation; this is done for all the internal and external factors introduced in Chapter 2.

In the following section, an overview is given of how state of the art research deals with end-of-life scenario uncertainty. Anticipating this, there is literature available\(^{96}\) that discusses the problems of uncertainty in end-of-life scenarios. It identifies probability theory as a widely accepted format for dealing with uncertainty but it recognizes that it does not deal with higher-order uncertainty (uncertainty about uncertainty) – an aspect of end-of-life uncertainty that is important. Also, the lack of empirical data to verify assumptions of probability distribution in many cases causes probability theory to be less useful.

It is shown that, although approaches are proposed to overcome the problem outlined above, in reality very few examples exist so far of successfully applying these approaches and incorporating scenario uncertainty issues into product end-of-life evaluation. For the very few examples that do exist, it will be shown in what way they do not meet the requirements set earlier in this dissertation.

Also, a theoretical framework is set up describing systematically every aspect of product end-of-life scenario uncertainty. The aim of this framework is to provide a basis for

a systematic approach to incorporate scenario uncertainty into product end-of-life evaluation assessment. Also, it lays the foundation for the development of two new approaches that will prove to be excellent tools for businesses for evaluating the end-of-life characteristics of their products.

3.1 Taking scenario uncertainty into account

Increasing landfill costs, public awareness to environmental problems, changing legislation and other environmental aspects force industry to consider end-of-life scenarios within the perspective of the total product life cycle. Especially during the product design phase it is important to realise that end-of-life aspects may play an important role. Nowadays it can be observed that companies often assume that end-of-life scenarios will be the same by the time products they are designing are discarded as they are during product design. This is not because companies do not realise that end-of-life scenario can vary over time, but it is just because they do not have enough information to predict changes and how to deal with them. The uncertainty regarding future developments is especially true for technological developments—a lack of insight and knowledge on future developments in this field forces companies to assume they will remain unchanged. In the limited amount of literature that exists on including uncertainty factors in the end-of-life stage into analysis, it is usually stated that technological aspects of end-of-life scenarios are assumed to be given. In another example risk and uncertainty assessments are disregarded completely, although it is stated that for example estimations on possible numbers of returned products are of fundamental importance for forecasting cost/revenues assessments.

In important issue from a business perspective is of course to determine the benefit of reducing uncertainty. Obviously, the more information on the subject (on any subject) is available, the better uncertainty is reduced, the better futures scenarios can be drawn, and the better the company is served. The question is of course at what effort and what cost can this be done.

To clarify this, the statement is made that dealing with end-of-life scenario uncertainty in essence means dealing with two major dilemmas. Starting from a company's perspective, an important question to be raised is whether it really needs to have insight in future scenarios, or whether using scenarios reflecting the current situation will do for its purposes.

The dilemma lies in the fact that the "correct" way to deal with scenario uncertainty would be using actual forecasts of future scenarios, but this is difficult, whereas using scenarios reflecting the current situation - although these might not properly represent the future to come - seems to be much easier. This leaves the question of which

---

97 References and examples are given later in this section.

Chapter 3: Scenario Uncertainty

approach to take. But even when this dilemma is solved, and if the choice is made to actually incorporate scenario uncertainty into end-of-life scenario assessment, a second dilemma will have to be dealt with; whether an elaborate approach is needed to deal with future scenarios, or whether a simplified approach, if such an approach exists, will do.

Here, the dilemma lies in the fact that coming up with a research methodology for the development of elaborate approaches seems (paradoxically?) to be relatively easier than to research simplified approaches. It can be argued that the development of elaborate approaches in theory means just doing a lot of work, for example assuming probability distributions for all unknown factors and interlinking them in a sensible way which in theory sounds very straightforward. The difficulty here is not in designing the models themselves, but in filling the databases needed to support calculations made in the model. An example here is the RELOOP approach, which will be discussed in Chapter 4. In this project the model is, or at least appears to be well developed, including the possibility to include uncertainty ranges for difficult to assess model parameters, but bringing the required databases up to standard remains a an important hurdle to be taken towards implementation of RELOOP in practical situations. Still, in theory, this would ‘only’ require an immense amount of work but is still straightforward. In this case, making proprietary information such as costs and revenues of recycling processes available is probably the biggest hurdle to overcome.

Developing simplified approaches on the other hand will require ways of carefully selecting which criteria are both (i) in the first place possible to assess, and (ii) significant or relevant enough in relation to other criteria (in which case significance levels should be addressed). Thirdly, the preferred accuracy of predictions needs to be decided. Performing these tasks for all uncertainty factors with the objective to consider incorporating them into a workable, reliable, simplified approach might even be a more formidable tasks than “just doing a lot of work” as would be necessary for an elaborate approach. In a sense, development of these envisaged simplified approaches will need a lot more ingenuity than developing elaborate approaches, hence the use of the word paradoxically in the previous section. Still, this should be weighed against the idea that the results of simplified approaches are probably much easier to handle in practice, whereas the results of elaborate approaches go into way too much detail to be practical in any way. So one is left with the question what approach to take. This understanding leads to the conclusion that in principle there are three approaches to take:

- To use scenarios reflecting the current situation only. This way future developments are not taken into account, and relevant information useful for answering the research questions is ignored. However, if no added value is to be expected from other approaches this might be a sensible approach;
- To use scenarios in which future developments are reflected, and to use simple approaches although these can at first not be developed in a straightforward way;
- To use scenarios in which future developments are reflected, but to use elaborate approaches, although they might not be practical to use in a company environment.

This dissertation will especially focus on taking the second approach. This means developing simple and practical approaches enabling companies to deal with uncertainty
regarding the end-of-life stage of their products. The results of this approach are discussed in Chapters 6 and 8.

The end-of-life scenario applied to a product after the usage phase strongly depends on the product type, properties and conditions, available processing technologies for worn out products as well as country specific constraints. Nowadays, researchers all over the world concentrate their research work on the development of end-of-life technologies for end-of-life scenarios for different product types. End-of-life technologies under investigation include manual, mechanical or automated disassembly, active disassembly or shredding. Other newer technologies, like nano-technology, are currently also under investigation. But one key issue is almost always missing: typical uncertainties during the whole product life cycle are not implemented and therefore the end-of-life scenarios and their associated financial implications are only based on known parameters. In most cases, no statements are made about the reliability or feasibility of the proposed approach. Researchers assume different scenarios applied to a product from their current point of view and do not consider changes over time, technologies and geographic locations. They then use these assumptions as basis for end-of-life value calculations.

When discussing the factors causing scenario uncertainty in an end-of-life context, it is obvious that time is at the basis of all factors. The fact that products produced today will on average not be discarded until 10 to 25 years from now leads to the fact that product designers today do not know how these products will be collected and processed in the future. However, the influence of time and hence the uncertainty about future end-of-life scenarios manifests itself in a number of difference forms. To analyse this, all factors leading to scenario uncertainty are categorized into five uncertainty types. This is depicted in Figure 17.

![Figure 17: Uncertainty factors influencing scenario uncertainty](image)

In sections 3.3 and onwards, these factors causing uncertainty will be discussed in more detail. Whereas in Chapter 2 for each factor the aspects were determined that were to some extent influential on end-of-life scenarios, in this chapter it will be investigated in what way these aspects lead to uncertainty. First however, in section 3.2 it is discussed in what way recent literature has taken the issue of end-of-life uncertainty as such into account.
3.2 The issue of scenario uncertainty in recent literature.

In this section it is investigated in what way recent publications have described the issue of incorporating uncertainty issues into the assessment of product end-of-life scenarios.

Some examples from the small amount of publications that specifically include uncertainty factors in life cycle cost modelling are based on Emblemsvåg work.\textsuperscript{99, 100, 101, 102} With respect to costs associated with the end-of-life stage, it is stated there that uncertainty must be included due to the predominant lack of hard data. The most simple example of this is that one can only actually measure the true environmental impact and the true economics of the end-of-life stage of a product once this products has ended its useful life and entered it is end-of-life stage, which can be 10 to 25 years from now.

Emblemsvåg distinguishes two ways in which uncertainty on end-of-life scenarios can be modelled,\textsuperscript{100} namely modelling uncertainty based on historical data and modelling uncertainty based on experience and qualified guessing. Whereas the second option would call for fuzzy analysis, quick and dirty approaches or even simple expert opinion, the first option would involve some form of statistical analysis. In the literature by Emblemsvåg uncertainty is dealt with by introducing an uncertainty distribution model. In this model, costs are determined for the different cost drivers in an activity-based costing model. Whenever there is a need to deal with uncertainty regarding a certain cost driver, a triangular uncertainty distribution is determined for such a cost driver. Using Monte Carlo analysis, values for the cost drivers are then determined. This approach also facilitates sensitivity analysis. However, one of the assumptions this model is based on, is the assumption that historical data can be used as a good guideline for future development. This means that this method is less useful for modelling for example technology changes, since these may appear "suddenly", and are not always a logical extrapolation of earlier developments. This is also acknowledged by Emblemsvåg, and he argues that the way his model deals with "fuzziness" is beneficial for the purposes of their research. The major drawback of this model is that it uses a considerable amount of input. This is not particularly a problem for Emblemsvåg's purposes, which include an activity-based LCA method, for which detailed data are required anyway. But the focus of this dissertation is about the assessment of end-of-life aspects relevant for business. Although this is done from a life-cycle perspective, inputs such as user phase energy costs are not required for this goal, and therefore the high amount of input data makes


\textsuperscript{101} Emblemsvåg, J. and Bros, B. (1999). Integrating Economic and Environmental Performance Measurements Using Activity-Based LCA, in the proceedings of the 3rd International Seminar on Life Cycle Engineering, June 21-23, Queen's University, Kingston, Ontario, Canada.

a second reason why the approach of Emblemsvåg is not particularly suited for the purpose of this dissertation. His work should be acknowledged though as prominent, and will be particularly relevant for studying in specific design cases where more detailed information and solution-finding is required regarding issues concerning costs and uncertainty in relation to the end-of-life stage of products. An extensive summary of the work is published in Emblemsvåg and Bras.\textsuperscript{103}

Another example of literature addressing the inclusion of uncertainty with respect to end-of-life issues is found in a publication by the Microelectronics and Computer Technology Corporation (MCC).\textsuperscript{104} They propose an approach where any input into a model may be entered as either a single value or as a distribution (normal, lognormal, triangular or uniform) to account for uncertainty in the data. In an example they use triangular distributions. It is stated that this is typically the simplest for the user in that it requires only the most likely value and the expected extremes. Next, in basically the same way as Emblemsvåg does, the use of Monte Carlo analysis is proposed based on a user specified confidence level. The model that is described in the MCC paper focuses on reuse of components within an identical product design and is therefore completely out of the scope of this dissertation (as stated in section 1.5). In the article it is stated however that the model could be expanded to include other end-of-life processes including re-use in other design, sub-component and material salvage, and recycling. However, no publication is known to the author where this expansion is explored.

Rose\textsuperscript{105,106} also addresses the issue of “predicting end-of-life strategies”. She proposes the use of a Classification and Regression Trees (CART) to map product characteristics to decision trees, as a result whereof appropriate end-of-life strategies can be determined. An iterative process of case studies is necessary to determine which product characteristics are most relevant to decide about the most appropriate end-of-life strategy. As Rose’s research focuses on the choice of the various strategies for end-of-life rather than on the uncertainty of various end-of-life developments, the metrics used in her research are of little relevance to this dissertation.

Muller\textsuperscript{107} tackles the issue of end-of-life yield estimation, not explicitly from a scenario


uncertainty point of view, but rather from a good bookkeeping point of view. The only uncertainty that is taken explicitly into account, is that in Europe (his work is written from an American point of view) take-back laws are expected and that therefore end-of-life costs are expected to increase significantly. Other so-called 'estimations' are rather predictions based on educated guesses.

In an Ecobalance study an analysis methodology is explained for comparing three different WEEE processing scenarios (the at that time current UK situation, a 100% landfill scenario, and the proposed requirements as set by the EU directive (see section 2.4)). The analysis methodology is stated to include a sensitivity analysis step for the identification of key variables affecting costs, and for the quantification of key differences with original scenarios. Further references in this study to this approach are however very limited and lead to believe that scenario uncertainty is only taken into account in a very limited and certainly not quantitative way.

3.3 Uncertainty because of legislative developments

In section 2.4 it was stated that legislation, or impending legislation, has been of major influence on the way end-of-life scenarios look like, or will look like in the future. At the moment of writing this dissertation, in several countries legislation concerning producer responsibility and take back of WEEE is in the process of being considered and draft ordinances are being or have been written. In countries such as The Netherlands, where a directive has been implemented, this has on the one hand greatly reduced uncertainty since now the responsibilities of the manufacturers and the importers are clear. That is, where the organization of end-of-life infrastructures are concerned. But on the other hand, uncertainty regarding the environmental benefits or losses due to the present system still prevails. Although larger quantities of WEEE are now being processed because of the take-back obligation, in the processing stage of end-of-life scenarios nothing much has yet been changed as a result of the recently implemented directive. Also, companies did not have to implement drastic measures as a result of the new legislation, since the costs of the system are passed on to the customers through the disposal levy, which was reported on earlier.

On a European level, legislation regarding the organisation of end-of-life infrastructures is still under debate, let alone that there is a clear view on the environmental consequences of potential infrastructures. Since 1997, four WEEE legislation drafts have been issued, and with every new draft amendments have been made, paragraphs have been changed, and new paragraphs have been added – leading to uncertainty with the companies involved as they have to prepare for the aspects of legislation that they expect will concern them.

The draft legislation for WEEE consists of a number of responsibilities, obligations and restrictions. Below, the most important of these are enumerated, and in a qualitative way it is discussed in short in what way these potential developments can lead to uncertainty. Any quantitative assessments will be made in section 6.4.
• An important aspect of WEEE legislation is the obligation to reach a certain recyclability percentage. This obligation aims to lead to products that are better designed from an end-of-life perspective, and material fractions that were previously not separated or recycled being in fact processed. This in turn might lead to increased economies of scale, larger quantities of certain materials being separated, affecting secondary markets and ultimately prices obtained for these fractions. On the negative side, processing costs might also increase as previous treatment processes and associated costs might not be existent. It is important to realize that the obligation to reach certain levels of recyclability as proposed in draft legislation can in theory also have counter effects. In a position paper\(^{108}\) by the EACEM (the European Association of Consumer Electronics Manufacturing) it is clearly stated that without balancing the required recyclability targets, the associated environmental gain and the costs involved of doing so, a situation might occur where the costs of recycling might become out of proportion, counteracting any positive effects that might have been realized in the first place. For example, reduction of recycling costs from increasing economies of scale might completely disappear when the costs of this process become to high.

• A second obligation for producers is establishing end-of-life collections systems. It is safe to assume that with the level of sophistication employed rising, also the positive effects on economies of scale will increase. With more sophisticated take-back systems, larger quantities of end-of-life equipment can be collected that are in excess of quantities that are collected with usual consumer behaviour. This will ensure more efficient processing reducing associated costs per kilogram as well as additional positive effects as laid out in the previous paragraph. On the other hand, with the organization of collection systems also additional costs are involved. In the Netherlands these collection costs are paid for through municipal fees.

• Another important aspect that comes with WEEE legislation is the restriction on incineration and landfill of certain products or material fractions. Such restrictions can lead to fractions that were previously landfilled or incinerated will now be recycled, leading to favourable economies of scale which can in turn lead to positive effects on prices and markets as mentioned above, but also to increased processing costs as recycling these fractions might be more expensive than incineration or landfill.

• Phasing out of the use of potentially hazardous substances such as lead, mercury, cadmium, hexavalent chromium and halogenated flame retardants are expected to make in the future more products and material fractions suitable for (less sophisticated) separation techniques. Not only will this reduce the need for expensive disassembly operations previously necessary to achieve recyclability targets, it might also increase by itself the volumes of products shredded and separated, with all positive economies of scale that can come of this.

Summarizing the effects mentioned above, legislative developments can lead to positive effects in economies of scale, processing costs and prices on secondary material mar-

kets. It may also stimulate technology development, which in itself has positive effects. On the other hand, processing costs themselves might increase compared to the previous situation when products or material fractions were not recycled at all. This may also be true for collection and further logistics processes. The bottom line here is that many effects can be expected, but the sum of the effects is in many instances so far unclear. An additional cause of uncertainty is the fact that it has not become clear yet what the consequences are of non-compliance with the future take-back legislation. The way the proposed draft legislation will or will not be enforced in the various EU member states will determine the success and the associated positive effects on the various developments and variables. In order to assess the balance of these developments, scenarios need to be drawn and for this the effects need to be quantified. This is done in section 6.4. Drawing these scenarios requires careful weighing of the possibly opposite effects involved. As no studies have been performed charting these effects, the drawing of the scenarios will unfortunately largely have to be a speculative process. This does not mean that much better insights are to be gained from this than those already present – there is always a least bad way to do something that is very hard to do. A useful article on recent developments regarding legislative developments in the EU is presented by Dammert et al.\textsuperscript{109}

3.4 Uncertainty because of technological developments

To many people active in Design for Environment, next to legislative developments, changes in technology comes up first when asked about what might have the biggest influence on future end-of-life scenarios. For this reason, a considerable part of Chapter 3 is devoted to discussing technological developments. Before going into detail on technological developments in future end-of-life scenarios, a brief description of some literature dealing with technology forecasting is presented, to provide a guideline for the remainder of this section.

In search for a method to quantify future technological developments, Twiss\textsuperscript{110} presents a step-wise approach to what he calls quantification of technical progress. According to this approach, four elements should be incorporated in any forecast:

- The event or phenomenon itself – a qualitative identification of what the forecast should be about;
- A measure of performance – the parameter by which the attribute can be assessed quantitatively,
- The time scale – linking a performance level of the parameter and a date in the future,
- A probability assessment – to reflect the inherent uncertainties of future developments. Such a probability assessment is usually subjective.


Twiss also states that the purpose of a forecast is to ensure that this view of the future reflects the best judgements that can be taken with the information available at the time it is made. But he also states that uncertainty, even thought it can be reduced, cannot be eliminated.

Following Twiss' steps, the development of technology as an uncertainty factor in end-of-life scenarios can be regarded from two perspectives: technology related to the design and manufacturing of products, and technology related to end-of-life processing. In this section it was chosen to focus almost exclusively on the latter perspective, but it should be realized that also technology developments related to the design and manufacturing stage of the life-cycle will have their impact on end-of-life scenarios. A number of such promising technology developments can be identified that will have the potential to cause end-of-life scenarios to look different than they currently do. An important example is (see also ZVEI84) the use of new materials for manufacturing printed wiring boards to eliminate environmentally relevant materials, such as the use of lithographic films111 as opposed to thick film and copper printed circuit boards, and the use of lead-free soldering techniques112,113. Another example is the development of new plastics that will phase out the need for the use of environmentally relevant additives in plastics still used in current plastics applications – such as flame retardants (for progress in this field of research see for example Bergendahl114 and Segerberg et al115).

In Chapter 6 however, some design and manufacturing related technological changes will be analysed, in particular those that will have a profound influence on the material composition of products and therefore on their end-of-life scenario. Examples will be the substitution of CRTs by LCD screens and the miniaturisation of electronics (see section 6.6).

Moving back to technological developments in the end-of-life stage, these appear to be especially relevant during the sorting and handling and end-of-life processing stage of the end-of-life cycle. Table 12 lists uncertainty issues related to technological developments for these stages. This table is based upon the division of technologies as given in section 2.5.

Chapter 3: Scenario Uncertainty

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Technological developments that may lead to uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorting and handling</td>
<td>Automatic detection of product type</td>
</tr>
<tr>
<td>technologies</td>
<td>Automatic detection of product brand</td>
</tr>
<tr>
<td></td>
<td>Automated detection of material content</td>
</tr>
<tr>
<td></td>
<td>Automated sorting of products</td>
</tr>
<tr>
<td>Disassembly technologies</td>
<td>Automated or robotised disassembly</td>
</tr>
<tr>
<td></td>
<td>Other artificially intelligent forms of disassembly</td>
</tr>
<tr>
<td>Shredding technologies</td>
<td>Reduction of particle sizes</td>
</tr>
<tr>
<td>Separation technologies</td>
<td>Automated sorting of non-ferrous metal waste streams</td>
</tr>
<tr>
<td></td>
<td>Automated sorting of mixed plastics waste streams</td>
</tr>
<tr>
<td></td>
<td>Automated sorting of mixed plastics and metals waste streams</td>
</tr>
<tr>
<td></td>
<td>Improvement of recovery grades</td>
</tr>
<tr>
<td>Smelting technologies</td>
<td>Improved smelting technology</td>
</tr>
</tbody>
</table>

Table 1.2: Areas where technological developments can cause uncertainty

The continuation, or the stagnation, of these technological developments will influence how future end-of-life scenarios will look like, and whether the focus of future end-of-life scenarios will be mainly on material recycling only, material recycling using prior disassembly, or disassembly.

Now that it has been determined what phenomena are addressed with respect to technological developments in the product end-of-life stage, these will be further discussed in the subsequent subsections. For each development, the three remaining steps from Twiss' model are applied.

Part of the text and the data presented in this subsection on future technological developments are based on the results of a Delphi study on future recycling technology, carried out in 1997. The full details of this study have been published by Boks and Tempelman.\(^{117}\) Also, two papers derived from this study have been published.\(^{117, 118}\) Most questions in the Delphi study referred to developments of a technology nature. However, also some questions on developments of geographical and economical natures were discussed. Originally, the Delphi study was carried out for both consumer electronic products and automobiles. Because of the scope of this dissertation, here only the results addressing consumer electronic products are presented. The results of


the Delphi study have been compressed and adapted considerably to fit the size and purpose of this dissertation. However, in Appendix 1 an explanation is given of what this Delphi study was about, with respect to the objectives, the panel that participated in the study and how they responded.

The following subsections address the different aspects of end-of-life technology as given in Table 12.

3.4.1 Future developments in sorting and handling technology

In end-of-life related literature not much attention is given to sorting and handling technology. The main reason for this could be the fact that the choice of which sorting and handling processes to use is not an autonomous process but depends completely on operations and activities before and afterwards. Operations that take place before the sorting and handling process refer mainly transportation of WEEE and the way this is organized locally. Relevant future developments in this process as such are not to be expected, although economies of scale can in this respect lead to improved efficiency in the logistics process. Such improvements will be discussed in section 3.5.2. Operations after sorting and handling takes places refer to the way recycling facilities organize the incoming volumes of WEEE. State-of-the-art recycling facilities often make it their business to sort incoming WEEE according material contents, the WEEE is therefore sorted into various streams such as CRT containing products, white goods, IT equipment, products with expected high copper contents, products with expected environmentally relevant components, etc cetera. Depending on which disassembly lines and shredding and separation processes are available, products and product streams are stored or processed, requiring various sorting and handling processes depending on the local situation.

Relevant future developments in this case are possible in the field of advanced product recognition techniques. Especially in relation with envisaged future developments, in particular automated disassembly, the application of bar codes on products (if not done already during the manufacturing process) and the subsequent use of bar code readers during the sorting and handling process are imaginable, though hardly researched. One of the first publications addressing this issue is from Grudzien and Seliger119, in which the idea for life long product supervision device (LCU = Life Cycle Unit) is introduced. This unit is supposed to capture data about the product during its useful life. Possible applications are the facilitation of recovery of valuable components and materials, extended quality assurance, and even 'a better documented basis regarding claims from product liability lawsuits'. Research developments like these may eventually lead to the ability to match product design and characteristics (from a specific brand) with the costs or revenues incurred during the end-of-life, which will make brand-specific processing superfluous.

In the current analysis, any positive economical or environmental effects that may come from these types of developments are not researched as such. Instead, they are assumed to be incorporated in either the effects of improved economies of scale, or in the effects of the implementation of sophisticated automated disassembly technologies.

3.4.2 Future developments in disassembly technologies

In this section a number of developments in disassembly technologies are discussed. The main focus will be on automated disassembly and active disassembly. Cryogenic disassembly and disassembly using nano-technology will be briefly mentioned.

Automated disassembly

One of the relatively new topics in the research on improving end-of-life scenarios is the development of automatic disassembly tools, systems or even plants. For people in the field of life cycle engineering, who are not mechanical or robotics engineers, the concept of automatic disassembly sometimes seems too futuristic. On the other hand, researchers in the field of automatic disassembly are not always aware that there are many technical, economical and even social issues that might hamper the successful implementation of their results. Hence, for both recycling and producing companies, the topic of automatic disassembly is surrounded by great deal of uncertainty.

• As discussed in section 2.5.2, theoretically the implementation of automatic disassembly systems could be beneficial because of several reasons:

• It could make the disassembly process cheaper because it greatly reduces the need for expensive manual labour.
• It could entail a shift between the product categories that are suitable for disassembly and shredding and separation
• It could enable a more precise separation of parts since it improves accuracy of the operations needed for disassembly.
• It could enable the disassembly of a wider range of products than can be economically disassembled using a manual process.

Discussing future developments in automated disassembly, two main questions come to mind.

• Feasibility of automated disassembly: when will automated disassembly be a feasible technology for application in end-of-life scenarios of WEEE? This issue can be subdivided in technical and economical feasibility.
• Implications of automated disassembly: to what degree will automated disassembly facilitate the envisaged benefits (as pointed out above)?

In the remainder of this section these questions will be further discussed.

Feasibility of automated disassembly

To answer the first question the Delphi Study introduced in section 3.1 can be regarded as useful investigation, since the topic of investigating future developments in automated disassembly processes took a substantial part. In this study, regarding the feasibility of automated disassembly processes, several objectives were set:
• An investigation on whether consensus could be reached among a substantial number of specialists in the field, concerning a prediction on when a breakthrough in the application of automatic disassembly could be reached or not.
• An investigation on where this might happen.
• An investigation on whether consensus could be reached on ranking the main obstacles for technical and economic feasibility of automatic disassembly.

In the Delphi study, the analysis was split up for separate product categories:
• Small household appliances (e.g. vacuum cleaners),
• Brown goods (e.g. TVs, audio and video equipment),
• White goods (e.g. freezers, washing machines).

Panel members were asked to comment on both technical feasibility and economic attractiveness, of limited (20-50% of all disassembly operations), partial (50-90%) and full automation (90-100%) of all disassembly operations. After analysing the first round responses in the Delphi Study, it became clear that the panel members did not distinguish significantly between the three product categories. Apparently, the specialists in the panel were of the opinion that automated disassembly would, if at all, be equally feasible for all three product categories. It was therefore decided that in the second round the same questions would be asked for the electrical and electronic products category as a whole.

Table 13 reflects the results of the Delphi panel responses on the question whether and when automatic disassembly would become technically feasible for the electrical and electronic consumer goods product categories given above. Table 14 does the same for economic feasibility. In both tables the cumulative percentages are included in brackets.

<table>
<thead>
<tr>
<th></th>
<th>Full</th>
<th>Partial</th>
<th>Limited</th>
</tr>
</thead>
<tbody>
<tr>
<td>By 1998</td>
<td>2%</td>
<td>7%</td>
<td>29%</td>
</tr>
<tr>
<td>By 2000</td>
<td>7%(9%)</td>
<td>28%(35%)</td>
<td>40%(69%)</td>
</tr>
<tr>
<td>By 2005</td>
<td>26%(35%)</td>
<td>39%(74%)</td>
<td>24%(93%)</td>
</tr>
<tr>
<td>By 2010</td>
<td>30%(65%)</td>
<td>14%(88%)</td>
<td>3%(96%)</td>
</tr>
<tr>
<td>By 2015</td>
<td>11%(76%)</td>
<td>10%(99%)</td>
<td>2%(98%)</td>
</tr>
<tr>
<td>By 2020</td>
<td>9%(85%)</td>
<td>2%(100%)</td>
<td>2%(100%)</td>
</tr>
<tr>
<td>Later/never</td>
<td>15%(100%)</td>
<td>0%(100%)</td>
<td>0%(100%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Full</th>
<th>Partial</th>
<th>Limited</th>
</tr>
</thead>
<tbody>
<tr>
<td>By 1998</td>
<td>4%</td>
<td>2%</td>
<td>12%</td>
</tr>
<tr>
<td>By 2000</td>
<td>5%(9%)</td>
<td>23%(25%)</td>
<td>25%(37%)</td>
</tr>
<tr>
<td>By 2005</td>
<td>11%(20%)</td>
<td>25%(50%)</td>
<td>39%(76%)</td>
</tr>
<tr>
<td>By 2010</td>
<td>14%(34%)</td>
<td>28%(78%)</td>
<td>14%(90%)</td>
</tr>
<tr>
<td>By 2015</td>
<td>23%(57%)</td>
<td>5%(83%)</td>
<td>2%(92%)</td>
</tr>
<tr>
<td>By 2020</td>
<td>12%(69%)</td>
<td>5%(88%)</td>
<td>5%(97%)</td>
</tr>
<tr>
<td>Later/never</td>
<td>31%(100%)</td>
<td>12%(100%)</td>
<td>3%(100%)</td>
</tr>
</tbody>
</table>

Table 13: Panel responses on technical feasibility of automated disassembly
Table 14: Panel responses on economical feasibility automated disassembly

It was suggested that panel members from countries like Germany and Japan, being the countries where a substantial amount of research in the field of automated disassembly is taking place, would be more optimistic about the technical feasibility and economical attractiveness of automated disassembly. However, no significant differences were found. Also, panel members from these countries did on average not rank themselves with a higher level of expertise in disassembly practice than other panel members.
As a follow up on these results, in Boks et al. \(^{118}\) an approach was suggested to quantify the degree of consensus reached, in order to reflect the group position in a more useful way — namely to determine an 'average year' in which feasibility will be reached. One point of attention here is how to quantify the later/never category that was used as a ticking option in the survey. To overcome this, the indication ‘later/never’ was replaced in the first instance by ‘the year 2025’. However, to determine the sensitivity to this – arbitrary – choice, an indicator was derived to determine the effect on the results in case another, later, year would have been used for replacing the “later/never” category.

In Table 15, the average consensus years for the different levels of disassembly have been determined. In this table, 2011 (0.8) in the table below means that the average year indicated by the panel members is 2011, adding 0.8 year for every extra 5 years in case these are added to 2025. For example, if someone would feel more comfortable with replacing the “later/never” category by 2045 instead of 2025, the average answer would be 2011 + 4 * 0.8 = 2014. Obviously, (0) in the table implies that no panel members ticked the category “later/never”.

<table>
<thead>
<tr>
<th>Technical feasibility</th>
<th>Economical attractiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full 2011 (0.8)</td>
<td>Full 2016 (1.6)</td>
</tr>
<tr>
<td>Partial 2005 (0)</td>
<td>Partial 2009 (0.7)</td>
</tr>
<tr>
<td>Limited 2001 (0)</td>
<td>Limited 2005 (0.2)</td>
</tr>
</tbody>
</table>

Table 15: Numerical results for electrical and electronic goods

From the above results it can be concluded that, in a 1998 context, no evidence was found that making products feasible for automated disassembly was a design issue, at least for products with a lifetime of over ten years, which goes for most consumer electronics. Although since then, no similar studies were carried out assessing the feasibility of automated disassembly systems, no evidence exists that this notion has changed by 2001.

**Obstacles for feasibility of automated disassembly**

An additional topic in the Delphi study concerned an investigation into the potential obstacles for the application of automated disassembly. To this end, the panel was invited to comment on this issue, as well as answering a second question. More precisely, the panel members were asked to identify the main obstacles preventing automated disassembly from becoming a commercially successful activity (apart from the availability of automated disassembly systems). A range of potential obstacles was given, but there was a possibility to add other potential obstacles. However, almost none of the panel members used this option. In the questionnaires, obstacles were to be ranked from 1 (most important obstacle) to 7 (least important obstacle). The panel was asked to consider both the years 2000 and 2015. The analysis procedure of this question resulted in an indicative ranking of the different obstacles. A more precise ranking of the obstacles was considered useless, since the differences between some of the obstacles were negligible. The results of this indicative ranking are displayed in Table 16.
<table>
<thead>
<tr>
<th>Obstacle</th>
<th>2000</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too many different types of products</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Amount of products of the same type is too small</td>
<td>2-3</td>
<td>2</td>
</tr>
<tr>
<td>General disassembly-unfriendly product design</td>
<td>2-3</td>
<td>3-5</td>
</tr>
<tr>
<td>General problems in return logistics</td>
<td>4-5</td>
<td>3-5</td>
</tr>
<tr>
<td>Variations in returned amounts of products to be disassembled</td>
<td>4-5</td>
<td>3-5</td>
</tr>
<tr>
<td>Product as a whole is too damaged</td>
<td>6-7</td>
<td>6-7</td>
</tr>
<tr>
<td>Connections are damaged or corroded</td>
<td>6-7</td>
<td>6-7</td>
</tr>
</tbody>
</table>

Table 16: Obstacles for automated disassembly

It is clear that most of the obstacles in Table 16 are of a return characteristics, logistics and economies of scale nature. In section 3.5, which specifically deals with this issue, it is explained how these obstacles lead to further uncertainty in future end-of-life scenarios. In the Delphi study itself, the possibility was given to add additional remarks on all topics under investigation. A majority of the panel members made use of this possibility, especially on the topic of automated disassembly. The remarks reflected the wide range of issues and opinions related to automated disassembly, and indicated that indeed variables such as logistics, reuse opportunities, economy-of-scale, legislation and product variety will clearly have an effect on whether automated disassembly will be an economically attractive activity in the future. It was also stated more than once that these variables cannot be influenced by designers, neither of products nor of automated disassembly systems.

In the Delphi study, regarding product variety the remark was made that automated disassembly is more likely to be successful when independent of uniform products. Logistics is another important variable. It was stated that an efficient collection system and a good market price for recycled materials will contribute more to successful disassembly than disassembly automation. Also, collection and transportation costs will always be too high to collect large quantities of whole products in lot sizes that are economically attractive for centralized automated sites.

As implicated earlier, literature on the feasibility of automated disassembly systems is virtually non-existent. One interesting fact however, outside the Delphi study, is the fact that the Fraunhofer Institut IKP in Stuttgart, one of the first institutes to develop an automated disassembly cell, was able to sell two cells to the telecommunications industry, hence leading to the suggestion that economical feasibility is in fact attainable. However, these cells were never put into successful use, not because of technical shortcomings but because of the fast developments in product design, and because of logistical (read: economies of scale related) problems resulting of the wide dispersal of end-of-life phones throughout Germany.
Breakthrough in automated disassembly

In this question, the panel was asked to predict where a breakthrough in automated disassembly is to be expected. In the first part of the question it was asked in what country such a breakthrough would occur. According to the panel, it appears most likely that a breakthrough in automated disassembly will occur in Germany (57% of all answers) or in Japan (26% of all answers). Other answers were the "rest of Western Europe" (8%), Northern America (6%) and Scandinavia (3%)

A few interesting figures: whereas 57% of the panel thinks a breakthrough will happen in Germany, only 35% of the German panel members agrees. On the other hand, 71% of the academia agrees with this, compared to 35% of the producers.

Secondly, the panel was asked in what kind of institution such a breakthrough would occur. 54% of the panel predicted this would occur inside a company. 12% predicted it would be in a university, and 22% predicted it would occur in another research institute. The remaining 12% predicted a combination of these possibilities, or gave answers like "in a joint Japanese company project" or "by private initiative supported by local government".

Several panel members stressed that research in this field will only be successful if a joint cooperation between research institutes and industry delegates will come into place. However, some panel members noted that the industry should perform a coordinating role, while others considered a more supporting role.

Conclusions on future developments of automated disassembly

Considering partial automated disassembly of consumer electronic goods, this is likely to become an economically attractive process before the current generation of products (products that are currently out on the market) will reach its end-of-life. For new designs, partial automated disassembly is definitively a factor to be taken into account. For the design practice it is recommended to at least make sure that housings and printed circuit boards can easily be disassembled, since this level of partial disassembly could well be accomplished in an economically attractive way in the near future. For TVs, the removal of picture tubes with automated disassembly is a relevant option. Pilot projects have in most cases taken the automated disassembly of picture tubes as a case study, and although many problems like the variety in products and the lack of economies of scale have to be overcome, the time and efforts devoted to research this issue promise a future business implementation of this technology.

Considering full-automated disassembly, for consumer electronic goods with a contemporary design that will reach their end-of-life within 5-8 years, full-automated disassembly is not perceived as an attractive alternative for conventional manual disassembly. Although in the short term it should be technically possible to have systems in place that can, to a certain extent, disassemble these products, it will at least take another generation of products to make this economically attractive. This means that for
products that are on the market now, automated disassembly does not seem relevant. This is even more so valid for automobiles.

Starting in the next few years, for certain categories of products it could however be valid to design them while keeping in mind that they could be fully disassembled when they reach their end-of-life phase. However, it is not clear yet what product categories are most likely to suit this process. For product categories such as brown and white goods, panel members made additional remarks in favour as well as against the idea of automatically dismantling them.

From the remarks brought forward by the panel members, it is clear that for automated disassembly to be attractive, there is a need for an economical incentive. Such an incentive could be a favourable development of recycling output prices. From one of the other questions in the Delphi study, it has become clear that prices for secondary ferrous metals and commodity plastics are not expected to rise significantly. For non-ferrous metals however, and for engineering plastics like HIPS or ABS, prices are expected to rise (but not more than double). When housings made of engineering plastics like these will yield a higher price, economical attractiveness of automated disassembly will be more easily attainable, once other restrictions regarding logistics and economy-of-scale have also been met. The matter of the development of market prices will be addressed further on in this dissertation.

**Future technological developments in active disassembly**

Research in the field of active disassembly is an even more recent development in DFE research. The main institute where research in this field is carried out is Brunel University in the United Kingdom, at the Cleaner Electronics Research Group. Thanks to excellent relationships with this group a cooperation project could be carried out in early 1999. This included a more in-depth study on the economic (im)possibilities of the application of active disassembly technology. In Appendix 4 a general description of this technology is given, followed by a number of sections that address the economic feasibility of the technology. In this appendix also the results of the part of the aforementioned Delphi study that addressed active disassembly are discussed.

**3.4.3 Future developments in shredding and separation technologies**

Zhang and Forssberg\(^70\) state that there will be a steady decrease of the use of precious metals in WEEE scrap, on the basis of which they conclude that conventional recycling techniques like pyrometallurgy may no longer hold promise for WEEE scrap recycling in the future. Although this may be true for the main plastics and metals dominated products, it is not necessarily true for precious metals dominated products. For future recycling of WEEE, Zhang and Forssberg favour (the development of) a number of processes.

- Application of improved eddy-current processes to maximise aluminium recovery.
- The use of high speed granulators for better liberation/unlocking of for example copper particles
- Improvement of air table separation by introduction of a shape separator for recov-
ery of aluminium foils that can currently not be separated by eddy-current processes.

- Optimisation of electrodynamic separation for maximising metals recovery from rejects produced by shape separation processes and air tables. It is expected to enhance the separation of metal particles from plastics to obtain a clean mix of plastics.

**Future technological developments in automated separation processes**

In both the consumer electronics product categories, it is inevitable that several types of plastics are applied in one product. The demands on the various plastic parts are so diverse, that it is not even theoretically possible to meet all the functional requirements like quality and affordability by applying only one type of plastic. Currently, there is a tendency towards diversification of applied plastic types. If recyclability were not a relevant issue, this tendency would even be stronger than it already is in this age of environmental awareness.

Assuming that different plastic types are best recycled separately, it is relevant to know if mixed plastics can be sorted by type in an automated, and thus probably economically attractive, process. This would greatly facilitate disassembly of end-of-life products: all plastic parts could then simply be put in one container. In current times however, mixed plastics separation is still a great challenge, particularly among complicated streams such as WEEE. Main reason is the fact that the basic plastics separation techniques, based on density, are usually inadequate because of the overlap in density distributions found in engineering plastics.

At Delft University of Technology, at the Raw Materials Technology department of the Faculty of Applied Earth Sciences, research devoted at the development of various automated sorting techniques for metals and plastics has been ongoing for a number of years. For metals, sophisticated technologies that make use of magnetic, conductive and density properties are relatively widespread (de jong). Still, the development of automated sorting machines for mixed plastics waste streams is uncertain. The aforementioned Delphi study was used to ask a panel of specialists to indicate when automated sorting of mixed plastic waste streams would become technically feasible and when this would become economically attractive. Table 17 shows the results of this question for electronics plastics. Cumulative percentages are given between brackets.

<table>
<thead>
<tr>
<th>Period</th>
<th>Technically feasible</th>
<th>Economically attractive</th>
</tr>
</thead>
<tbody>
<tr>
<td>By 1998</td>
<td>25%</td>
<td>0%</td>
</tr>
<tr>
<td>By 2000</td>
<td>44% (69%)</td>
<td>18% (18%)</td>
</tr>
<tr>
<td>By 2005</td>
<td>18% (87%)</td>
<td>31% (49%)</td>
</tr>
<tr>
<td>By 2010</td>
<td>13% (100%)</td>
<td>31% (80%)</td>
</tr>
<tr>
<td>By 2015</td>
<td>0% (100%)</td>
<td>14% (94%)</td>
</tr>
<tr>
<td>By 2020</td>
<td>0% (100%)</td>
<td>4% (98%)</td>
</tr>
<tr>
<td>Later</td>
<td>0% (100%)</td>
<td>2% (100%)</td>
</tr>
</tbody>
</table>

*Table 17: Delphi panel results addressing automated sorting of mixed plastics waste streams*
The panel was also asked to rank a number of currently existing sorting techniques for mixed plastics according to their expected importance for the year 2010. The results for this question are given in Table 18.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Rank (1=best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorting using infrared spectroscopy</td>
<td>1-2</td>
</tr>
<tr>
<td>Sorting based on simultaneous detection of a number of material properties</td>
<td>1-2</td>
</tr>
<tr>
<td>Electrostatic sorting</td>
<td>3-4</td>
</tr>
<tr>
<td>Sorting using spectral analysis</td>
<td>3-4</td>
</tr>
<tr>
<td>Wet sink-float sorting</td>
<td>5-6</td>
</tr>
<tr>
<td>Dry sink-float sorting in fluidised beds</td>
<td>5-6</td>
</tr>
<tr>
<td>Froth flotation</td>
<td>7</td>
</tr>
<tr>
<td>Sorting by shape</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 18: Ranking of sorting techniques

Also, to conclude this section, the Delphi panel was consulted with respect to their ideas about an automated, input-independent sorting machine. Since waste streams come in a very large variety, it is usually only attractive to develop an automated sorting machine that can deal with a certain stream when that stream is relatively large, like in the case of car scrap. Most of the smaller streams have to be dealt with by handpicking; human workers are then doing the sorting. While handpicking has unparalleled flexibility, in Western Europe it is expensive. It would therefore be convenient to have a machine that can replace hand pickers: an automated sorting machine. To be able to deal with different waste streams, it would need to be input-independent. The panel was asked to indicate when such an automated, input-independent sorting machine will be technically feasible and when its operation will become economically attractive. Results are given in Table 19. Again, cumulative percentages are given between brackets.

<table>
<thead>
<tr>
<th>Period</th>
<th>Technically feasible</th>
<th>Economically attractive</th>
</tr>
</thead>
<tbody>
<tr>
<td>By 1998</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>By 2000</td>
<td>16% (23%)</td>
<td>12% (14%)</td>
</tr>
<tr>
<td>By 2005</td>
<td>21% (44%)</td>
<td>12% (26%)</td>
</tr>
<tr>
<td>By 2010</td>
<td>21% (65%)</td>
<td>17% (43%)</td>
</tr>
<tr>
<td>By 2015</td>
<td>14% (79%)</td>
<td>20% (63%)</td>
</tr>
<tr>
<td>By 2020</td>
<td>12% (91%)</td>
<td>8% (71%)</td>
</tr>
<tr>
<td>Later</td>
<td>9% (100%)</td>
<td>29% (100%)</td>
</tr>
</tbody>
</table>

Table 19: Feasibility of an automated, input-independent sorting machine

---

For both questions, panel analysis showed no significant differences between the subsets of the panel were found. The only apparent difference is that producers seem to agree more when it comes to the technical feasibility of the machine compared to the academia: almost all answers in the extreme categories ("by 1998" and "later") were given by academia.

### 3.4.4 Future developments in smelting technologies

In section 2.5.7 the application of recycled CRT glass (ECORAM) in the production of new CRT glass was discussed. In ZVEI\(^\text{84}\) it is stated that it is expected that ultimately cone glass will be recycled as cone glass and screen glass will be recycled as screen glass. Preconditions for this are an economically justified separation process of the different glass types during the recycling process. Due to the scope of this dissertation further discussions about CRT recycling are omitted, but an overview of developments is available from for instance Monchamp et al.\(^\text{28}\)

### 3.4.5 Conclusions on the feasibility of the application of future technologies

In the previous subsections it has become clear that a variety of new and/or improved technologies for end-of-life processing are likely to be technically feasible in the next decade or so. Also, comments on economical feasibility have made clear that for a part of the technologies discussed, at least in theory these could be well worth implementing in the end-of-life cycle of consumer electronics.

However, some caution is appropriate here: both envisaged technical and economical feasibility are not necessarily enough to predict the actual implementation of new technologies. Twiss\(^\text{110}\) mentions four reasons why technical developments might not be exploited immediately:

- There may be no industrial incentive to accept the risks inherent in technological innovation. In the current context, this means that although recycling companies in theory would benefit from implementing new, cost-reducing (for example automated) technologies, they might not be convinced that they can oversee all the risks involved in doing so and therefore postpone new technology acquisition. Important to mention here is what is sometimes referred to as a typical "chicken and the egg" problem: for recycling companies, investing in new technologies may only prove worth while in case there is a guarantee that manufacturing companies adjust their product design to these technologies. On the other hand, for manufacturing companies it may only prove worth while to adjust their product designs, if they are guaranteed that recycling companies will invest in appropriate processing techniques. Breaking this circle might take years after the technology is in principle available\(^\text{122}\).

- The step from knowledge to application of new technologies may have to wait until an individual with insight or creativity sees in it a potential, which has not previously been noted or appreciated.

\(^{122}\) See for another "chicken and the egg problem" the issue of the development of markets for secondary plastics in section 3.5.
The release of the potential may depend on advances in other technologies. For example, active disassembly (see sections 2.5.2 and 3.4.2) can only be feasible when appropriate smart materials can be produced on a large enough scale, and when manufacturing companies find ways to embed the fixing of smart material fasteners into their assembly process.

The market potential of the new technology might be difficult to assess. For example, laboratory scale experiments with robots for the disassembly of television sets have turned out to be feasible, and even preliminary calculations of the economics involved might turn out promising. But a large-scale implementation implying capital investments in both the manufacturing and the recycling process combined with adjustments of return logistics infrastructures and the uncertainty on future WEEE volumes feasible for automated disassembly makes it difficult to assess the true market potential for disassembly robots.

The investments in new technology will under normal market circumstances only occur once the technology to be replaced is fully depreciated. Only when premature depreciation is compensated for by immediate benefits from investing in new technology, such investments may prove to be justifiable.

Taking these reasons into account, it should be clear that it is not possible to make exact statements on when the new end-of-life technologies discussed in this chapter will be implemented on a large scale in the recycling industry. Consequently, for answering the first main research question (see section 1.1), and in order to be able to continue with answering the other two research questions, further analysis of technological developments will be done on a what-if basis. In this chapter the uncertainties associated with technological developments have been charted, and indications have been given on what directions these could take, and even some probability assessments have been given based upon the Delphi Study. In Chapter 6 the consequences and implications of these developments will be further investigated.

3.5 Uncertainty because of economical developments

In section 2.3 aspects of economical developments were identified that have a specific impact on the evaluation of end-of-life scenarios. These included:

- Return characteristics (see section 2.3.1)
- Economies of scale and return logistics (see section 2.3.2)
- Market prices for secondary materials (see section 2.3.3)
- End-of-life processing costs (see section 2.3.4)

In this section it will be investigated in what way these aspects of economical developments lead to uncertainty in end-of-life scenarios.

3.5.1 Uncertainty because of return characteristics

In section 2.3 the importance of the so-called ensemble issue has been discussed. There, two streams of WEEE were defined, namely the ones before and after the actual end-of-life processing in recycling facilities. Both streams are subject to uncertainty, but clear
distinctions can be made as to the type of the associated uncertainty. WEEE streams before end-of-life processing are subject to uncertainty regarding mainly their volume, as discussed in section 3.5.2, and their product type content. Waste streams after end-of-life processing depend not only on the outlet channel specifications, but also on the end-of-life processing itself, and of course on the characteristics of the WEEE streams before end-of-life processing in the first place.

The most important uncertainty factors associated with WEEE streams before and after end-of-life processing are:

- The percentage of the initial start-of-life stream (i.e. the volume of products that are put on the market) will actually reach end-of-life. The size of these streams, and their associated uncertainty will greatly depend on the organisation of the reverse logistic process – see also the discussions on economies of scale.
- The product composition present in WEEE streams before they are processed. This makes that the material content per stream is uncertain since on beforehand it is unknown what product are in the stream.
- The material composition present in the products that make up the WEEE streams. It should be noted that also material content per product can have been changed during product life due to repair, upgrade etc.
- There is uncertainty on where which product will eventually end up: the product dispersion profile is often hard to assess and especially for brand-specific processing this can be a major cause for uncertainty.

As for the ensemble issue, comparatively very little research is known that addresses the ensemble issue, and from that it can be concluded that it is probably an issue that is very difficult to solve, and can perhaps only be solved on a company level. None of the collection trial report mentioned previously in this chapter address the issue specifically, but Gupta\textsuperscript{123} introduces a theoretical mathematical approach that addresses the issue from a remanufacturing perspective.

3.5.2 Uncertainty because of developments in economies of scale and logistics

In section 2.3 the issue of economies of scale in return logistics and end-of-life processing has been discussed. It was explained that the presence or absence of economies of scale can in many cases be the determining factor whether a return logistics infrastructure can be organised or not. It was also stated that the presence or absence of economies of scale in principle mainly depends on the availability of large enough volumes of WEEE, which makes this issue the main source of uncertainty.

Assessment of future economies of scale and in particular their influence on decisive parameters such as transport and processing costs and secondary market prices is a difficult task that is addressed by few research projects. It requires a thorough understanding

of reverse logistics and recycling processes including hard data on a relatively non-transparent industry. Moreover, this industry is usually organized on a regional level causing differences across end-of-life infrastructures, which makes generalization difficult. This observation is also confirmed by Hansen[124] who states that the probability of return of WEEE depends on local conditions and the product categories to be collected.

It is likely that these are some of the reasons that there have been no specialised studies on a European level on the minimal, or preferable, economies of scale for processing appliances at the end-of-life stage. This is clearly an omission because the lack of economies of scale potentially influences both the efficiency of recycling and its associated costs in a negative way, and research in this field should therefore be a main concern for policy makers.

In the subsequent subsections it is tried to determine trends in the development of expected volumes of WEEE as these will have the main influence on economies of scale. Further on, uncertainty issues will be discussed as regards to where developments in economies of scale will have major impact.

The estimation of expected volumes of WEEE

The best way to start analysis of developments in economies of scale is by determining the amount of WEEE that will end up in recycling facilities for end-of-life processing. In Figure 18 it is shown how the amounts of products produced are reduced through several stages to the amounts of products that are actually processed. In order to assess the latter amount, it is therefore logical to assess the fractions of volumes (possibly) lost in each stage and to these the following fractions, used in Figure 18, have been defined.

• $x_1$ is the fraction of volumes produced that will actually be sold on the market
• $x_2$ is the fraction of volumes sold on the market that will actually be discarded other than by storing them inside homes
• $x_3$ is the fraction of volumes discarded outside homes that will actually be collected
• $x_4$ is the fraction of volumes collected that will actually be processed in an end-of-life system

Here it is assumed that the volumes produced that are not sold will always be processed as pre-consumer WEEE, which is in line with current practices in most countries.

Volumes $V_0, V_1, V_2, V_3$ and $V_4$ will under normal circumstances differ because of export, storage and products being collected outside the regular collection system.

---

In order to assess \( x_1, x_2 \) and \( x_3 \), it is important to note that these are time-dependent variables. As the time horizon becomes longer, these values will approach 1. Assessing \( x_1 \) involves studying the selling figures, and \( x_2 \) will depend on consumer behaviour, also accounting for a percentage of products that will not end up as WEEE because they are stored (also referred to bottom drawer stock, see McLaren\(^{125}\) et al for a discussion on this). Assessing \( x_3 \) depends also on the collection efforts as organised by municipalities. In the subsequent subsections these issues are discussed further.

**The amount of new products entering the market**

In a 1997 study\(^{126}\) by AEA Technology performed for the European Commission DG XI data has been gathered regarding the expected volumes of WEEE. In this study, figures per product category as well as for the whole of WEEE are given where possible. For brown and white goods the following figures were gathered:

- **Brown goods**: According to EACEM predictions, the market for TVs in the EU is about 22 million sets per year, and the forecasts for future sales are stable. TVs are claimed\(^{115}\) to have an average lifetime of about 15 years (although the Apparetour report\(^{10}\) states that the TV sets collected in that trial showed an average of 21 years). Assuming an average weight for a TV set of 25 kilograms, the total weight of TVs reaching end-of-life in the EU would be about 500 million tonnes. Also, it is believed that TVs account for 50% of the total weight of brown goods consumer each year. Combining these figures gives an estimation of about 1 million tonnes of brown goods consumed each year in the EU. For the brown goods category in total future sales could see an increase because of product replacements due to increasing use of digital technologies leading to improved functionality.

- **White goods**: The same European Commission report states that the total consumption of white goods in the EU is likely to be close to 2 million tonnes per year, though it is stated that this figure depends on estimations of the weight per appli-


ances which in turns depends on which products are included in the definition of white goods. The white goods market is believed to be relatively stable as well, although in relatively new areas such as dishwashers increases can be expected.

In the same European Commission report some further indications on how to determine future trends are mentioned. In this report, it is estimated that future quantities of WEEE will be over 20 kg per person per year, of which the consumer sector will account for 12 kg and the industrial sector for 5 kg. In this figure, also cables are included, accounting for 3 kg per person per year. 70% of the total WEEE stream is expected to come from white and brown goods, and IT and office equipment. Moreover, a growth percentage is estimated of just less than 3% in overall electronics consumption in Western Europe.

As this is only a small percentage, this figure alone will clearly not influence economies of scale in a significant way. This leads to the conclusion that the first variable is not likely to cause significant increases in the expected volumes of WEEE.

**Collection rates of end-of-life products**

In recent years, several WEEE collection trials have been reported on. The aim of these collection trials is usually directed at reducing uncertainty on a number of issues:

- To determine the volumes of WEEE that can be expected to be returned at the end-

---


of-life, and their composition. Although theoretical calculations methods are used, it is necessary to determine if the theoretical volumes of returned WEEE match the volumes that are returned in practice;

• To determine the preferred processing steps by comparing different recycling approaches and methods and their associated costs and environmental impacts;
• To determine the economical and environmental feasibility of setting up a WEEE collection and processing infrastructure, or to determine whether a present return logistics and end-of-life processing infrastructure is sufficiently sophisticated to handle the expected volumes of returned WEEE.

Although these aims do not as such focus on determining future economies of scale, selected results from these reports can be useful for reaching this objective since any substantial literature on establishing future trends in economies of scale does not appear to be available.

In the previously mentioned publication by Hansen\textsuperscript{124} it is also stated that the present return rate for brown goods is about 10\%-20\%, but that specialised redistribution systems, for single products of certain companies such as Siemens Nixdorf attain rates of up to 38\%\textsuperscript{135}. In the Netherlands, the organisation of the current take-back infrastructure has led to much higher return rates, as previously indicated in section 2.3.2.

In Hansen\textsuperscript{124} it is stated that the disposal of wastes on waste dumpsites or in incineration plants will be increasingly centralized. A number of reasons are given for this:

• High operating and investment costs
• Higher mechanization of these plants
• The lack of acceptance among the public

Centralization of recycling facilities, waste dump sites and incineration plants will lead to a significant reduction of the number of such facilities. Hansen states\textsuperscript{136} that in Germany, such facilities for storing and processing household wastes will probably have been reduced in numbers from over 500 in 1993 to approximately 150 dump sites and 55 incineration plants by the year 2005. He also states that, although several municipalities and manufacturers have set up recycling systems which can process more than 100000 tons of WEEE per year, there is still a great lack of efficiency in processing WEEE. He therefore introduces a recycling network planning methodology for increasing efficiency and hence reducing transport costs as well as the environmental impact from transport as a result of moving WEEE from collection to processing sites. However, no attention is given in this work to the potential benefits of economies of scale when processing larger quantities per recycling facility.


Conclusions on the estimated volumes of WEEE

In the previously mentioned European Commission report the following figures for estimated volumes of WEEE for the EU are given: 4.0 to 6.0 million tonnes for 1992. Figures for forecasts (at that time) include for the EU 5.4 to 6.7 million tonnes for the late 1990s. This agrees with an increase of 10%-25%. Assuming a growth of products put on the market of 3%-5% this would mean an increase of somewhere between 5% and 20% due to more sophisticated collection infrastructures.

The aforementioned EC report also offers an alternative estimation method for household WEEE. In this method, it is considered what items of electrical and electronic equipment a typical household would contain and how many items would be replaced over a twenty-year period, based on typical service lifetimes.

Uncertainty as regards the impact of economies of scale on various aspects of end-of-life scenarios

In this section it will be discussed where changes in economies of scale will have impact on end-of-life processing scenarios, and thus on the economical and environmental performance of products and products streams in those scenarios.

Based on experiences of several collection projects, it is expected that problems with economies of scale will affect the processing of small household appliances with a relatively high plastics content in particular. The processing of CRT-containing brown goods will probably suffer the least from the absence of economies of scale since these products will need to be recycled in any case.

Three separate aspects of end-of-life scenarios can be identified where economies of scale potentially can have an important positive or negative effect. These are:

- **Processing costs:** The variable component of end-of-life processing costs is usually determined by the capacity use of recycling processes (disassembly lines or shredding and separation processes). Favourable economies of scale mean better use of capacity potentially leading to lower processing costs. Uncertainties however could lead to lack of investments, eventually leading to underperformance, both in terms of environmental performance and (competitive) processing costs.

- **Recovery percentages and grades:** An increase in volumes of WEEE collected for end-of-life processing means in general also an increase in the volume of the different product categories that make up the total WEEE stream. Moreover, it could also lead to distinguishing between additional product categories that consisted previously of too little products to justify separate treatment. An example in this case is for example the end-of-life processing of cellular phones. In the early days of cellular phones ending up as WEEE, volumes returned were too small to justify separate recycling – basically, phones were recycled together with other small electronic products. This way, potential benefits from valuable materials in the phones were lost, as recycling processes for small electronic products were not aimed at the recovery of these valuable materials. Nowadays, volumes of returned cellular phones
have increased up to a point where separate collection and processing of phones could be justified\textsuperscript{97}.

- **Secondary markets**: Secondary markets for materials exist by the grace of supply to these markets. If supply of a certain material is limited or unstable, prices will be set ad-hoc rather than through a dependable market mechanism. This in turn will lead, especially in the case of end-of-life processing, to a limited focus of supplying (potential) markets with materials – a kind of chicken and the egg problem. An example will clarify this issue: a market for secondary plastics of a specific type or purity grade can only exist if supply is beyond a certain minimal level since for the reapplication of such plastics (in for example TV housings) requires a steady supply. If this supply is not guaranteed, producers will change to a different plastic. But if demand for reapplication is limited, recycling facilities will lack the incentive for separate collection of this plastic, as it is uncertain what price can be obtained and therefore the effort of separate collection may not be economically justified. However, a significant increase in WEEE product categories that contain parts made out of such plastics will stimulate separation, and therefore supply to the secondary plastics market. If producers are convinced that supply is guaranteed because of these higher volumes, demand will also increase, with a positive effect on the secondary market price for in this case the plastic.

The uncertainty on the expected streams of WEEE and the associated uncertainty with respect to economies of scale lead in turn to uncertainty how processing costs, recovery percentages and grades, and secondary market prices will develop in future end-of-life scenarios. These uncertainties are further quantified in section 6.4.

**Uncertainty because of developments in reverse logistics systems**

The primary focus of this work is not on reverse logistics systems. In the introduction chapter of this dissertation is explained why this subject is not addressed as such. Nevertheless this dissertation would not be complete without at least some introductory remarks on this subject.

Several studies have clearly shown that reverse logistic systems lack efficiency and that the portion of logistic costs is 5 to 10 times higher than on the supply-chain. Here a lot of work has to be done. There is however some literature focusing on this issue\textsuperscript{14, 137, 138, 139}.


3.5.3 Market prices for secondary materials

Johnson and Wang\textsuperscript{15} state that 'the actual dollar value derived from disassembly and recycling seems to be rather precarious in an economy subject to low virgin material costs and a changing market demand for materials. However, times are changing, and worldwide trends (...) seem to indicate the need for an emphasis on material recovery (...'). Statements such as this one substantiate the statement that considerable uncertainty is involved with the assessment of the monetary effect of end-of-life developments, and that an analysis of future developments with respect to market prices is a relevant study topic. This section aims to provide such an analysis.

Metals

For a few metals, it is rather obvious that they should be considered in economical and ecological evaluations of consumer products. Especially copper and aluminium but also ferrous metals can be found as constituent materials in a variety of products, and yield revenues to some extent in the end-of-life stage. However, there are also a variety of other metals, in particular precious metals, that will have a substantial impact on ecological or economical scores, or both, and that are less obvious to identify because they are found on printed circuit boards rather than as constituent materials. To determine which metals are relevant to consider and to incorporate into the PMRCM, an analysis is here presented that examines the correlation of three quantities:

- Market prices of metals
- Environmental impact of metals
- Concentration of metals in products

If two or more of these variables are of significant magnitude, they should be considered as potentially influencing either economical or environmental results, or both. For this analysis, the data were collected as follows:

**Market prices:** To collect a dependable set of up-to-date market prices for a set of metals is not straightforward. Since few sources give prices for only a selective amount of metals, several sources need to be used. With this the problem arises that prices are determined at different points in time, on different markets, and for different grades of purity. However, one source was found that gives market prices for a wide range of metals present in consumer electronics, namely the World Metals Information Network\textsuperscript{140}. The analysis below is based given on the prices made available through this network since the use of a single source rather than dispersed sources outweighed any negative influences caused by considerations as outlined above. However, once the relevant metals had been determined, it was decided to fix the default values for these metals (given in Table 30), needed to facilitate further calculations in this dissertation, based on current market developments (that were unfortunately not available for all metals in great detail).

\textsuperscript{140} http://www.amm.com
This economical quantity is expressed from a yield perspective, a similar quantity could be defined from a penalty perspective in order to determine which metals are relevant for further study based on penalties that should be paid before processing, in case these are present in products. However, the second quantity discussed below refers to the environmental score of metals, and since financial penalties are in principle a direct derivative of the (unfavourable) environmental score of metals, penalties are not explicitly taken into account as a variable here. A further consideration is the fact that for individual elements potentially causing penalties no data were available with respect to their concentrations on the analysed printed wiring boards. It should be noted that for the default example products considered for the analyses in this dissertation (as presented in Chapter 5), it was assumed that no important penalty elements were assumed to be present.

**Environmental scores of metals:** For this purpose, the internal database of Philips Consumer Electronics was used. The environmental scores are Ecoindicators, expressed in millipoints, according to the normalisation method described in the Dutch EcoIndicator Method. In this method, a lower Ecoindicator expresses a lower environmental impact.

**Concentration of metals in products:** Again, this is not necessarily a straightforward choice. Since the range of products considered in this dissertation exhibits a metal concentration profile that varies considerably, it was decided to choose one product for this purpose. The product chosen in this case was a cellular phone, being the only product available with a detailed printed circuit board analysis enabling the incorporation of a wide range of metals. Also, in this product a relatively large concentration of especially precious metals is present. The fact that precious metals influence both environmental and economical performance to a considerable extent also supported this choice.

In Figure 19 to Figure 21, data on the above three quantities are plotted in pairs, to determine which metals are relevant for inclusion in the various analyses in the remainder of this dissertation. In each of these figures, a number of dots are presented without further explanation about the type of metal they are associated with, these dots represent metals that are clearly less interesting for analysis as they score already low on two out of three of the variables discussed above. Such metals include for example chromium and titanium.

In order to determine the correlation between metal concentrations in the case product and the environmental scores, these data were plotted in Figure 19. The use of a logarithmic scale was necessary since especially the environmental scores differ in order of magnitude for the various groupings of metals.

Interpreting this figure, it can be seen that both gold and palladium stand out as metals that have both a high concentration on the printed circuit board of the phone and that also have high ecoindicators. Furthermore, silver, antimony and copper can be found in similar concentrations but have significantly lower ecoindicators. The rest of the metals score insignificant values on one or both of the scales.
In order to analyse the concentration of metals on the PWB and their market value, these data were plotted in Figure 20.

Interpreting this figure, it is obvious that again gold and palladium are the most relevant candidates for thorough analysis since these precious metals are found in high concentrations on the PWB and also have a very high market price. Although platinum and rhodium exhibit similar high market prices, their concentrations are so low (even below the threshold detection value) that no significant environmental impact or financial revenue can be expected from these elements.

Finally, the market price and the environmental scores of the metals are plotted in Figure 21. Here, it can be seen that the precious metals gold, palladium, platinum and rhodium exhibit the highest market prices as well as the highest environmental impact. Silver scores less on both scales but still significantly more than the other elements.
Figure 21: Correlation between the environmental impact of metals and their market value

From these analyses, the following elements can be identified as scoring high for at least two of the three quantities market price, concentration on the PWB, and environmental impact:
- Gold
- Palladium
- Silver
- Antimony
- Platinum
- Rhodium

Of these elements, rhodium and platinum will not be considered any further. The reason for this is that the concentration of these elements is so low that any significant impact is not to be expected. Antimony should only be considered in environmental analyses as the market value is too low to influence financial results in any significant way.

Therefore, apart from the constituent metals ferrous metals, copper and aluminium, only gold, silver and palladium are identified as being relevant to incorporate for further analysis in this dissertation. In the paragraphs below, for a number of relevant materials the price developments since 1992 have been charted and conclusions are drawn on the amount of uncertainty these developments bring with respect to the prediction of future costs or revenues from end-of-life processing of consumer electronics. Ferrous metals are not addressed here separately since the market price for ferrous metals is very close to zero and is expected to remain that way.

**Gold**

Gold has traditionally been used as a safe-haven asset to protect countries from fluctuating currencies, and has therefore been a relatively stable metal from a market price perspective. Still, as can be seen from Figure 22, the price of gold has fluctuated enough to refrain from setting a default gold price for end-of-life calculations for a prolonged period of time (i.e. several years).
Gold prices 1992-2000
in March in US$/kg

Figure 22: Gold prices 1992-2000

To analyse the sensitivity of end-of-life yields of products in future end-of-life scenarios to fluctuating gold prices, from Figure 22 it was analysed how big sensitivities are. To determine what fluctuations are relevant to investigate in scenario analyses (which is done in section 6), in Table 20 the number of different sized relative changes in material prices are determined, using both a monthly and a yearly count.

<table>
<thead>
<tr>
<th>Number of relative changes falling in this category (monthly count)</th>
<th>Number of relative changes falling in this category (yearly count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than -10%</td>
<td>0</td>
</tr>
<tr>
<td>-10% to -5%</td>
<td>5</td>
</tr>
<tr>
<td>-5% to -1%</td>
<td>28</td>
</tr>
<tr>
<td>-1% to 1%</td>
<td>36</td>
</tr>
<tr>
<td>1% to 5%</td>
<td>21</td>
</tr>
<tr>
<td>5% to 10%</td>
<td>2</td>
</tr>
<tr>
<td>More than 10%</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 20: Fluctuation count for gold prices 1992-2000, monthly and yearly

The data in Table 20 shows that the monthly chance in the gold price stayed within 1% in absolute terms in 36 out of 93 observations (almost 40%), and within 5% in 85 observations (over 90%). So, for short-term predictions, changes of more than 5% should not be expected. As for the yearly fluctuations, changes of −10% to −15% have occurred in the last five years and should not be ignored for long-term predictions.
Silver

Like gold, silver has exhibited a relatively stable price development as well, as can be seen from Figure 23.

![Silver prices 1992-2000](image)

*Figure 23: Silver prices 1992-2000*

Using the same metrics as in the gold case, it can be seen from Table 21 that also in the silver case over 90% of all monthly relative changes were within 5% in absolute terms. With respect to the yearly count, price changes of over 25% have occurred in the last decade (1993 and 1997). The last increase however has been annulled to a large extent in 1998.

<table>
<thead>
<tr>
<th>Number of relative changes falling in this category (monthly count)</th>
<th>Number of relative changes falling in this category (yearly count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than −10%</td>
<td>0</td>
</tr>
<tr>
<td>−10% to −5%</td>
<td>8</td>
</tr>
<tr>
<td>−5% to −1%</td>
<td>28</td>
</tr>
<tr>
<td>−1% to 1%</td>
<td>23</td>
</tr>
<tr>
<td>1% to 5%</td>
<td>18</td>
</tr>
<tr>
<td>5% to 10%</td>
<td>9</td>
</tr>
<tr>
<td>More than 10%</td>
<td>5</td>
</tr>
</tbody>
</table>

*Table 21: Fluctuation count for silver prices 1992-2000, monthly and yearly*

Palladium

Of all materials that have a significant contribution to either economical or environmental results in end-of-life scenarios for WEEE, palladium prices have behaved the least stable. In Figure 24 it can be seen that as of early 2000, prices had become about six times as high since 1992.
A number of reasons for this price increase can be given for this:

- The increasing number of miniaturized products, and the increasing level of miniaturization itself increased the demand for palladium resulting in higher prices.
- Besides the application in electronics components, palladium is also an essential component in the production of auto catalysts, which significantly reduce harmful emissions from automobiles. As legislation enforcing stricter vehicle emission limits is expanding worldwide, the demand for palladium continues to increase, leading to higher prices\(^1\).
- About two-thirds of the world's palladium is produced in Russia\(^2\). The lack of stability in the Russian economy, and the associated uncertainty regarding supply of palladium because of export delays (because of red tape and legislative hurdles\(^3\)), has had a rising effect on palladium prices because of 'panic' purchases by manufacturers of electronics parts. Though this effect was significant in early 2000, it is expected that it will not sustain over the longer term\(^4\).

**Addendum:** The development of the palladium price has however seen a significant drop since early 2001, as can be seen in Figure 25. This development only confirms the uncertainty associated with the palladium price. As most calculations in this dissertation were done before the turning point in early 2001, most scenarios refer to an increase in the palladium price. It should be clear from the below figure that nowadays decreases in palladium prices are a factor to be considered even more. This however does not affect the conclusions presented in the remainder of this dissertation. The effects of changes in the palladium price, be it positive or negative ones, remain among the largest effects of all developments considered in this dissertation.

---


\(^3\) CBS Marketwatch, February 14, 2000. (http://cbs.marketwatch.com)
Figure 25: Palladium price development until November 2001

Because of the increasing prices on the palladium market, the counts in Table 22 exhibit a deviating pattern compared to the ones for the gold and silver prices presented above. It can be seen that monthly changes of higher than 5% are significantly more frequent. Yearly increases of over 10% dominate by far and can be as high 60%.

<table>
<thead>
<tr>
<th>Number of relative changes falling in this category (monthly count)</th>
<th>Number of relative changes falling in this category (yearly count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than -10%</td>
<td>3</td>
</tr>
<tr>
<td>-10% to -5%</td>
<td>5</td>
</tr>
<tr>
<td>-5% to -1%</td>
<td>23</td>
</tr>
<tr>
<td>-1% to 1%</td>
<td>16</td>
</tr>
<tr>
<td>1% to 5%</td>
<td>19</td>
</tr>
<tr>
<td>5% to 10%</td>
<td>19</td>
</tr>
<tr>
<td>More than 10%</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Table 22: Fluctuation count for palladium prices 1992-2000, monthly and yearly

Copper

In Figure 26 the development of the price of copper is given. Compared to the previous figures, this one appears to be significantly more whimsical.

Copper prices 1992-2000
in March in US$/kg

Figure 26: Copper prices 1992-2000
Table 23 confirms this pattern, and both positive and negative price developments seem to be likely to happen, although a downward trend can be observed for the last five years.

<table>
<thead>
<tr>
<th>Number of relative changes falling in this category (monthly count)</th>
<th>Number of relative changes falling in this category (yearly count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than -10%</td>
<td>3</td>
</tr>
<tr>
<td>-10% to -5%</td>
<td>12</td>
</tr>
<tr>
<td>-5% to -1%</td>
<td>24</td>
</tr>
<tr>
<td>-1% to 1%</td>
<td>11</td>
</tr>
<tr>
<td>1% to 5%</td>
<td>29</td>
</tr>
<tr>
<td>5% to 10%</td>
<td>11</td>
</tr>
<tr>
<td>More than 10%</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 23: Fluctuation count for copper prices 1992-2000, monthly and yearly

Aluminium

Figure 27 reflects the development of the aluminium price. The behaviour has been similar to the behaviour of the copper price.

Aluminium prices 1992-2000 in March in US$/kg

Figure 27: Aluminium prices 1992-2000

<table>
<thead>
<tr>
<th>Number of relative changes falling in this category (monthly count)</th>
<th>Number of relative changes falling in this category (yearly count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than -10%</td>
<td>0</td>
</tr>
<tr>
<td>-10% to -5%</td>
<td>7</td>
</tr>
<tr>
<td>-5% to -1%</td>
<td>30</td>
</tr>
<tr>
<td>-1% to 1%</td>
<td>21</td>
</tr>
<tr>
<td>1% to 5%</td>
<td>21</td>
</tr>
<tr>
<td>5% to 10%</td>
<td>13</td>
</tr>
<tr>
<td>More than 10%</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 24: Fluctuation count for aluminium prices 1992-2000, monthly and yearly
General remarks on price developments for metals.

On a more limited impact level, in some countries or regions seasonal weather conditions will also have an impact on the price of non-ferrous scrap. A Recycling Today publication\(^{144}\) reports that the reduced collection and processing of non-ferrous scrap because of stormy and conditions can lead to regional shortages. Although these shortages may not have the same fundamental effect as expanded primary production or growing consumption figure, short-time pricing fluctuations are common.

Plastics

A discussion on future market price developments for secondary plastics is not as straightforward as for metals, and justifies an elaborate study on its own as little knowledge is available in literature. Since a what-if approach suffices for the remainder of this dissertation, rather than a detailed overview of what actually can or will happen, this section will be limited to an overview of where uncertainties lie. In Chapter 6 these uncertainties are quantified wherever possible.

The Apparetoir report\(^{30}\) states that the plastics fraction from WEEE, in particular from CRT-containing products (since these have often large plastic encasings) will become more interesting (read: from an economical point of view) provided that during design a number of aspects are taken into account. These aspects include (see also the beginning of section 3.4):

- The use of monomaterials;
- Minimalisation of additives;
- Elimination of halogenated flame retardants.

In a study by MBA Polymers\(^{120}\) a number of success factors are discussed for the recovery of secondary valuable plastics from electronic equipment. A business model is introduced consisting of three segments: sourcing, processing, and sales and marketing. The model provides, from a plastics recycler’s perspective, important factors to be addressed when recycling plastics, and provides a useful framework for determining which factors lead to the uncertainty associated with the determination of secondary plastics prices. From the model, two main factors are derived that have a determining impact on secondary plastics prices:

- **Availability of markets:** The effort put in finding appropriate applications and markets for secondary plastics. Since because of technical reasons closed loop applications are often not possible, often lower-end applications need to be found. Another solution is upgrading secondary plastics by purification or the addition of virgin material to meet higher material specifications. Another problem associated with the availability of markets features what the MBA Polymers study refers to as a “chicken and the egg” problem”. For plastics recyclers, it makes only sense to commit themselves to large-scale plastics recycling if they are assured of a large enough market for selling the recycled material on. On the other hand, customers will only

\(^{144}\) Recycling Today (2000). And now, the weather …., February 2000 issue.
buy from plastics recyclers if they are guaranteed to obtain a constant supply of material with constant material specifications. If material specifications would change too frequently, the customer would need to change their own processing characteristics or end up with higher reject rates, reducing or erasing the economic advantages of using recycled plastics in the first place. So, currently, little incentive exists for recycling companies to separate plastics fractions for recycling as long as there are no buyers for these materials and prices are low. At the same time, OEMs will have little opportunity to start a large-scale application of recycled plastics in their products as long as the recyclers do not separate these. In Dillon,\textsuperscript{145} this is also acknowledged. Here it is also stated that technology is not perceived as an obstacle for end-of-life plastics processing. Considerable amounts of research addressing plastics sorting and separation have ensured that. However, in these publications little focus has so far been on the economics of plastics recycling – at most the problematic situation of immature recycled plastics markets is noted and/or sketched. Some publications however have acknowledged this and have reported on recent public/private initiatives aiming at stimulating the secondary plastics markets\textsuperscript{120, 145, 146}.

- **Variation in supply**: A constant and reliable supply of high enough volumes of material is necessary to keep processing lines running. Also, consistent processing and performance properties of the material supplied are highly preferred. Both issues however are difficult to obtain for plastics recyclers since variations in material properties of incoming streams are hard to control. A solution to this could be to significantly narrow the scope and amounts of materials processed, but narrowing the scope could lead to losing economies of scale advantages such as material acquisition costs.

The aforementioned study does not mention a third important prerequisite for the existence of plastics recycling. The relation between virgin plastics prices and secondary plastics prices is an important factor as well. The preparation of secondary plastics for application in new products, which includes cleaning, melting, filtration and extrusion, is relatively expensive (up to € 1.00 per kg). This means that if the prices of virgin plastics drop beyond a level close to € 1.00 per kg, the recycling of plastics will become too expensive, and no market will exist.

It can be concluded that with respect to the determination of secondary plastics prices, not enough market information is presently available to base reliable plastics prices on – a high amount of uncertainty exists.


\textsuperscript{146} Fisher, M. Voluntary public-private partnership for the recycling of End-of-Life-Electronics in the USA. Identiplast, April 2001, Brussels, Belgium.
3.5.4 End-of-life processing costs

To facilitate discussion on the developments in end-of-life processing costs (being the actual costs to process volumes of WEEE, and not the total end-of-life costs), a distinction needs to be made between two kinds of developments:

- Changes in the cost of the process (or sequence of processes) itself, keeping both the size and the composition of the material stream entering the process as given
- Changes in the cost of processing for a particular product or material stream, keeping the process as given. These changes can be due to either the size or the composition of the material stream entering the process, or both.

The effects of a number of occurring types of structural changes on the processing costs are given in Table 25.

<table>
<thead>
<tr>
<th>Possible development influencing processing costs</th>
<th>Possible effect on processing costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changes related to the size of the WEEE stream to be processed</td>
<td></td>
</tr>
<tr>
<td>• (Developments in economies of scale leading to) overcapacity</td>
<td>Decrease</td>
</tr>
<tr>
<td>• (Developments in economies of scale leading to) undercapacity</td>
<td>Increase</td>
</tr>
<tr>
<td>Changes related to the composition of the WEEE stream to be processed</td>
<td></td>
</tr>
<tr>
<td>• Phase out of difficult or expensive to process components</td>
<td>Decrease</td>
</tr>
<tr>
<td>• Simplification of product architecture</td>
<td>Decrease</td>
</tr>
<tr>
<td>Changes related to the process itself</td>
<td></td>
</tr>
<tr>
<td>• Stricter smelter specifications leading to necessary process improvements</td>
<td>Increase</td>
</tr>
<tr>
<td>• Investment in mechanical processing technology</td>
<td>Increase</td>
</tr>
<tr>
<td>• Use of improved mechanical processing technology</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

Table 25: Structural effects of developments on processing costs

From Table 25 it is clear that there are a variety of developments that have positive as well as negative influences on the processing costs. However, over the past decade it can be learned that processing costs have remained unchanged or have even decreased, mainly because of more efficient use of (improved) technology and favourable economies of scale. As an example, IBM\(^1\) gives an overview of process improvements that they have been able to make over the years as a result of a growth in input volume to their computer recycling facilities. These improvements are said to have increased productivity greatly. On the other hand, achievements from the past decade do not necessarily guarantee future developments as this area can still be regarded to be in its infancy, with new developments being possibly implemented in the near future.

When resulting from technology developments and better economies of scale, changes in processing costs can be regarded as happening on a medium to long-term basis, and

therefore as structural changes. Changes on a short-term basis can occur when there is a change in process capacity use. This could for example happen when a temporary lack of products to be processed will cause the end-of-life process to operate at less than full capacity, causing the processing costs per kilogram to be higher. In the same vein, a capacity increase in a recyclers processing facility potentially will decrease processing costs per kilogram. This relates to economies of scales issues as discussed in previous sections.

Although the actual processing costs may vary over time, for different reasons discussed above, it is unlikely that on a short term basis recycling companies will charge these changes to the parties that offer products to the recycling company. Rather, recycling companies will cope with these fluctuations by maintaining sufficiently large overhead margins. Therefore, from a producer’s perspective, only medium to long-term changes are relevant to study in the current context.

Hardly any literature is available that addresses predictions for developments of end-of-life processing costs and the reasons that may cause them to change. One reference is made in the Apparatour report\textsuperscript{30} with respect to the future processing costs of television sets: here it is stated these costs are expected to drop by some 30\% by the year 2008 (assuming a supply of a certain number of end-of-life sets). This decrease is expected to happen because of changes in the product architecture.

In conclusion, it is expected that the positive effects such as improved infrastructures and economies of scale, will on the medium to long term outweigh any negative effects on the end-of-life processing costs. As such, processing costs per kg of returned WEEE are expected to drop. This is reflected also in section 6.3.3, where the effects of changing end-of-life processing costs will be further investigated on a quantitative basis.

3.6 Uncertainty because of environmental developments

In section 2.6 the importance of uncertainty because of certain ‘environmental’ developments has been acknowledged. For example, if ‘new’ scientific research would show that ABS or any other plastics would be similarly controversial as PVC, or that the environmental impact of the recovery of copper from WEEE would become 50 times as much, this would have a considerable effect on the conclusions drawn from the analysis in this dissertation. Although these particular occurrences may seem unlikely, large differences occur between consecutive generations of environmental impact databases (for example between the Ecoindicator‘95 and Ecoindicator‘98 databases). Another example of what is referred to here as an environmental development could be the case where the general public would become more or less environmentally concerned due to a variety of developments. A shift in the division among the consumer types as listed in Table 11 in section 2.6 could eventually lead to alternative valuations of all aspects that have to do with the end-of-life stage of products, and thus influence the results derived in this dissertation. Evidently, researching this subject further would require a completely different approach (for example building on social, psychological and political sciences) from the relatively economically or technically oriented subjects further
discussed in this paper. Therefore it was decided that at this stage no scenarios were to be included related to the uncertainty issues because of environmental developments as discussed in this paragraph. For issues relating to changing customer awareness leading to changing volumes of collected WEEE it is referred to changes in economies of scale discussed under economical developments.

3.7 Concluding remarks about future developments in end-of-life scenarios

In this chapter a number of future developments have been discussed, in particular with respect to the uncertainty associated with them. As was previously stated, for example at the end of section 3.4, the main purpose of this analysis has not been to make bold statements on when and where things will happen, but to create a basis for scenario and sensitivity analysis. In these analyses, an approach on a what-if basis will be taken, analyzing the consequences of likely and/or less likely developments. The scenario and sensitivity analyses are presented in Chapter 6.

However, below a short overview is given for general developments that are expected to take place in the near future according specialists. Table 26 gives a schematic representation of relevant aspects of future recycling processes.

<table>
<thead>
<tr>
<th>Applicable product category</th>
<th>Future development</th>
</tr>
</thead>
<tbody>
<tr>
<td>In general</td>
<td>• More efficient reverse logistic systems will be set up to be able to attain the economies of scale required for an efficient recycling process</td>
</tr>
<tr>
<td></td>
<td>• Improved sorting at the beginning of the recycling process will be necessary to enable higher processing efficiency</td>
</tr>
<tr>
<td></td>
<td>• Sorting of incoming WEEE streams will be on the basis of (i) content of hazardous substances such as batteries, and (ii) presence of copper and precious metals</td>
</tr>
<tr>
<td>CRT-containing brown goods</td>
<td>• Increasing amount of automated disassembly, focused on removing the CRT</td>
</tr>
<tr>
<td>Remaining fractions from</td>
<td>• Disassembly of rechargeable batteries (i.e. from VCRs)</td>
</tr>
<tr>
<td>CRT-containing brown goods</td>
<td>• Fractions will mainly be shredded immediately to enable material recycling</td>
</tr>
<tr>
<td>and CRT-free brown goods</td>
<td>• Improved focus on ensemble issue: certain sensible combinations of</td>
</tr>
<tr>
<td></td>
<td>• fractions will be jointly recycled to increase economies of scale</td>
</tr>
<tr>
<td>Smaller appliances</td>
<td>• Low value of remaining fractions might not justify expensive material processing techniques</td>
</tr>
<tr>
<td></td>
<td>• As a result, more sophisticated thermal treatment processes will be used to concentrate metal fractions</td>
</tr>
</tbody>
</table>

Table 26: Qualitative overview of likely end-of-life scenarios developments

In this chapter, step 2 of the research methodology introduced in section 1.1 has been taken. For each factor influencing end-of-life scenarios, identified in Chapter 2, it has been investigated in which way this factor leads or can lead to uncertainty. From this investigation it can be learned that legislative developments are still (at the time of writing this dissertation) 'under way', and that it is not yet clear how they will crystallize out
in terms of applicable product categories, required recycling percentages and implementation time frames. It has also been shown that market developments, and in particular the development of metal prices, are such that it is likely that economical performance of end-of-life scenarios will be influenced significantly by these. Fluctuations (in particular increases) in for example the precious metals prices could in theory even lead to a situation where it may profitable to recycle a certain waste stream in a certain year, while this was not the case in the previous year. Also, significant changes in plastics prices as a result of the immaturity of secondary plastics markets are not to be ruled out and can in theory lead to similar situations.

Concerning technological developments, it is clear that although shredding and separation appears to be an economically and ecologically justified process, advanced disassembly is still regarded by many as a viable technology applicable for many product categories in the future. Whatever the standpoint, it any case it is not yet clear how this 'battle of technologies' will eventually work out. More likely, it will be a continuous process of development, depending also on geographical circumstances and economies of scale.

These economies of scale form at the same time perhaps the most uncertain relevant factor to be considered. As has been pointed out, economies of scale at least theoretically can 'make or break' end-of-life scenarios. They will determine the choice of applied technology, the existence or non-existence of dependable markets for secondary materials, the implementation of return logistics infrastructures, and therefore the feasibility of end-of-life scenarios as a whole. It has been clear that sufficient knowledge to exactly point out the mechanisms of economies of scale, and all associated sensitivities involved, is not yet available, but the analysis at hand suffices to at least be able to develop some scenarios useful for further investigation. This is especially the case since the research methodology in this dissertation requires the uncertainties to be reduced to quantified model parameters in order to be able to use a calculation tool to assess different end-of-life scenarios. This way, many of the details can be disregarded for now (although they are clear candidates for further research, see section 9.4) and only the aggregated effects have to be analysed. For instance, it is not difficult to analyse a scenario that shows an 10% decrease in processing costs, a 20% rise in recycled plastics prices and a 2% better recovery grade, whereas it is much more difficult to exactly describe under what circumstances these developments may occur exactly.

Before the most important uncertainties factors in end-of-life scenarios can be determined, which is done in Chapter 6 and onwards, first the question how to evaluate end-of-life scenarios is dealt with in the next two chapters. In Chapter 4, a literature review of existing methods for end-of-life scenario evaluation is presented. This leads to the introduction of the PMRCM in Chapter 5, which is the method that will be used in this dissertation to evaluate end-of-life scenarios and the associated uncertainties.
4. End-of-Life Scenario Evaluation

Chapters 2 and 3 have focused exclusively on the description of factors related to the end-of-life stage of products and the way these factors cause uncertainty in end-of-life scenarios. This chapter focuses on the discussion how to evaluate scenarios. To this end, two perspectives are relevant.

An ecological perspective in end-of-life scenario analysis means that the environmental profile of a certain product, product category or waste stream is charted. In a classic Life Cycle Assessment (LCA) approach this is based on emissions that occur during the end-of-life, as well as the energy use of processes. A more thorough environmental profile should also include environmental issues that are so far not addressed very well by LCA such as the issue of embedded potential toxicity (see also section 1.4).

The main quantity into which the ecological perspective is reflected in the analyses presented in the subsequent chapters is a recyclability score. Traditionally, the 'environmental performance' of electronic products has always been described using recycling quotes related to weight only. Since the environmental load of various types of materials differs considerably and recycling itself has an environmental impact as well, this is an incorrect description from both a scientific and an environmental point of view. But since it is still the main 'language' among for example legislative bodies and businesses, the conventional notion of recyclability will be used. In section 5.4 the concept of Environmentally Weighted Recycling Quotes, which is major improvement over the concept of weight-based recyclability scores will be introduced.

An economical perspective in end-of-life scenario analysis means that the financial costs and benefits of all material fractions as well as the underlying processes to obtain them are calculated.

In Boks et al.\textsuperscript{148} several alternatives are discussed for economical and ecological quantities, in order to investigate possible definitions of eco-efficiency. An eco-efficiency approach takes both ecological and economical considerations into account. Principally, the quotient of the ecological and economical scores is calculated to arrive at a figure, which will give the amount of environmental (non-)performance per monetary unit spent. However, it is important to note that in the context of this dissertation this concept is applicable in only a limited number of cases. Eco-efficiency in principle refers to the possibility to use this concept as a decision variable, because it gives the marginal change in one performance indicator given the fact that the other indicator is changed.

Therefore, by appointing an eco-efficiency score to a development such as a legislative or a technological one, it is implicitly assumed that these developments can be influenced; a certain dynamic character is assumed for the applicable developments. However, for these examples in the current context this is not a valid assumption. If an eco-efficiency score is appointed to a legislative development, it refers to a static situation – for a company the possibilities to tune this (part of a) scenario are extremely limited and therefore the eco-efficiency concept cannot properly serve its purpose. In section 8.2 a further discussion is dedicated to the degree to which companies can influence the developments addressed in this dissertation. There it will be shown that only product design itself has the dynamic characteristics required for using eco-efficiency scores. For legislative, technological and economical developments this is much less so. For these reasons eco-efficiency will not be used as a performance indicator throughout this dissertation. However, in section 7.5.3 some remarks are made based on simultaneous observation of both the economical and environmental performance indicator. There, once again the precarious interpretation of such an ‘eco-efficiency’ indicator is pointed out.

The structure of this chapter is as follows. In section 4.1 an overview will be given of existing tools, methodologies and approaches for end-of-life scenario evaluation. These are discussed in section 4.2 to establish in what way they can or cannot contribute to evaluating uncertainties as a result of future developments in end-of-life scenarios as discussed in the previous chapter. In section 4.3 conclusions are drawn based on this evaluation.

4.1 Existing tools and methodologies for end-of-life scenario evaluation

In recent years a number of Design for Environment (DFE) tools have been developed in order to assist developers and designers in making the right choices. All these tools differ when it comes to scope, methods used, applicability to certain products and level of sophistication, and usually only one or a few aspects of the design process are considered. Also, some of these tools have applications when it comes to the end-of-life phase of a product. The purpose of this chapter is to objectively compare the scope and the applicability of these tools, and this exercise should be regarded as a necessary stepping stone for the introduction of the Product Material Recycling Cost Model in Chapter 5 and the motivation for using this particular tool in the assessment of uncertainties of future developments regarding the end-of-life stage.

Although several methodologies regarding the end-of-life phase have appeared in recent literature, few have actually materialised into software tools, let alone released as a commercial product. Only three such tools were identified by Mizuki, the same number by Hninyak et al.149, and only two of them by Poyner150.


Whereas Troy\textsuperscript{151} states that software for product retirement planning would play an increasingly important role in the future, the situation in the succeeding years has been that this software is still not widely used in industrial environments. Dieterle\textsuperscript{152} concludes the same and states that this may be due to an exclusive orientation on aspects of product construction. It is more likely however that the main reason for this lies in the lack of reliable data sets on disassembly times, processing costs, reuse values and the like. Bakker\textsuperscript{153} even states that "the right tools seem to be lacking", which for that matter not only refers to the end-of-life phase. Recently, Furuholmen\textsuperscript{5} has identified a gap in previous research, since he was not able to identify a method or approach that defines, at the necessary level of detail but still with sufficient scope, how the end-of-life aspect could be taken into consideration in all stages of the product development process.

In this paragraph, in addition to Emblemsvågs work discussed in section 3.2, an overview will be presented of approaches for end-of-life evaluation that have been developed at companies and research institutes across the world. The overview will be presented in chronological order, as far as possible. Some approached have been omitted from this overview. This occurred whenever they considered either very specific issues in product retirement analysis (such as disassembly sequence planning), or, as argued above, when they are of a qualitative nature only, limited to giving guidelines.


ReStar was developed at Carnegie-Mellon University in the early nineties. In early publications, it has always presented itself as a very sophisticated and therefore very promising software tool for end-of-life evaluation (see for example Navin-Chandra\textsuperscript{154,155}). In practice, the tool has never been released successfully because of problems with the software – the first Sun-version had running difficulties, while the second PC version was never successfully released (attempts at Delft University of Technology to obtain a copy were not successful). For these reasons, in Boks\textsuperscript{156}, evaluation of ReStar had to be based on information brochures and publications.


\textsuperscript{155} Navin-Chandra, D. (1994). ReSTAR. Design for Recovery: Disassembly, Recycling, Remanufacture and Reuse. Information brochure issued by the Green Engineering Project, Pittsburgh, USA

LASeR (1994-1996)

This tool has been developed at Stanford University (Ishii\textsuperscript{157, 158, 159}). Originally developed as a Design for Serviceability tool, it was extended to also carry a Design for Product Retirement module. With LASeR, the user was asked to identify so-called ‘clumps’ of a product – subassemblies that could be disassembled for further processing. Some simple metrics were used to calculate disassembly costs. Around 1997, the development of LASeR software was put on hold, supposedly for re-evaluation of the product retirement analysis. Also, plans existed to include other modules into the tool such as the Reverse Fishbone Diagram tool (Ishii\textsuperscript{160}). These plans however have not been completely carried out and after that, not much work has been carried out to further develop LASeR.


The End-of-Life Cost Model was developed and used for a number of years (1995-1997) at the Environmental Competence Centre of Philips Consumer Electronics in Eindhoven, The Netherlands. This tool was able to determine the end-of-life yield of a wide range of products in the brown goods category, as well as the economically most feasible recycling strategy according to current technology and tariffs (Brouwers\textsuperscript{161}). The tool was used internally for product benchmark purposes for a number of years, but after an unsuccessful attempt in cooperation with a software development company to develop the methodology into a user-friendly software tool, further implementation of the model was halted.

AMDEL (- 1996)

A method designed to cope with financial variability in a life cycle perspective is described in (Rose\textsuperscript{162}), and is known as the AMDEL method, which stands for “A methodology for the Design of Economically superior Life cycles”. The principle of this method is based upon identifying the main drivers of financial variability within a product life cycle design. Using the principle of AMDEL to regard the End-of-Life stage only

\textsuperscript{157} Ishii et al. (1994). LASeR User’s Manual, Ohio State University


(which is relatively easy to do), it may answer questions like: “What are the main reasons for the uncertainty of end-of-life yield estimations?” It is commonly agreed upon that in case of disassembly manual labour is the main cost driver. Using the principle of AMDEL, this can be checked. It may even be possible to define if certain cost drivers are relatively ‘steady contributors’. Furthermore, it can also evaluate if other cost drivers, like storage, transport, which are usually seen as overhead variables, can be regarded as separate variables. Therefore it needs to be defined what level of financial variability is ‘allowed’ to identify this kind of variables as a separate variable.

Resuming, AMDEL may not be in the first place be used as a tool to estimate end-of-life yields as such as its principle goal is to contribute in defining which cost drivers need to be examined more closely in order to determine where the uncertainties that come with the estimation of end-of-life yields are.


This tool was developed to assess ease-of-disassembly for virtually all products. It is based on work measurement analysis (Hanft\(^\text{163}\)), using standard times for human physical operations to evaluate the duration of manual disassembly operation, and was therefore focused on determination of manual disassembly times only. In Boks et al.\(^\text{59}\) the theoretical derivation of disassembly operation durations was compared with observations of actual disassembly operations. It was concluded that the results of both models correspond very well, which in itself was no surprise as the ‘theoretically derived’ data finds its origin in numerous motion-time studies of workers under real-life conditions. Plans to develop the tool into commercially available software were postponed around 1998 due to lack of resources.

**DFE (1996- now)**

The first released version of this software tool named Design for Environment (DFE), was developed in a collaborative effort between TNO in the Netherlands and the US based company Boothroyd Dewhurst Inc. (BDI). It combines the experience in Design for Assembly present at BDI with the knowledge on recycling processes present within TNO. An impression of the output given by the tool can be found in Harjula\(^\text{164}\) as well as in Okada\(^\text{165}\). In his article, Okada discusses the use of DFE within Sharp. Some of his conclusions are that the database figures for disassembly times are similar to what can be observed on-site (though actual disassembly times for joints were still found to be almost 70% higher than DFE database values), but that other operations such as removing labels and other cleaning operations in reality take much longer (5-6 times)


than as assessed by DFE. Another remark about DFE can be found in Murtagh\textsuperscript{166}, where he mentions that problems with DFE include 'the inability to edit or update the database and the lack of environmental impact analysis for the complete product lifecycle'. At the time of completion of this dissertation, a second version of DFE, tentatively named DFE 2.0 or EcoScan–Dare, was being developed to include experiences from another TNO tool, named DFMR (Design for Material Recycling)\textsuperscript{167}. The purpose of this tool is to suggest end-of-life routes for consumer electronic products based on environmental and economical considerations. With this launch, DFE still appears to be the only end-of-life evaluation tool (obviously apart from LCA software tools) successfully released on the market. As a result of a cooperation between TNO and Delft University of Technology, in Korse-Noordhoek et al.\textsuperscript{168} an overview is given of the considerations that are underlying the development of tools such as EcoScan–Dare, especially in terms of trade-offs between functionality of the tool and the user-friendliness for the envisaged user.

**Reloop (1998 -)**

Reloop is a project running since January 1998 and sponsored by the European Commission. It focuses on the development of models and methods supporting the management of take-back logistics and recycling chains and networks\textsuperscript{139}. Currently, an integrated model is available that is supposed to be able to

- Compare alternative end-of-life processing scenarios
- Optimise collection and distribution
- Assess financial and environmental aspects
- Support network and chain management
- Create reports

A visit to the first information workshop in October 2000 revealed that in essence, the tool is comprised of a logistics planning module and a processing evaluation module. The combination is supported by a module that creates reports, as well as a search function for companies involved with logistics and processing of WEEE. Supposedly, all modules can be used separately. The conclusion about RELOOP based on the information provided in this workshop is threefold:

- In theory, the processing evaluation module RecyclePro appears to be well-structured. In particular, the possibility to deal with uncertainty by providing the tool with data such as 'between 10,000 and 20,000' rather than '15,000' makes it less rigid. On the other hand, it is not to be expected that the extensive databases that support calculation of processing costs and procedures can be filled as easily as the developers


\textsuperscript{168} Korse-Noordhoek, M., Boks, C., Stevels, A. Pros and cons of adjusting and extending functionality of first generation end-of-life evaluation tools in relation to user requirements. Ecodesign 2001, December 12-15, Tokyo, Japan
appear to expect. Currently, the available data originates from the United Kingdom but for the majority of process related parameters dummy data are said to be used. The counterargument given by the RELOOP development team that this is exactly why the functionality of including uncertain data is integrated in the model does not withstand the fact that multiplication of uncertainties will greatly reduce useful opportunities for interpretation of the results. Another problem with the application of this module is the fact that there appears to be a discrepancy between the envisaged users of RELOOP and the functionality these users are looking for in reality. This is true since most recycling facilities already know how to do business in an economically efficient way based on their specific circumstances, and have little or nothing to gain from a software tool that has been developed for generic application and has insufficiently filled databases.

- The logistics planning module, when used separate from the processing evaluation module, does not have additional value over already existing logistics planning software, an issue brought forward by workshop participants. Therefore, this feature alone is no incentive to use RELOOP.
- The synergy of combining both the processing evaluation and the logistics planning module, though in theory present since it optimises over the entire chain, will in practice not come to the surface since there is no market for simultaneous optimisation. Recyclers have little to gain from optimising themselves route planning for transportation activities that are outsourced. At the same time, logistics operators have little to gain from optimised recycling processes. Only on a political umbrella level it is imaginable that combining the functionality of both modules will be considered useful.

ELDA (1997-)

The End-of-Life Design Advisor (ELDA) as developed at the Manufacturing Modeling Lab of Stanford University by Rose et al.\textsuperscript{169,170} guides product developers to specify the preferred end-of-life strategies on which their work has to be based. ELDA allows to select in an early design stage end-of-life design options, which are most fitting to the product characteristics. Possible strategies are based on Figure 15 and include

- Life-time extension (service)
- Reuse
- Remanufacturing
- Recycling (disassembly first)
- Recycling (shredding first)
- Disposal

ELDA uses technical product characteristics, that is, those aspects of a product which can be most influenced by designers and product managers. An extensive analysis showed that the technical product characteristics given in Figure 28 are relevant for the strategy prediction.


An investigation of some 40 cases showed that the ELDA prediction of end-of-life strategies agrees for 90% with current best practices. This allows for the conclusion that ELDA can give in principle important focus in Design for End-of-Life efforts. For instance:

- Life-time extension (service) - easy accessibility of relevant parts and subassemblies;
- Remanufacturing - modular architecture of the product (complete or as far as relevant);
- Recycling (disassembly first) - choose fixtures with low disassembly time;
- Recycling (shredding first) - design for agreeable chemical content, good separability;
- Disposal - design for disposal.

It is important to stress here that design strategies should relate to best practice rather than current (average) practice. Rose et al. show that there is a substantial gap between the two; in more than half (54%) of the investigated cases current end-of-life treatment included a strategy that was lower on the list in Figure 15. This gap can be explained on basis of the Environmental Value Chain concept (see Chapter 2), it will be shown there that this gap is basically due to non-technical issues which have not been resolved yet, either between stakeholders or in the internal value chain of one of the stakeholders involved. As it is to be expected that during the life-time of the product to be analysed the value chain will improve and show more transparency, design for end-of-life has to be oriented to the future rather than to the present.

**Mitsubishi**

In Murtagh et al. a Design for Environment tool is described that is supposed to enable DFE to be integrated into the conventional design process. It relies on 3D CAD databases which should make as much information available beforehand to reduce required designer input. The tool is called D4N and is said to go beyond conventional lifecycle analysis to include all end-of-life issues, not only from an environmental but also from an economical point of view. The latter is done by including, for each material, both the end-of-life destination as well as the end-of-life processing or recycling costs. Output is given in three principal parameter evaluation sets: end-of-life costs, recycle rate data and environmental impacts. However, for this tool, the required user input still considerable and in essence does not differ from other approaches. The user has to define,
for each part, the material and the basic connection information, so the basic geometrical structure. Also the fact whether a part is likely to be difficult to remove or not is required, an input that for example in Kroll’s approach would already made unnecessary for the user to provide. Therefore, the Murtagh’s remark that this tool enables designer to evaluate their designs “quickly and with minimal effort” cannot be justified, at least when compared with other approaches.

Various other tools

Although the purpose of this section is not to be exhaustive, some other initiatives are mentioned here that included at least some aspects of end-of-life scenario evaluation in a business context, but are not reported on further mainly due to lack of information about how these have progressed since they were first reported on. At the Technion in Haifa, Israel a tool named MoTech was under development around 1995. This tool was supposed to evaluate the end-of-life value of a mechanical product design. Some theoretical background on the tool can be found in Pnueli but no further publications were found elaborating on that. A tool named TOPROCO with similar goals like ReLoop has been under development since around 1996 and has been reported on in Engelborghs and Bopp et al. In cooperation with the Technical University of Braunschweig, LG Electronics in South Korea have developed a tool named ATROiD (Assessment Tool for Recycling Oriented Design) to assist them in their strategy to deal with end-of-life issues. Recent communication with LG Electronics however indicates that a successful implementation into their business is still lacking. The tool is discussed in Kang et al. In 2001, a visit from a LG Electronics delegation to TU Delft indicated that a successful implementation into their business is still lacking. A next publication does present further development of the tool (and mentions for example the inclusion of a PWB evaluation module), but no evidence is presented of actual implementation of ATROiD in LG operations. An example of research on product end-of-life alternatives and their associated economic impacts is the work of Low. Using telephone handsets as exemplar products, in this research economic models are described that

---


aim to be a practical design tool enabling the user to quickly assess the trade-offs between different end-of-life strategies without much compromise in its accuracy. At the University of Karlsruhe in Germany two tools have been developed for taking the complete life cycle of a product into consideration. These computer-aided methods are REKON (recycling oriented design tool) and LICCOS (Life Cycle Costing tool)\textsuperscript{179}. Recent Japanese initiatives to develop recyclability evaluation tools within the Toshiba and Hitachi corporations are reported on in Oyasato et al. and Hiroshige et al.\textsuperscript{180,181}

4.2 Critical evaluation of existing software tools

In section 4.1 a number of existing tools for the evaluation of end-of-life scenarios has been discussed. These tools vary not only in 'chosen' aspects such as scope or focus, but also in performance, accuracy et cetera. From the enumeration it can be seen that only very few tools have materialised into a commercial software tool.

The most important question to be answered in the remainder of this chapter is whether the existing tools and methodologies can be useful in assessing the uncertainties associated with the product's end-of-life stage that were addressed in Chapter 3. For this purpose, tools will need to quantitatively assess the importance of the different uncertainty aspects and come to a prioritisation of issues for business attention.

In order to present a comparative overview of existing end-of-life assessment methods, contributions by Mizuki\textsuperscript{8} and Troy\textsuperscript{151,182} comprised surveys of tools listing differences in scope, but without using any quantitative examples. As a first initiative to provide such a quantitative overview, in Boks\textsuperscript{156,183} the applicability of a number of DFE tools that were available at that time was tested in an industrial environment. For this purpose, a real-life industrial example was used to test the tools with, since the ultimate criterion is whether a tool really works in industrial design practice. In Boks\textsuperscript{156} a set of criteria to evaluate end-of-life evaluation tools was given. These criteria included:

- The objective or scope of the tool. This referred to the tasks the tool was supposed to perform, the end-of-life options it is supposed to consider, and whether it was sup-


posed to be a tool assisting designers, giving design recommendations, or a tool focusing on evaluating products by benchmarking them. Other aspects focused on included whether the tool would supply the user with an end-of-life strategy and the range of products the tool had been developed for.

• **The accuracy level of specification of the product.** This criterion focused on the level of detail that the tool required concerning data on the construction and geometry of the analysed product, for example whether it was possible or needed to give a detailed description of every part of the product and whether parts and joints were to be identified separately.

• **The required data for the tool.** Here it was determined whether the user had to enter his/her own data (on for example materials, tariffs and disassembly times) or whether extensive databases were incorporated in the tool. Also, completeness and reliability of the data were addressed.

• **Disassembly and mechanical processing.** This aspect dealt with the way disassembly and mechanical processing options were taken into account. For example, whether (optimal) disassembly sequences were generated, and whether the person operating the tool was required to allocate end-of-life options for different parts of the product or if this was done automatically. Also, it was investigated what shredding and separation technologies are considered?

• **Output of the program.** Here it was examined if the output of the tool was stated in financial or environmental terms, and whether this output could be easily be interpreted. Also, opportunities to derive design recommendations were assessed.

For the purpose of evaluating the different tools a Philips colour television set was used as a reference product. The evaluation procedure used in the 1997 survey consisted of the following steps:

• **Step 1:** Entering the product's configuration (weight, material, geometry);
• **Step 2:** Entering life-cycle data such as tariffs, labour cost et cetera, where necessary;
• **Step 3:** Calculating the outcome of the tool;
• **Step 4:** Evaluating the performance and outcome of the tool according to a list of predetermined criteria, as given above.

In the evaluation procedure careful consideration was given to the fact that every tool was tested with the same data collection. The most important result of the evaluation overview was the conclusion that no single tool yielded satisfactory results on all criteria. As several tools were still prototypes of some kind, their applicability was limited. Of the two tools that overall showed the most promise in terms of maturity, Kroll's Method only addressed disassembly issues.

The other exception, the DFE tool co-developed by TNO, was the only tools that since then was upgraded, and therefore these analysis results can still be considered valid. The DFE tool from TNO since then evolved into a relatively successful software tool that still can be regarded as a state of the art tool in assessing end-of-life scenarios from both an economical and ecological perspective. However, since the tool is primarily disassembly-based with limited applicability for shredding and separation based scenarios, it does not completely fulfil the requirements of assessing end-of-life scenarios for product cate-
gories that will primarily see such mechanical processing in the end-of-life. With the new generation of DFE, tentatively titled DFE 2.0 as indicated in the previous subsection, some of these shortcomings may however have been coped with in this future release.

4.3 Conclusion from review of existing end-of-life evaluation tools

In this dissertation, the main goal in evaluating end-of-life scenarios lies in assessing the uncertainties associated with economic, political and technological developments. In Chapters 2 and 3 these uncertainties have been discussed. Taking a look forward, in Chapter 6 these uncertainties will be quantified in order to be able to perform sensitivity and scenario analysis. The ultimate goal of these analyses is to obtain a prioritisation of uncertainty issues, and to give recommendations where attention should be focused in an industrial context (see the third main research question in section 1.1).

To be able to analyse uncertainties as described a tool is needed that is suited for performing scenario analyses, in a way that default variables can be changed 'at will' to determine the effects of alternative scenarios. This means that the parameters in which the effects of technological, political and economical developments are reflected should be 'accessible' as 'knobs' that the user of the tool can turn as he or she likes.

Therefore, in addition to the criteria set out in the previous section, a further set of preferred tool specifications can be given:

- An end-of-life evaluation tool should reliably incorporate current recycling process information into an orderly application, using both economical data reflecting actual recycling process and data reflecting the environmental impact of the recycling process;
- An end-of-life evaluation tool should be able to be operated by any product designer without knowledge on environmental issues such as recycling process information and environmental impact score databases;
- An end-of-life evaluation tool should be able to generate useful information without having to gather additional information on the product (such as financial or marketing-related information) other than product characteristics;
- An end-of-life evaluation tool should allow for extensive scenario analysis to account for scenario uncertainty.

In this respect, De Jong and Kalisvaart\textsuperscript{184} state also a number of requirements for a product end-of-life evaluation tool, which should be able to:

- Determine if a product has a positive or a negative value in the end-of-life;
- Determine advantages and disadvantages of design option;
- Determine the potential material recovery of a product and enable comparison of the recyclability of different products;
- Trace the source of a recycling bottleneck.

In Korse-Noordhoek and Boks' it is discussed that five scopes need to be addressed for the successful application of end-of-life evaluation tools in a business context. These are listed in Table 27.

<table>
<thead>
<tr>
<th>Scope</th>
<th>Relevant questions and choices to be made</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applicability</td>
<td>What is a relevant discrimination regarding different product categories?</td>
</tr>
<tr>
<td></td>
<td>What type of outcomes will be generated?</td>
</tr>
<tr>
<td></td>
<td>Should manufacturing and recycling companies both be included in the target audience?</td>
</tr>
<tr>
<td></td>
<td>Should analysis be product or materials based?</td>
</tr>
<tr>
<td>User scope</td>
<td>Who are envisaged users? Managers, designers and/or policy makers?</td>
</tr>
<tr>
<td></td>
<td>What type of parameters should be considered as defaults, and which ones should be suitable for adjustment by envisaged users?</td>
</tr>
<tr>
<td>Availability</td>
<td>How do the requirements for user-friendliness interfere with (extended) functionality for these types of tools?</td>
</tr>
<tr>
<td>Technology scope</td>
<td>What are the relevant separation and recovery processes to be included in a commercial tool?</td>
</tr>
<tr>
<td></td>
<td>Should separability and unlocking characteristics be included?</td>
</tr>
<tr>
<td></td>
<td>In what way poses the availability and accuracy of data a problem?</td>
</tr>
<tr>
<td>Temporal scope</td>
<td>Is it meaningful or useful to increase tool functionality with the possibility to include uncertainty considerations about future technology, legislation and economy?</td>
</tr>
</tbody>
</table>

Table 27: Relevant questions for a second-generation end-of-life evaluation tool

All requirements enumerated above by De Jong and Kalisvaart and Korse-Noordhoek and Boks are in itself useful and even necessary for determining which end-of-life strategy is most preferred for a product, as well as for deriving (re)design options. However they focus on the successful implementation of a tool within a business context, rather than giving the necessary preconditions for being able to perform scenario analysis for reducing uncertainty as do the first four tool specifications – that is why these latter specification form the main requirements for an end-of-life evaluation tool suitable for the purposes of the current research.

The conclusion of the survey in the previous section is that no single available end-of-life evaluation method serves the purpose of quantitatively assessing uncertainties related to the end-of-life of products in a satisfactory way (especially compared to the PMRCM, a method that will be introduced shortly), in a sense that the variables to which the uncertainties can be deduced can be used for scenario analysis.

The conclusion from observing current end-of-life scenarios has made clear that a clear distinction can be made between products that are suitable for disassembly (in principle products with CRTs only), and those that are suitable for shredding and separation only. Keeping also in mind the purpose of the method that is needed, which is evaluating different scenarios by variation of end-of-life scenario parameters, separation of disassembly evaluation and shredding and separation evaluation can be justified. This is also true because products that are disassembled can after this step be regarded as products suitable for shredding and separation. In cases where there should be doubt
whether products should undergo a prior disassembly step or not, by the time this dissertation is published, TNO's DFE 2.0 tool can most likely be used to assess which process is preferred.

There is one important reason why the envisaged DFE 2.0 tool is not suitable for the scenario analysis as it will be carried out in this dissertation. In this tool, many of the inputs are linked to each other. An important example is the case of processing costs. In the DFMR module, processing costs per kilogram are calculated on the basis of various inputs regarding materials and particle characteristics. Once these inputs have been entered, the processing costs are automatically calculated. For example: a material mix with odd-sized particles will automatically lead to higher processing costs compared to material mix with only round particles. This has on the one hand the advantages that it reduces the need to enter specific data (in this case on processing costs) for each calculation, but on the other hand it is not possible to vary the processing costs separately. Consequently, in the same example a future scenario in which technology is assumed to better handle odd-sized particles and will result in lower processing costs cannot be properly assessed due to the linked inputs. Therefore it is not suitable for scenario analysis.

The next chapter will describe a calculation module for end-of-life yield and recyclability evaluation that is not yet addressed in the previous survey of tools and methodologies. This method fulfils the tool specifications stated earlier in this section, and moreover, it is suitable for the objectives in this dissertation because all the relevant input parameters can be tuned separately, which is of importance for conducting scenario analysis. In Chapter 5, the ins and outs of this module, entitled the Product Material Recycling Cost Model (PMRCM), will be thoroughly explained. In Chapter 6 it is shown how the PMRCM was used for end-of-life scenario analysis.
5. The Product Material Recycling Cost Model

The PMRCM calculates the costs or revenues of mechanically processing a product, based on the materials composition of that product, as explained in section 2.5. The yield of the process is determined by the costs and/or revenues that are incurred and/or obtained via various market outlets for the material fractions that result from the mechanical processing of discarded electronics products.

As said, the PMRCM calculates the results of a mechanical material recycling process. Disassembly is not an integral part of the PMRCM. This choice was made since the analysis of disassembly operations is a separate activity, easily analysed separately from the material recycling process. In principle, a disassembly process evaluation consists of matching product information regarding product geometry (connection types, number of occurrence, and order in which loosening connections is possible) with a standard disassembly times database. Multiplication of the number of times the required disassembly operations occur with the standard disassembly time for those operations yield the total disassembly time. This total can be multiplied with the labour rate to calculate the total disassembly cost. Approaches such as the DFE software from TNO (see section 4.1) already perform these analyses very well, and therefore it was chosen not to include disassembly analysis in the PMRCM. Also, the focus of this dissertation is on consumer electronics, and these products are almost exclusively recycled using a shredding and separation process. The only notable exceptions are TVs and monitors being CRT based products. In section 5.3.4 it is explained how these products are dealt with in the current context, and how they can be dealt with in other applications.

History of the PMRCM

As a follow-up on the increased awareness about environmental issues (as described in Chapter 2) within Philips Consumer Electronics, measures were taken around 1996/1997 to try to come up with a calculation sheet for determining end-of-life yields of products. Consequently, at the Philips Centre for Manufacturing Technology, a Mathcad\textsuperscript{185} tool was developed that was able to determine end-of-life yields based on a number of product characteristics. This tool was called the Product Material Recycling Cost Model (PMRCM). The first incarnation of the PMRCM was developed as part of a Brite-Euram project and at that time was named 'Design and Evaluation Method for the Recyclability of Electromechanical Products' (DEMROP). This method was developed in a cooperation between Siemens, Siemens Nixdorf, Philips, SEL Alcatel, AGFA and TH Darmstadt\textsuperscript{41}. The only internal Philips report\textsuperscript{186} describing the tool showed that using

\textsuperscript{185} Mathcad Plus 6.0, a commercial software tool.

the PMRCM end-of-life yields and material recycling efficiencies could be examined for a number of consumer electronics such as a soundmachine, a fax and an audio mini system. In 1999, as part of the research towards the present dissertation, the PMRCM was adapted and improved into a Microsoft Excel spreadsheet, making it easier to work with and more suitable to perform sensitivity analyses with it. Also, an environmental evaluation module was added, which made it possible to assess end-of-life scenarios not only according to their economical merits, but to also assess the environmental impact of the chosen scenarios, using weight-based recyclability scores.

In the original PMRCM, the recycling process was chosen to be a constant parameter. The chosen process consisted of shredding, magnetic separation and eddy current separation, as previously shown in Figure 14, section 2.5. This is a robust process suited for recycling of a waste stream consisting of a mix of consumer electronics products without CRTs.

5.1 Input and output variables for the PMRCM

The PMRCM in essence provides two scores in order to assess end-of-life scenarios.

- An economical score: the monetary revenues or costs from the end-of-life processing of a certain product, based upon a number of relevant, default input parameters (product, process and market parameters) representing a state-of-the-art material recycling process for WEEE. It is up to the user of the model to decide if this is done on a per product basis, or an a per kilogram basis.

- An environmental score: a weight-based material recyclability score for a certain product, based on the material composition of that product and a number of parameters representing the recovery characteristics of the recycling process.

In order to be able to calculate these scores, the PMRCM requires input on three categories of factors, namely product parameters, process parameters and market parameters. In Table 28 all input parameters for the PMRCM are given.

The product parameters in Table 28 are supplied by the user of the PMRCM, although for each main product category a complete set of product parameters is given as default values (see section 5.3). The most important reason to enter product parameters in terms of percentages rather than absolute values is the fact that this way comparison between different products is made easier. Therefore the default input value for weight is 1 kg.

For the process and market parameters a set of default values is used to calculate the results for current actual recycling processes. In the paragraphs below these default values are discussed in short. By choosing alternative values for these parameters, reflecting an end-of-life scenario change, the user of the PMRCM can assess the influence of such a change on the performance indicators.
<table>
<thead>
<tr>
<th>Product parameters</th>
<th>Process parameters</th>
<th>Market parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal content</td>
<td></td>
<td>Metal prices</td>
</tr>
<tr>
<td>Weight percentage ferrous metals</td>
<td>Processing costs</td>
<td>For iron</td>
</tr>
<tr>
<td>Weight percentage copper</td>
<td>Cost of recycling process per kg</td>
<td>For copper</td>
</tr>
<tr>
<td>Weight percentage aluminium</td>
<td>Cost of incineration per kg</td>
<td>For aluminium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For gold</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For silver</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For palladium</td>
</tr>
<tr>
<td>Plastics content</td>
<td></td>
<td>Plastics prices</td>
</tr>
<tr>
<td>Weight percentage type 1 plastics</td>
<td>Recovery percentage</td>
<td>For recoverable plastics type 1</td>
</tr>
<tr>
<td>Weight percentage type 2 plastics</td>
<td>For ferrous metals</td>
<td>For recoverable plastics type 2</td>
</tr>
<tr>
<td>Weight percentage type 3 plastics</td>
<td>For aluminium</td>
<td>For recoverable plastics type 3</td>
</tr>
<tr>
<td>Weight percentage non-recoverable plastics/waste fraction</td>
<td>For copper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For gold</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For silver</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For palladium</td>
<td></td>
</tr>
<tr>
<td>Precious metals content</td>
<td>Recovery grade</td>
<td>Incineration prices</td>
</tr>
<tr>
<td>Concentration of gold in ppm</td>
<td>For ferrous metals</td>
<td>For the non-recoverable</td>
</tr>
<tr>
<td>Concentration of silver in ppm</td>
<td>For aluminium</td>
<td>plastics/waste fraction</td>
</tr>
<tr>
<td>Concentration of palladium in ppm</td>
<td>For copper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For gold</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For silver</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For palladium</td>
<td></td>
</tr>
</tbody>
</table>

Table 28: Input parameters for the PMRCM

<table>
<thead>
<tr>
<th>Default process parameters</th>
<th>Recovery percentage</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic materials</td>
<td>90%</td>
<td>95%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>Copper</td>
<td>95%</td>
<td>100%</td>
</tr>
<tr>
<td>Gold</td>
<td>95%</td>
<td>100%</td>
</tr>
<tr>
<td>Silver</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>Palladium</td>
<td>92%</td>
<td>100%</td>
</tr>
<tr>
<td>Plastics of type 1 and 2</td>
<td>0% or 50%</td>
<td>85%</td>
</tr>
<tr>
<td>Plastics of type 3</td>
<td>0% or 75%</td>
<td>85%</td>
</tr>
</tbody>
</table>

Table 29: Input process parameters for the PMRCM

Recovery percentages are assumed given based upon current values as presented in Table 29. The grades of the recovered materials play a role in determining the value of the material fractions that remain after processing. In Table 29 the grades that are assumed in the default situation are given as well. The default values used for market parameters in the PMRCM calculations are given in Table 30, and based on the current (2000) market situation, for the grades given in Table 29.
Market parameters:

<table>
<thead>
<tr>
<th>Metal prices:</th>
<th>€</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of magnetic metals</td>
<td>0.05/kg</td>
</tr>
<tr>
<td>Price of aluminium</td>
<td>1.50/kg</td>
</tr>
<tr>
<td>Price of copper</td>
<td>2.00/kg</td>
</tr>
<tr>
<td>Price of gold</td>
<td>10000/kg</td>
</tr>
<tr>
<td>Price of silver</td>
<td>175/kg</td>
</tr>
<tr>
<td>Price of palladium</td>
<td>15000/kg</td>
</tr>
<tr>
<td>Yield of plastics type 1</td>
<td>0.10/kg</td>
</tr>
<tr>
<td>Yield of plastics type 2</td>
<td>0.12/kg</td>
</tr>
<tr>
<td>Yield of plastics type 3</td>
<td>0.75/kg</td>
</tr>
<tr>
<td>Processing costs</td>
<td>0.17/kg</td>
</tr>
<tr>
<td>Incineration costs</td>
<td>0.12/kg</td>
</tr>
</tbody>
</table>

Table 30: Input market parameters for the PMRCM

It should be noted here that in particular the default value for palladium is nothing but a recorded moment in time; in section 3.5 it has already been shown that especially for this precious metal the market price behaves relatively unstable. In Chapter 6 it the uncertainty associated with this unstable behaviour is analysed.

Plastics prices in the PMRCM

As regards plastics prices: in the PMRCM it is chosen to distinguish between three types of recoverable plastics. This makes the PMRCM equipped to include the benefits of different ways to separate plastics from the same product or product stream in order to obtain monetary benefits from this. Theoretically, the PMRCM can be equipped with a larger number of different plastics, but for reasons of transparency, and considering the intended application of the PMRCM in the context of this dissertation, the distinction in three types only was considered useful. For applications of the PMRCM that aim at detailed calculations for individual products or product streams, it is simple to extend the number of plastic types and to set plastics prices as appropriate to those particular applications. The three types used in the current applications are:

- **Recoverable plastics of type 1:** These include plastics that are recovered to reduce the costs of processing them together with the non-recoverable plastics fraction. So, plastics of this type do not yield money, but it costs less (€ 0.10 per kg) to dispose of them when separated, than when mixed with non-recoverable plastics in the waste fraction (€ 0.12 per kg).

- **Recoverable plastics of type 2:** These include plastics that, when recovered, yield a small revenue of € 0.12 per kg.

- **Recoverable plastics of type 3:** These include plastics that, when recovered, yield a larger revenue of € 0.75 per kg.

It is up to the user of the PMRCM to determine which plastics in a product fall in which category. It is important to note here that determining the monetary benefits from plas-
tics separation in the PMRCM could be done only in a speculative way since no stable market can currently be identified for the recycling of plastics from consumer electronics. Therefore, the distinction in three types of plastics is important from the perspective of allowing to distinguish between valuable and less valuable plastics, but the actual level of the default prices per kilogram are less important – the choice for the default values is based on roughly averaging existing market information. Another important issue to note is that in current practice, technology in general is not equipped to separate as many plastics type in an economically justified way. With these remarks in mind, exercises including analysis of in- or excluding plastics recycling in scenarios are mainly to be performed in order to analyse effects on recyclability rates rather than on end-of-life yields. Also, although the model is suited to analyse future developments in plastics recycling, for analysis of current end-of-life routes the weight percentage(s) of high-yield recoverable plastics in products will in general need to be set at zero.

In Table 29 it is shown that a distinction is made between the recovery percentages for the different types of plastics. For type 1 and 2 plastics, a default recovery percentage is assumed of 50%, whereas for type 3 plastics a 75% recovery percentage is assumed in the plastics recycling scenario. This distinction is made because for the relatively expensive type 3 plastics, recovery is relatively more worthwhile but also easier; in fact, the plastics are of type 3 because they can be well recovered, rather than the other way around.

In most default product material compositions, presented in section 5.3, only recoverable plastics of type 1 are included. Only in the case of CRT-based products, type 3 plastics are included as well. The reason for this is that in the latter type of products, housings are often made of large chunks of mono material plastics (such as ABS or PC). Since these plastics can be separated and collected in an efficient way due to relatively high volume and weight per separated part and the relatively good quality of these parts, a higher price for these plastics can be expected. In the other categories, plastics types are assumed to be more diverse, and of a relatively more diverse quality as well, and therefore categorised as type 1 plastics. However, in the scenario analysis presented in Chapter 6, scenarios are drawn that reflect the substitution of (a part of the) type 1 plastics with type 2 and 3 plastics.

Another important aspect to notice is that these default market parameters will in principle yield costs or revenues that should be regarded as gross values. Apart from logistics costs that are not included (according to Philips CE sources, return logistics costs in the Netherlands tend to be around € 0.10 per kg, with a small mark-up for bigger end-of-life appliances), also a number of location-specific overhead costs, but most of all profit margins for recyclers are not included. In theory this will lead to revenues that are at first sight on the high side, or costs that will appear very low. However, a number of considerations have led to the used procedure:

- By stripping cost and revenue parameters down to basic values without adding mark-ups subjective to time and/or location, insights obtained from the present analysis are not obscured by such subjective observations.

- The main purpose of the present analysis is to compare the relative impacts of various scenarios rather than to establish absolute economical and environmental
scores. Therefore the present accuracy of the default input values is regarded as sufficient; any improvement would only suit the purpose of using absolute figures for, for example, commercial objectives.

**Product design parameters**

At present, the PMRCM does not take any product design parameters such as unlocking or separability characteristics into account. Main reasons for this choice are the fact that for the moment these parameters are both hard to quantify and that no extensive research has yet been carried out how these parameters actually influence both end-of-life yields and material recycling efficiencies.

**Eco-efficiency scores**

Based on the absolute deviations from the default input parameters for a certain product that is analysed, the quotient 'change in material recycling efficiency' divided by 'change in cost or revenue' is calculated. By Stevels 187 this quotient is defined as the eco-efficiency of a product design change. It serves as an indicator where the highest environmental gain can be obtained at the cost of one monetary unit, in this case from an end-of-life perspective only: other life-cycle influences are not taken into account in this figure. Stevels argues that the way eco-efficiency should be calculated and used depends heavily on the reason what purpose the use of the eco-efficiency concept should serve (see for a further discussion section 9.4.9).

The discussion on the eco-efficiency results from the scenario analyses that will be presented in Chapter 6 will not commence until Chapter 7, once the results on both other performance indicators have been presented and discussed. In this dissertation, eco-efficiency should not be regarded as a performance indicator itself, although it is discussed briefly how eco-efficiency could be used as a means to interpret the effects on end-of-life yields and recyclability scores.

**5.2 Internal mathematics in the PMRCM**

In the previous sections the different elements of the PMRCM have been discussed. In this section the coherence of all elements of the model is discussed.

The mathematics of the PMRCM are based on a decision tree that determines which end-of-life processes will be applied to the different fractions of a product, based on real recycling processes as found in the Dutch recycling industry. In a very simplified way this is shown in Figure 29. In Appendix 1, the mathematical model that is the basis of the PMRCM is presented.

The oval at the top of the figure represents the whole product, consisting of magnetic materials, non-ferrous metals, noble metals, recoverable and non-recoverable plastics. The processes embedded in the PMRCM methodology assume that magnetic materials, recoverable plastics and non-ferrous metals are in any case recovered. For the remaining fraction, consisting of mainly non-recoverable plastics but including noble metals and especially copper, it is determined whether the embedded value is higher than the incineration costs of this rest fraction. This embedded value is calculated by first determining the gross smelter value, i.e. the intrinsic value of the copper and the noble metals in the fractions. Subsequently, the net smelter value is determined by subtracting the refining charges, the treatment costs, penalties and other overhead costs that are made to retrieve these valuable metals. If this a priori net smelter value outweighs the incineration costs, the rest fraction is sold to a copper smelter at a price equal to the a posteriori net smelter value. In practice, this happens when the Cu percentage is equal or higher than approximately 20%. In that case, the remaining materials in the rest fraction (mainly unrecoverable plastics) are co-processed cost-neutrally.

5.3 Evaluation of current (default) end-of-life scenarios

This section has two purposes. The first goal is to show how the PMRCM can be used to evaluate end-of-life scenarios. This is done using a number of product examples. These product examples are selected on the basis of the product category they belong to. As explained in the 'return characteristics' subsection in section 2.3, WEEE can be divided into four product categories. For each product category, a product is taken to feature as an example for that category. For each example product, a PMRCM analysis is given to reflect the default situation based on the default input parameters presented in section 5.1. The results that are thus derived are the basis for the second purpose.
of this section – to function as a basis for comparison of different end-of-life scenarios. In Chapter 6, a number of scenarios will be evaluated – scenarios that are drawn from quantifying those uncertainties discussed in Chapter 3. The results from these scenario analyses are compared to the default assessment done in this section in order to assess their relative impact on economical and environmental results.

The example products in the subsequent subsections are partly based on a Philips report on the eco-efficiency of recycling processes\textsuperscript{186}.

### 5.3.1 Metals dominated products

In Table 31 the default material composition for the example metals dominated product, in this case an audio mini system, is given. The material composition is translated to the input parameters for the PMRCM.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Weight percentage, material content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous metals</td>
<td>66%</td>
</tr>
<tr>
<td>Copper</td>
<td>6%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>6%</td>
</tr>
<tr>
<td>Recoverable plastics type 1</td>
<td>4%</td>
</tr>
<tr>
<td>Non-recoverable plastics + rest</td>
<td>18%</td>
</tr>
<tr>
<td>Gold content</td>
<td>80 ppm</td>
</tr>
<tr>
<td>Silver content</td>
<td>215 ppm</td>
</tr>
<tr>
<td>Palladium content</td>
<td>90 ppm</td>
</tr>
</tbody>
</table>

*Table 31: Input values for the example metals dominated product*

The results of the assessment with the PMRCM based on this default material composition, using the default input parameters presented in section 5.1 are given in Table 32.

<table>
<thead>
<tr>
<th>No plastics recycling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>yield of a shredding and separation oriented end-of-life scenario, excluding logistics:</td>
<td>69.9%</td>
</tr>
<tr>
<td>Weight-based recyclability score</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plastics recycling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>yield of a shredding and separation oriented end-of-life scenario, excluding logistics:</td>
<td>71.9%</td>
</tr>
<tr>
<td>Weight-based recyclability score</td>
<td></td>
</tr>
</tbody>
</table>

*Table 32: Default PMRCM results for the example metals dominated product*

### 5.3.2 Plastics dominated products

The default material composition for a plastics dominated product, translated to the input parameters for the PMRCM, is shown in Table 33.
<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Weight percentage, material content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous metals</td>
<td>34%</td>
</tr>
<tr>
<td>Copper</td>
<td>4%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0%</td>
</tr>
<tr>
<td>Recoverable plastics type 1</td>
<td>35%</td>
</tr>
<tr>
<td>Non-recoverable plastics + rest</td>
<td>27%</td>
</tr>
<tr>
<td>Gold content</td>
<td>8 ppm</td>
</tr>
<tr>
<td>Silver content</td>
<td>33 ppm</td>
</tr>
<tr>
<td>Palladium content</td>
<td>8 ppm</td>
</tr>
</tbody>
</table>

Table 33: Input values for the example plastics dominated product

The results of the assessment with the PMRCM based on this default material composition, using the default input parameters presented in section 5.1 are given in Table 34.

<table>
<thead>
<tr>
<th>No plastics recycling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield of a shredding and separation oriented end-of-life scenario, excluding logistics:</td>
<td>€ -0.24 per kg</td>
</tr>
<tr>
<td>Weight-based recyclability score</td>
<td>34.4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plastics recycling</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield of a shredding and separation oriented end-of-life scenario, excluding logistics:</td>
<td>€ -0.24 per kg</td>
</tr>
<tr>
<td>Weight-based recyclability score</td>
<td>51.9%</td>
</tr>
</tbody>
</table>

Table 34: Default PMRCM results for example plastics dominated product

5.3.3 Precious metals dominated products.

Although the precious metals dominated product category is a category with relatively little variety among products, it relatively difficult to decide on an 'average product' to represent this category. This is due to the wide variety of designs for the electronics within these products. Where for the other product categories this may also be the case, in the precious metals dominated products case the design of the electronics in the product is very much more important since precious metals are almost exclusively found in the electronics fraction. It will be shown later on in this dissertation that in particular the gold and palladium concentrations determine to a very large extent the economical performance of products in this category. Precious metals content analyses of various precious metals dominated products show gold and palladium concentrations that are far apart (also for cellular phones of similar age and functionality) and will consequently lead to considerable differences in economical performance. The difficulty of this issue is confirmed by Mirec, Netherlands' most renowned recycling company. The chosen default precious metals concentration for this product category should therefore be interpreted with care; other products in this product category may exhibit considerable higher or lower concentrations of precious metals, leading to considerable higher or lower economical results. However, based on available analysis results a default material composition was decided upon for a precious metal dominated product. Translated into PMRCM input parameters it is shown in Table 35.
The following table shows the weight percentage and material content for different input parameters:

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Weight percentage, material content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous metals</td>
<td>31%</td>
</tr>
<tr>
<td>Copper</td>
<td>26%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2%</td>
</tr>
<tr>
<td>Recoverable plastics type 1</td>
<td>6%</td>
</tr>
<tr>
<td>Non-recoverable plastics + rest</td>
<td>35%</td>
</tr>
<tr>
<td>Gold content</td>
<td>709 ppm</td>
</tr>
<tr>
<td>Silver content</td>
<td>1938 ppm</td>
</tr>
<tr>
<td>Palladium content</td>
<td>438 ppm</td>
</tr>
</tbody>
</table>

Table 35: Input values for the example precious metals dominated product

The results of the assessment with the PMRCM based on this default material composition, using the default input parameters presented in section 5.1 are given in Table 36.

<table>
<thead>
<tr>
<th>No plastics recycling</th>
<th>Yield of a shredding and separation oriented end-of-life scenario, excluding logistics: € 12.41 per kg</th>
<th>Weight-based recyclability score: 54.2%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics recycling</td>
<td>Yield of a shredding and separation oriented end-of-life scenario, excluding logistics: € 12.44 per kg</td>
<td>Weight-based recyclability score: 57.2%</td>
</tr>
</tbody>
</table>

Table 36: Default PMRCM results for the example precious metals dominated product

Depending on the type of product, the yield of a shredding and separation scenario for precious metal dominated products varies. For a car stereo set, the yield will be ca. € 0.20, and a walkman will yield a slightly higher yield due to a slightly higher precious metal content. A cellular phone may yield as much as € 2.30, including logistics.

5.3.4 CRT containing products

As explained at the beginning of this chapter, the PMRCM does not analyse disassembly. Disassembly however is a necessary step to process CRT containing products at the end-of-life. This is true because CRTs cannot be processed in mechanical processes.

To be able to analyse CRT containing products with the PMRCM, products in this product category are regarded as they would have no CRT meaning that the remainder of the product is regarded as the product itself - which is in essence true since the remainder will indeed be processed mechanically. The costs associated with the dismantling of the CRT can be calculated using regular disassembly analysis approach (matching occurring disassembly operations with standard disassembly times and multiplying the result with an appropriate labour rate). These disassembly costs can then be added to the economical results of the PMRCM to obtain total processing costs. In cases where the PMRCM is applied to individual product or product stream evaluations for which disassembly operations are applicable, an alternative (to using a disassembly
times database) is to adjust the default prices obtained for various material fractions. For instance, if a major plastic part such as a housing part is separated using disassembly before a product is further mechanically processed, and if this part is sold, an additional plastics type can be defined for this, with a default plastics price per kilogram from which the appropriate disassembly costs per kilogram have been subtracted. This way, the disassembly costs are included in the calculations without actually having to explicitly use additional calculation modules.

To obtain the default material composition for a product containing a picture tube, the breakdown from Table 11 is translated into the input parameters for the PMRCM, plus a percentage for glass. The result is given in Table 37.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Weight percentage, material content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous metals</td>
<td>6%</td>
</tr>
<tr>
<td>Copper</td>
<td>3%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1%</td>
</tr>
<tr>
<td>Recoverable plastics</td>
<td>15%</td>
</tr>
<tr>
<td>Non-recoverable plastics + rest</td>
<td>13%</td>
</tr>
<tr>
<td>Glass</td>
<td>62%</td>
</tr>
<tr>
<td>Gold content</td>
<td>15 ppm</td>
</tr>
<tr>
<td>Silver content</td>
<td>590 ppm</td>
</tr>
<tr>
<td>Palladium content</td>
<td>40 ppm</td>
</tr>
</tbody>
</table>

Table 37: Weight percentages example CRT containing product, including glass

Leaving out the glass fraction, and regarding the remainder as a separate product yield the following material breakdown:

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Weight percentage, material content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous metals</td>
<td>16%</td>
</tr>
<tr>
<td>Copper</td>
<td>8%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>3%</td>
</tr>
<tr>
<td>Recoverable plastics</td>
<td>39%</td>
</tr>
<tr>
<td>Non-recoverable plastics + rest</td>
<td>34%</td>
</tr>
<tr>
<td>Gold content</td>
<td>15 ppm</td>
</tr>
<tr>
<td>Silver content</td>
<td>590 ppm</td>
</tr>
<tr>
<td>Palladium content</td>
<td>40 ppm</td>
</tr>
</tbody>
</table>

Table 38: Input values for the example CRT containing product, without glass

The results of the assessment with the PMRCM based on this default material composition, using the default input parameters presented in section 5.1 are given in the next table.

188 Precious metals contents from Technical report Apparetaur
No plastics recycling
Yield of a shredding and separation oriented end-of-life scenario, excluding logistics: € 0.04 per kg
Weight-based recyclability score 24.4 %

Plastics recycling
Yield of a shredding and separation oriented end-of-life scenario, excluding logistics: € 0.21 per kg
Weight-based recyclability score 43.9 %

Table 39: Default PMRCM results for the example CRT containing product

5.3.5 Synthesis

In Table 40 the weight based recyclability scores and the end-of-life yields are summarized for the different product categories, based on a shredding and separation scenario.

<table>
<thead>
<tr>
<th>Product category</th>
<th>Recyclability score</th>
<th>End-of-life yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal dominated products</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Plastics dominated products</td>
<td>0/-</td>
<td>-</td>
</tr>
<tr>
<td>Precious metals dominated (miniaturized) products</td>
<td>0/+</td>
<td>++</td>
</tr>
<tr>
<td>Products originally containing a CRT, but with CRT removed</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 40: Overview of MRE and end-of-life yields for different product categories

The contents of table 40 need to be carefully interpreted, since a (partially) wrong conclusion is easily drawn. For example: one might argue that there exists a strong preference for metals dominated products over plastics dominated products. After all, metals dominated products result in a higher material recycling efficiency scores as well as in more favourable end-of-life yields. However, from a life cycle perspective it is not necessarily wise to choose metals over plastics for the same function. When other life cycle phases like raw materials extraction and refining, and manufacturing are included in the analysis, plastics might be preferred over metals anyway. For instance, according to the Dutch Ecoindicator method, the production of iron and steel score 20 mPt/kg or more, while the production of plastics score in general between 8 and 10 mPt/kg.

5.4 Environmentally Weighted Recycling Quotes

As discussed previously in section 2.4, both on a European Union level and also in several member states individually, take-back and recycling systems for electronic products are discussed. Until now, the required 'environmental performance' for electronic products has always been described using recycling quotes related to weight only (material recycling efficiency – MRE). Since the environmental load of various types of materials differs considerably and recycling itself has an environmental impact as well, this is an incorrect description from both a scientific and an environmental point of view. For this reason, a new concept has been developed to better describe the actual problem. The advantages of this new concept are the inclusion of the environmental burden of recy-
clling processes, clear quantification of the environmental losses and broad applications for determining the relation between product and end-of-life. This concept has been developed at Delft University of Technology and has been reported on in various publications\(^{89,190,191}\). The full concept is described in Huisman et al\(^{192}\). In the new concept the weight percentages of the material fractions of a product are weighed using ecoindicators as weighting coefficients. The result is transferred to a 0% to 100% scale. In the traditional approach, the weight percentages of the recycled material fractions are simply added to obtain the total weight based recyclability score for a product. In Appendix 5 the concept of Environmentally Weighted Recycling Quotes is further explained. In section 9.4 it is further discussed in what way EWRQ can be used for more meaningful descriptions of the environmental issues during the end-of-life of products.

Environmentally Weighted Recycling Quotes, renamed Quotes for Environmentally Weighted Recyclability (QWERTY) in 2001, are a serious improvement over weight-based recyclability scores as currently used in the PMRCM. Although the principle how to determine these quotes is clear, at the time of completion of this dissertation they are not fully developed yet for a large enough range of product categories. Also, it is yet unclear what database of environmental impact factors should be used for what application, although preliminary results\(^{192}\) indicate that the method is indifferent as to the choice of database. These are some of the arguments why further analysis using environmentally weighted recycling quotes is not yet done in this dissertation. However, in Appendix 5 the most up-to-date publication describing the full concept is included to provide the necessary background information. Another motivation is to stress the importance of this concept for the environmental assessment of end-of-life issues in the future.

5.5 Justification and limitations of the PMRCM

In Chapter 4 it has been shown that publicly available methodologies, approaches and tools for evaluating end-of-life scenarios are not, in a satisfactory way, suited for the goals in this dissertation. In the current chapter, it has been shown that the PMRCM does in fact fulfil the necessary conditions for independent input parameters and overall transparency of the method. However, these arguments by themselves do not nec-


essarily validate the use of the PMRCM throughout this dissertation. Additional argu-
ments are therefore brought forward here for justification.

- As explained at the beginning of this chapter, the origin of the PMRCM can be traced
back to a large European project, in which Siemens, a company well known for its
advanced policies regarding environmental issues including product take-back and
recycling issues, had a major role in the development of the tool. Also the inputs of
Philips, then owner of Mirec, contributed in the form of providing detailed informa-
tion about various material recycling processes. Opportunities for additional verifi-
cation with more recent developments in recycling technology in order to validate
the PMRCM have since then been extremely limited due to the changes in the rela-
tions between the various former project partners. However, based on communica-
tions over the past years with Mirec, no evidence was found to justify changes in the
mathematic structure used within the PMRCM. Moreover, at various (though sparse)
occasions where analysis results were communicated with Mirec, these results were
found to be in accordance with practical experiences.

- In 2001, a large portion of student graduation project\(^{167}\) carried out at TNO
Industry was devoted to comparing PMRCM results with the results of some of the
algorithms to be used in the next generation DFE software from TNO, which should
be regarded (or at least is supposed to become) the state-of-the-art in evaluating
product end-of-life issues. It turned out any differences between PMRCM and DFE
outcomes were relatively easily explainable and often originated from differing
assumptions. These findings support the supposition that the PMRCM still delivers
state-of-the-art results.

As with any model or mathematical structure however, there are some limitations to
the PMRCM as well, although most of them depend on the context in which the
PMRCM is used.

- As put forward before in this chapter, there is no disassembly module embedded in
the PMRCM. This prevents the analysis of shredding and separation scenarios versus
disassembly scenarios in one tool, and for example to determine break-even points
related to this issue. On the other hand, the non-presence of a disassembly module
is not experienced as an omission once the context is limited to shredding and sep-
oration scenarios only. It has also been pointed out previously that ample means are
available to perform additional disassembly analyses and to integrate these results
with results obtained through the PMRCM.

- In the PMRCM, no extensive use is made of specific data from for example copper
smelters or other outlet channels for various material streams. A database with
penalty elements, such as for example those listed in Table 9, could be included in
the PMRCM. In addition, the way such elements hamper the recovery of the main
materials, and the financial consequences thereof, could be modelled within the
PMRCM. Then, with a more elaborate set of input product parameters to include
specific information on contaminations in the product to be analysed, the true con-
sequences on the impacts of the presence of penalty elements would be possible to obtain. Similar extensions to the PMRCM could be made to include data on separability and unlocking characteristics of product parts and components, as will be discussed in section 6.3.2. There are two reasons however, which prevent these 'perceived' omissions from becoming a problem in the context of this dissertation. First of all, extending the scenario analysis (that will be presented in the next chapter) with complications of this nature (e.g. including an analysis of the consequences of the presence of penalty elements) will distract from the main issue under investigation which is researching the relative importance of the various external developments in relation to each other. Though the inclusion of more specific data would in theory give more accurate absolute results, this would in most cases have little influence on the relative differences.

The way that different plastics categories are included in the PMRCM is perhaps regarded as a limitation to the PMRCM. By assigning three 'general' categories (four if the non-recoverable plastics or waste fraction is included), rather than explicitly including data for specific plastics such as ABS or PC, it is left to the user to determine in which category a certain material fraction should be placed. This responsibility is perhaps perceived as a difficult one. However, this issue should not be regarded so much as a limitation of the PMRCM but rather as a limitation caused by the immaturity of secondary plastics markets, an issue discussed at various places throughout this dissertation.

In conclusion it can be stated that the main limitation of the PMRCM are not relevant within the context of this dissertation, as the limitations refer mainly to the accuracy of results and the truthfulness of the absolute data. As the current context is mainly of a relative nature, the limitations of the PMRCM hardly interfere with the purpose of this dissertation.

5.6 Conclusions

In this chapter a method has been introduced for evaluating end-of-life scenarios on their economical and their environmental performance. It has been explained which model parameters were included and why. For these model parameters, default values have been chosen that represent current end-of-life processing. Also, for four main product categories default material compositions have been chosen. With these default setting of market, process and product parameters, default end-of-life scenarios have been constructed resulting in default performance indicators. In the next chapter, alternative scenarios are drawn, partly based on the analysis of uncertainty factors presented in Chapter 3. These are compared to the default scenarios in order to analyse the differences in end-of-life yields and recyclability scores.
The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios
6. Scenario Analysis

In Chapters 2 and 3 it has been discussed which factors related to the end-of-life stage have a potentially significant influence on the environmental and economical performance of products during the end-of-life stage, and are therefore relevant to analyse. These factors could potentially develop in a way that they cause uncertainty when it comes to evaluating future end-of-life scenarios. So far, this identification process has been of a qualitative nature only. In this chapter the step is made from a qualitative to a quantitative analysis. To clarify this, in Figure 30 it is shown which parts of the analysis are of a qualitative or quantitative nature.

![Figure 30: Overview of the qualitative and quantitative analysis aspects](image)

Quantitative analysis of future developments for which only very limited empirical back up exists is a less than straightforward exercise. The fact that for a quantitative comparison of diverse developments such as technological and political ones on one or two single outputs (in this case end-of-life yield and weight-based recyclability) a common basis is required, makes it necessary, at times, to take a 'scientific shortcut'. Whereas for the quantitative assessment of individual developments (for example in technology) methods are proposed in literature (for example the Delphi method), the aggregation of results in such a way that they can be used for further calculations (i.e. the translation into model parameters of the same model) is quite problematic. Before the approach that was taken to deal with this issue is explained, the theoretically correct way to go about is set out in short, with the purpose of clarifying and backing up some of the assumptions and choices that had to be made.

The analysis of the effects that developments in the organisation of end-of-life infrastructures have on one of the future performance indicators can be explained by the next equation.
\[ \Delta I = \frac{\delta I}{\delta x_1} \Delta x_1 + \frac{\delta I}{\delta x_2} \Delta x_2 + \frac{\delta I}{\delta x_3} \Delta x_3 + \ldots \]

In this equation \( I \) is the performance indicator and the \( x_i \) are the parameters that affect the performance indicator, in the current context the input parameters for the PMRCM. The \( \delta I/\delta x_i \) are the elasticities, or the sensitivities of the performance indicator with respect to the input parameters, and the \( \Delta x_i \) are the actual changes in the input parameters. The elasticity times the change, \( \delta I/\delta x_i \times \Delta x_i \), is the actual effect of a change of input parameter \( x_i \) on the performance indicator, and is in the current analysis calculated as the effect of a scenario change.

Assuming the availability of a model like the PMRCM and a default setting of parameters as given in Chapter 5, determination of the elasticities is a straightforward mathematical exercise. In the current context it means the determination of the effect on both performance indicators, end-of-life yield and weight-based recyclability, of a change in the input parameters.

In addition, in order to perform scenario analysis, the \( \Delta x_i \) have to be decided upon rather than calculated. This step is considerably less straightforward. For a certain development, or rather scenario, two things are required:

- A translation of a ‘development’ into one or more relevant parameters of the PMRCM (choice of parameters)
- A decision on which delta (or deltas if more than one relevant parameter is applicable) best represents the development to be analysed (size of parameter change)

As for the first requirement, for some developments such as metal prices the translation into PRMCM input parameters is simple. For other developments however, such as better economies of scale or arising automated disassembly processes, the translation is less straightforward. This is particularly so when these developments have an effect on multiple input parameters. Still, choices and assumptions have been made in this chapter based on available literature and expert opinion.

As for the second requirement, it was determined, partly based upon the analyses on future developments presented in Chapter 3, what likely (or at least ‘imaginable’) developments can be ‘expected’, or better, what the \( \Delta x_i \) are, for every \( x_i \), that are relevant to analyse. To clarify this statement, assume that the cumulative probability that a change of \( \Delta x_i \) will happen to parameter \( x_i \) is normally distributed as depicted in Figure 31.
This means that whatever change in $x$, scores a cumulative probability of 50% can be regarded as 'most likely' to occur. Since the main objective of scenario analysis in this dissertation is to determine priorities for addressing, by business management, of uncertainty factors, it is relevant to assess, for the present range of uncertainties, scenarios that are equally likely to occur. In this respect it is regarded as useful to not only address scenarios that are most likely to occur, but also scenarios that are less likely to occur. To reach the objective stated, one preferably determines, for all input parameters that were translated from uncertainty developments, scenarios that are 'equally less likely to occur'. In order to be more exact than just playing around with words such as 'pretty likely', 'relatively unlikely' or even 'almost unlikely but still quite likely', this discussion is presented in order to provide a better basis for choosing these scenarios. In the following scenario analysis, for each input parameter it has been tried to pinpoint scenarios that have, in addition to the most likely scenario reflecting a cumulative probability of approximately 50%, a cumulative probability of approximately 25% and 75%. These scenarios are considered relevant for analysis as they do not represent best case or worst case scenarios – which are scenarios that for some purposes might be interesting to assess but will yield little 'feeling' for priority setting and are therefore regarded as not useful for answering the research questions in this dissertation – but rather scenarios that business has a reasonable chance of being faced with in the future.

A useful distinction can be made here between scenario analysis and uncertainty analysis. Whereas the analysis of uncertainty, in Chapter 3 defined as a qualitative expression of lack of information, in essence focuses on the way the relevant parameters to a model are distributed and uses the distributions to determine the way the output parameters of a model are distributed, scenario analysis in its presently used form adds an additional reasoning step: it investigates (in applicable cases only qualitatively) how the underlying developments can be reasonably expected to change, instead of the variety of parameters that might change because of these developments. This is exactly why methods such as Monte Carlo simulation (see section 3.2) of PMRCM input parameters, or perturbation methods (such as described in Sakai et al.\textsuperscript{193}) are not applied here, since these methods only address the uncertainty of individual model parameters and not the uncertainty associated with underlying scenario developments, having in most cases impacts

on multiple model parameters. In that sense, these methods are mathematically correct but provide little practical relevance. An additional argument can also be presented here: the ranking of importance of the different scenario developments is more important than assessing the absolute uncertainties of the individual developments themselves.

In conclusion, for reasons discussed above, in the subsequent scenario analysis for each uncertainty factor three scenarios are chosen.

- The average scenario reflects a 'normal' development of the applicable uncertainty factor, matching a cumulative probability of 50%. This scenario can therefore be regarded as the most likely development for this factor.
- The progressive scenario reflects a development matching a cumulative probability of 75% (assuming that scenarios with higher cumulative probabilities score better performance indicators — if not, the progressive scenario becomes the conservative scenario and vice versa). It should be regarded as reflecting a development that is financially more beneficial than the average scenario. This scenario is not necessarily a best-case scenario but rather a scenario that of all well-imaginable scenarios scores the best performance indicator.
- The conservative scenario reflects a development matching a cumulative probability of 25%, and shows relatively negative results.

Although scenarios could be constructed for different time horizons, the scenario chosen here will reflect in general developments that are likely in a 1-5 year period. Although the scope of this dissertation was stated to include the end-of-life of products that are currently designed, meaning that this end-of-life stage would occur up to 15-25 years from now, from the analysis of uncertainty factors in preceding chapters no evidence was found that would make it necessary to include and assess additional developments other than those relevant for a period of up to 5 years from now. An exception may be the analysis of technological developments, as in the Delphi study a time horizon was used spanning a few decades. However, in order to compare technological developments with economical and legislative ones, here also a similar time horizon of 5 years from now is used. It should be useful to note that, especially in the context of this dissertation, which is ultimately about directions and not precise figures, it is not considered relevant to appoint exact time horizons of all individual developments under consideration.

Though considerable attention is given above to the motivation of choosing average, progressive and conservative scenarios, this does not solve the problem itself. Instead, the problem has merely shifted from picking the right $\Delta x$, to determining a cumulative probability distribution that correctly represents 'the future'. In the further analyses, determination of cumulative probability distributions will be on the basis of expected importance in future end-of-life scenarios, expected likelihood of developments indeed taking place, and the ease of translating uncertainty factors into input variables. It should be noted though that for none of the input parameters, cumulative probability distributions are explicitly derived, simply because the data for doing so are just not there. Rather, this is implicitly done.
As said before, the results of the scenario analysis will be evaluated against the default situations presented in section 5.3 to assess their relative impact and importance. This will then function as a basis for drawing conclusions and recommendations for industry where to focus main attention, as presented in Chapter 8.

Since this chapter is supported by a large number of calculations, it is chosen to not include them all in the main body of this dissertation. References to relevant appendices will be made where appropriate.

6.1 Structure of this chapter

This chapter is structured in the following way. First a subdivision is made in scenarios per type of development. Based on the discussion of uncertainties related to internal and external uncertainty factors in sections 2.1 and 2.2, a selection is made of the factors that are believed to have a potential significant impact on future end-of-life scenarios. Like in Chapters 2 and 3, these are divided in

- Technological developments (6.2)
- Economical developments (6.3)
- Developments in economies of scale and return characteristics (6.4)
- Legislative developments (6.5)

Apart from these developments, also the influence of changing product material compositions is analysed. As briefly discussed in section 3.4, these are not caused by changing end-of-life related factors, but mainly instigated by technological innovations for the design and manufacturing stage, as well changing consumer behaviour, but also because of the design tradition inherent to a company. To investigate this issue, in section 6.6 a number of material substitution scenarios are drawn and subsequently analysed in order to assess their importance relative to each other.

In this chapter, for each type of development one or more scenario types are analysed, as shown in Table 41. Furthermore, for every scenario in Table 41 results are presented per main product category. As usual in this dissertation this means a that the results are presented for metals dominated products, plastics dominated products, precious metals dominated products and CRT based products.

<table>
<thead>
<tr>
<th>Division in type of development</th>
<th>Division in type of scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology developments</td>
<td>Technology improvement scenarios</td>
</tr>
<tr>
<td>Economical developments</td>
<td>Metal price change scenarios, Recoverable secondary plastics price scenarios, Incineration cost change scenarios (non-recoverable plastics cost scenarios), End-of-life processing cost scenarios</td>
</tr>
<tr>
<td>Economies of scale developments</td>
<td>Economies of scale scenarios</td>
</tr>
<tr>
<td>Legislative developments</td>
<td>Rate requirement scenarios (top-down legislative scenarios)</td>
</tr>
<tr>
<td></td>
<td>Bottom-up legislative scenarios</td>
</tr>
</tbody>
</table>

Table 41: Division in scenarios
6.2 Quantified scenarios for technological developments

Following the analysis in section 3.4 about uncertainties with respect to technological changes, a number of more or less likely developments are derived in sections 6.2.1 to 6.2.3.

6.2.1 Developments in sorting and handling technologies

As argued in section 3.4.1, developments in sorting and handling technologies are assumed to be incorporated in either the effects of improved economies of scale, or in the effects of the implementation of sophisticated automated disassembly technologies, and will therefore not be investigated as such.

6.2.2 Developments in disassembly technologies

Developments in disassembly are mainly related to either manual or automated disassembly. As for manual disassembly, fluctuation in the labour costs needed to do so have not been researched. One reason is the fact that the main focus in this dissertation is on mechanical recycling, and secondly, in Western Europe these costs are not likely to fluctuate significantly. For specific disassembly operations such as copper wiring stripping in third world countries it may relevant to analyse labour costs, but these are outside the scope of this dissertation.

Results from the Delphi study as presented in section 3.4.2 have shown that a significant number of panel members think that economical feasibility of automated disassembly is likely in the next decade. If 'economical feasibility of automated disassembly systems' in this context can be translated as 'being competitive with shredding and separation technologies' this means that the disassembly costs could be brought down to a level as low as the costs for shredding and separation technologies. Since the default shredding and separation costs were set in the previous chapter at € 0.17, it can be argued that disassembly costs for the applicable product categories can be brought down to this level or below. Based on this reasoning, scenarios with disassembly costs as low as € 0.12-0.25 instead of € 0.50 per minute are relevant to investigate for future applications.

6.2.3 Developments in shredding and separation technologies

In this section it will be discussed to what extent developments in shredding and separation technologies can be translated in parameter changes that will affect PMRCM results. In practice it will turn out that this translation is everything but straightforward. Nevertheless, for the purpose of scenario analysis, and with the aim in mind that the first goal is comparison with other developments, scenarios can be drawn relatively easily for metals because of the way default parameters are set. For plastics, though results are derived in a similar way, the advantage is less present since default values were set in a more speculative way as was explained in Chapter 5.
Recovery percentages

It has been stated before in this dissertation that the recovery of metals, in particular non-ferrous and precious metals, is an important economical driver for shredding and separation. Therefore it is to be expected that technological improvements in this kind of technology will focus on the improvement of metal recovery percentages, and on improvements of the grade of the recovered material fractions. Such improvements can for example be achieved by increasing the performance of the suction power of air classifiers as this can be regarded as one of the main determinants of the recovery percentage. But in this context it is avoided to discuss the technicalities of such developments in detail, because the underlying principle is in essence quite straightforward: the performance of regardless which shedding and separation process is in principle mainly a question of investment effort. With higher financial efforts, higher recovery percentages that can be obtained, and also the higher the purity grades of the recovered material. From this perspective it is more relevant to make an assessment of what is or could be the performance of state-of-the-art shredding and separation technology rather than to investigate the technical specifications of such technology. The logic of this reasoning is supported by the fact that the performance of the processes is reflected in the PMRCM by a single parameter (for every relevant material): the recovery percentage. So, scenario analysis on developments in shredding and separation technology should in fact only be focused on these recovery percentages. That is, given a fixed material input stream. Economies of scale and the ensemble issue theoretically and also practically have a considerable impact on the recovery grades of materials. For example, mixing copper rich streams with streams that contain less copper will have a negative effect on the recovery percentage of copper, given the fact that the same processing steps are used. This issue will be dealt with later, in section 6.4.

The question that remains to be answered is the magnitude of possible future improvements in the recovery percentage — for example whether an improvement of 1% is likely to occur per year or per decade. To quantify the matter to such an extent and to be able to back up results with either empirical or theoretical data, a large amount of research would be necessary. On the other hand, based upon the limited insights currently available, a number of remarks can be made. First of all, it is likely that future recovery percentages will be at least as good as current percentages. No developments can be identified that would lead stakeholders in the end-of-life stage to accept lower percentages, whereas on the other hand several (legislative) incentives exist for trying to improve them. This leads to the choice that for the conservative scenario a zero percent point increase in the recovery percentage is assumed. Since the current default recovery percentages for most relevant materials are already 90% or higher, 1 and 2 percent point improvements are assumed to be logical choices for the average and the progressive scenarios, respectively. The exceptions in this case are the scenarios for aluminium, since aluminium has a relatively low default recovery percentage of 80%. Because of this fact, and because it is expected that aluminium recovery technology will see improvements instigated by the automotive industry (because of increased application of light weight materials such as aluminium) for the average and progressive scenarios improvements of 2% and 4% are suggested.
As for plastics, as said two default recovery percentages are used in the present analysis. Scenarios without plastics recycling have a default setting of 0%, whereas scenarios with plastics recycling have a default setting of the recovery grade of plastics of 50% for type 1 and 2 recoverable plastics, and 75% for type 3 recoverable plastics. The drawing of scenarios for plastics recovery percentages is even less straightforward than for metals. First of all, plastics as such is a term representing a wide range of different plastics, all with their own characteristics. Secondly, the choice of separation technique for plastics is far less obvious that for metals. Apart from the choice what should be the best separation technology for a particular kind of plastics, the chance that this plastic will actually be processed using that technology is small, since this would mean a huge number of different techniques employed for different types of plastics. In practice, if plastics are processed at all, the technology employed will be the one of, at best, a limited number of available ones since it is unlikely that any recycling facility has a large number of separation technologies at its disposal. Another reason for the speculative nature of predicting future recovery percentages of recovery percentages for plastics compared to those of metals is the fact that for obvious reasons it is easier to draw a scenario based on a default parameter setting of 95% than of 50% — in the latter case simply more possibilities exist. Besides, the 50% and 75% values are set in way that they are assumed to reflect the average performance of a number of separation technologies, whereas the recovery percentages for metals have been determined in practice for a specific metal and are therefore more reliable default values.

**Scenario analysis for recovery percentages**

As discussed in the previous sections, the choices for the conservative, average, and progressive scenarios for all relevant metals except aluminium show an increase of 0, 1 and 2 percent points, respectively. For aluminium, the scenarios account for changes of 0, 2, and 4 percent points. For type 1 plastics, the conservative, average, and progressive scenarios show increases of 0, 10, and 20 percent points. Scenarios for recovery percentages for type 3 plastics exhibit increases of 0, 5, and 15 percent points. However, since in the default situation no type 3 plastics are present in the example products (see Chapter 5), scenarios that only exhibit changes in recovery percentages for type 3 plastics have no influence on the performance indicators. However, further in this chapter when economies of scale and legislative scenarios are drawn in which the substitution of type 3 plastics are included, these changes in recovery percentages do play a role and are therefore included. In Table 42 all applicable scenarios for recovery percentages are enumerated.
<table>
<thead>
<tr>
<th>Material</th>
<th>Default recovery percentage</th>
<th>Progressive scenario recovery percentage</th>
<th>Average scenario recovery percentage</th>
<th>Conservative scenario recovery percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>95%</td>
<td>97%</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>80%</td>
<td>84%</td>
<td>82%</td>
<td>80%</td>
</tr>
<tr>
<td>Gold</td>
<td>95%</td>
<td>97%</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>Silver</td>
<td>90%</td>
<td>92%</td>
<td>91%</td>
<td>90%</td>
</tr>
<tr>
<td>Palladium</td>
<td>92%</td>
<td>94%</td>
<td>93%</td>
<td>92%</td>
</tr>
<tr>
<td>Ferrous metals</td>
<td>90%</td>
<td>92%</td>
<td>91%</td>
<td>90%</td>
</tr>
<tr>
<td>Plastics type 1</td>
<td>50%</td>
<td>70%</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>Plastics type 2</td>
<td>50%</td>
<td>70%</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>Plastics type 3</td>
<td>75%</td>
<td>90%</td>
<td>80%</td>
<td>75%</td>
</tr>
</tbody>
</table>

Table 42: Scenario analysis for recovery percentages

Scenario analyses for grades

As far as recovery grades are concerned, in the PMRCM the default values for copper, gold, silver and palladium are set at 100% as is in accordance with current state-of-the-art technology. For iron and aluminium, the default values are set at 95% and 90%, respectively. To determine likely scenario changes for these input parameters, similar reasoning can be followed as is done in the previous section for recovery percentages. This leads to setting the conservative, average and progressive scenario values at 0, 1 and 2 percent points for both metals. For plastics, the default value for the recovery grade is set at 85%. For previously stated reasons such as plastics being a non homogenous group of materials and the dependence on available separation technologies, in the scenario analyses this parameter is increased with 0%, 5% and 10% for the conservative, average and progressive scenarios, purely on a speculative basis. In Table 43 all applicable scenarios for recovery grades are enumerated.

<table>
<thead>
<tr>
<th>Material</th>
<th>Default recovery grade</th>
<th>Progressive scenario recovery grade</th>
<th>Average scenario recovery grade</th>
<th>Conservative scenario recovery grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>100%</td>
<td>92%</td>
<td>91%</td>
<td>Scenario analysis not relevant</td>
</tr>
<tr>
<td>Aluminium</td>
<td>90%</td>
<td>92%</td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>Gold</td>
<td>100%</td>
<td>97%</td>
<td></td>
<td>Scenario analysis not relevant</td>
</tr>
<tr>
<td>Silver</td>
<td>100%</td>
<td>97%</td>
<td></td>
<td>Scenario analysis not relevant</td>
</tr>
<tr>
<td>Palladium</td>
<td>100%</td>
<td>97%</td>
<td></td>
<td>Scenario analysis not relevant</td>
</tr>
<tr>
<td>Ferrous metals</td>
<td>95%</td>
<td>97%</td>
<td>96%</td>
<td>95%</td>
</tr>
<tr>
<td>Plastics type 1</td>
<td>85%</td>
<td>95%</td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td>Plastics type 2</td>
<td>85%</td>
<td>95%</td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td>Plastics type 3</td>
<td>85%</td>
<td>95%</td>
<td>90%</td>
<td>85%</td>
</tr>
</tbody>
</table>

Table 43: Scenario analysis for recovery grades
6.3 Scenarios for economical developments

Following the analysis in section 3.5 about uncertainty with respect to economical changes, this section deals primarily with scenarios reflecting developments in market prices for secondary materials. Also, scenarios for incineration costs incurred for the non-recoverable rest fraction are drawn. Finally, scenarios for end-of-life processing costs are drawn.

6.3.1 Scenarios for metal prices

For a given product, the end-of-life yield depends heavily on the prices that material fractions yield after material processing. Traditionally, especially metals are both relatively easily separated from discarded products and yield the highest revenues. This is especially true for consumer electronics, as they contain printed wiring boards (PWBs), which in turn contain valuable precious metals. Precious metals are specifically found in small devices like integrated circuits (ICs), used in miniaturized products. In the conventional determination of end-of-life costs and revenues there has been hardly attention for investigating the influences of fluctuations in material prices on the total end-of-life yields. Using scenario analysis based upon PMRCM calculations it is easy to make these influences visible.

Below, changes in the market prices of the most important metals will be examined.

Gold

In section 3.5 it has been shown that over the past decade, the gold price has slightly decreased. Also, for short-term predictions, fluctuations of up to 5% (progressive or conservative) are likely to occur. For long-term prediction, i.e. several years, the consequences of price decreases of 10% to 15% are relevant to analyse. Based on these observations, it is chosen to assume for the average scenario a gold price decrease of 5%. The conservative scenario is based on a decrease of 15%, while the progressive scenario exhibits an increase of 15%.

<table>
<thead>
<tr>
<th>Material price scenario</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive gold price scenario</td>
<td>% increase in gold price</td>
</tr>
<tr>
<td>Average gold price scenario</td>
<td>5 % decrease in gold price</td>
</tr>
<tr>
<td>Conservative gold price scenario</td>
<td>15% decrease in gold price</td>
</tr>
</tbody>
</table>

Silver

In Chapter 3, silver prices were found to show comparable fluctuations to the gold price. On the other hand, the silver price did not see a slight downward slope as the gold price. Therefore, the average scenario for the silver price contains no fluctuations in the current analysis. Progressive and conservative scenarios exhibit changes of plus and minus 5%.
<table>
<thead>
<tr>
<th>Material price scenario</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive silver price scenario</td>
<td>5% increase in silver price</td>
</tr>
<tr>
<td>Average silver price scenario</td>
<td>No change in silver price</td>
</tr>
<tr>
<td>Conservative silver price scenario</td>
<td>5% decrease in silver price</td>
</tr>
</tbody>
</table>

**Palladium**

Palladium prices were found to exhibit relatively large fluctuations compared to other precious metals. Even on a yearly basis, fluctuations of more than 10%, and even price increases of more than 25% are likely to happen. From 1997 to 1998, a price increase of 60% even occurred. For these reasons, apart from small fluctuations, also large fluctuations need to be examined. For the current scenario analysis, a 15% increase in the palladium price is chosen as the average scenario, with 5% and 50% increases as the conservative and the progressive scenarios, respectively.

<table>
<thead>
<tr>
<th>Material price scenario</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive palladium price scenario</td>
<td>50% increase in palladium price</td>
</tr>
<tr>
<td>Average palladium price scenario</td>
<td>15% increase in palladium price</td>
</tr>
<tr>
<td>Conservative palladium price scenario</td>
<td>5% increase in palladium price</td>
</tr>
</tbody>
</table>

**Copper**

Examination of the copper prices in the past decade as done in Chapter 3 shows that the copper prices does fluctuate more than the gold and silver price, but is less uncertain than the palladium price. Also, whereas the palladium price exhibits a basically upward motion, the copper price has seen both increases and decreases in the past years, where yearly changes of 25% were no exception, both in progressive and negative direction. This is why the progressive and conservative scenario will exhibit a 25% increase and decrease, respectively. The average scenario is set at a decrease of 5% because the copper price has seen a predominantly downward slope in the past 5 years.

<table>
<thead>
<tr>
<th>Material price scenario</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive copper price scenario</td>
<td>25% increase in copper price</td>
</tr>
<tr>
<td>Average copper price scenario</td>
<td>5% decrease in copper price</td>
</tr>
<tr>
<td>Conservative copper price scenario</td>
<td>25% decrease in copper price</td>
</tr>
</tbody>
</table>

**Aluminium**

The analysis in Chapter 3 has shown that the fluctuation of the aluminium price in the past decade are similar to those of the copper price. Therefore, the same changes are examined here as likely scenarios.
<table>
<thead>
<tr>
<th>Material price scenario</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive aluminium price scenario</td>
<td>25% increase in aluminium price</td>
</tr>
<tr>
<td>Average aluminium price scenario</td>
<td>5% decrease in aluminium price</td>
</tr>
<tr>
<td>Conservative aluminium price scenario</td>
<td>25% decrease in aluminium price</td>
</tr>
</tbody>
</table>

6.3.2 Scenarios for secondary plastics prices

In Chap. 5 has been explained that the category plastics was differentiated in 4 categories:
- Plastics of type 1 with a default yield of € -0.10 per kg
- Plastics of type 2 with a default yield of € 0.12 per kg
- Plastics of type 3 with a default yield of € 0.75 per kg
- Non-recoverable plastics with a default yield of € -0.12 per kg,
where the latter category is principally the waste fraction, and where the cost of € 0.12 is the incineration cost. It has also been explained that extension of the number of plastics types, with different associated prices if appropriate, is easily implemented in the PMRCM.

It has been pointed out in section 3.5.3 that these yields cannot be based on actual price developments in secondary plastics markets, partly due to the immaturity of such markets as a consequence of fluctuating supply and demand, and due to the large variety of different plastics. Instead, default values have been determined based on a limited number of observations and expert opinions. Scenarios for the development of secondary plastics prices have been drawn in a similar way. Although it is reasonable to assume that prices for secondary plastics are related to both prices for oil and natural gas, as well as to virgin plastics production, the immaturity of the secondary plastics markets and the consequences thereof are assumed to be the decisive factor in most cases. Therefore, no analysis was made of oil, gas, and virgin plastics production and prices. Since the default values as given are above are a mere indication of price for different categories themselves, it suffices here to draw progressive, average and conservative scenarios here in straightforward way as done below, based on available bandwidth resulting from the way price categories are chosen.

Another remark refers to the inclusion in the plastics price scenarios of additional cost incurred in the plastics recovery process. Such costs could be resulting from for example bad unlocking properties, the presence of toxic substances such as flame retardants or the presence of other price decreasing additives. It should be noted that in the present form of the PMRCM, these costs are not explicitly included in the calculations. Main argument for this is, again, to compare different end-of-life developments without unnecessarily complicating the default scenarios. However, it is useful to know that if the PMRCM were to be used for a more accurate, detailed evaluation of individual products or product streams, additional costs as indicated below can be included in the analysis by assigning appropriate values to the input plastics prices.

194 Boks, C. and Stevels, A. Maturing markets for recycled plastics from WEEE: An elaboration on the consequences for the evaluation of future end-of-life scenarios. Ecodesign 2001, December 12-15, Tokyo, Japan
For type 1 plastics, the bandwidth is between € −0.12 and € 0.00, under the condition that type 1 plastics are plastics that do incur costs, but less than those incurred as a waste fraction. Hence the following scenarios have been drawn:

<table>
<thead>
<tr>
<th>Secondary plastics cost scenario</th>
<th>Price under the assumed scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 progressive scenario</td>
<td>€ 0.00</td>
</tr>
<tr>
<td>Type 1 average scenario</td>
<td>€ −0.05</td>
</tr>
<tr>
<td>Type 1 conservative scenario</td>
<td>€ −0.10</td>
</tr>
</tbody>
</table>

In the default situation no type 2 or 3 plastics are present in the example products, scenarios that only exhibit changes in the type 2 and 3 plastics prices have no influence on the performance indicators. A similar situation exists with scenarios for plastics recovery percentages, as was explained in section 6.2.3. Like in that case, scenarios are drawn here nevertheless since further in this chapter these scenarios are used in economies of scale and legislative scenarios.

For type 2 plastics, the bandwidth is between € 0.00 and € 0.75, leading to the following scenarios:

<table>
<thead>
<tr>
<th>Secondary plastics cost scenario</th>
<th>Price under the assumed scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 2 progressive scenario</td>
<td>€ 0.50</td>
</tr>
<tr>
<td>Type 2 average scenario</td>
<td>€ 0.25</td>
</tr>
<tr>
<td>Type 2 conservative scenario</td>
<td>€ 0.12</td>
</tr>
</tbody>
</table>

For type 3 plastics, the following scenarios are assumed (like above, no price decreases are considered – in those cases the plastics would simply fall in a category of a lesser type:

<table>
<thead>
<tr>
<th>Secondary plastics cost scenario</th>
<th>Price under the assumed scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 3 progressive scenario</td>
<td>€ 2.50</td>
</tr>
<tr>
<td>Type 3 average scenario</td>
<td>€ 1.25</td>
</tr>
<tr>
<td>Type 3 conservative scenario</td>
<td>€ 0.75</td>
</tr>
</tbody>
</table>

Clearly, a type 3 progressive scenario implies a well-developed market for these kinds of plastics and may be unlikely, but is nevertheless included to assess its effects in comparison with other scenarios.

For non-recoverable plastics, scenarios are drawn that exhibit cost increases. Because, as stated, the non-recoverable plastics fraction is essentially a waste fraction, these cost developments can also be regarded as incineration cost developments. The conservative scenario, which for all scenarios discussed here reflects little change compared to the current situation, in this case assumes the cost to be constant. The other scenarios exhibit cost increases since historical developments learn that incineration costs will probably be on the increase in the years to come, for example because of increasing legislation on the purification of incineration plant exhausts. Therefore, in the progressive scenario it is assumed that these costs will increase considerably.
<table>
<thead>
<tr>
<th>Non-recoverable plastics cost scenario</th>
<th>Price under the assumed scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-recoverable plastics progressive scenario</td>
<td>€ -0.50</td>
</tr>
<tr>
<td>Non-recoverable plastics average scenario</td>
<td>€ -0.25</td>
</tr>
<tr>
<td>Non-recoverable plastics conservative scenario</td>
<td>€ -0.12</td>
</tr>
</tbody>
</table>

In addition, scenarios are drawn that combine price developments recoverable type I and non-recoverable plastics. Although there is no clear evidence for this, some correlation between the costs or yields incurred for the various types is to be expected, since favourable (or less favourable) conditions for a single plastics type market are likely to also affect the markets for the other plastics types.

<table>
<thead>
<tr>
<th>Combined plastics price/cost scenario</th>
<th>Includes the following partial scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined progressive scenario low and high costs plastics only</td>
<td>Progressive scenarios for type I and non-recoverable plastics only</td>
</tr>
<tr>
<td>Combined average scenario low and high costs plastics only</td>
<td>Average scenarios for type I and non-recoverable plastics only</td>
</tr>
</tbody>
</table>

### 6.3.3 Scenarios for end-of-life processing costs

In section 3.5 the developments influencing end-of-life processing costs were discussed. It was concluded that little data is available on the (future) developments of end-of-life processing costs, but that it is reasonable to expect that end-of-life processing costs (again, being the costs of the actual mechanical processing itself rather than the total end-of-life costs) will decrease because of technology improvements, favourable economies of scale and better outlet channels for secondary materials. Also, competition could become a price-decreasing factor.

Based on this reasoning, for the average scenario a 20% reduction of processing costs is investigated. The progressive scenario will examine a 50% reduction of processing costs, a number that could become likely if new technologies such as automated and active disassembly do indeed yield the efficiency that researchers hope they will do.

On the other hand, in section 3.5 it was also addressed that cost increasing effects can be anticipated, for example related to stricter specifications from outlet channels leading to the necessity to implement expensive, more sophisticated technology. To account for developments like these, for the conservative scenario a processing cost increase of 15% is assumed.

<table>
<thead>
<tr>
<th>Processing cost scenarios</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive processing cost scenario</td>
<td>50% reduction in processing costs</td>
</tr>
<tr>
<td>Average processing cost scenario</td>
<td>20% reduction in processing costs</td>
</tr>
<tr>
<td>Conservative processing cost scenario</td>
<td>15% increase in processing costs</td>
</tr>
</tbody>
</table>
6.4 Scenarios for developments in economies of scale and return logistics

In section 3.5 the uncertainties associated with return characteristics, economies of scale and return logistics were discussed. In the same section it was concluded that scenarios reflecting these uncertainties principally have an effect on three types of PMRCM parameters:

- Processing costs
- Recovery percentages and grades, in particular those of plastics
- Secondary market prices, in particular those of plastics

Also, some other effects are to be expected in the recovery percentages and grades of metals, these will however be relatively small since the room for improvement is small here. Also, the effects of changes in these parameters on the performance indicators are relatively small compared to for example those of changing processing costs.

The scenarios reflecting developments in economies of scale (EOSS) are drawn using the single parameter change scenarios drawn in the previous subsections of Chapter 6, resulting in scenarios exhibiting simultaneous parameter changes for the applicable PMRCM input parameters. For the effects on plastics prices, use was made of the combined plastics prices scenarios rather than scenarios affecting only one plastics type.

In EOSS 1, the most favourable situation is reflected, which means that for all applicable parameters progressive scenarios are drawn.

<table>
<thead>
<tr>
<th>Economies of scale scenarios (EOSS)</th>
<th>Effect on processing costs</th>
<th>Effect on plastics recovery percentages and grades</th>
<th>Effects on plastics prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOS 1</td>
<td>Progressive</td>
<td>Progressive</td>
<td>Progressive</td>
</tr>
</tbody>
</table>

In EOSS 2.1-3, average scenarios are drawn, but with still one parameter reflecting a progressive development. These scenarios are applicable in the case where economies of scale might have an effect especially on one of the parameters involved.

<table>
<thead>
<tr>
<th>Economies of scale scenarios (EOSS)</th>
<th>Effect on processing costs</th>
<th>Effect on plastics recovery percentages and grades</th>
<th>Effects on plastics prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOS 2.1</td>
<td>Progressive</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>EOS 2.2</td>
<td>Average</td>
<td>Progressive</td>
<td>Average</td>
</tr>
<tr>
<td>EOS 2.3</td>
<td>Average</td>
<td>Average</td>
<td>Progressive</td>
</tr>
</tbody>
</table>

Scenario 3 reflects a situation where economies of scale will develop in a relatively steady way, exhibiting average developments in all parameters involved. Similarly, scenario 4 exhibits conservative developments.

<table>
<thead>
<tr>
<th>Economies of scale scenarios (EOSS)</th>
<th>Effect on processing costs</th>
<th>Effect on plastics recovery percentages and grades</th>
<th>Effects on plastics prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOS 3</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>EOS 4</td>
<td>Conservative</td>
<td>Conservative</td>
<td>Conservative</td>
</tr>
</tbody>
</table>
Since economies of scale are expected to improve rather than worsen, scenarios exhibiting conservative developments may well be less likely than those exhibiting average developments. Still, scenario 4 is included to assess its impact compared to other scenarios drawn in this dissertation.

The economies-of-scale related scenarios drawn so far do not assume any changes in product compositions. However, it has been argued before that increased yields from processing secondary plastics will stimulate the use of such plastics. Therefore a number of scenarios are drawn as well that, in addition to the parameter changes in the scenarios drawn above, assume the substitution of a percentage of the non-recoverable plastics used in the default examples into type 3 plastics. This percentage depends on the type of effect on plastics prices assumed in the previous scenarios: for a progressive scenario it is assumed that 50% of the weight of the non-recoverable plastics fraction is changed into type 3 plastics, for the average scenario this percentage is 25%, and for the conservative scenario the percentage is 0% since under this scenario the plastics prices remain at their default values and no positive effect from this on the use of type 3 plastics can be expected.

<table>
<thead>
<tr>
<th>Economies of scale scenarios (EOSS)</th>
<th>Effect on processing costs, plastics recovery percentages and grades, and plastics prices</th>
<th>Percentage of type 3 plastics substituted for non-recoverable plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOSS 1a</td>
<td>Like in previous scenarios</td>
<td>50%</td>
</tr>
<tr>
<td>EOSS 2.1a</td>
<td>Like in previous scenarios</td>
<td>25%</td>
</tr>
<tr>
<td>EOSS 2.2a</td>
<td>Like in previous scenarios</td>
<td>25%</td>
</tr>
<tr>
<td>EOSS 2.3a</td>
<td>Like in previous scenarios</td>
<td>50%</td>
</tr>
<tr>
<td>EOSS 3a</td>
<td>Like in previous scenarios</td>
<td>25%</td>
</tr>
<tr>
<td>EOSS 4a</td>
<td>Like in previous scenarios</td>
<td>0% —— this scenario is the same as EOSS 4</td>
</tr>
</tbody>
</table>

6.5 Quantification of legislative developments

In the context of this dissertation, two types of scenarios are drawn that address the quantification of uncertainty related to legislative developments. The first approach way focuses in particular on recyclability targets and is referred to as addressing top-down legislative scenarios. This term is used because in this case, the starting points are the (proposed) recovery rates according to (draft) legislation; from there it is investigated which parameters could or should change in a way that these rates are attained.

The second approach focuses on effects that legislation might have on end-of-life systems in more general terms. Here, a number of effects that can be expected from developing legislation are combined into so-called bottom-up scenarios.

It should be clear that for the current context, scenarios are drawn on a what-if basis. Further applications could include a reverse approach, i.e. to determine what would be wise scenarios from a legislation point of view, given feasibility of such legislation. That however is an application of the current methodology rather than an element of the
methodology itself. In section 9.4.10 further research directions are suggested to explore this application.

6.5.1 Rate requirement scenarios (top-down legislative scenarios)

The scenarios that are drawn in this subsection to address the quantification of uncertainty related to legislative developments, focus on one issue in particular: recyclability targets. To incorporate future expected recyclability targets in legislative scenarios, a type of back-casting approach is taken contrary to most other cases. First of all it is observed what the level for the performance indicators (in particular the recyclability score) should be in order to meet proposed recyclability targets, and next it is analysed in what way the PMRCM input parameters should change in order to meet this level. In the other cases of scenario drawing, first it is assumed in what way the parameters are likely to change before the effects on the performance indicators are calculated. But with both approaches, scenarios are drawn that can be regarded as similar in likelihood.

The approach taken in this section is to come up with scenarios using a combination of an iterative trial and error approach and expert opinion. To clarify this statement: it is the kind of approach one uses to produce a 1000 calories diet: an absolute optimum is not the goal since the possibilities are almost unlimited and this would require a mathematical exercise that is not in proportion to the objective, rather an acceptable combination of meal possibilities that reasonably satisfies both the appetite and the calorie limit. In the current context, through taking on assumptions, assessing their feasibility, checking the effects on the performance indicators and adjusting necessary parameters it is tried to draw the most feasible scenarios ensuring meeting proposed recyclability rates.

In the final draft of the EU WEEE legislation\textsuperscript{195}, for products recovery and recyclability percentages are proposed as being required by December 2005 at the latest. Per product category, both recovery and recyclability targets are proposed. The distinction between recovery and recyclability is not yet unambiguously defined, but for the current context the recyclability percentages as requested by the draft legislation will be used as guide for the following analysis, and will be assumed to match the definition for recyclability given in this dissertation and which is calculated by the PMRCM. In Table 9 it is shown how this translates to the requirements for the recyclability percentages for the default products that are representative of the four main product categories throughout this dissertation. Here it assumed that metals and plastics dominated products as well as CRT based products are mainly to be found in WEEE category 4 (Consumer equipment) and precious metals dominated products in WEEE category 3 (IT & Telecommunication equipment).

\textsuperscript{195} can be obtained via http://europa.eu.int
<table>
<thead>
<tr>
<th>Main product category</th>
<th>WEEE category</th>
<th>Recovery requirement</th>
<th>Recyclability requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals dominated products</td>
<td>4</td>
<td>85%</td>
<td>70%</td>
</tr>
<tr>
<td>Plastics dominated products</td>
<td>4</td>
<td>85%</td>
<td>70%</td>
</tr>
<tr>
<td>Precious metals dominated products</td>
<td>3</td>
<td>85%</td>
<td>70%</td>
</tr>
<tr>
<td>CRT based products</td>
<td>4</td>
<td>80%</td>
<td>75%</td>
</tr>
</tbody>
</table>

This means that for each of these products, future scenarios can be drawn that will represent ways to meet the proposed targets.

In each of the following calculations a plastics recycling scenario will be assumed. The main reason for this is that for all main product categories except for metals dominated products, the plastics content is already higher than 100% minus the proposed targets, so it is evident that meeting the targets will at least require some sort of plastics recycling.

It should be noted that all scenarios in this section are drawn without explicitly taking the life-cycle into account. This means that scenarios do not necessarily represent an environmental improvement from a full life cycle perspective, even when they appear to do so from an end-of-life perspective only. In section 8.2 an example is included which is illustrative for this situation.

**Metals dominated products**

In the default scenario pointed out in Chapter 5, a weight-based recyclability score of 69.9% is already achieved. This means that any current or future legal requirements to attain proposed recyclability scores for this product category are unnecessary. Moreover, the recyclability score for metals dominated products might even improve without such incentives. For example, autonomous improvements in processing costs, material (in particular plastics) prices and/or economies of scale are likely to lead to improved recyclability scores (and economical performance) for metals dominated products as well, assumed that the processing of these products are part of the same end-of-life infrastructure.

**Plastics dominated products**

In the default scenario, a recyclability score of 34.4% is achieved for a scenario without plastics recycling, and 51.9% for a scenario with plastics recycling. In order to attain the required 70%, a number of scenarios can be drawn.

- Substituting non-recoverable plastics by any material contributing to recyclability. In the default material composition for plastics dominated products, 27% of non-recoverable plastics are assumed to be present. Since not every kilogram of material does contribute equally to recyclability due to differences in recovery grades and percentages, in the table below it is shown what the utopic situation of substituting the non-recoverable rest fraction with any other material would yield towards the required 70%.
<table>
<thead>
<tr>
<th>Substitution of 27% non-recoverable plastics with 27% of</th>
<th>Recyclability score</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrous metals</td>
<td>76.2%</td>
<td>20% is needed to obtain 70%</td>
</tr>
<tr>
<td>Copper</td>
<td>77.5%</td>
<td>23% is needed to obtain 70%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>73.5%</td>
<td>22.7% is needed to obtain 70%</td>
</tr>
<tr>
<td>Recoverable plastics of type 1</td>
<td>65.4%</td>
<td>Still 4.6% short of 70%</td>
</tr>
<tr>
<td>Recoverable plastics of type 2</td>
<td>51.9%</td>
<td>No change as default recovery percentage is the same in type 1 and type 2 case</td>
</tr>
<tr>
<td>Recoverable plastics of type 3</td>
<td>72.2%</td>
<td>Enough to reach the target, replacement of 24% is enough to obtain 70%</td>
</tr>
</tbody>
</table>

Looking at these options for substitution the following remarks can be made. Substitution with ferrous metals would change the plastics dominated product into a metals dominated product, taking on the more favourable performance indicators of products in this category (not taking into account the life cycle perspective!). Substitution with copper is obviously out of the question for many reasons including costs, weight, aesthetics et cetera. Substitution with aluminium is a possibility though unlikely for similar reasons. Because of the assumed plastics recovery rate of 50%, using recoverable plastics of type 1 or 2 alone is not enough to obtain a recyclability rate of 70%. A recovery rate of at least 57.5% would be necessary to bridge the distance to the required 70%. Since plastics of type 3 have a higher default recovery rate of 75%, replacing 24% out of 27% of the non-recoverable plastics is enough to reach 70%.

**Legislation scenario 2.1:**
- Percentage recoverable type 3 plastics increases to 24%
- Percentage non-recoverable plastics decreases to 3%

However, in many applications it is unlikely that such a big percentage of the non-recoverable plastics fraction can be replaced with high-yield plastics. Besides, this non-recoverable plastics fraction not only constitutes plastics but is in essence a rest or waste fraction, and also because not always feasible replacements for non-recoverable plastics exist, the assumption is justified that at least 15% out of the original 27% can not be substituted for recoverable plastics. Since compared to the default situation, substitution of 12% of the non-recoverable plastics with type 1 recoverable plastics yields a recyclability scores of 57.9% only, a recovery rate of 75.8% (for type 1 plastics) would be required to obtain a 70% recyclability score (not addressing changes to other parameters).

**Legislation scenario 2.2:**
- Percentage type 1 recoverable plastics increases to 47%
- Percentage non-recoverable plastics decreases to 15%

Recovery percentage for type 1 plastics increases to 75.8%. In this legislation scenario, type 1 plastics can also be replaced by type 2 plastics. From a recyclability point of view this would make no difference as type 1 plastics and type 2 plastics both have the same
recovery percentages. From an end-of-life yield point of view however, this would improve results considerably since the type 2 plastics exhibit a yield in contrast to type 1 plastics that exhibit a small cost per kilogram. For the purpose of being complete, a type 2 plastics scenario is also included here:

Legislation scenario 2.2.1:
• Percentage type 2 recoverable plastics increases to 47%
• Percentage non-recoverable plastics decreases to 15%

Recovery percentage for type 2 plastics increases to 75.8%. In case the 12% that can be substituted would be substituted with type 3 plastics rather than type 1 plastics, the recyclability rate would be 60.9%. In this case the recovery percentages for type 1 and 3 plastics should take for example one of the following combinations as given in scenarios 2.3.1-3 to attain a 70% recyclability rate.

Legislation scenario 2.3.1:
• Percentage type 3 recoverable plastics increases to 12%
• Percentage non-recoverable plastics decreases to 15%
• Recovery percentage for type 1 plastics increases to 76.0%
• Recovery percentage for type 3 plastics remains 75.0%

Legislation scenario 2.3.2:
• Percentage type 3 recoverable plastics increases to 12%
• Percentage non-recoverable plastics decreases to 15%
• Recovery percentage for type 1 plastics increases to 74.5%
• Recovery percentage for type 3 plastics increases to 80%

Legislation scenario 2.3.3:
• Percentage type 3 recoverable plastics increases to 12%
• Percentage non-recoverable plastics decreases to 15%
• Recovery percentage for type 1 plastics increases to 72.5%
• Recovery percentage for type 3 plastics increases to 85.0%

A solution like this would in practice mean a compromise between efforts from both the manufacturing industry and the recycling industry. For the manufacturing industry, few other means are at hand to increase recyclability rates than through design changes. For the sake of comparison, another scenario is drawn where the reduction in non-recoverable plastics is balanced by an increase in both type 1 recoverable plastics (4%) and ferrous metals (8%). This scenario would be more applicable in cases where parts of plastic housings can be substituted with metals – again shifting from plastics to metals dominated products. In this respect it can be calculated that at a fixed level of a 50% type 1 recovery percentage for plastics, and assuming a minimum of 15% non-recoverable plastics in the material composition, products with a ferrous metals percentage higher than 64% meet the 70% recyclability target.
Legislation scenario 2.4:
• Percentage type 1 recoverable plastics increases to 39%
• Percentage ferrous metals increases to 42%
• Percentage non-recoverable plastics decreases to 15%
• Recovery percentage for type 1 plastics increases to 75.8%

Precious metals dominated products

In the default setting, for a no plastics recycling scenario, the recyclability rate for precious metals dominated products is 54.2%, and in a plastics recycling scenario 57.2%. The small difference is obviously caused by the relatively small amount of recoverable plastics assumed to be in the default material composition. This means that few possibilities exist to increase the recyclability rate by assuming that legislation will prove to be an incentive for improving the recovery percentage for plastics – this alone will have little effect. From a manufacturing point of view, opportunities may exist to increase the percentage of recoverable plastics at the expense of non-recoverable plastics. Calculations with the PMRCM show that the recoverable plastics percentage will need to be increased from 6% to 32% in order to reach the 70% recyclability target. A feasibility check for this option shows that this option is barely possible as the housing of for example a cellular phone, being the only part that is a candidate for substituting non-recoverable plastics with recoverable plastics, makes up 25-30% of the total product weight. If this fraction would be considered as recyclable (which would have considerable design implications), it would leave about 10% for the non-recoverable plastics/waste fraction, which may in most cases not be enough.

Because of these reasons it is not considered relevant to draw top-down legislation scenarios for the precious metals dominated product category in the way it was done for the plastics dominated product category. In section 6.5.2 however, bottom-up legislative scenarios are drawn that apply to all main product categories.

CRT based products

For CRT based products, the default recyclability score in a plastics recycling scenario is 43.9%. In the default case recoverable plastics make up 39% of the product, and non-recoverable plastics account for 34% of the product.

The recyclability target for this product category is 75%. However, since the default material composition is based on the case where the CRT is removed (see section 5.3.4), the adapted recyclability target can be calculated as (75-62)/38 = 34.2%, assuming that all of the 62% glass is considered as contributing to the recyclability score. This means that in the default scenario, the recyclability target is already met, in which case, like in the metals dominated products case, drawing top-down legislative scenarios is not relevant.

However, scenarios have been drawn based on a recyclability target of 90% that was used in earlier drafts of VVEEE legislation. Although this target is no longer applicable, it is chosen here to nevertheless include these scenarios here, with the objective to
show possibilities for changing the material composition of CRT based products in order to attain higher recyclability targets.

Hence, the scenarios drawn in the remainder of this section have been drawn based on a recyclability target of 90%, which corresponds with an adapted recyclability target of \((90 - 62)/38 = 73.7\%\).

Increasing the amount of recoverable materials: based upon the assumption that at least 20% of the weight of the product (without CRT) will account for the rest fraction (electronics, etc.), 14% of the non-recoverable rest fraction is 'left' for substitution with recoverable fractions. Not considering copper (analogous to the plastics dominated case), the following options remain in the plastics recycling scenario case:

<table>
<thead>
<tr>
<th>Substitution of 14% non-recoverable plastics with 14% of:</th>
<th>Recyclability score: (43.9% is default)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>55.1%</td>
</tr>
<tr>
<td>Ferrous metals</td>
<td>56.5%</td>
</tr>
<tr>
<td>Recoverable plastics of type 1 or 2</td>
<td>50.9%</td>
</tr>
<tr>
<td>Recoverable plastics of type 3</td>
<td>54.4%</td>
</tr>
</tbody>
</table>

Clearly, in all cases the results remain far from the 73.7% recyclability target. In order to draw scenarios that meet this target, scenarios can be investigated that include increases in the recovery percentages of the different recoverable materials. However, the remaining fraction of 53% recoverable plastics (keeping the ferrous metals content constant) would need an average recovery percentage of 93% in order to meet the 73.7% target. This is considered too unlikely to be included as a scenario to be compared with the other scenarios drawn in this chapter. Since ferrous metals have a higher recyclability percentage than plastics, therefore a scenario is drawn which includes partial substitution of plastics with ferrous metals. However, even when the ferrous metals content is doubled, and when the recovery percentages are set at 85% for all recoverable plastics, a 70% recyclability score is barely met, still falling 3.5% short of the 73.7% target. The only option left to meet this target is to even further reduce the non-recoverable rest fraction. The following scenarios are drawn based on a non-recoverable rest fraction of 10%, and all meet the 73.7% target.

**Legislation scenario 4.1:**
- Percentage ferrous metals increases to 29%
- Percentage type 1 recoverable plastics decreases to 10%
- Percentage type 3 recoverable plastics increases to 40%
- Percentage non-recoverable plastics decreases to 10%
- Recovery percentage for type 3 plastics increases to 80%
- Recovery percentage for type 1 plastics increases to 55%

In scenario 4.1 most variables are used to change in a way the recyclability target is met (a little bit of everything). In scenario 4.2, the default ferrous metals content is kept, and the changes are in the recovery percentages mainly, and in the use of type 3 plastics.
**Legislation scenario 4.2:**
- Percentage type 1 recoverable plastics decreases to 17%
- Percentage type 3 recoverable plastics increases to 46%
- Percentage non-recoverable plastics decreases to 10%
- Recovery percentage for type 3 plastics increases to 85%
- Recovery percentage for type 1 plastics increases to 60%

In scenario 4.3 exhibits a significant increase in the ferrous metals content, keeping the recovery percentage at their default values.

**Legislation scenario 4.3:**
- Percentage ferrous metals increases to 42%
- Percentage type 1 recoverable plastics decreases to 7%
- Percentage type 3 recoverable plastics increases to 30%
- Percentage non-recoverable plastics decreases to 10%

In scenario 4.4 the option of exchanging a plastic encasing with an aluminium one is investigated. In order to meet the recyclability target, the ferrous metals content is increased by 5% as well.

**Legislation scenario 4.4:**
- Percentage ferrous metals increases to 21%
- Percentage aluminium increases to 45%
- Percentage type 1 recoverable plastics decreases to 3%
- Percentage type 3 recoverable plastics increases to 13%
- Percentage non-recoverable plastics decreases to 10%

Another option is to assume an improved (progressive) aluminium recovery percentage, reflected in scenario 4.5.

**Legislation scenario 4.5:**
- Percentage aluminium increases to 45%
- Percentage type 1 recoverable plastics decreases to 4%
- Percentage type 3 recoverable plastics increases to 17%
- Percentage non-recoverable plastics decreases to 10%
- Aluminium recovery percentage increases to 82%

### 6.5.2 Natural effect (bottom-up) legislative scenarios

In section 6.5.1, scenarios were drawn based on a target recyclability score. In this section, it will be investigated how effects that 'naturally' originate (partly) as a consequence of legislative developments will influence the end-of-life performance in the default scenarios. Therefore this can be regarded as a bottom-up approach rather than a top-down approach.
As explained at the end of section 3.3, drawing scenarios on the basis of legislative developments is a complicated issue as many effects related to processing costs, material (in particular plastics) prices and economies of scale are involved, sometimes with opposite effects. It may also stimulate technology development, which in itself has positive effects. On the other hand, processing costs themselves might increase compared to the previous situation when products or material fractions were not recycled at all. This may also be true for collection and further logistics processes. The bottom line here is that many effects can be expected, but the sum of the effects is in many instances so far unclear. In order to assess the balance of these developments, scenarios are drawn that include the various effects, again in particular focusing on processing costs, material (in particular plastics) prices and economies of scale. For economies of scale, in section 6.4 developments were quantitatively assessed. Since there it was assumed that increasing economies of scale have in particular an effect on (again) processing costs, (again) plastics prices and plastics recovery rates, it can be concluded that the three main parameters to take into account here are the latter three parameters

- processing costs
- plastics prices
- plastics recovery rates

Scenarios for ceteris paribus changes in processing costs, plastics prices, and plastics recovery rates have been analysed in previous sections. It is assumed here that in bottom-up legislative scenarios the effects of legislative developments on these individual factor are no greater than those analysed in the ceteris paribus cases. This means that for drawing these bottom-up scenarios, effects can be combined of the ceteris paribus results. Using this approach, the legislative bottom-up given in Table 44 scenarios were investigated. In order to avoid unnecessary increasing the number of scenarios, for the mixed scenarios only combinations of progressive and conservative estimates were taken into account. For the effects on plastics prices, use was made of the combined plastics prices scenarios rather than scenarios affecting only one plastics type.

<table>
<thead>
<tr>
<th>Legislative scenario</th>
<th>Type</th>
<th>Effects on processing costs</th>
<th>Effects on plastics prices (type 1, 2, and 3)</th>
<th>Effects on plastics recovery rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Progressive Bottom-up</td>
<td>Progressive</td>
<td>Progressive</td>
<td>Progressive</td>
</tr>
<tr>
<td>2</td>
<td>Average Bottom-up</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>3</td>
<td>Conservative Bottom-up</td>
<td>Conservative</td>
<td>Conservative</td>
<td>Conservative</td>
</tr>
<tr>
<td>4</td>
<td>Mixed Bottom-up 1</td>
<td>Progressive</td>
<td>Progressive</td>
<td>Conservative</td>
</tr>
<tr>
<td>5</td>
<td>Mixed Bottom-up 2</td>
<td>Progressive</td>
<td>Conservative</td>
<td>Progressive</td>
</tr>
<tr>
<td>6</td>
<td>Mixed Bottom-up 3</td>
<td>Conservative</td>
<td>Progressive</td>
<td>Conservative</td>
</tr>
<tr>
<td>7</td>
<td>Mixed Bottom-up 4</td>
<td>Progressive</td>
<td>Conservative</td>
<td>Conservative</td>
</tr>
<tr>
<td>8</td>
<td>Mixed Bottom-up 5</td>
<td>Conservative</td>
<td>Progressive</td>
<td>Conservative</td>
</tr>
<tr>
<td>9</td>
<td>Mixed Bottom-up 6</td>
<td>Conservative</td>
<td>Conservative</td>
<td>Progressive</td>
</tr>
</tbody>
</table>

Table 44: Legislative bottom-up scenarios included in the analysis

For example, bottom-up scenario 1 which is the most progressive one in Table 44 translates to a scenario in which, compared to the default scenario, the following changes are
analysed: a 50% reduction in processing costs, combined with a 20 percent point increase (to 70%) in the recovery percentage for type 1 plastics, with a 95% grade, and with the following plastics prices: € 0.00 (type 1 plastics), € 0.50 (type 2 plastics), € 2.50 (type 3 plastics), and € −0.50 for the non-recoverable plastics. So, this represents a very favourable situation in which all applicable model parameters are set at progressive values. This particular scenario is meant to represent a situation in which legislative effects have ensured an efficient end-of-life infrastructure.

In theory, extremely rigid future legislation could lead to cases where the above assumption that the effects of legislative scenarios on the three parameters under consideration are individually larger than those assumed in the ceteris paribus scenarios, needs to be dropped. An example would be the case where processing costs or secondary plastics markets are externally heavily subsidised in order to make sure recyclability targets set by the EU can be met. Such cases are in the current context not considered as 'equally likely' (see the beginning of Chapter 6 for a discussion on this matter) compared to other scenarios analysed in this chapter and therefore disregarded here.

It should be noted that a number of the bottom-up legislative scenarios drawn in this section are very similar to some of the economies of scale scenarios drawn in section 6.4. This is because both developments were found to have effects mainly on processing costs, plastics recovery percentages and secondary plastics prices (although in the economies of scale scenarios developments in recovery grades are also included). Scenarios are included in both sections however since the interpretation of all scenario analysis results requires the identification of developments that are the basis of these scenarios.

6.6 Quantification of developments in design – analysis of material substitution scenarios

As stated in Chapter 3, most technological changes so far investigated in this chapter are related to end-of-life technology. In addition, also a number of additional scenarios are investigated here that are based on changes related to other life-cycle stages, in particular design and manufacturing. Included in the analysis are a number of developments relevant for drawing future end-of-life scenarios as that relate directly to product design. These include changing technical and functional requirements (for example because of digitalization of miniaturization), and also developments in ergonomics and style (for example because of changing customer preferences). Such developments all require product specifications that in the end result in a certain material composition for the product itself. This very material composition determines for a significant part the economical and environmental performance of the product in the end-of-life stage of the life cycle.

From a WEEE perspective and also from a cost of ownership perspective, it is important for firms to know what possibilities exist to redesign products in order to meet recyclability targets and to minimize end-of-life costs. The scenarios drawn in this section represent changes in the material composition of products as a result of possible developments in design, based on practical design solutions found in the benchmarked products.
Changes in weight percentages of materials in products have in a sense a dual effect: when the weight percentage of one material changes, the weight percentage of at least one other material has to change as well. Therefore, changes in weight percentages cannot be analysed autonomously. In principle, every design change will have its own effect, and all these effects can be calculated with the PMRCM. For scenario analysis, it is clear that choices have to be made here, and that ‘general developments’ will have to be analysed in order to compare effects with effects of other developments analysed in this chapter. To deal with analyses of material composition changes exhibiting a change in only one of the constituent material categories, the most obvious choice is to lower the weight percentage of plastics that are not recovered when the weight percentage of another material is increased. Since the fraction of plastics that are not recovered is in a sense a rest fraction – all material that cannot be categorised in one of the other fractions is subsumed here – a decrease of this percentage more or less always represents a design improvement from an end-of-life perspective. Clearly, another approach needs to be taken when real material substitution is analysed – substitution between materials not belonging to the rest fraction. For example, analysis of changing a steel cover into an aluminium cover requires lowering the weight percentage of ferrous metals and increasing the weight percentage of aluminium. Therefore, a number of material substitution scenarios are included in the present analysis as well, and these are discussed after the scenarios in which the weight percentages of the constituent materials are lowered at the cost of plastics that are not recovered.

In this section a number of relevant material substitution scenarios are evaluated. The material substitution scenarios entail increasing the weight percentage of one material category (ferrous metals, copper, aluminium, plastics that are recovered, plastics that are not recovered) at the expense of another. It should be noted again that, like with all scenarios drawn in this chapter, these scenarios are drawn without explicitly taking the lifecycle into account. The main goal is to determine the effects on the end-of-life performance indicators as defined in section 5.1. Additional applications of the analysis of material substitution scenarios can for example include the derivation of specific design recommendations. Such an activity would ideally be part of an elaborate study to exploit combined environmental benchmark results as opposed to the exploitation of individual benchmark results. Only this way, structurally different design solutions in comparison to those of the competition and across more than one product category, can be detected and dealt with if necessary, underperformance. In section 9.4.13 this issue is formulated as a possible direction for further research.

Drawing scenarios for material substitution, especially when regarding them as future developments, is not straightforward. Although design changes can be assessed with respect to the consequences for material composition, the hard part is to assess how ‘likely’ these scenarios are. Therefore, this can only be done speculatively, probably more so when compared to other (technological, economical) developments.

In the current context, a number of scenarios are drawn for the main product categories, encompassing relevant material substitutions as a consequence of possible redesign directions. Use is made here of benchmark reports produced by Philips
Consumer Electronics. In these benchmark reports, differences in design given similar product functionality are reported on and are therefore helpful in analysing the consequences on material composition of different design options. Material substitution scenarios may therefore refer less to future (technological) developments, but rather to choices that are made in the (re)design process. To arrive at approximately equally likely scenarios for material substitution, in general the following procedure was taken: from the benchmark reports the two products with the highest and the lowest weight percentage for two relevant materials were identified. The material substitution scenario then entailed the necessary adjustments to make the one product similar to the other in terms of weight percentages for these two materials.

Unfortunately but understandably because of the high costs, no data on precious metals content was collected during the benchmarking of the products other than the precious metals dominated products discussed in this section. This means that drawing material substitution scenarios for precious metals content in the remaining three main categories can be done only very speculatively. However, because of the potentially (relatively) large effects of changes in precious metals content on the end-of-life revenues, some scenarios have been drawn nevertheless.

Because of the nature of these material substitution scenarios, no distinction will be made between progressive and conservative scenarios. Merely, just he substitution itself is presented as a scenario and will be compared with scenarios discussed in the previous sections as such.

Also, it should be noted that the material substitutions represented in the scenarios in this section do not always necessarily imply environmental improvements. Even scenarios that score positive effects from an end-of-life perspective, may lead to environmental or economical costs when the complete life-cycle is considered (see section 8.2 for an illustrative example). Again, scenarios are drawn because they represent an observation made from benchmarking products with similar functionality.

### 6.6.1 Metals dominated products

In the environmental benchmark report on VCRs\(^\text{196}\) a difference is reported on the material use for the frame. Both plastic and metal frames are used, leading to a 15% difference in the weight percentage for ferrous metals and plastics. Since the material composition of the products with a metal frame is very similar to the default material composition for metals dominated products, from this a material substitution scenario is derived in which 15% of the weight of the product is changed from ferrous metals into non-recoverable plastics. In material substitution scenario 1.2 it is also investigated what the effects are from substituting the metals with recoverable, low yield plastics.

<table>
<thead>
<tr>
<th>Material substitution scenario 1.1:</th>
<th>Default ferrous metals w% / non-recoverable plastics w%</th>
<th>New ferrous metals w% / non-recoverable plastics w%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>66% / 18%</td>
<td>51% / 33%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material substitution scenario 1.2:</th>
<th>Default ferrous metals w% / recoverable plastics w%</th>
<th>New ferrous metals w% / recoverable plastics w%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>66% / 4%</td>
<td>51% / 19%</td>
</tr>
</tbody>
</table>

In material substitution scenario 1.2.1-2 the effects of substituting partly and completely with high-yield plastics are investigated.

<table>
<thead>
<tr>
<th>Increase in high-yield plastics w%</th>
<th>Increase in low-yield plastics w%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 1.2.1:</td>
<td>15%</td>
</tr>
<tr>
<td>Material substitution scenario 1.2.2:</td>
<td>7%</td>
</tr>
</tbody>
</table>

In the environmental benchmark report on CD recorders\(^{197}\) all benchmarked products are clearly dominated by ferrous metals, although the weight percentages range from 48% to 61%. The products with the lowest ferrous metal weight percentages have the highest plastics weight percentages, but more importantly, the weight of the motors and the wirewound components are also significantly higher for these models. Though from the benchmark report any causal relation for this cannot be determined, it is clear that a significantly higher weight percentage for the motor and wirewound components (15% for two CDRs compared with 4% for two others) will have a decreasing effect on the weight percentage of any other material fraction with all other things being held equal. As the ferrous metal fraction is in metals dominated products by far the largest, it will be assumed that a change in the copper percentage will affect this material category the most, and in the example, exclusively. As motor and wirewound components on average consist of 8% resp. 16% copper, this gives occasion to include two copper related material substitution scenarios.

<table>
<thead>
<tr>
<th>Material substitution scenario 1.3:</th>
<th>Default ferrous metals w% / copper w%</th>
<th>New ferrous metals w% / copper w%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>66% / 6%</td>
<td>63% / 9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material substitution scenario 1.4:</th>
<th>Default non-recoverable plastics w% / copper w%</th>
<th>New non-recoverable plastics w% / copper w%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18% / 6%</td>
<td>21% / 9%</td>
</tr>
</tbody>
</table>

Because no data is available from the benchmark reports on the precious metals content of any metals dominated product. For this reason, the following scenario featuring changes in precious metal concentration is drawn purely speculatively. Anticipating an elaboration on this particular issue, presented in the precious metals dominated products section fur-

ther down this section (presented there since this topic particularly influences that main product category), material substitution scenarios 1.5 to 1.8 are drawn below.

<table>
<thead>
<tr>
<th>Material substitution scenario</th>
<th>Default scenarios (Au, Ag, Pd in ppm)</th>
<th>Substitution scenario (Au, Ag, Pd in ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>80/215/90</td>
<td>160/215/90</td>
</tr>
<tr>
<td>1.6</td>
<td>80/215/90</td>
<td>80/430/90</td>
</tr>
<tr>
<td>1.7</td>
<td>80/215/90</td>
<td>80/215/180</td>
</tr>
<tr>
<td>1.8</td>
<td>80/215/90</td>
<td>160/430/180</td>
</tr>
</tbody>
</table>

Table 45: Material substitution scenarios related to precious metals content in metals dominated products

6.6.2 Plastics dominated products

From the environmental benchmark report on audio systems\(^{198}\) it can be learned that the material composition of these products resembles the default material composition for plastics dominated products, especially when the wooden parts are regarded as non-recoverable plastics (as this fraction can be regarded as the rest fraction). The products examined in this benchmark do exhibit very similar material compositions. One dissimilarity stands out however; the aluminium content of one of the product is 5% compared to the other products that have a 1% aluminium content, which is reflected in their ferrous metals content which is 4% higher. This fact is used to draw an aluminium substitution scenario.

<table>
<thead>
<tr>
<th>Material substitution scenario 2.1</th>
<th>Default aluminium w%/copper w%</th>
<th>New aluminium w%/copper w%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%/4%</td>
<td>4%/0%</td>
</tr>
</tbody>
</table>

From the environmental benchmark report on faxes\(^{199}\) it can be learned that plastics content of the analysed products ranges from some 40% to 60% concurring with the default material composition for plastics dominated products. In the cases of high plastics content the ferrous metals content is considerably lower. Among the products, plastics content/metal content ratios occur as high as 3 and as low as 1. From this, material substitution scenarios can be drawn as done in the next table. Since in the default situation for plastics dominated products, recoverable and non-recoverable plastics are present in a 35/27 ratio, it is assumed in this scenario that an increase of 20% in the plastics percentage is attributed for 11% in the recoverable plastics percentage and for 9% in the non-recoverable plastics percentage.


Further scenarios are drawn to assess the effects of substitution with high-yield plastics. In scenarios 2.2.1-3, the 20% increase in the plastics weight percentage is distributed in three ways over high-yield, low-yield and non-recoverable plastics.

<table>
<thead>
<tr>
<th>Material substitution scenario</th>
<th>Increase in high-yield plastics w%</th>
<th>Increase in low-yield plastics w%</th>
<th>Increase in non-recoverable plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.1</td>
<td>10%</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>2.2.2</td>
<td>10%</td>
<td>10%</td>
<td>0%</td>
</tr>
<tr>
<td>2.2.3</td>
<td>20%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

In the benchmark sample, also copper content among the faxes varies from 2% to 7%. Since from the benchmark it cannot be derived which material is the obvious candidate for substituting copper with, it will be assumed that this is either the ferrous metals or the aluminium fraction. Since in scenario 2.1 an aluminium substitution was already included, in material substitution scenario 2.3 a copper/ferrous metals substitution scenario is examined.

<table>
<thead>
<tr>
<th>Material substitution scenario</th>
<th>Default ferrous metals w% / copper w%</th>
<th>New ferrous metals w% / copper w%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>34%/4%</td>
<td>31%/7%</td>
</tr>
</tbody>
</table>

Similar to the procedure carried out for metals dominated products, for changes in precious metals content for plastics dominated products scenarios material substitution scenario 2.4-7 are drawn below.

<table>
<thead>
<tr>
<th>Material substitution scenario</th>
<th>Default scenarios (Au, Ag, Pd in ppm)</th>
<th>Substitution scenario (Au, Ag, Pd in ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>8/33/8</td>
<td>16/33/8</td>
</tr>
<tr>
<td>2.5</td>
<td>8/33/8</td>
<td>8/66/8</td>
</tr>
<tr>
<td>2.6</td>
<td>8/33/8</td>
<td>8/33/16</td>
</tr>
<tr>
<td>2.7</td>
<td>8/33/8</td>
<td>16/66/16</td>
</tr>
</tbody>
</table>

Table 4b: Material substitution scenarios related to precious metals content in plastics dominated products

### 6.6.3 Precious metals dominated products

Both miniaturisation of electronics and increased functionality and function integration as future design have in common that these objectives are reached by an increase of the use of printed circuit board technology. This increase in sophisticated technology will potentially cause an increase of precious metals concentrations in PWBs because of the
increased need for fast high-conductivity parts. However, it is problematic to back up any quantified estimates for this process by hard data. Reasons for this are the fact that material analyses are very expensive to perform in the first place, let alone to do this for products spanning generations enabling extrapolation of trends. A second difficulty that was found is that even for products from the same generation, very different concentrations of precious metals can be found that cannot be traced back to differences in functionality. For example, in a printed circuit board analysis performed in 1999, covering a sample of five Philips cellular phones from the same generation, differences in gold concentrations on printed circuit boards only were identified ranging from 614 to 952 ppm, for silver the result where between 1900 ppm and 4439 ppm, and for palladium the range was from 348 to 661 ppm. Additionally, analysis results that were obtained through analysis by the same laboratory that provided the previous analysis results, show completely different ranges of 6500-9200 ppm for all precious metals jointly. Assumed that these data apply to the complete phone, this would mean multiplication by a factor 3 to obtain concentration on the printed circuit boards only, assumed that all precious metals are located there. Lastly, analysis of a single cellular phone in 2000, again by the same laboratory, exhibited results for gold and palladium within the range of the Philips test (but on the lower end of the spectrum), but for silver the results were significantly lower (390 ppm only). The large differences in precious metals concentration in phones (from different brands) of similar functionality and age are confirmed by Mirec BV in Eindhoven.

These results lead to the conclusion that since the analysis of phones in the present does not even lead to uniform results, predicting concentrations of precious metals in future designs for the whole spectrum of precious metals dominated products is an unfeasible task. Although a general trend towards reduction of the use of precious metals out of cost considerations is to be expected, there is no reason to assume that the currently existing bandwidth for use of precious metals will become smaller. This makes it virtually impossible, for individual phones, to estimate the precious metals content without detailed, thus costly analysis. And even if such analyses are performed, the value thereof can be regarded as very limited as generalisations are hard to made, due to the size of that very bandwidth.

These considerations may hold even more truth for products from the other main product categories, since for these the degrees of freedom for material application are for the main constituent materials like ferrous metals, aluminium and plastics even larger because of the size of the products. This is reflected in Table 47.

<table>
<thead>
<tr>
<th>Precious metals dominated product category</th>
<th>Other main product categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of uncertainty about future material concentrations regarding precious metals</td>
<td>High</td>
</tr>
<tr>
<td>Amount of uncertainty about future material concentrations regarding constituent materials</td>
<td>Lower</td>
</tr>
</tbody>
</table>

*Table 47: Uncertainty about material concentrations*
Still, in order to be able to include developments in precious metals content and to be able to compare these with other developments, scenarios have been drawn speculatively. It is realised that technically, these scenarios are not actually material substitution scenarios, since the increased concentrations of precious metals do not actually substitute any other material (that is analysed in the current analysis), however for the sake of aligning these analysis steps with the other scenarios drawn in this section, it was decided to name these scenarios material substitution scenarios as well.

- **Material substitution scenario 3.1**: Based on the available data of precious metal contents in cellular phones, a large bandwidth exists for the precious metal concentrations in an average product, even for products with the same or similar functionality. This is even true to an extent that the concentrations for the applicable metals on the high end of the bandwidth spectrum are double to those on the low end of the bandwidth. Thus, duplication scenarios are drawn for gold, silver and palladium separately, and for all three precious metals simultaneously. The scenarios that are derived this way are listed in Table 48.

<table>
<thead>
<tr>
<th>Material substitution scenario</th>
<th>Default scenarios (Au, Ag, Pd in ppm)</th>
<th>Substitution scenario (Au, Ag, Pd in ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 3.1</td>
<td>709/1938/438</td>
<td>1418/1938/438</td>
</tr>
<tr>
<td>Material substitution scenario 3.2</td>
<td>709/1938/438</td>
<td>709/3876/438</td>
</tr>
<tr>
<td>Material substitution scenario 3.3</td>
<td>709/1938/438</td>
<td>709/1938/876</td>
</tr>
<tr>
<td>Material substitution scenario 3.4</td>
<td>709/1938/438</td>
<td>1418/3876/876</td>
</tr>
</tbody>
</table>

Table 48: Material substitution scenarios related to precious metals content in precious metals dominated products

- In the environmental benchmark report on cellular phones\textsuperscript{201} the significant differences in material content between various phones are to be found in particular for the batteries and adapters. As these are not considered in the default description of precious metals dominated products as discussed in this dissertation, these differences are not relevant to be discussed here. The remaining main difference between phones analysed in this benchmark report is the weight ratio between housing and PWB. This ratio ranges roughly between 0.75 and 2.5, meaning that a phone with a ratio of 30 (grams housing)/40 (grams PWB) could also be designed as a phone with a ration of 50 (grams housing)/20 (grams PWB), retaining similar functionality. Assuming that plastics housings of these phones are recoverable, this would lead to a substitution of about 50% of the non-recoverable plastics fraction for recoverable plastics (since the PWB exists for the largest percentage of non-recoverable plastics, and for the rest out of valuable materials). Translated to the default precious metals dominated product this would concur with a recoverable/non-recoverable plastics ratio of 23% over 18% instead of the default 6% over 35%. This

\textsuperscript{200} obtained through the Nokia Research Center in Helsinki, Finland

scenario is currently not likely to happen, as housings from phones are usually non-recoverable. Therefore, this scenario should be considered as relevant only in situation in which for example an active disassembly infrastructure, as discussed in 3.4.2 and Appendix 4, is implemented.

<table>
<thead>
<tr>
<th>Default recoverable plastics weight percentage / non-recoverable plastics weight percentage</th>
<th>New recoverable plastics weight percentage / non-recoverable plastics weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 3.5 6%/35%</td>
<td>23%/18%</td>
</tr>
</tbody>
</table>

- In the environmental benchmark report on DECT cordless telephones, significant differences are found in the weight percentages of the plastics housings. From this, one more material substitution scenario is derived. As the total plastics weight percentage of this type of phones is lower than the default percentage for precious metals dominated products, an increase of 10% in the recoverable plastics weight percentage at the cost of 10% of the weight percentage of ferrous metals can be considered a likely substitution (scenario 3.6).

<table>
<thead>
<tr>
<th>Default ferrous metals weight percentage / recoverable plastics weight percentage</th>
<th>New ferrous metals weight percentage / recoverable plastics weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 3.6 31%/6%</td>
<td>21%/16%</td>
</tr>
</tbody>
</table>

6.6.4 CRT-based products

As explained previously in this dissertation, CRTs themselves are not considered here and placed outside the context of this dissertation. The reason for this is that in current end-of-life scenarios CRTs are removed from the encasings for separate treatment, and hence the remainder of the product can be regarded as a separate product. This is, as explained, also the reason why the default material composition for CRT based products is also given for the product without the CRT, and as such this default material composition is the basis for the material substitution scenarios discussed in this section. This means that only those design changes (read: material composition changes) are regarded that do not include the materials used in the actual CRT (or its replacement).

- In the environmental benchmark report on upmarket televisions, four TV sets weighing around 50 kilograms are benchmarked. After examination of the weight percentages for the different modules, and recalculating the weight percentages for the product without the CRT, the number of striking differences is limited. One interesting aspect is the fact that the two sets with the lowest weight percentage for housing have the highest weight percentage in both electronics parts and wiring. The

The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios

total weight percentage for these fractions is for the first two sets on average 22%, and for the second two sets 34%. The differences in weight percentage for the housings are not that far apart, only 4%. Based on this, it is estimated that the weight percentage of copper (present almost exclusively in the PWBs and the wiring) in the second two sets is about 50% higher than in the first two sets. Since the default weight percentage for copper is 8%, it seems relevant to examine a material substitution scenario in which the copper weight percentage increases by 4% to 12%, at the expense of the weight percentage of recoverable plastics.

<table>
<thead>
<tr>
<th>Material substitution scenario</th>
<th>Default copper weight percentage / recoverable plastics weight percentage</th>
<th>New copper weight percentage / recoverable plastics weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>8%/39%</td>
<td>12%/35%</td>
</tr>
</tbody>
</table>

- In the same series as the Philips Environmental Benchmark reports, also a report was written comparing the environmental performance of standard CRT monitors with LCD monitors. The material substitution on the body of the monitor (so, the monitor without the tube) as a result of this design change is assessed from the benchmark report and then used to compare the material composition of the default CRT-based product with the one of the adapted product.

In the Philips study, for the CRT monitor the absolute weight of the plastic housing is considerably higher (3-4 times) than the absolute weight of the housing of the LCD monitor. However, in weight percentages the housings in both cases account for about 16% of the total weight. If also the housing of the pedestal is included, the weight percentage of (assumed) recoverable plastics increases in the CRT case to 18%, but in the LCD case to 26%. The weight of the PWBs plus cables is in both cases similar, about 20%, which leads to the assumption that the copper weight percentage in both products is similar. The EMC shielding however is in the LCD case relatively more heavy, 7% against 3%, indicating a higher metal content in the LCD based product.

To be able to draw scenarios that are aligned with the default material composition for CRT based products, the material weight percentages have to be adapted for products without the display unit. This leads to a somewhat different view since the weight of the display unit in the CRT case makes up half the weight of the total monitor, whereas the weight of the LCD display is only 28% of the total product. This makes that the weight percentages of the other material fractions increase relatively more in the CRT case than in the LCD case, when the display units are not included. This has an equalizing effect on the plastics content for both types, the difference is now only 3% as opposed to the 8% calculated above – so no material substitution scenarios are drawn from this. Whereas the weight of the cables and PWBs was similar in the first case, the effect now is that the weight percentage of this fraction in the LCD case is 7 percent points lower than in the CRT case (36% versus 29%). It is assumed that this reduction of 20% also means a reduction in the copper weight percentage of 20%. In the case of the EMC shielding, the effect is somewhat less but still significant, 10% in the in the LCD case against 6% in the CRT case.
Two material substitution scenarios that reflect a design change from CRT based to LCD based monitor are drawn from this. In scenario 4.2, it is assumed that in the LCD case the weight percentage of copper decreases by 20%, leading to a decrease of the default 8% to 6% (rounded number). In this case it is assumed that the weight percentage of recoverable plastics will increase from the default 39% to 41%. It should be noted that the direction of this change is opposite to the one analysed in material substitution scenario 4.1.

<table>
<thead>
<tr>
<th>Default copper weight percentage / recoverable plastics weight percentage</th>
<th>New copper weight percentage / recoverable plastics weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 4.2</td>
<td>8%/39%</td>
</tr>
<tr>
<td>6%/41%</td>
<td></td>
</tr>
</tbody>
</table>

As for the shielding example, in the default case the weight percentage of ferrous metals is 16%. It will be assumed that of this percentage, 6% is because of the shielding, with 10% made up by other metal parts. Since the increase in EMC shielding accounts for an increase of 4 percent points in the ferrous metals weight percentage, in scenario 4.3 the ferrous metal weight percentage is increased with 4% to 20%. It is assumed here that is balanced by a decrease in the recoverable plastics percentage.

<table>
<thead>
<tr>
<th>Default ferrous metals weight percentage / recoverable plastics weight percentage</th>
<th>New ferrous metals weight percentage / recoverable plastics weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 4.3</td>
<td>16%/39%</td>
</tr>
<tr>
<td>20%/35%</td>
<td></td>
</tr>
</tbody>
</table>

A third material substitution scenario relevant to analyse follows from this: in scenario 4.4 the two previous scenarios are combined by substituting 3% of the copper weight percentage by 3% of the ferrous metals weight percentage, keeping the recoverable plastics percentage constant.

<table>
<thead>
<tr>
<th>Default copper weight percentage / ferrous metals weight percentage</th>
<th>New copper weight percentage / ferrous metals weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 4.4</td>
<td>8%/16%</td>
</tr>
<tr>
<td>5%/19%</td>
<td></td>
</tr>
</tbody>
</table>

- As was done for both metals dominated and plastics dominated products, also scenarios are drawn for changes in precious metals content for plastics dominated products. These are represented in Table 49.

<table>
<thead>
<tr>
<th>Default scenarios (Au, Ag, Pd in ppm)</th>
<th>Substitution scenario (Au, Ag, Pd in ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material substitution scenario 4.5</td>
<td>15/590/40</td>
</tr>
<tr>
<td>Material substitution scenario 4.6</td>
<td>15/1180/40</td>
</tr>
<tr>
<td>Material substitution scenario 4.7</td>
<td>15/590/80</td>
</tr>
<tr>
<td>Material substitution scenario 4.8</td>
<td>15/1180/80</td>
</tr>
</tbody>
</table>

Table 49: Material substitution scenarios related to precious metals content in CRT based products
Summary of the material substitution scenarios

In this section, material substitution scenarios have been derived from analyzing benchmark reports provided by Philips Consumer Electronics. Like for all other scenarios drawn in Chapter 6, these will be analysed for their effects on end-of-life costs/revenues and recyclability scores in Chapter 7. Obviously, not all imaginable changes as a result of choices or developments in the design of consumer electronics are addressed here. A more elaborate analysis of differences between products, in particular when using a broader range of products as well as a larger number of the same type of products, will no doubt yield additional substitutions. However, already considerable differences in design solutions were found, and it is believed that the scenarios derived in this section give a useful overview of what can be considered as relevant scenarios for analysis.
7. Overview and Interpretation of Results from the Quantitative Scenario-based Uncertainty Analysis

In the previous chapter a large number of scenarios have been drawn that reflect a wide range of possible developments affecting future product end-of-life scenarios. These scenarios have been drawn for four main product categories. In this chapter, the results from the quantitative PMRCM evaluation are presented in a way that facilitates interpretation and the derivation of conclusions and recommendations. Therefore, in this chapter only the results from the scenario analysis are presented without much further interpretation. In Chapter 8, these results will be discussed from a business perspective, and in relation to each other, which leads to the conclusions and recommendations presented there.

- **Presentation and discussion of individual results.** For every combination of a product category and a performance indicator the effects of the different evaluated scenarios are presented in a figure, which can be found in Appendix 2.1. For this purpose, scenarios are in some cases grouped together when they give a similar score or to show the distance between progressive and average, or average and conservative scenarios. Also, positive and negative effects are given in separate figures to increase readability. Per figure, results are discussed and explained. This is done in sections 7.1 to 7.4.

- **Comparison of results across product categories and scenario types.** Here, the results of the scenario analysis per product category are compared in order to analyse whether similarities or differences exist in the results for the different product categories. These results are given in section 7.5.

### 7.1 Overview and interpretation of results for metals dominated products

In Appendix 2.1 the results from this subsection are graphically presented, but below a graph is already included to show the five scenarios with the largest effects on end-of-life revenues.

![Graph showing top 5 relative positive effects on EOL revenues in % (metals dominated products)](image)

*Figure 32: End-of-Life revenues for metal dominated products*
7.1.1 End-of-life revenues

Positive effects

Of all scenarios analysed, the effects of scenarios that are related to palladium have the largest impact. Price changes as well as Pd concentration changes result in relative increases of the end-of-life revenues of 70% to over 100%. Also, the results are very sensitive to change in the concentration of gold in this product category.

The economies of scale scenarios are the next category of largest effects. Clearly, when these scenarios include substitution of non-recoverable plastics with high-yield plastics results are the best; in these cases the positive effects of the plain economies of scale scenarios (2.3 to 5.5 %) can be multiplied by up to five. The average economies of scale scenario with one progressive component (processing costs, plastics recovery rates or plastics prices) score in between. In the case of substitution with high yield plastics, the effects are amplified more in the case the progressive component is related to recovery rates compared to the case where it is related to prices.

The third category of effects is associated with a number of legislative bottom-up scenarios. Bottom-up scenarios that have a progressive end-of-life processing cost component score have slightly larger effects (a few percent more) than scenarios with an average or conservative one.

These scenarios so far make up all scenarios with a positive effect on end-of-life revenues larger than 5%. Next, there are a number of scenarios that have smaller effects in the range 1% to 5%. These include material substitution scenarios related to copper where the copper content increases at the cost of the ferrous metals or non-recoverable plastics fractions. Also, an increase in the silver concentration causes effects of similar size, as do progressive scenarios for the gold and copper price, and the aluminium price to a lesser extent. Scenarios related to average to progressive improvements in the recovery percentage of ferrous metals, palladium and gold cause positive effects of around 1% on end-of-life revenues.

Lastly, scenarios reflecting improvements in the recovery percentage of type 1 and 2 plastics and aluminium cause only small positive effects of less than 1%, as do scenarios for price increases for type 1 and 2 plastics and silver.

Negative effects

Among the scenarios investigated for the metals dominated product category, scenarios that cause negative effects are in the minority. Also, the sizes of the effects are smaller than those for the positive effects. Material substitution scenarios reflecting a reduction in the ferrous metals content of the product have relatively the largest effect (of up to 7-8%), even when substituted for high-yield plastics. Average to conservative gold price developments can cause negative effects of up to 6-7%. A number of conservative legislative and economies of scale scenarios also cause negative effects of up
to 1.5 percent. A conservative development of the end-of-life processing costs causes a negative effect of the same order of magnitude.

A number of average to conservative scenarios has negative effects of less than 1%, namely those for copper and aluminium prices, and those for ferrous metals and aluminium recovery grades.

7.1.2 Recyclability

Positive effects

As for effects on recyclability, economies of scale scenarios that result in an increased use of high-yield plastics have the largest effect on recyclability. These scenarios can result in relative improvements of up to 12.5%, which means that the recyclability scores for metals dominated products in this case will increase to over 80%. Various other economies of scale scenarios that do not result in this kind of substitution score up to 1% improvement in recyclability.

Material substitution scenarios in which the copper content is increased can have relative positive effects on recyclability of up to 4% (resulting in an absolute increase of the recyclability score of up to 3%). A scenario in which the ferrous metals recovery percentage is increased will result in relative effects of up to 2%. All other scenarios result in even smaller effects, these include selected legislative bottom-up scenarios and scenarios with improved recovery percentages for copper and aluminium.

Negative effects

Of all scenarios analysed for metals dominated products, only two scenarios result in negative effects on recyclability, namely the material substitution scenarios that include a reduction of the ferrous metals content. The fact that ferrous metals are easily recovered using magnetic separation and therefore have a high default recovery percentage makes these metals to the main contributor to recyclability rates. In Chapter 8 this issue is further discussed.

7.2 Overview and interpretation of results for plastics dominated products

In Appendix 2.2 the results from this subsection are graphically presented, but below a graph is already included to show the five scenarios with the largest effects on end-of-life revenues.
7.2.1 End-of-life revenues

Positive effects

The results for plastics dominated products are, perhaps more so than for the other product categories, interesting to analyse. This is mainly because the legislative and economies of scale scenarios show stronger effects here in comparison to the other product categories. This is a result of the fact that economies of scale scenarios and legislative scenarios were found to have a particular impact on plastics prices and recovery rates, which is an area that is still underdeveloped as discussed before in this dissertation. Since several scenarios include simultaneous, and sometimes opposite effects on both plastics prices and recovery rates, the sum of the effects of the individual developments for the different scenarios resulted in either positive or negative effects for the complete scenario.

The largest effects originate from economies-of-scale scenarios including substitution with high-yield plastics, that result in a change of the sign: the default total end-of-life costs change into an end-of-life revenue of up to about the same size of the default cost – an improvement of up to 200% provided the partial effect on the plastics recovery rates is of a progressive nature. If this effect is only of an average nature the positive effect is still considerable but the sign of the result does not change, instead the costs are about halved. Also, material substitution scenarios including substitution with high-yield plastics score well with a cost reduction of over 40%.

The next largest set of effects originates from the series of top-down legislative scenarios. These scenarios lead to end-of-life cost reduction of 25% to 70%. In section 7.5 and further on in Chapter 8 it is argued that although effects on end-of-life yield and recyclability point into the same direction, costs will probably be incurred in the other stages of the product’s life cycle.

In the same order of magnitude a number of the bottom-up legislation scenarios can be found. Here, an interesting aspect can be observed: progressive bottom-up scenar-
ios with a conservative effect on plastics prices score better than overall progressive bottom-up scenarios. This is due to the fact that in the overall progressive scenario one effect is included that has a reverse effect on the end-of-life yield: in this scenario the cost for the non-recoverable rest fraction is assumed to increase from € -0.12 to -0.50. This cost increasing factor outweighs any positive effects from increasing the yields for the other plastic types. In the progressive scenario with conservative effects on plastics prices however, this inverse effect is reduced considerably resulting in a better overall economical performance. Even conservative legislative bottom-up scenarios will score well (around 35% cost reduction) as long as they include progressive effects for the processing costs. Logically then, similar effects are the result of average to progressive end-of-life processing cost scenarios.

Progressive to average economies-of-scale scenarios without high-yield plastics substitution score around 15%-25%. Similarly sized effects are the result of material substitution scenarios with limited high-yield plastics substitution, or with aluminium for copper. The latter effect needs some explaining: although copper price are higher than aluminium prices, and although recovery percentages for copper are higher than for aluminium, situations can occur where reducing the copper content and increasing the aluminium content can have a cost reducing effect. This is particular true in the case of plastics dominated products, where precious metals concentrations are so low that the combined value of the copper and precious metals is too low to justify sending it to the copper smelter, and instead these fractions are considered as waste. Aluminium however is in the modelled process always recovered. Further calculations show that the threshold value for the default situation is at a copper percentage of 10%; if this percentage is higher, retrieval of copper starts to become worthwhile.

Some scenarios result in effects of less than 10%, which is considered to be relatively low since the default end-of-life costs are close to zero. These scenarios include progressive to average price change scenarios for low cost (type 1) plastics, scenarios where the palladium concentration is doubled, and progressive to average scenarios for improving the recovery percentage for ferrous metals and type 1 and 2 plastics.

**Negative effects**

As explained above, the effects of increasing the cost for the non-recoverable plastics fraction have a major effect on the results and even outweigh any price increasing effects for more sophisticated plastics. As a result, scenarios that include a progressive cost increasing component for non-recoverable plastics score the highest negative effects (minus 30-40%, or 20-25% for average cost increasing component). This also includes the bottom-up legislative scenario where these cost increasing effects are not neutralised by reverse effects from decreasing processing costs or improved recovery rates. Material substitution scenarios showing a reduced ferrous metals content cause negative effects of up to around 15%. Also, a number of conservative scenarios (legislative, economies of scale, processing costs) result in negative effects of around 10%.
7.2.2 Recyclability

Positive effects

In the discussion on how to draw legislative scenarios for plastics dominated products the point was made that significantly increasing recyclability rates for this category can only be done by considerable changing the default material composition, and in addition by increasing recovery percentages. These parameter adjustments were used to draw the top-down legislative scenarios that all arrived at a recyclability score of 70% (constituting a relative improvement of about 35%). It is no surprise that these scenarios also have the largest positive relative effects on recyclability. Only progressive to average economy-of-scale scenarios including substitution with high-yield plastics score near this result — some of these scenarios are quite similar to the top-down legislative scenarios.

Scenarios that include progressive plastics recovery rates are in the next largest order of effects (5-15%, relatively). Improved copper recovery percentages and material substitution scenarios showing an increased copper content have almost negligible effects on recyclability.

Negative effects

Similar to the metals dominated products case, also in the plastics dominated products case the material substitution scenarios featuring a reduction of the ferrous metals content show considerable negative effects. In this case, the effects are even relatively larger (up to 25%, relatively) since in a plastics dominated product with a default low amount of recoverable plastics, the ferrous metals are virtually the only material contributing to recyclability.

7.3 Overview of results for precious metals dominated products

In Appendix 2.3 the results from this subsection are graphically presented, but below a graph is already included to show the five scenarios with the largest effects on end-of-life revenues.

![Graph showing the five scenarios with the largest effects on end-of-life revenues](image-url)

*Figure 34: End-of-Life revenues for precious metals dominated products*
7.3.1 End-of-life revenues

Positive effects

For precious metals dominated products, it is obvious that only scenarios related to precious metals content or price have a significant effect on end-of-life revenues. For the individual precious metals, duplication of the gold content would result in the largest effect (+53%), almost paralleled by the effect (+47%) of a duplication in the palladium content. Relatively, the palladium effect is larger since the default palladium concentration is smaller than the default gold concentration. This is also reflected in the result that progressive to average palladium price scenarios have a positive effect of about 5-25% whereas progressive gold price scenarios score a positive effect of less than 3% — similar to a conservative palladium price scenario. Silver price scenarios, even when progressive, have a negligible effect of only 0.1%. A scenario where the silver concentration is doubled has an effect of +2.3%.

Progressive to average economies of scale scenarios, including substitution with high-yield plastics result in effects of maximally 5%. All other scenarios score positive effects of less than 1%. It should be noted though that the default result for precious metals dominated products is high compared to other product categories, that is why absolute results need to be analysed as well — this is done in section 7.5 where result across the different product categories are compared. Scenarios that result in positive effects of up to 1% include, in order of magnitude, scenarios with improved recovery percentages for gold and palladium, progressive copper price scenarios, progressive economies of scale scenarios, a number of progressive to average bottom-up legislative scenarios and progressive to average end-of-life processing cost scenarios.

Negative effects

By far the largest negative effect can be expected from average to conservative gold prices, since these imply a price decrease (in this respect it should be noted that even conservative palladium price scenarios still imply a price increase). Conservative copper price result in negative effects of up to 1%, however the remainder of the negative effects are even smaller, and include effects from a variety of conservative economies of scale and legislative scenarios.

7.3.2 Recyclability

Positive effects

Two scenarios with positive effects on recyclability are worth mentioning here: progressive to average economies of scale scenarios with high-yield plastics substitution score relative improvements of up to 30% here. Material substitution scenarios that reflect an increased use of recoverable plastics at the cost of non-recoverable plastics result in an effect of about half that size. Various technology, legislation and economies
of scale scenarios that include progressive effects on plastics recovery percentages result in a relative effect of about 2%.

**Negative effects**

Like in the previous two cases, also here the scenario reflecting the reduction of the ferrous metals content results in a negative effect on the recyclability (7%, relatively).

### 7.4 Overview and interpretation of results for CRT based products

In Appendix 2.4 the results from this subsection are graphically presented, but below a graph is already included to show the five scenarios with the largest effects on end-of-life revenues.

![Diagram showing top 5 relative positive effects on EOL revenues in % (CRT based products)](image)

*Figure 35: End-of-Life revenues for CRT based products*

#### 7.4.1 End-of-life revenues

First of all it should be clear that the relative effects on end-of-life revenues found for this product category are much larger than those for the other product category, because the default result (€ 0.21) is so close to zero. This also means that in the presentation of results below more scenarios are included than done for the previous product categories – for business purposes such insights with little absolute impact but with a considerable relative impact may still be of importance. In section 7.5 it is discussed how the results in absolute terms compare with the absolute results for the other product categories.

**Positive effects**

As with metals dominated products and precious metals dominated products, also for CRT based products scenarios related to the palladium concentration have a major impact. In a scenario combined with other precious metals the relative effect is 360%, of which more than 250% is because of the duplication in the palladium concentration. Scenarios related to palladium prices however have a lesser effect, due to the relatively low default palladium concentration. Here, for the progressive scenario an effect of
about 100% is calculated, for average to conservative scenarios the effects are 10-30%. Economies of scale scenarios with progressive effect on plastics prices, end-of-life processing costs and plastics recovery rates leading to substitution with high-yield plastics have a positive effect of around 330%. Average scenarios with still one progressive component and with substitution result in effects between 130% and 200%, without a progressive component a result of 109% is calculated.

In the previous chapter, five top-down legislative scenarios were drawn. Two of these include an increase in the aluminium content; these scenarios have also large effects of around 350%. The other three top-down scenarios that included increases in mainly the ferrous metals content and the high-yield plastics content result in effects of 240-310%.

The remainder of the scenarios all score less than 100%. Of these scenarios, legislative bottom-up scenarios have the largest effects, up to 90%. If one conservative effect is included, effects drop to 75% (plastics prices conservative), 52% (plastics recovery rates conservative) or 35% (processing costs conservative). For a conservative legislative bottom-up scenario but with progressive processing costs, a positive effect of almost 42% is calculated. A legislative bottom-up scenario where all parameters are kept on their average level scores 40%. Progressive to average economies of scale scenarios, without substitution with high-yield plastics, result in effects of 33-76%.

In the default material composition, the silver concentration is relatively high compared to the gold concentration. Still, the effects of increasing the gold concentration (67%) are higher than the effects of doing so with the silver concentration (41%), but these results indicate that compared to the other product categories, silver has a larger effect on the end-of-life revenues.

Three more of the scenarios investigated score effects larger than 20%. These are progressive to average scenarios in which the prices for type 1 and 2 plastics are increased (16-32%), conservative legislative bottom-up scenarios with progressive effects on plastics recovery rates (20%), and material substitution scenarios showing an increase in the copper or ferrous metals content at the cost of the recoverable plastics content (8-20%).

The lowest non-zero effects are caused by changes in the prices and recovery percentages of the different materials (2-15%), except palladium prices, which have a larger effect as indicated above.

**Negative effects**

The largest negative effect found for CRT based products are the effects of conservative copper prices (14.5%). In the same range (12.5%) are the effects of conservative economies of scale scenarios, legislative bottom-up scenarios, and processing cost scenarios. Material substitution scenarios exhibiting a reduction of the copper content result in a negative effect of around 10%. Finally, a conservative gold price scenario results in a negative effect of 8%.
7.4.2 Recyclability

Positive effects

Five top-down legislative scenarios were investigated for CRT based products, all these result in a recyclability score of 73.7%, which constitutes a relative improvement of 68%. It should be noted though that these scenarios, as explained in section 6.5.1, are representative of a situation in which a recyclability target of 90% is assumed, as opposed to the current 75% target.

Only progressive to average economies of scale scenarios, with progressive plastics recovery rates and high-yield plastics substitution, result in effect of the same order of magnitude, namely 53%. All other scenarios with positive effects result in scores of less than 25%, namely average economies of scale scenarios with progressive effects on processing costs or plastics prices, with high-yield plastics substitution, progressive to average economies of scale scenarios, without high-yield plastics substitution, progressive to average type 1 and 2 plastics recovery percentage scenarios, and progressive to average legislative bottom-up scenarios (all 10-20%).

Material substitution scenarios with increase in copper or ferrous metals content at the cost of recoverable plastics have a relative effect of around 4%, and progressive to average recovery percentage scenarios for ferrous metals, copper or aluminium have a relative effect of less than 1%.

Negative effects

Only material substitution scenarios with reduction of copper content show a negative effect of up to 2%.

7.5 Comparison of results across product categories

From the results of the scenario analyses presented above, a number of conclusions can be drawn. The conclusions in this section are based merely on the results stemming from the analysis. Further elaboration, assessing business consequences and derivation of industry recommendations will be presented in Chapter 8.

This section is structured in the following way. First, in section 7.5.1 a number of general observations are given that address the results as a whole. In section 7.5.2, per type of scenario an overview of results is given.

7.5.1 General observations from the ranking of results

- For all product categories, the scenarios investigated in this dissertation result in majority in positive effects on the end-of-life yield as well as on recyclability scores. However, this is only true for the majority of the progressive scenarios and most of
the average scenarios. The majority of the conservative scenarios however lead to inverse effects. It is dangerous to conclude from this result, that improving recyclability scores automatically will yield a positive financial result. The following issues should be carefully taken into account:

- Many of the progressive to average scenarios reflect a future in which end-of-life infrastructures have become more efficient, due to increased recovery percentages, material prices that have gone up, and the increased use of recoverable plastics. In such cases, indeed an increase in recyclability will coexist with an improved financial result. Conservative scenarios however in many cases reflect an unchanged end-of-life infrastructure, which means that when (parts of) the current infrastructure are assumed constant, improving recyclability will lead to negative financial consequences.

- It is also important to realize that improving recyclability scores has not only financial consequences in the end-of-life stage, but also in other parts of the product's life cycle. For example, while an increased use of high-yield plastics will both lead to improved recyclability scores and to a higher price obtained for secondary material fractions, the implementation of actually using these types of plastics will usually incur additional costs in purchasing, design and manufacturing. Such costs are not included in the present analysis. Considerations like these have been used to formulate a recommendation for further research (see section 9.4.4).

- The (positive and negative) effects on the end-of-life yield are relatively larger than those on recyclability scores, although a few of the material substitution scenarios included, especially those related to reduction of the ferrous metals content, have considerable negative impact on the recyclability scores.

- So far in this chapter, results have only been given in relative terms in order to compare them to the default scenario. In order to analyse results across product categories, comparing relative changes has no meaning since the default result are different for the different product categories (a high yield per kilogram for precious metals dominated products, a lower yield for metals dominated products, a positive yield close to zero for CRT based products (CRT removed), and a cost close to zero for plastics dominated products). In absolute terms, the following conclusions can be drawn:

  - By far the largest absolute effects are the result of palladium related scenarios for precious metals dominated products, including a gold concentration duplication scenario. Here, absolute end-of-life revenue increases in the range € 2.50 to € 12.50 per kilogram have been found. Precious metals related scenarios for the metals dominated and CRT based product categories result in absolute end-of-life revenue increases in the range of € 0.25 to € 2.00 per kilogram.

  - The top-down legislative scenarios for CRT based products that are related to an increase in aluminium content result in an increase of around € 0.60 per kilogram. The remaining top-down scenarios show an increase of around € 0.25 per kilogram.

  - The various economies of scale scenarios that lead to substitution with high-yield plastics are the next set of scenarios when ranked to absolute effects. Here, the first scenarios for the plastics dominated products category appear in the ranking. In Figure 36 the ranges are given for each product category with respect to the
absolute increases in the financial result. For CRT based products the effects are largest. In the metals dominated products case, the range is by far the smallest, indicating that the uncertainty of the size of the effect is here limited. This is easily explained since the metals dominated products category have a low plastics content, and since the partial effects of economies of scale scenarios depend considerably on plastics recovery rates and prices, the differences between the different economies of scale scenarios can be expected to be small for this product category.

![Diagram showing ranges of absolute positive effects from economies of scale scenarios per product category]

**Figure 36: Range of absolute positive effects from economies of scale scenarios per product category**

- Although palladium related scenarios for the precious metals dominated product category are clearly causing the largest effects, the remainder of the scenarios are well mixed across the different product categories though the scenarios for precious metals dominated products result on average in the highest effects, and the plastics dominated products score on average lower absolute effects. Considering negative effects a slightly different picture can be drawn; here also the precious metals dominated products category 'suffers' the largest negative effects, especially from average to conservative gold price scenarios and conservative copper price scenarios (€ $-0.12$ to € $-1.00$ per kilogram). Next, scenarios drawn for plastics dominated products are in the majority, mainly because of the relatively high negative effects of conservative scenarios for plastics prices (€ $-0.05$ to $-0.10$ per kilogram), and those for legislative bottom-up scenarios with conservative effects on processing costs (effects up to € $-0.10$ per kilogram as well).

- Noteworthy is also that the material substitution scenarios for metals dominated products exhibiting a decrease in ferrous metals content also score comparably high negative effects, in the range of € $-0.025$ to $-0.12$. The remainder of the scenarios that score negative effects have a negative effect of € $0.025$ or less per kilogram.

### 7.5.2 Observations per type of scenario

In this subsection it will be made clear, per type of scenario, what the similarities and differences are when the results for these scenarios are compared across product categories.
• **Scenarios related to precious metals**: Scenarios related to developments in palladium prices, palladium concentrations and to a lesser extent in palladium recovery percentages cause generally the largest effects of all scenarios analysed. Scenarios related to developments for gold also have a significant impact. Developments for silver however have relatively little effect, even for precious metals dominated products. These conclusions are especially true for precious metals dominated products, but also for metals dominated products and to a lesser extent for CRT-based products. The precious metals content in plastics dominated products is too low however to make scenarios related to palladium and other precious metals matter for this product category.

• **Scenarios related to non-ferrous metals**: Scenarios related to aluminium have usually negligible effects on the results, except in the top-down legislative scenarios where housings of CRT-based products were assumed to be made of aluminium rather than plastics. For plastics dominated products, material substitution scenarios where aluminium was substituted with copper resulted in a relative effect of 15%-25%. Aluminium price changes or recovery percentage increases do not lead to significant effects whatsoever which is obviously due to the low aluminium content in the analysed products. Copper related scenarios do in some cases lead to noteworthy effects. For metals dominated products, material substitution scenarios with copper substitution have relatively smaller effects (1%-5%) than for plastics dominated products. But similarly to aluminium, effects of changing copper prices and recovery percentages are very small (though larger than for aluminium since the copper content in products is higher than the aluminium content).

• **Scenarios related to ferrous metals**: In both the material substitution scenarios and the top-down legislative scenarios frequent use was made of changing the ferrous metals content in products. The most important thing about ferrous metals is the fact that in a relatively large number of products the ferrous metals content is high whereas the market price for ferrous metals is very close to zero. This leads to a situation where changes in the ferrous metals content lead to large differences in the weight-based recyclability percentage, especially if the substituted or substituting material has a much lower recovery percentage than ferrous metals. The effects on the economical performance indicator may be much smaller, for example when the alternative material is a low-yield or low-cost plastic, and even more so when it is a material that is processed cost neutrally together with valuable material fractions (for instance in a copper smelting process).

• **Scenarios related to plastics**: The effects of the scenario analysis related to plastics issues become most apparent for the plastics dominated products category. Therefore it is referred to 7.2 for an overview of these effects. Also, the economies of scale scenarios and the legislative scenarios are particularly relevant since these include effects on plastics prices and recovery rates.

• **Scenarios related to economies of scale**: These scenarios are, next to scenarios related to precious metals, of major importance compared to other types of sce-
scenarios. Only in the case of CRT based products, legislative scenarios that include an increase in the use of aluminium score higher effects. Differences between the different economies of scale scenarios are most apparent depending on whether an effect on plastics markets is assumed or not. In the case where increased economies of scale have such a stimulating effect on these markets, leading to the increased application of high-yield plastics, large positive effects can be observed for all product categories. This applies to especially the financial effects but also to the effects on recyclability, although the latter are less in relative terms. When such an effect on the plastics markets is not assumed, the effects become considerably less, except in the case of the metals dominated products category where the plastics content is too low to make a significant differences.

- **Scenarios related to legislative developments:** Because of the way legislative top-down scenarios are drawn in this dissertation, the results in this case show an increase in recyclability combined with a financial benefit. Although this is essentially correct, such results should be very carefully interpreted. They do not mean that increasing recyclability yields money, neither vice versa. It is only logical to see that an increase in the use of high-yield plastics that are both better recyclable and will therefore yield more money will indeed have benefits both ways. However, it is not taken into account here that such an increase in use of a certain type of plastics will also have repercussions on costs as well as environmental impacts incurred in other phases of the life cycle such as during design, purchasing and manufacturing. For a further discussion on this topic is referred to Chapter 8. Also, in this example the increased use of high-yield plastics may call for more sophisticated and therefore more expensive recycling technologies and thus have an increasing effect on the processing costs. Such effects are taken into account in the bottom-up legislative scenarios – the top-down scenarios were in the first instance drawn to show what requirements need to be set to technology and material use in order to meet recyclability targets.

As for the bottom-up legislative scenarios, the partial effects of changing processing costs are higher than the partial effects of changing plastics prices or plastics recovery rates. Generally, conservative effects on processing costs outweigh any positive effects on the plastics prices or recovery rates, and vice versa.

For legislative scenarios differences can be observed across product categories. In the first place, top-down scenarios were drawn for only two of the four main product categories because of the perceived irrelevance of doing so for the metals dominated category — because in the default situation high recyclability rates are already achieved — and for the precious metals dominated category — because for this product category high recyclability rates are considered practically impossible, see section 6.5.1). For both other categories, analysis results show that in the case of plastics dominated products end-of-life revenues rise by 25%-70%, and in the CRT-based products case this is 125%-288%. Also in absolute terms this latter increase is much higher due to the inclusion of aluminium substitution.
• **Material substitution scenarios:** In the case of no plastics recycling, it is clear that the scenarios related to changes in the precious metal concentrations show a larger impact than the scenarios related to changes in the other materials. This was to be expected since in particular gold and palladium concentrations influence the revenues of end-of-life processing because of their price/concentration index, as has been analysed in detail in a previous publication\textsuperscript{204} for precious metals dominated products, but which is also true for other product categories. Another reason is that the scenarios related to precious metals concentration changes (for example 1.5-1.8 in the metals dominated products case) represent as such increases that are percentage-wise much higher that in the other scenarios (1.1-1.4) though not necessarily less likely.

For metals dominated products, substituting copper for non-recoverable plastics or ferrous metals improve both end-of-life yield and recyclability, where the economical effect of substituting for non-recoverable plastics is almost double that of substituting for ferrous metals (again, based on the assumption that both substitutions are as likely). The effect on recyclability is almost 10 times the economical effect. Here it is important to realize that this does not include the full life-cycle perspective. It has already been explained in section 5.4 that for this purpose a different assessment method has been developed that calculates environmental effects based on environmental criteria rather than on weight.

Scenarios in which ferrous metals are substituted with plastics yield negative results, both for recyclability and for the end-of-life yield. If a plastics recycling scenario is considered with a 50% recovery percentage (keeping in mind that also the default values for the performance indicators change), the negative effects are reduced, in particular for the case where ferrous metals are replaced with recoverable plastics. But the relative sizes of these (negative) effects are still more than three times larger than the (positive) effects of the copper related scenarios 1.3 and 1.4 – even though in a plastics recycling scenario the relative effects of the copper related scenarios are less distinct than in a no plastics recycling scenario.

Considering plastics dominated products, substituting aluminium with copper gives a relatively large economical effect though the effect on recyclability is negligible. The substitution of ferrous metals with plastics gives similar economical results though the effects on recyclability are 10 to 20 times higher. When only high-yield plastics are used for the substitution, the economical effect becomes considerably more favourable in relative terms (although in this category’s case the margins are small since the default economical result is close to zero). Finally, substituting copper for ferrous metals like in scenario 2.3 only results in marginal changes compared to the other scenarios.

\textsuperscript{204} Boks, C., Huisman, J. and Stevels, A. "Combining economical and environmental considerations in cellular phone design", proceedings of the 2000 IEEE International Symposium on Electronics and the Environment, May 8-10, San Francisco, USA.
As for the results of material substitution scenario analysis for precious metals dominated products, few interesting conclusions can be drawn. The large effects of the precious metals content prevail, and the remainder of the product is comparatively irrelevant.

Considering CRT based products, material substitution scenario 4.2 and 4.4 in which copper is substituted with recoverable plastics and ferrous metals exhibit decreases in EOL yield of about 10%. A substitution the other way around as examined in material substitution scenario 4.1 yields a positive effect of about 20%. A substitution between ferrous metals and plastics as seen in material substitution scenario 4.3 yields a relative low effect compared to the other, non precious metals related scenarios. For the material substitution scenario analysis for CRT based products it can also be concluded that the relative effects are smaller than those for the other product categories. An explanation for this fact is the fact that designs for this product category are more similar than compared to the other product categories. Apparently, less degrees of freedom exist to design the product geometry and material application around a CRT.

- **Scenarios related to recovery rates:** Compared to most other scenarios analysed in this dissertation, scenarios that are based on improvements in recovery rates have little to no impact on the results.

### 7.5.3 Combining economical and environmental effects

At the beginning of Chapter 4 it has been explained why eco-efficiency is not used as a performance indicator for end-of-life scenarios throughout this dissertation. In section 9.4.9 it is indicated why further research about the definition and implementation of eco-efficiency concepts is considered necessary. In this section some remarks are nevertheless made about observations that can be made when interpreting simultaneously the economical and environmental performance indicator for an end-of-life scenario. For this purpose, a new performance indicator is calculated as the absolute effect on the economical score divided by the absolute effect on the recyclability score. This quotient gives a figure that can be interpreted as the economical investment or benefit associated with an increase of recyclability score of 1 kg of the applicable product by 1 percent point. Analysis of the thus derived indicators reveal the following observations.

- For all product categories the majority of legislative and economies of scale scenarios exhibit the highest economical benefits associated with a fixed increase in recyclability score. This means that compared to the other types of scenarios investigated, here the monetary rewards for doing well from a (weight-based) recycling perspective are the highest.
- Technology scenarios score comparatively low, for all product categories, in comparison with legislative and economies-of-scale scenarios, because of the very small economical benefits that may result from technological improvements. If a subdivision is made further, it can be concluded that technological improvements for aluminium recovery lead to the highest economical benefits given a fixed increase in product recyclability score, followed by technological improvements in copper and
ferrous metals recycling. In the current situation, with no stimuli for improving the secondary plastics markets, assumed prices for plastics are so low that ceteris paribus improvements in plastics recycling technology (so without the assumption that this will in turn lead to maturing secondary plastics markets) result in comparatively very low monetary benefits. However, when these positive effects on the markets are assumed, as is done in the various economies-of-scale scenarios, it is clear that technological improvements in plastics recycling can be part of a successful scenario, as indicated above. Thus, here it is shown again that the interpretation of the various scenarios from an eco-efficiency perspective needs to be made very carefully, since by losing the context of a scenario one runs the risk of drawing the wrong conclusions.
8. Conclusions and Recommendations for the Industry

In the previous chapter an overview was given of the effects of the different scenarios investigated in this dissertation. So far, plain results have been given only, without elaborating on their effects for the manufacturing industry. In this chapter, it will be discussed in what way the previous results should be interpreted, what effects they will have on choices to be made, and directions for priority setting will be derived so businesses can act in a more proactive way than before to the various developments discussed in this dissertation.

In this chapter, the research questions put forward in the first chapter form the basis for the way the issues are addressed in this chapter. In particular the second part of the third question, asking which focal areas can be identified for manufacturing companies to facilitate the generation of business opportunities is addressed here.

This chapter is structured in the following way. The results presented in the previous chapter are first grouped and ranked to provide an overview which types of developments cause the major influences on the performance indicators for the different product categories. Next, for the various developments an overview is presented in which the ability of companies to influence the various discussions is discussed. Both results are then combined in section 8.3 to determine the relative importance of the various end-of-life developments based on both arguments. In addition, in sections 8.4-8.6 general recommendations are derived for the three cornerstones design, technology and policy.

8.1 Summary of previous results

From the scenario analysis results derived in Chapter 7, scenarios can be grouped per product category so that they reflect their order of importance based on the size of their relative effects in comparison with the default scenarios. This ranking is done for the economic performance indicator in Table 50, and for the recyclability score in Table 51. In these tables only positive effects are shown. As can be recalled from Chapter 7, only a limited number of negative effects were analysed. It should be noted though that if Table 50 is interpreted without paying attention to sign, the results are generally true as well.
<table>
<thead>
<tr>
<th>Metals dominated products</th>
<th>Plastics dominated products</th>
<th>Precious metals dominated products</th>
<th>CRT based products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Largest effects scenarios</td>
<td>Palladium related scenarios</td>
<td>Palladium and gold related scenarios</td>
<td>Palladium related scenarios</td>
</tr>
<tr>
<td>Second economies of scale scenarios</td>
<td>Top-down and bottom-up legislative scenarios</td>
<td>Economies of scale scenarios</td>
<td>Top-down legislative scenarios related to aluminium increase</td>
</tr>
<tr>
<td>Third Bottom-up legislative scenarios</td>
<td>Economies of scale scenarios, copper price scenarios without substitution</td>
<td>Recovery percentage scenarios, economies of scale scenarios without substitution, processing cost scenarios</td>
<td>Economies of scale scenarios</td>
</tr>
<tr>
<td>Fourth Material substitution</td>
<td>Remaining top-down legislative scenarios</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 50: Ranking of grouped relative effects per product category (for economical performance indicator)

From Table 50 the following conclusions can be drawn:

- Palladium price or concentration related scenarios result in the largest effects for all product categories, except in the plastics dominated products case.
- Economies of scale related scenarios that lead to material substitution with high-yield plastics result for all categories in the second largest effect, except for the plastics dominated products category where it gives the largest effects. For CRT based products, material substitution scenarios related to an increase in the aluminium content also show large effects.

From this it can also be concluded that the main priorities for all four product categories are similar, with the exception of plastics dominated products where the lack of precious metals content makes scenarios related to this issue relatively unimportant.

- For metals dominated products, because of the low plastics content, not much difference exists between economies of scale scenarios with and without high-yield plastics substitution.
- Except for the precious metals dominated category, legislative scenarios result in the third largest effects. Top-down legislative scenarios do have a higher impact than bottom-down legislative scenarios. It should be noted though that top-down legislative scenarios are to be considered as forced measures which will have many (negative financial) consequences in other aspects of business as they often imply a radical change in material application with all its associated financial as well as environmental impacts, as well as an increase in recovery percentages for which technology investments will probably be paid for, directly or indirectly, by manufacturing businesses as well.

For the precious metals dominated products category, legislative scenarios play a lesser role in comparison to most other scenarios such as recovery percentage scenarios, copper price scenarios and processing cost scenarios.
The material substitution scenarios (other than related to precious metals) as investigated in this dissertation do play a minor role compared to economies of scale and legislative scenarios. However, these scenarios are far better to influence by companies than most of the other investigated scenarios and are therefore still of importance. This issue is further discussed in section 8.2.

<table>
<thead>
<tr>
<th>Metals dominated products</th>
<th>Plastics dominated products</th>
<th>Precious metals dominated products</th>
<th>CRT based products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Largest effects scenarios with substitution</td>
<td>Economies of scale scenarios, economies of scale with substitution</td>
<td>Economies of scale scenarios with substitution</td>
<td>Top-down legislative scenarios, progressive economies of scale scenarios with substitution</td>
</tr>
<tr>
<td>Second largest effects scenarios with recoverable for non-recoverable materials</td>
<td>Material substitution scenarios, bottom-up legislative scenarios, economies of scale recoverable materials (no substit.)</td>
<td>Material substitution scenarios with recoverable for non-recoverable materials</td>
<td>Plastics recovery rates scenarios, selected average economies of scale scenarios</td>
</tr>
<tr>
<td>Third largest effects substitution), ferrous metals recovery percentage scenarios, various legislative scenarios</td>
<td>Economies of scale copper recovery percentage scenarios scale and legislative scenarios with progressive effects on plastics recovery percentages</td>
<td>Various economies of scale and legislative scenarios with</td>
<td>Legislative bottom-up scenarios, economies of scale scenarios (no substitution)</td>
</tr>
</tbody>
</table>

Table 51: Ranking of grouped relative effects per product category (for recyclability score)

From Table 51 the following conclusions can be drawn:

- Scenarios reflecting improvements in economies of scale and that are assumed to lead to substitution for high-yielding recoverable plastics, yield for all product categories the largest positive effects. Economies-of-scale scenarios that do not assume substitution yield mostly third order effects.

- For the plastics dominated product category and the CRT-based product category, top-down legislative scenarios have comparably large effects, but here it is noted again, like above, that top-down legislative scenarios will have considerable (negative financial) consequences in other aspects of business.

- For the same two product categories, that have a comparatively high amount of plastics, the second largest effects are to be expected from scenarios in which the plastics recovery rates increase. For this reason, effects from legislative bottom-up scenarios with a progressive component for plastics recovery rates score in the same order of magnitude for plastics dominated products. For the metals and precious metals domi-
anted product categories, the second largest effects come from material substitution scenarios in which non-recoverable materials are replaced with recoverable ones.

- Scenarios reflecting improvements in recycling technology performance score comparatively small effects. Some progressive scenarios reflecting improvements in the recovery of ferrous metals and copper yield minor effects.

8.2 The ability of companies to influence various developments

For the majority of developments discussed in this dissertation it is evident that they are outside the influence of business. In this subsection, this issue is discussed in short for each of the main uncertainty factors in discussed in this dissertation.

Material prices

Companies have no alternative but to regard material prices as a given. Since from Table 50 it is evident that relatively, the largest effects originate from price developments, companies may want to look for ways to reduce uncertainties associated with these kinds of developments. However, it is unlikely that the fluctuations in material prices will actually affect manufacturing business in a serious way. On the contrary, on a short-term basis only recycling companies are likely to experience such effects. Only in the case where dropping material prices will negatively affect the revenues for recycling companies, they are likely to increase the fees or lower the prices of processing end-of-life products – and only then manufacturing companies will be affected. In the case of positive price developments, the recycling companies are likely to “keep” the benefits from this as long as competition permits.

For plastics prices, the situation might be different, especially in the case of very immature plastics markets. It has been pointed out previously that the manufacturing industry as a whole can stimulate the maturing of these markets by ensuring that plastics parts are eligible for recycling by avoiding contaminations that will frustrate the recycling process. For the individual company the ability to influence this process will be very limited. However, in case of brand specific processing, companies might reap the benefits of good ecodesign if this results in less plastics waste or even revenues from plastics recycling. Still, this will depend greatly on the available volumes of WEEE for a particular brand and the demand for such recycled plastics (see also the paragraphs below on economies of scale).

Material substitution

Of all types of scenarios investigated in this dissertation, material substitution scenarios provide theoretically the best options for companies to influence the performance indicators. Although choices in material composition always have to be balanced with other usually important business factors, almost always some degrees of freedom exist to improve a product from an end-of-life point of view. The most important consideration that should be taken into account here is the life-cycle perspective. Several mate-
rial substitution scenarios analysed in this dissertation show that an increase in ferrous metals at the cost of other constituent materials (mostly plastics) will increase both recyclability and end-of-life revenues. However, many examples exist where the use of plastics from a life-cycle perspective is preferred over the use of metals, as can be seen in Table 52 in which an example shows that having a metal housing of some kind is preferred over having a plastic (in this case PVC) housing when only end-of-life considerations are taken into account (see the row marked ‘End-of-life recycling’). However, when the total life cycle, including the complete production process and prevented emissions from recycling are included (row marked ‘Total life cycle’), the PVC option is preferred over the steel option. For comparison, also a HIPS and an aluminium example are included, which both score worse over the whole life-cycle in comparison with steel and PVC. However, when a correction for volume is taken into account, as is done in the last row, it becomes clear that the steel option has become the worst option. This is because of the high specific gravity of steel, which makes that for the same functionality (a housing in this case) more material on a weight basis is required in comparison with the plastics options and the aluminium option.

<table>
<thead>
<tr>
<th>Environmental impact (based on Eco-indicator 99, in mPt):</th>
<th>Steel option</th>
<th>PVC option</th>
<th>High Impact Polystyrene option</th>
<th>Aluminium option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete production process</td>
<td>258.8</td>
<td>337.7</td>
<td>674</td>
<td>841</td>
</tr>
<tr>
<td>End-of-life recycling</td>
<td>48.5</td>
<td>80.1</td>
<td>80</td>
<td>26.9</td>
</tr>
<tr>
<td>Prevented emissions</td>
<td>-88.9</td>
<td>-233</td>
<td>-313</td>
<td>-526</td>
</tr>
<tr>
<td>Total life-cycle</td>
<td>218.4</td>
<td>184.8</td>
<td>441</td>
<td>341.9</td>
</tr>
<tr>
<td>Total life-cycle with correction</td>
<td>1622.7</td>
<td>237.6</td>
<td>441 (norm)</td>
<td>879.2</td>
</tr>
</tbody>
</table>

Table 52: Example of the end-of-life perspective versus the life-cycle perspective

So, the result which material scores best over the full life cycle depends on the characteristics of the raw materials extraction process, the manufacturing processes as well as on the way material fractions are treated in the end-of-life stage. Also, the material application itself should be considered, as is shown in the volume correction example. The main issue here is that generalisations are not always possible, and that it is therefore advisable to always include an environmental analysis when generating options for environmentally improved design. This is also acknowledged in for instance the description of the Philips environmental benchmark method. Here, it is prescribed that after the benchmarking of the five green focal areas of a product (energy, weight, hazardous substances, packaging and recyclability) an abridged LCA is carried out to assess total environmental impact. The results of this analysis are to be weighed with other feasibility criteria in order to arrive at a meaningful prioritisation of green design options.

Processing costs

Processing costs are incurred by recycling companies, and are determined based on the costs necessary for processing end-of-life equipment. These costs depend both on the characteristics of the streams of products are material fractions that are processed and on the potential retrieval of valuable fractions included in these material streams. In this light, the way products are designed determine the processing costs, and manufacturing companies do have some (indirect) influence on them. However, since the bulk of WEEE is usually processed as a mix of products from a wide range of different brands, product generations and product types, adjusting product designs to influence processing costs only makes sense in the case of brand specific, but also product (generation) specific processing. In the case a manufacturing company is convinced that their products have a potential benefit over products from other brands in terms of ease of processing, or embedded value, or generally in terms of 'good' ecodesign, brand specific processing could be considered, and processing costs are potentially influenced (see also section 9.4.3). A prerequisite in this case is always the economies of scale; although theoretically streams of WEEE of a specific brand could be processed cheaper because of the reasons stated above, when combined with streams of WEEE from other brands costs could be lower because of economies of scale even though some of the embedded value might be lost when products of this specific brands are processed with products from brands that are 'less ecodesigned'.

Technology and recovery rates

Unless manufacturing companies are in a position to invest in or closely cooperate with recycling companies they have few options to influence the recovery percentages and grades associated with recycling processes. These are usually autonomously set by recycling companies as they have to deal with multiple input streams including products from many brands, and consequently the process parameters are chosen by the recycling company to optimise their revenues. Examples exist however of brand specific processing — in such cases, under the assumption of favourable economies of scale, the process parameters can be set to optimally retrieve the benefits of good ecodesign efforts of the applicable manufacturing company. This way the company can theoretically improve the recyclability performance of its products through indirectly increasing the recovery rates. But generally, manufacturing companies should not regard influencing recovery rates as a possibility to improve end-of-life performance of their product or to reduce uncertainty. However, using the results of the analysis presented in this dissertation, it is possible to determine where investments will lead to the best results, in case such investments are considered or possible.

Legislation

In this dissertation a distinction was made between bottom-up and top-down legislative scenarios. Top-down legislative scenarios were included to compare the effects of different solutions that make attaining recovery rates set by legislation possible, and to compare such effects with other scenarios. The top-down scenarios consist of a com...
bination of effects, related mainly to material content and recovery percentages. In the previous subsections it was pointed out that changes related to the material content of products are among the factors that can to a certain degree be influenced by manufacturing companies (though this is largely a financial issue where the boundaries of competitiveness determine the design bandwidth), for recovery rates this is much less so. The main conclusion that can be drawn from drawing top-down legislation scenarios is that through such analyses it can be determined which options exist for attaining required recyclability rates, if balanced by important elements of business. From this perspective, it is obvious that some top-down scenarios contain more opportunities for control by companies than others, depending on the amount of using material substitution to reach required recyclability rates. Whereas some top-down scenarios are based mainly on material substitution alternatives, other scenarios depend rather on changing recovery percentages, implying that companies have little opportunity to actually realize these scenarios by their own. Here, companies have to depend on what opportunities the recycling infrastructure offers.

**Bottom-up scenarios** were drawn to reflect various settings of parameters that are likely to be influenced by developing legislation. The developments reflected in these parameters (processing costs, plastics prices and recovery rates) are even more so to be regarded as largely outside the influence of the manufacturing company. The use of monitoring these developments is not in the first place in being able to influence or counteract the effects on the model parameters, but rather to be able to assess the magnitude and relative importance of the sizes of these effects in comparison to the effects of other developments. Also, in a legislative context it is important to see confirmed that a distinction in product categories as made in this dissertation is warranted by the analysis results. Although a general ranking of scenarios can be observed, the differences in material composition between the four main product categories are thus that differences in the economical/environmental results profile are clear. For plastics dominated products, both top-down and bottom-up legislative scenarios have relatively large effects. For top-down scenarios this is due to the fact that default recyclability scores are low, so that default recyclability score and target recyclability score are far apart, asking for 'drastic' parameter adjustments resulting in large effects. For bottom-up legislative scenarios this is because these scenarios in particular include effects related to the plastics fraction, which is obviously high for this product category. For metals dominated category much less uncertainty as regards to legislative developments is present since high recyclability rates are already presents, and because of the low plastics content bottom-up scenarios have little effect. As for precious metals dominated products, the material composition here causes other developments to be of much higher importance. For CRT-based products, top-down scenarios that include an aluminium substitution component rank relatively high, to the remainder of the legislative scenarios a relative importance can be addressed similar to the plastics dominated products category, be it that in contrast to the latter category, for CRT-based products case precious metals related scenarios rank higher than legislative scenarios.

Based on these arguments it is clear that discussions on setting recyclability targets for consumer electronics products should be based on a relatively detailed product cate-
gory level, or rather a product characteristics level. A distinction in branch organizations (white goods, brown goods, IT equipment etc.) will lead to cases where the roughness of the distinction leads to unattainable recyclability targets. The best example for this is the precious metals dominated products case for which it has been shown that recyclability targets of as high as 70% are unrealistic using material recycling processes. The material composition of these products includes a relatively high amount of non-recyclable material, which would even prevent disassembly to be a solution for attaining higher recyclability targets. Recycling and the recovery of value of these products will occur anyway because of the high monetary yields embedded in the product, and the sophisticated processes needed for retrieving this value will guarantee an environmentally sound way of taking care of the non-recyclable parts of these products.

Economies of scale

Economies of scale are attained by increasing WEEE collection rates, efficient organization of logistics processes and recycling infrastructures as a whole. In general, manufacturing companies have little say in these matters as they are determined by (investment) planning of other companies and municipal or governmental bodies. Only by cooperation, lobbying and proactively taking part in (the organization) of end-of-life infrastructures, manufacturing companies can contribute in establishing efficient WEEE processing and participate in reaping the benefits of favourable economies-of-scale. Especially in the consumer electronics industry however, no single company is large enough to influence economies of scale by itself. It was already determined that the most important benefits of economies of scale are likely to be found in reduction of processing costs and in the increase of secondary plastics prices and recovery rates.

The degree to which return logistics is to be regarded as an external influence depends on the size of the company. For smaller and medium-sized companies, an existing return logistics infrastructure is to be assumed as given, as little possibility exists for these companies to exert any major influence on this, except perhaps by representation through a branch organisation. For multinationals the influence they can have on the initiation and organisation of return logistics infrastructures can in some cases be bigger. In the Netherlands, Philips Consumer Electronics was closely involved in setting up the present collection infrastructure.

Conclusion

In conclusion, for individual companies limited opportunity exists to influence the developments of external factors discussed in this dissertation. Exceptions are obviously the opportunity to manufacture well-ecodesigned products, but it is unlikely that producers will directly reap the benefits of this except when these products are processed through a brand specific recycling system. In such a system, products of a single brand are isolated from ill-designed brands, and the benefits of this distinction can potentially be attributed to a specific producer. Considerations like these form the basis for justification of a collaboration between stakeholders in the chain, an issue that is addressed further on in this chapter.
In this section the opportunities for influencing developments have been addressed for individual companies only. Currently however, through lobbying, for example via representing branch organisations such as the FIAR (the Dutch branch organisation for brown goods manufacturers) and EACEM (the European Association of Consumer Electronics Manufacturing), the national and international legislation processes can be influenced to some extent. This applies not only to the content of the legislation but also to the proposed time schedules for implementation. Also, from forming consortia of producers that have reached a similar level of ecodesign sophistication, benefits are to be expected in various fields. Apart from more effective lobbying, from an economies of scale perspective, volumes of ecodesigned products from different brands that are processed together will potentially positively influence processing costs and stimulate markets for recycled materials. An analysis of the potential effects of such a lobby and consortia-forming process requires a clear view on all applicable (internal and external) environmental value chain factors. It is beyond the scope of this dissertation to fully address these issues here. The importance of further research on environmental value chain subjects is stressed in section 9.4.7.

8.3 The relative importance of end-of-life developments

In this section, the conclusions of the two previous sections are used to derive recommendations for priority setting. More precisely: the ranking of results as given in 8.1 is now put into the proper business perspective by using the considerations outlined in 8.2 regarding the ability of companies to influence the various developments discussed in this dissertation. Hence, in the subsequent subsections the conclusions of the previous subsections are combined, for each product category separately. Although the ranking of the effects, although different in relative size, is similar for all product categories, enough differences were found from the results of the scenario analysis (see also Table S2) to warrant a separate prioritisation.

The recommendations brought forward in this section are initially derived based on economical considerations. The reason for this is that it has been shown that for the reviewed scenarios, the effects on recyclability scores are in general smaller than those on the end-of-life yield. Due to the nature of the scenarios drawn, a considerable part of the scenarios has no effect on the recyclability score at all.

The interpretation of the terminology in this section should be done in relation to the research questions put forward in the first chapter of this dissertation. By 'relative importance of end-of-life developments' it is meant that based on the scenarios drawn and evaluated in this dissertation, it can be concluded that some scenarios have a larger impact on performance indicators for these scenarios than other scenarios, under the assumption that they are about equally likely to happen, as discussed in Chapter 6. The associated priority setting is then implicitly made: the one development results in larger effects than the other, and companies should thus be aware that it could pay off to monitor the former more closely than the latter – issues that are discussed further on in this chapter.

218
8.3.1 Priority setting for metals dominated products

The prioritisation matrix for focal areas in the case of metals dominated products is given in Table 53.

<table>
<thead>
<tr>
<th>Focus area</th>
<th>Relative size of expected effects</th>
<th>Ability to influence developments</th>
<th>Combined effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material application</td>
<td>++</td>
<td>-</td>
<td>0/+</td>
</tr>
<tr>
<td>in case of precious metals</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>in case of other metals</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>in case of plastics</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Recycling technology</td>
<td>-</td>
<td>--</td>
<td>--/-.</td>
</tr>
<tr>
<td>Legislation</td>
<td>0</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Economies of scale</td>
<td>+</td>
<td>--</td>
<td>0/-.</td>
</tr>
</tbody>
</table>

Considering the first column, the following legend applies:

++ no focal area with larger effect.
+ only one focal area with a larger effect
0 noticeable effect, but several larger
- no or almost no effect

For the second column, the following legend applies:

+ through proper design some influence can be exerted
0 possible to influence with substantial (financial) efforts
- very difficult to influence, maybe through suppliers
-- generally impossible to influence

Table 5.3: Prioritisation matrix for focal areas for metals dominated products

It is evident that a focus on the application of metals in metals dominated products should be the main priority. If this issue is well taken care of, uncertainty regarding the effects on end-of-life yields is limited. Although the expected relative size of increased/reduced precious metals use or fluctuations in gold and palladium prices is relatively largest, companies are not always in a position to influence electronics design as electronics parts are often bought from suppliers. If however a company is in a position to pay attention to environmentally conscious electronics design and/or supply management, the ability to influence and control the effects of precious metals applications will increase.

Compared to metals, the issue of plastics applications is relatively unimportant for this product category. The expected effects of economies of scale scenarios have potentially larger effects, however the ability to influence these developments is limited.

8.3.2 Priority setting for plastics dominated products

The prioritisation matrix for focal areas in the case of plastics dominated products is given in Table 54. For the applicable legend for this table please refer to section 8.3.1.
Table 54: Prioritisation matrix for focal areas for plastics dominated products (for legend, see Table 53)

In was already pointed out that compared to metals dominated products, the application of precious metals is irrelevant for plastics dominated products. In the above table, focusing on plastics as well as ferrous and non-ferrous metals applications is considered equally important. It is has become clear that the advantages of using plastics suitable for recycling are relatively large, and that the negative consequences of failing to do so are equally present. However, the opportunities for companies to make sure that the embedded plastics value of well-ecodesigned products is actually retrieved in end-of-life infrastructures, is limited. The potential benefits of careful monitoring the application of metals are relatively smaller, but once this is done properly, the advantages of doing so are less uncertain.

No distinct difference was found for the effects of legislation and economies of scale developments in general. However, favourable economies of scale leading to more mature secondary plastics markets will have a particularly positive effect for the plastics dominated and result in larger effects compared to legislative developments. If such effects on plastics markets are assumed to be absent, the effects will be smaller than those of legislative developments.

8.3.3 Priority setting for precious metals dominated products

The prioritisation matrix for focal areas in the case of precious metals dominated products is given in Table 55. For the applicable legend for this table please refer to section 8.3.1.

Table 55: Prioritisation matrix for focal areas for precious metals dominated products (for legend, see Table 53)
For precious metals dominated products a similar situation as for metals dominated products occurs. The expected effects of focusing on precious metals application in particular are partly outweighed by the fact that companies are relatively limited in the flexibility of the design and application of electronics fractions. The recommendation for this product category is thus to attempt to take control of this issue in similar ways as for the metals dominated products category. The relatively high copper content for precious metals dominated products is also mainly applied in relation to electronics design (but also in the remainder of the product) and attention for this issue should be included simultaneously. Due to the size and functionality requirements of the plastics parts in these products the application of plastics should receive relatively less focus. This could change however if for example in the case of cellular phones future legislation will demand separation of LCD parts – if at the same time plastic cover parts can also be separated the importance of using plastics fit for recycling becomes increasingly important.

8.3.4 Priority setting for CRT based products

The prioritisation matrix for focal areas in the case of CRT based products is given in Table 5.6. For the applicable legend for this table please refer to section 8.3.1. This matrix should be carefully interpreted as it applies only to the product from which the CRT has been removed. In case the whole product is considered, including CRT removal, it is likely that recycling technology, or in this case disassembly technology, increases in importance as a focal area.

<table>
<thead>
<tr>
<th>Focus area</th>
<th>Relative size of expected effects</th>
<th>Ability to influence developments</th>
<th>Combined effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• in case of precious metals</td>
<td>++</td>
<td>-</td>
<td>0/+</td>
</tr>
<tr>
<td>• in case of other metals</td>
<td>0</td>
<td>+</td>
<td>0/+</td>
</tr>
<tr>
<td>• in case of plastics</td>
<td>+</td>
<td>0</td>
<td>0/+</td>
</tr>
<tr>
<td>Recycling technology</td>
<td>-</td>
<td></td>
<td>-/-</td>
</tr>
<tr>
<td>Legislation</td>
<td>+/-</td>
<td></td>
<td>Q/-</td>
</tr>
<tr>
<td>Economies of scale</td>
<td>0</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.6: Prioritisation matrix for focal areas for CRT based products (for legend, see Table 5.3)

It was already pointed out that the characteristics of CRT based products are a mix of the characteristics of all other product categories. They contain a relatively high concentration of precious metals, but often contain plastics parts that are potentially eligible for recycling. This makes that the remarks regarding precious metals made for the (precious) metals dominated categories are also valid for CRT based products and are not be elaborated further on here. This is also true for the application of plastics in the light of plastics markets developments. As for metals, the researched top-down legislative scenario that assumed the application of aluminium in housing parts was found to have large effects. Not assuming this application, attention for legislative developments should receive less attention than those for economies of scale.
In the subsequent sections 8.4 to 8.6 recommendations will be made for OEMs related to the three cornerstones design, technology and strategy. These are distilled from the scenario analysis results and the previous discussions on prioritisation.

**8.4 Recommendations for design**

For several reasons (legislative, economies-of-scale related, and also technological) the application of plastics in products is one of the most important, and especially omnipresent issues that will affect end-of-life scenarios. Therefore, this issue should be well addressed. Three important types of considerations are applicable here. First of all the application of plastics versus alternative (construction) materials should be well considered. If the choice for a plastics application is made, the type of plastic is the next important choice to be made. Thirdly, the way the chosen type of plastic is applied is of relevance to end-of-life scenarios. With respect to the first two considerations, these should not be made from an end-of-life perspective only. Moreover, end-of-life considerations are probably a factor of limited importance — this is true from a life-cycle environmental perspective, but even more so from a total business perspective where cost, quality and image play important roles. Still, degrees of freedom will exist, which has been shown to be likely from the analysis of the benchmark reports, from which the material substitution scenarios presented in section 6.6 have been derived. The application of plastics that are not contaminated with various coatings and additives is in many cases possible even when the usual business criteria have been applied. Moreover, in the light of impending legislation, in particular in the case of plastics dominated products, companies will have to consider these actions anyway or otherwise they will not meet recyclability requirements. As for the third consideration pointed out above, a range of design guidelines exists to facilitate both disassembly and recycling, focusing on the fixation of plastic parts, addressing unlocking and separability characteristics, avoiding stickers et cetera. These guidelines can usually be applied without interfering with other criteria or environmental performance in other life-cycles, and should therefore be carefully applied. As for metals, similar considerations are important, though differences will generally be smaller, especially from an economic point of view.

It has been suggested to better include electronics design as a part of the product design. The presence of electronics fractions, and especially depending on their precious metals content, can greatly determine the end-of-life route, and in particular the way of (post)processing that will be applied to a product. Guidelines addressing the positioning of electronics fractions in products are important here, but should be coordinated with product design itself. Efforts to position certain electronics parts for easy disassembly or separation may be futile if these apply to relatively worthless fractions. This depends also greatly on the product category they are used in since this often determines the appropriate end-of-life scenario.
8.5 Recommendations for technology

It has been shown that changing recovery percentages and grades have comparatively little effect on the performance indicators for end-of-life scenarios. This leads to the conclusion that investments in recycling technology are not to be given high priority for reducing end-of-life costs, increasing end-of-life revenues or improving recyclability rates. This is true even when it is considered that companies have little opportunities for doing so. Only when the possibility arises to organise an agreement with a recycling company about brand specific processing, opportunities increase, provided economies of scale are favourable.

8.6 Recommendations for policy

At various stages in the structure of this dissertation the importance of the environmental value chain has been stressed. Research results have little meaning if no attention is given to their further dissemination through appropriate channels in a company. Even quantitative results and representing them in business terms are no guarantee for acceptance and implementation. This is especially true for environmental topics as these are still often perceived as a threats rather than opportunities.

Value chain analysis as explained in Stevels and Ishii is likely to prevent this from happening. These considerations are not only valid on a company level, but can be important advice for ‘the next management levels’ as well. When deciding upon a strategy concerning end-of-life issues (but this is also valid for other issues), this strategy should be aligned with the opinions, values and priorities of external stakeholders.

The end-of-life stage is part of a life-cycle. Product design itself is part of a chain of activities as well. Supply management is one of the activities in this chain. In the consumer electronics industry OEMs purchase a large number of components and subassemblies rather than manufacturing these themselves. It has been pointed out that including end-of-life (and other environmental) considerations in the selection of suppliers and in maintaining contacts with them, the presence of relevant materials in these components and subassemblies can be kept under control. Not only will this potentially benefit the performance of products during the end-of-life, but will have many more positive side-effects such as the prevention of unexpected occurrences of unwanted materials in products. This is very important since such occurrences can have drastic consequences for example brand image.

The importance of lobbying in politics and stakeholder groups, for example by means of participation in the formulation of legislative directives, but also the organisation in branch organisations and forming consortia with recycling companies and/or other OEMs has been pointed out in this dissertation. For the majority of companies this is the only way to gain some degree of control as to what happens with their products in the end-of-life stage. This is particularly true with respect to having some influence in legislative processes and ensuring favourable economies of scale for the collection and
processing of end-of-life products. Based on these considerations, the following generalising statements can be substantiated for the product categories and scope considered in this dissertation:

- Considering end-of-life issues, manufacturing companies should make at least a minimum effort as required by legislation to avoid negative consequences from non-compliance.
- Little benefits are to be expected from doing slightly better than the minimal requirements, as any monetary benefits that may result from this will probably end up in the recycler's pocket and not the manufacturing company itself. However, some indirect positive effects may result from marketing these better than minimal efforts.
- Considerable (monetary) benefits can be expected from doing considerably better than the minimal requirements, provided that a company becomes horizontally as well as vertically integrated with other stakeholders in the chain. In horizontal terms, this refers to coalition or consortia forming with competitors with similar objectives. In vertical terms, this refers to consortia forming with suppliers as well as recycling companies.

Lastly, in section 9.4 a large number of suggestions are done for future research, either by academia or by businesses themselves. Addressing these research topics can be an important part of strategy as well. They should be considered as an important result of this dissertation.
The Relative Importance of Uncertainty Factors in Product End of Life Scenarios
9. Discussion, Contributions, Future Research

9.1 Discussion

In the past ten years the issue of take-back and recycling of waste of electrical and electronic equipment (WEEE) got an increasing amount of attention. In many respects, the first initiatives that led to the German 1991 draft ordinance for recycling of waste from electric and electronic equipment (WEEE) can be seen as the starting point for the societal, technical, juridical and scientific debates about this subject. Since then, producers of electrical and electronic products, as well as research institutes across the world have increasingly tried to tackle issues related to the product’s end-of-life stage.

The difficulties encountered among stakeholders to agree about setting up recycling infrastructures for WEEE is reflected by the fact that so far in few countries public take-back and recycling systems really operate: Austria (refrigerators and freezers), Denmark, the Netherlands, Norway and Switzerland (all electronics). Although in the years to follow several countries (Belgium, Japan, Sweden and perhaps others) will join this list, it is clear that it will take many years before take-back and recycling of electronics will have been implemented on a comprehensive scale in the various regions of the world.

In research so far, the end-of-life issue has been described mainly from a point of view where existing infrastructures have been assessed, through pilot projects on a regional scale. Lack of knowledge regarding future developments have caused this research to be of a static nature mainly (section 1.2.2), without assessing possible future developments in technology and economy. And since the vast majority of legislative initiatives has not crystallized out yet, also developments because of these legislative developments have not been explored to their full potential. In short, the assessment of uncertainties with respect to future developments has not been systematically explored yet (section 3.2).

As a result, tools available for original equipment manufacturers are available in only a limited way (section 4.3). Tools exist for local or regional situations, but in these tools many developments are assumed constant or as given. So far, system boundaries were set locally. This way, only limited insights exist on how various issues such as economies of scale and market and technology developments will or can affect future end-of-life scenarios. Especially quantitative analyses are practically unavailable.

The present research has taken a view that is wider than was common to do so far. Uncertainties with respect to economic, legislative and technological issues have been systemically researched (Chapter 3), which has lead to an overview of developments that are, or at least could be, relevant to assess in order to fully understand where the gains and the losses, both economically and ecologically, are found.
Although the much-wider-than-usual scope has made the above possible, it should nevertheless be understood that also the present research has 'conveniently' remained within system boundaries, as pointed out in Chapters 1 and 2. In particular, the focus on external developments rather than explicitly including developments internal to a company -- for example those as described by the Environmental Value Chain theory which is still in its infancy -- has led to results unspoil by such considerations. In section 1.5 examples are given of internal factors that can distort, amplify or soften the effects of external developments. In addition, in section 9.4.7 it is briefly pointed out that research work is to be done here. Also the summary attention of issues related to developments in reverse logistics processes, changing emotional considerations among society and customers in particular, and general world-wide economical developments is a clear limitation of scope, which however is to a more or lesser extent inherent to any type of research.

In Chapter 6 it has been pointed why the scenario-based approach presented in this dissertation was chosen over any alternative method that, though possibly theoretically better grounded, would presumably not have led to satisfying conclusions. The argumentation for this supposition bears reference to the inability to determine cumulative distribution functions for the various developments for reasons of lack of data, and consequently the problem of assessing equally likely future developments for those very developments. At the same time, it has been shown that the chosen scenario-based approach has lead to satisfying results regarding the research questions put forward in section 1.1.

Under the subsequent headings in the remainder of this section, the developments as researched in this dissertation are recapitulated.

Technology

In the first half of the past decade, focus has been given by the majority of researchers active in design for end-of-life to cost-based disassembly analysis leading to design for disassembly guidelines (section 4.1). Main reason for this was probably the fact that research in this field was mainly initiated in mechanical engineering and machine design environments – areas where traditionally manufacturing research took place, and where many started to focus on demanufacturing as a (at the time) logical step towards environmentally sound products. Alternative (or supplementary) processing technologies such as shredding and separation for material recycling did not receive much attention until several years later when researchers realized that cost factors and stakeholder opinions played a role as well – and still these technologies do not receive as much attention as they perhaps deserve (section 2.5).

As a result of the disassembly-oriented product evaluation methods that kicked off many design for recycling related research projects (mainly at universities but also within companies), a wide variety of disassembly focused support tools were developed in the 1992-1996 period, in order to assess the economical consequences of deploying the various new insights on how end-of-life products should be disassembled (section 4.1). Initial attempts to design a generic end-of-life tool failed, mainly due to lack of sufficient
and reliable recycler information, often accompanied by operating difficulties, lack of industry support and principally not taking environmental value chain and life-cycle perspective issues into account.

The fact that in theory, disassembly of end-of-life appliances serves the environmental priorities best has no doubt contributed to the heavy focus on these design for disassembly (DFD) approaches. By dismantling end-of-life appliances, environmentally relevant fractions can best be isolated and appropriately treated thereafter (section 2.5). Producers face however the fact that manual disassembly is very costly, and can therefore only be applied to a limited number of product categories. The fact itself that a significant part of the DFD research focused on other than these appropriate product categories also contributed to the fact that recycler data and support were limited.

Since this time, it has become clear to many people that from a total systems perspective, and without heavy subsidies, disassembly is often not a feasible option. In particular this applies to competitive, non-subsidized recycling markets. Because of these facts, in several Western European countries nowadays more than half (on a weight basis) of all discarded electronic appliances are shredded and subsequently separated into various material streams. This has lead to the approach that the determination of end-of-life scenarios requires primarily a perspective based on the output of the recycling process rather than on the input of the process. It has become clear that for shredding and separation, end-of-life processing is about material streams and about separating or joining them, rather than about individual products (section 2.5). Hence, design actions aiming solely at individual product improvement will have only limited improvement potential.

With the emergence of ecodesign projects and take-back pilot studies funded by the European Union, possibilities increased to form consortia that included different stakeholders in the product’s life cycle such as producers, recyclers and logistics operators. These co-operations enabled a better reflection of actual recycling practice, including all business-related aspects thereof. In some of the consortia (such as the one in which the foundation of the PMRCM was laid, see Chapter 5) tools were developed that took actual recycling processes as a basis (rather than disassembly operations analysis performed at office desks with chronometers). This lead not only to the understanding that mechanical treatment, i.e. shredding and subsequent material separation is in most cases the preferred end-of-life strategy based on economical considerations, but also to an increased focus on mechanical treatment processes as such, not only by recyclers but also by research groups focusing on ecodesign. In the most recent years this has lead to the notion that with state-of-the-art mechanical treatment processes for most product categories acceptable recyclability scores can be obtained at acceptable costs (section 5.3). In Table 40 it was shown that on the basis of a mechanical treatment strategy four product categories can be distinguished, each exhibiting their own recyclability scores and costs/yield profile. This is an important notion towards establishing design priorities for different product categories.
Economies of scale and the ensemble issue

From the research conducted for this dissertation economies of scale and the ensemble issue have been recognized, more so than in previous research, as issues that are of critical importance when evaluating end-of-life scenarios. This has now also been backed up by quantitative research results (section 6.4). Reasons for this that were identified are the fact that without the availability of large enough volumes of WEEE, collection and transport costs might be too high to justify economical investment. Also, the environmental impact associated with for instance transport of WEEE (fuel and material use) can not be justified if it is not balanced by environmental benefits from recycling enough volumes of WEEE. Also, without sufficient economies of scale there will be no satisfactory return on economical investment of setting up recycling facilities, for example because the capacities of end-of-life processing lines or technologies used might not be used fully which could lead to economical disadvantages as well as environmental disadvantages.

The ensemble issue refers to the problems associated with the transgression from the in general product type dominated WEEE streams entering a recycling facility to an in general material type dominated stream leaving the same facility. Depending on the outlets and the specifications required for concentrations of materials, mixing WEEE into separate batches or streams entering the recycling process is in many cases a relatively delicate matter. The important issues here include the concentration of metals and potentially toxic substances. As far as metals are concerned, especially copper and precious metals are important as these materials yield the highest revenues, and therefore may or may not make the chosen end-of-life strategy viable. For example, copper smelters will generally accept a batch of printed circuit boards (or batches with other parts having relatively high concentrations of copper, like deflection units or wiring) if the perceived concentration of copper is 20% or higher. From a recycler's perspective, it may therefore prove worth while to mix a batch of products or product parts that has a copper concentration higher than 20% with a batch of products or product parts that have a copper concentration less than 20% — to end up with a batch that has a copper concentration exactly or slightly over 20%. This would enable a recycler to obtain the same price for a batch of WEEE while also selling a stream that on its own would yield a considerably lower price. Further of importance is the fact that precious metals (Pd, Au, Ag) are being paid for even when present in very low concentrations, provided that they are in the copper stream. However, a threshold applies. Diluting the precious metals concentration below this threshold while enriching a fraction in copper could therefore be counterproductive. With respect to potentially toxic substances, their concentration is an important characteristic for a WEEE stream as the presence of these may dominate the way the stream is processed. However, for many recyclers mixing different WEEE streams in order to reduce the concentration of these substances is an integral part of business. Making sure concentrations are below certain threshold values could be in favour of a cheaper material treatment process with associated higher revenues or lower costs.
Beyond current system boundaries

Another important aspect of end-of-life scenarios that has been acknowledged and understood in the present research is that the assessment of end-of-life scenarios is not just a matter of counting disassembly times, mixing waste streams, determining material contents and recovery grades, and adding gains and losses. It is also about understanding the intangibles present in all end-of-life infrastructures, issues that cannot be easily quantified but do play a significant role in what is happening (section 2.1), such as communication between company departments, supplier relationships, and personal commitment or preferences with employees. Although the development of environmental value chain analysis is still in its infancy, present insights already lead to believe that the importance of understanding these intangibles is more important than has been acknowledged so far. In that respect, system boundaries should be set even wider than is done in this dissertation, beyond legislation and technology development, and beyond collection infrastructures and secondary markets.

9.2 Scientific contributions

There are several reasons to argue that the work presented in this dissertation is not what is generally referred to as ‘hard science’ – whatever this term may represent. The fact that applied environmental design, especially when focused on end-of-life considerations, is such a young discipline is a fact that should be considered here. It is in particular a multidisciplinary subject, which learns from design theory, mechanical and other engineering disciplines but increasingly also from economical disciplines like finance, marketing, consumer research et cetera. Moulding all these more established disciplines into a new application is a process that will take a multitude of the years ‘spent’ so far. Like with any new discipline, or science, it will need to start off with practical experimenting, the collection of empirical data, the moulding of new ideas into useful concepts, rather than to start off with solely theoretical arguments.

This dissertation has contributed at least is in one respect to science – it provides for the first time an approach to assess uncertainties involved with the end-of-life stage of products in a structured way that has previously not been attempted. From that, in this dissertation the relative importance of the various uncertainties has been addressed which has not been done before. Based on practical observations it takes a leap into the future to assess what developments might be expected, rather than to assume current technological and economical circumstances as a given.

Probably because uncertainty is a prominent concept in this dissertation, rather often speculative statements had to made to prevent the analysis from stranding halfway. At the same time, this has provided a lot of insight on which issues are still relatively unresearched but need to be considered as important to analyse. This is a scientific contribution in itself. In section 9.4 many suggestions for future research are made.
It should be noted that in itself, conclusions as to the importance of for example economies-of-scale issues, as made in the first part of this chapter, are in principle not to be regarded as new insights; with many concerned with research in end-of-life developments, it is already known that economies-of-scale are of the utmost importance. However, previously no research was published that has attempted some sort of quantification, in particular in relation to other important aspects of end-of-life (such as design, technology or legislation). Quantitatively pointing out the relative importance of the various developments – to which the title of this dissertation refers – is probably the biggest scientific contribution.

The use of the PMRCM in order to generate quantitative results in this dissertation has been discussed in Chapter 5. For the first time a mathematical structure has been published that enables calculating the end-of-life yields and recyclability scores that result as a consequence of a number of assumptions regarding the product composition of a consumer electronic appliance as well as a number of assumptions regarding the process and the market context in which it is processed. Although a number of limitations to the PMRCM have been accounted for in section 5.5, it is concluded there that the context in which the PMRCM is currently applied ensures that the findings in this dissertation did not suffer from these limitations.

As for the research questions put forward in section 1.1, firstly the most important factors and developments associated with the end-of-life stage of consumer electronics have been discussed in Chapter 2. Subsequently, in Chapter 3 the main uncertainty factors for these developments have been assessed. Secondly, in Chapter 4 the existing literature has been reviewed to examine ways to answer the second research question about how uncertainty factors can be quantified according to indicators relevant to businesses. It has been shown that existing tools and methodologies provide only limited means to assess the impacts of various uncertainty factors on the business criteria as proposed in this dissertation. Thus, in Chapter 5 a new model has been introduced which does satisfy these requirements.

The third research question required an answer to the question what developments associated with the end-of-life stage of consumer electronics have the largest impacts on the economical and environmental performance of discarded products during the end-of-life. To answer this, and to provide a prioritisation of focal areas in order to facilitate the generation of business opportunities related to the end-of-life of consumer electronics, in Chapter 6 a scenario-based approach has been followed to quantify the aforementioned uncertainty factors in a way that has enabled a ranking of the effects of the various scenarios. This ranking provided answers to the third research question, which have been elaborated on in Chapters 7 and 8.

9.3 Practical contributions

The main practical contribution of this dissertation is answering the research questions stated in the first chapter. The discussion on external developments related to the prod-
uct's end-of-life stage, and the discussion of uncertainty regarding these developments, will provide these companies with a broad overview, though not exhaustive, of issues that they can expect to be confronted with. With the ranking of these developments according to business criteria, companies are assisted in setting priorities for monitoring or ignoring selected developments. Here also, the relative importance of the various issues that have been discussed may well be an important means for understanding what influences are important to monitor and which ones are not. Using the angle of scenario analysis has provided new insights not published before – no documentation was until now available that addresses technological as well as economical as well legislative issues in a quantitative way.

The fact that this was done using a future time-horizon (as also addressed in the previous subsection) in contrast to assuming various aspect constant, has contributed a new aspect of end-of-life scenario evaluation as well.

9.4 Recommendations for future research

In this section a number of research issues are discussed that are touched upon in this dissertation, but that have not been fully researched, either because of lack of dependable information, lack of time, or because they were outside the scope of this work. Several of the issues themselves have been highlighted though as being relevant for developing economically and ecologically preferred end-of-life scenarios.

It is very important to note here that the recommendations for future research listed below are to be regarded as recommendation within the field of end-of-life related research. In a broader perspective, by no means these recommendations should automatically be interpreted as having priority from an environmental point of view or even a business point of view. A wide range of other topics outside the end-of-life perspective is a lot more important. End-of-life issues are not the most important environmental issues in the world. And designing 'green' products, even if they do not just perform well during the end-of-life but also throughout the life-cycle, makes no sense if you can't make or market them.

Supposing that research focusing on the issues below will yield useful results, then these will at most improve the performance in an area, end-of-life, that matters relatively little, both from an economical and environmental perspective. Over the full life-cycle, and in a societal context, the size of improvements stemming from areas dealing with reducing the need and use of energy may be measured in terms of order of magnitude instead of incremental improvements. Consequently, they may be categorised as level 3 or 4 improvements rather than level 1 or 2 improvements, in terms of the 'levels of ecodeign framework' mentioned in section 1.3. On the other hand it can be argued that in situations where (financial) margins are very small, and where legislation will need to be obeyed, focusing on end-of-life issues in a smart way can make things a lot easier if the right topics are addressed. This has been the aim of this dissertation, and is also the aim of the future research recommendations.
For each of the subsequent topics for future research the following issues have been indicated:

- Whether the topic should be addressed in the first instance by manufacturing companies, universities, recyclers or governments
- Whether the topic is mostly relevant for design, technology or policy

### 9.4.1 Methodological framework building for eodesign related research

In Chapter 1 it has been discussed that methodological frameworks for positioning and assisting research in eodesign related areas are everything but abundant. This is especially true in cases where research goes beyond a broad approach, for example in cases such as in this dissertation where a multidisciplinary approach is taken, or in cases where a specific issue is dealt with in detail. Though customised approaches depending on the research perspective may prove very helpful, it should be useful to investigate the possibilities for methodological framework building that provide guidance and reflection beyond initial issues. It is particularly relevant to study ways to provide methodological assistance for not only the identification of problem areas and the subsequent derivation of data on various environmental issues, but also for the further implementation and providing solutions for these. See also future research issues discussed in sections 9.4.7 and 9.4.13.

→ Relevant primarily for universities. Design, technology and policy considerations should all be included.

### 9.4.2 Economies of scale

It has been shown in this dissertation that economy-of-scale issues are of major importance for setting up and maintaining end-of-life infrastructures. It has also been shown that in this area much is to be improved. In particular for plastics dominated products, the lack of economies of scale so far frustrates an economically and ecologically sound end-of-life infrastructure. This is in particular true when it comes to plastics recycling, but maturing plastics markets resulting in better recovery percentages and higher, stable market prices for secondary plastics will have to potential to change this situation around. However, more favourable economies of scale are a prerequisite. In case the barriers for starting off such research can be overcome, research in this area will probably provide the lowest hanging fruits in this research area. Such barriers might exist because a lack of information on various issues, either because information is usually proprietary, or simply non-existent. These issues can include

- Insight on how the different links in the internal as well as external value chain are connected;
- Lack of information on outlet channels and lack of understanding how transactions between recycling companies and these outlet channels take place — recycling companies regard this as confidential information;
- Geographical and temporal differences; in order to understand how economies of scale work, detailed information on many issues needs to be collected and interpreted. For practical reasons the scope of such a research project might therefore
have to be limited geographically. But as economies of scale issues such as the development of secondary plastics markets are likely to be of an international nature, such a limitation might prevent the realisation of meaningful results.

A research project addressing these matters in detail, provided it is set up from a holistic perspective, will greatly increase the knowledge and understanding how improved economies of scale can contribute to improving the economical and ecological performance of plastics dominated products — but also of other product categories — in the end-of-life.

It is important to note that adjacent research areas will most likely benefit from increased knowledge about the effects of economies of scale as well. Such areas include energy efficiency during the different stages of the life-cycle, transport, spatial planning, public investments end-of-life infrastructures and recycling technology development. The importance of this lies is specifically due to the fact that a number of these areas have a much larger environmental impact than the end-of-life stage of products.

→ Relevant primarily for universities and governments. Technology and especially policy considerations play a role here.

### 9.4.3 Brand-specific processing

One opportunity that manifests itself in cases where favourable economies of scale exists, is brand specific processing. In section 8.2 it was already indicated that companies can reap the benefits of good ecodesign by separate end-of-life processing of their products, provided that enough eligible products can be collected. As regards brand specific processing, in particular two issues lend themselves for further research:

- To address the boundary conditions for separate treatment by determining minimum levels of goods to be collected and minimum levels of improvement in ecodesign necessary to make separate treatment worthwhile;
- To research the physical requirements as well as restrictions for enabling the collection, handling, treatment and in particular for the physical and financial bookkeeping of the brand specific system. The impacts on these aspects of the end-of-life stage are most probably considerable. Some of the relevant issues as well as existing research in this area have already been discussed briefly in section 3.4.1.

→ Relevant primarily for recyclers, in cooperation with manufacturing companies. Universities and other research institutions should assist with the necessary scientific back-up. Eventually, governments should address legislative issues appropriately once the practical foundations are laid. Technology and later on policy considerations are relevant, but once brand-specific processing is feasible it may have repercussions on design issues as well.
9.4.4 Business implementation of end-of-life knowledge – extension of the system boundaries to include other than end-of-life considerations.

In section 7.5 it was already indicated that it is dangerous to draw conclusions from end-of-life considerations alone. From a financial point of view, this is most apparent when failure to include additional costs incurred in earlier stages of the life-cycle, through purchasing, design and manufacturing for example, may lead to the conclusion that under assumption of progressive scenarios the improving of recyclability will in many cases automatically lead to more favourable end-of-life yields. Although in itself this may be true, end-of-life costs are only (a small) part of the total product-related costs incurred by a company.

It is therefore recommended that further research is carried out that will include these other considerations as well. It would be most interesting to for example extend analysis per scenario to include additional costs incurred. Ranking would then not only take place on the basis of end-of-life yields but based on total costs incurred which would lead to probably more meaningful results – these results would not only provide insights in what issues matter in the end-of-life, but they might actually form the basis for business decisions.

Problems that will be encountered when exercising these ideas are however manifold. For example, information should be made available on the possibilities and the associated costs of the new material applications – the lack of empirical data in this area, especially for large-scale applications will currently imply an enormous hurdle to be taken. Also, the effects on other business aspects such as quality issues, customer satisfaction, design implications, competition elements need to be taken into account for providing a complete picture that goes beyond guesstimating and speculative assumptions. To do this for even a small number of scenarios is an immense task.

\[\rightarrow\] Relevant primarily for manufacturing companies, assisted by universities for providing the necessary scientific back-up. This is essentially a policy issue, but design and technology issues should be properly addressed.

9.4.5 Design optimisation based on legislative restrictions or restrictions otherwise

The approach taken in the main body of this dissertation has mainly been a one-way street: first scenarios were drawn, then the effects on the performance indicators were calculated and interpreted. Another approach would be to use the preferred score of the performance indicators as an input, and have the PMRCM or another tool have the optimal design calculated through linear programming or some other mathematical theory. In fact, most business managers would kill for such a tool, especially if it would take also other parameters into account such as quality, manufacturability, financial considerations, consumer preferences etc.
Since the PMRCM uses in fact only ten parameters to represent the design of a product, such a tool would be theoretically conceivable for end-of-life purposes only, though only in the case where a lot of restrictions are imposed that would ensure feasible optima. These restrictions would have to prevent infeasible optima such as the TV made of 100% pure copper.

In order to come up with useful results, the number of parameters representing design would probably have to be much larger, not only focusing on material content but also product geometry aspects including joints etc. This depends of course on the type of product that is to be designed. For some products, outcomes like ‘47% ferrous metals, 17% copper, 36% type 3 plastics’ might be enough to produce the actual product that meets these specifications, but for most consumer electronics they are probably not. Increasing the number of parameters representing the design probably also implies the sophistication of the PMRCM, representing the end-of-life infrastructure better, et cetera.

Though in a context of limited size such as end-of-life these ideas may be feasible, attempts this way have not been made in this dissertation due to the limited applicability. However, further research could show if there is a need for such solutions, and it could perhaps identify areas or subareas where ideas like this would be useful. In this respect, fulfilling legislative obligations by having to meet a certain recyclability targets is one possible application. Such an application would be a formidable sophistication of the top-down legislative scenarios drawn in section 6.5.1 of this dissertation.

→ Relevant primarily manufacturing companies. This is an area where design and policy issues go hand in hand.

9.4.6 Design and end-of-life

In this dissertation, relatively little attention has been given to design aspects on a product level. Although conclusions have been drawn on which future developments are most relevant for economical and environmental performance indicators, no translation back to design has been provided. Firstly, this was not the scope of this dissertation, but more importantly, such considerations would need to include a much wider perspective as explained in the previous subsection 9.4.5. Once the conditions set out in that section are met, including life-cycle considerations that go beyond the end-of-life stage only, more sophisticated design recommendation can be given than those that go beyond “reduce the number of screws”, “limit the use of incompatible coatings” and “avoid penalty elements in the copper fraction”. Research addressing such relatively straightforward guidelines that are applicable in most cases is already abundant, and it is not recommended that much further effort be devoted to this subject.

→ Relevant primarily for manufacturing companies, but universities and other research institutions should continue to assist with the necessary scientific back-up. Design and technology consideration should be combined and eventually support corporate policy-making.
9.4.7 Environmental Value Chain Analysis

A third issue is related to the previous two indicated in this section. Apart from aspects of the product's life cycle itself, many other circumstances make or break the successful application of end-of-life considerations into the business. In Chapter 2, it was already explained that the concept of environmental value chain analysis takes these other aspects such as stakeholder and supply chain issues into account. However, little work has been done to develop this concept into a scientific theory, let alone to develop it into a business tool that goes beyond merely providing the notion of the existence of such issues.

It is therefore recommended that the initial work of Stevels, Ishii and Rose be further developed. Further empirical data will need to form the basis of a sound theory, but this will only be the easy part. So far, it merely indicates a structured way of explaining the existence of value chain aspects, but how to deal with unfavourable circumstances is a territory yet to be fully explored. Moreover, validation of environmental value chain analysis issues will be tricky since this will probably call for turning business upside down – to get to the core of issues that might often be traced back to proprietary or even personal characteristics has often proven to be impossible for outside research. An additional complicating factor may be that for addressing more sophisticated environmental value chain elements businesses will have to be studied that are already experienced in dealing with more basic environmental issues (in this case: end-of-life related issues) – and such companies are still not abundant.

Though environmental value chain analysis is emphatically more than juggling with existing environmental data, it may be greatly facilitated by the emergence of systems that enable globalisation of information. Though research in the latter area should not necessarily specifically be aimed at the management of environmental data alone, work such as presented in Sriram et al.207, designing systems for effective collaborative green design using heterogeneous environmental-related databases can provide a starting point for providing such infrastructures.

→ Relevant in particular for manufacturing companies, but universities will be needed for objective project management and providing scientific back-up. Recyclers and governments should of course be considered as stakeholders in the external environmental value chain and hence participate in projects. Results could greatly influence corporate policy-making.

9.4.8 Plastics markets

Most of the equipment covered in the EU legislation for WEEE contains high quantities of plastics, and many different types of plastics too. A market for these plastics is currently relatively unexplored, but favourable economies of scale due to both increasing amounts of WEEE and expected higher recyclability targets may become beneficial for the development of these secondary markets. Research in this field, especially on an aca-

demic level, is still virtually non-existent. It is extremely important here to address the usual business conditions like quality and price in an analysis of the potential for maturing secondary plastics markets. The feasibility of reductions in the number of different plastics applied in consumer electronics as well as the feasibility of the reduction of additives and other contaminating factors need to be aligned with the preconditions for stable markets. Such preconditions include:

- Quantity: High enough levels of supply and demand will assure the selling potential for recycling companies for fair prices;
- Specifications: The supply of secondary plastics should meet the specifications as required by outlet channels;
- Continuity: Both the levels of supply and demand of plastics of the required specifications should maintain a sufficiently high level over longer periods of time;
- Price: The price of secondary plastics should be competitive, in particular when compared with the price of virgin plastics which depends on the currently low petroleum prices. A necessary precondition for this price level is sufficient economies of scale.

Only when these preconditions are met, manufacturing companies will gain incentives to start applying these plastics in their products.

Research in this area should be initiated by recycling companies, as recycling technology is the precondition for success in this area. But as this issue is a question of making supply and demand meet, manufacturing companies are to be involved early in the process. Governments should provide the necessary boundary conditions in terms of regulations and for example appropriate subsidising efforts. Apart from the technology component, successful results in setting up secondary plastics markets will only be accomplished by taking into account design considerations such as quality and functionality specifications as they exist within manufacturing companies. As this topic affects the complete value chain, obviously policy considerations are relevant as well.

9.4.9 Elaboration of eco-efficiency concepts related to end-of-life issues

The matter of eco-efficiency is touched upon only very lightly in this dissertation. This was done on purpose. Eco-efficiency is still not a very well defined concept. Clearly, in case it is defined as some indicator for the efficiency of investments in terms of environmental gain, it should be a fraction in which the numerator includes some environmental performance indicator and where the denominator includes some economical performance indicator. Although the latter quantity may be obvious, the numerator can be defined in many ways as was indicated in Stevels. The definition depends on the context in which the concept of eco-efficiency is to be used.

It can be argued that the concept of eco-efficiency is only meaningful if it addresses a quantity, or perhaps a policy instrument, that can be influenced by the one to use the

---

concept. It has been discussed in section 5.1 that in many cases in the context of this dissertation, eco-efficiency defined as weight-based recyclability over end-of-life yield is a static quantity rather than a dynamic one. For example, it may indicate a result of a legislative development without the possibility for the user of the concept to influence or 'play' with the concept. In addition, in the context of this dissertation the use of eco-efficiency as a performance indicator is limited since a large number of the scenarios that were drawn focus on economic developments only (such as material prices). As these scenarios do not affect recyclability scores, for these scenarios no eco-efficiency scores can be calculated.

Translation of eco-efficiency scores in meaningful concepts so they can be used as a policy instrument would be an extremely useful research topic. Provided that the concepts are well defined and agreed upon by applicable stakeholders, eco-efficiency will perhaps be one of the most important criteria for decision making on both a micro and macro level, since it would provide a quantitative tool to incorporate both economical and environmental criteria. It should be noted that in particular the definition of the environmental numerator should give the proper attention. The environmentally weighted recyclability scores concept is an excellent candidate for this, therefore eco-efficiency research should be seen as an extension of the QWERTY concept. Perhaps also indicators such as defined in section 7.5.3 can also be translated in useful concepts, provided the proper context is always taken into account.

→ Relevant primarily for manufacturing companies, but initial work should be done by universities and other research institutions as for now the methodological background needs to be set up. Manufacturing companies and recyclers should provide the necessary data and cooperation. Eventually, governments should take results as a basis for more 'refined' legislation, that serves economical as well as environmental considerations. Clearly, this topic will eventually relate to many if not all design, technology and policy aspects.

9.4.10 Effects of future legislation on end-of-life scenarios

Legislation on producer responsibility and take-back of discarded products is expected to become stricter in the coming decades. Just as has been observed in the car industry, where initial environmental legislation proved to be only the beginning of a number of follow-up laws, the electronics industry will be required to meet higher recyclability percentages, use less potentially toxic substances and put more effort into reverse logistics infrastructures in order to attain better collection rates. Needless to say that this will have an impact on end-of-life scenarios and all associated aspects of design, technology and policy implementation.

Based on the results of the priority setting it can be stated that the effects of legislation can have a considerable effect on the evaluation scores of end-of-life scenarios. Therefore it is recommended that legislative processes be continuously monitored to assess their effects.
Legislative issues should always consider the interests of all stakeholders in the chain, so this issue is relevant for manufacturing companies, recyclers and governments. Universities and other research institutions should be the partners for evaluating the effects of future legislation. Iterative improvement of legislation, considering design and technology aspects should be a prime goal of this research.

9.4.11 Further development of the PMRCM

Although extensive use has been made of the PMRCM to calculate the relative effects of end-of-life scenarios, the main purpose of the research presented in this dissertation was not to provide a tool to calculate end-of-life yields and recyclability scores to be used in the design process. To use the PMRCM (solely) for this purpose, it would need a more careful setting of default parameters, probably using a more refined distinction across product categories since for different product categories different standard end-of-life scenarios apply. To investigate what a useful balance is between the number of different process settings and the applicability of the tool is probably an extensive research project itself, and depends greatly on the demands from future users and the infrastructural circumstances around these users.

Also, the tool would probably need to be extended to better include other product categories such as white goods, a disassembly module would increase possibilities for analysis, and also the number of material fractions would need to be increased to include glass, different types of laminates, more refined plastics categories et cetera. Such demands are included for example in the list of requirements for other software tools under commercial developments such as DFE 2 (see section 4.1). This way, and by carefully examining and re-evaluating the most recent end-of-life infrastructures rather than those of a number of years ago on which the PMRCM is based, calculation results in absolute terms will become more meaningful and can be used in addition to the relative results for which it is used now.

It is recommended therefore that knowledge from the PMRCM be incorporated in tools like this one, rather that to further develop the PMRCM in an academic project. However, for academic purposes the PMRCM is in particular useful because of its clearness and because of the possibilities to use multiple parameter settings in a practical way — for professional users these possibilities are probably a mere distraction. In an academic setting however, opportunities exist to further apply the PMRCM in particular in order to deal with the assessment of environmental impacts during the end-of-life phase in relation to other life cycle stages. The next issue for future research is an example of such an elaboration.

Relevant primarily for manufacturing companies, in cooperation with recyclers and universities for providing and analysing data. Further development of tools like the PMRCM can assist in providing quantitative back-up for most if not all of the research topics discussed in this chapter. They should be able to combine design, technology and policy considerations in order to cover the whole playing field.
9.4.12 Adaptation of environmentally weighted recyclability scores to fit scenario-based uncertainty analysis

In section 5.4 the importance of the issue of environmentally weighted recyclability scores versus weight-based recyclability scores has been addressed. It is recommended that once the theory on environmentally weighted recyclability scores has been further developed, it is incorporated into scenario-based uncertainty assessment. By enhancing PMRCM-like calculations with life-cycle considerations to better assess the environmental impact of end-of-life scenarios, the recyclability scores become considerable more meaningful.

→ This topic should be seen as an extension of the previous research topic, and once developed in a reliable concept it should be taken onboard by governments so that legislative developments and policy-making will be increasingly environmentally justified.

9.4.13 Exploitation of multiple benchmark reports across product categories

In a recent journal article\footnote{Boks, C. and Stevels, A. "Theory and Practice of Environmental Benchmarking for Consumer Electronics", submitted for publication in: Benchmarking - an International Journal special issue on Corporate Environmental Benchmarking.} the theory and practice of corporate environmental benchmarking for consumer electronics has been discussed. Here, the practice of environmental benchmarking as done at the Environmental Competence Centre (ECC) at Philips Consumer Electronics in Eindhoven is explained. To date, about 40 environmental benchmarks have been performed and reported on at this department. Products covered in these benchmark reports cover most of the brown goods consumer electronics category, ranging from cellular phones to large 55" projection TVs, including audio sets, VCRs, CD players, DVDs and a large range of TV sets and monitors. This has resulted in a large reservoir of information. Whereas the individual benchmark reports have contributed to product improvements, cost reductions and general environmental awareness through the organisation, it is believed that from combining data from individual benchmark reports additional data and pointers for improvement can be generated. Thus, this should be seen as an important topic for future research. In theory, such an umbrella view would provide information about the following items:

- Structural over- and/or underperformance in relation to competitor performance;
- The performance according to environmental characteristics of products over time;
- Opportunities for further exploitation of results for communication purposes (internal and external);
- The effects of, as well as the need for, (structural) design improvements;
- Priority setting for further research.

The large amount of available benchmark reports would make it possible, in theory, to obtain information about these items would for individual products, as well as per product category but in particular also across product categories. In 2001, projects have already been carried out in which the exploitation of multiple benchmark results have initially been explored\footnote{Boks, C. and Stevels, A. "Theory and Practice of Environmental Benchmarking for Consumer Electronics", submitted for publication in: Benchmarking - an International Journal special issue on Corporate Environmental Benchmarking.}.\footnote{Boks, C. and Stevels, A. "Theory and Practice of Environmental Benchmarking for Consumer Electronics", submitted for publication in: Benchmarking - an International Journal special issue on Corporate Environmental Benchmarking.}
Environmental benchmarking is relevant primarily for manufacturing companies, and a large portion of the work can be carried out by themselves. However, research carried out by universities and other research institutions should further research the opportunities that come with multiple benchmark analysis, in cooperation with industry. One of the areas in which corporate policy-making is likely to benefit from multiple environmental benchmarking is the derivation of recommendations for improved (eco-)design, but (as a result) corporate benefits are likely to extend beyond just design.

\text{Delft University of Technology, Subfaculty of Industrial Design Engineering, graduation report, November 2001} \\
\text{211 Werkhoven, A. (2001), Various intermediate reports of a graduation project carried out at Philips} \\
\text{Consumer Electronics, Delft University of Technology, Subfaculty of Industrial Design Engineering, graduation} \\
\text{report in progress, November 2001}\]
Appendices

Appendices 3, 4 and 5 included in this dissertation are adaptations of papers that have previously been published. Although they provide much detail compared to the way most issues are discussed in the main body of the text, they are included to provide more insight on selected topics and should therefore not be regarded as necessarily contributing to the main structure of this dissertation.
Appendix 1: Mathematical Model of the Product Material Recycling Cost Model.

1.1 Input product parameters

\[\begin{align*}
\text{PercFe} & \quad = \text{percentage magnetic materials in the product (per kg)} \\
\text{PercCu} & \quad = \text{percentage copper in the product (per kg)} \\
\text{PercAl} & \quad = \text{percentage aluminium in the product (per kg)} \\
\text{PercNRP} & \quad = \text{percentage non-recoverable plastics in the product (per kg)} \\
\text{PercRP1} & \quad = \text{percentage recoverable plastics of type 1 in the product (per kg)} \\
\text{PercRP2} & \quad = \text{percentage recoverable plastics of type 2 in the product (per kg)} \\
\text{PercRP3} & \quad = \text{percentage recoverable plastics of type 3 in the product (per kg)} \\
\text{ppmAu} & \quad = \text{parts per million of gold in the printed wiring board(s)} \\
\text{ppmAg} & \quad = \text{parts per million of gold in the printed wiring board(s)} \\
\text{ppmPd} & \quad = \text{parts per million of gold in the printed wiring board(s)}
\end{align*}\]

1.2 Input process parameters

\[\begin{align*}
\text{RecFe} & \quad = \text{recovery percentage ferro metals} \\
\text{RecCu} & \quad = \text{recovery percentage copper} \\
\text{RecAl} & \quad = \text{recovery percentage aluminium} \\
\text{RecAu} & \quad = \text{recovery percentage gold} \\
\text{RecAg} & \quad = \text{recovery percentage silver} \\
\text{RecPd} & \quad = \text{recovery percentage palladium} \\
\text{RecPI1} & \quad = \text{recovery percentage plastics of type 1} \\
\text{RecPI2} & \quad = \text{recovery percentage plastics of type 2} \\
\text{RecPI3} & \quad = \text{recovery percentage plastics of type 3}
\end{align*}\]

\[\begin{align*}
\text{GrFe} & \quad = \text{grade ferrous metals} \\
\text{GrAl} & \quad = \text{grade aluminium} \\
\text{GrPI} & \quad = \text{grade plastics} \\
\text{PrC} & \quad = \text{process costs per kg} \\
\text{TrCh} & \quad = \text{treatment charges per kg} \\
\text{AnAd} & \quad = \text{analysis and administration costs per kg} \\
\text{Pen} & \quad = \text{penalties per kg}
\end{align*}\]
1.3 Input market parameters

PrFe  = market price ferrous metals per kg
PrCu  = market price copper per kg
PrAl  = market price aluminium per kg
PrAu  = market price gold per kg
PrAg  = market price silver per kg
PrPd  = market price palladium per kg

PrP1  = yield for plastics of type 1
PrP2  = yield for plastics of type 2
PrP3  = yield for plastics of type 3

UDCu  = unit deduction copper (%)
UDAu  = unit deduction gold (%)
UDAg  = unit deduction silver (%)
UDPd  = unit deduction palladium (%)

RefCu = refining charges copper per kg
RefAu = refining charges gold per kg
RefAg = refining charges silver per kg
RefPd = refining charges palladium per kg

LfC  = landfill costs

1.4 Calculation scheme

Decision variables:

*Material recycling efficiency:*

\[
MRE = \text{PercFe}\times\text{RecFe} + \text{PercCu}\times\text{RecCu} + \text{PercAl}\times\text{RecAl} + \\
\text{PercP1}\times\text{RecP1} + \text{PercP2}\times\text{RecP2} + \text{PercP3}\times\text{RecP3} 
\]

(1)

*End-of-life yield:*

\[
EOLC = \text{RevFe} + \text{RevAl} + \text{RevCuPM} + \text{RevP1} + \text{RevP2} + \text{RevP3} - \text{PrC} 
\]

(2)

with:

- RevFe  = revenues from ferrous metals
- RevAl  = revenues from aluminium
- RevCuPM = revenues from copper and precious metals
- RevP1  = revenues from plastics type 1
- RevP2  = revenues from plastics type 2
- RevP3  = revenues from plastics type 3
The above revenues are calculated as follows:

\[ \text{RevP1} = \frac{\text{RecP1} \cdot \text{PercP1} \cdot \text{PrP1}}{\text{GrP1}} \quad (3a) \]

\[ \text{RevP2} = \frac{\text{RecP2} \cdot \text{PercP2} \cdot \text{PrP2}}{\text{GrP1}} \quad (3b) \]

\[ \text{RevP3} = \frac{\text{RecP3} \cdot \text{PercP3} \cdot \text{PrP3}}{\text{GrP1}} \quad (3c) \]

Equations 3a-3c determine the revenues from the various recoverable plastics fractions.

\[ \text{RevFe} = \frac{\text{RecFe} \cdot \text{PercFe} \cdot \text{PrFe}}{\text{GrFe}} \quad (4) \]

The revenues from ferrous metals are calculated as the weight of the fraction in which the recovered ferrous metals are contained, times the price for this fraction.

\[ \text{RevAl} = \frac{\text{RecAl} \cdot \text{PercAl} \cdot \text{PrAl}}{\text{GrAl}} \quad (5) \]

The revenues from aluminium are calculated as the weight of the fraction in which the recovered aluminium is contained, times the price for this fraction.

\[ \text{RevCuPM} = \text{NSVpost} \cdot \text{Tail} \quad (6) \]

The revenues from copper and precious metals are calculated as the a posteriori net smelter value times the tail. Here we have

- **NSVpost** = Net smelter value a posteriori
- **Tail** = The weight of the fraction that will be smelted for copper and precious metals recovery

The tail equals one kg minus the fractions that contain the recovered ferrous metals, aluminium, and recoverable plastics:

\[ \text{Tail} = 1 - \left( \frac{\text{RecFe} \cdot \text{PercFe}}{\text{GrFe}} \right) - \left( \frac{\text{RecAl} \cdot \text{PercAl}}{\text{GrAl}} \right) - \left( \frac{\text{RecP1} \cdot \text{PercP1}}{\text{GrP1}} \right) - \left( \frac{\text{RecP2} \cdot \text{PercP2}}{\text{GrP1}} \right) - \left( \frac{\text{RecP3} \cdot \text{PercP3}}{\text{GrP1}} \right) \quad (7) \]

So, the revenues from copper and precious metals are determined by the value that the copper smelter is ready to pay for the copper rich fraction that the recycler offers him. This value is called the "a posteriori" net smelter value, and is determined as follows:

\[ \text{NSVpost} = \text{MAX} (\text{NSVprior}, L_f C) \quad (8) \]

- **NSVprior** = Net smelter value a priori

The a posteriori net smelter value is the maximum of the a priori net smelter value and
the landfill costs. This means that the remaining copper rich fraction will only be smelted if this costs less than landfilling the fraction, and preferably it should generate benefits.

The a priori net smelter value is determine as follows:

$$NSV_{\text{prior}} = BSV - TotRef - TrCh - AnAd - Pen$$  \hspace{1cm} (9)

- $BSV$ = Gross smelter value
- $TotRef$ = Total refining charges

So, the a priori net smelter value equals the gross smelter value less the total charges (see Eq. 15) and other costs and penalties associated with smelting the fraction.

The gross smelter value is calculated as

$$BSV = BSVCu + BSVAu + BSVAg + BSVPd$$  \hspace{1cm} (10)

where

- $BSVCu$ = Gross smelter value for copper
- $BSVAu$ = Gross smelter value for gold
- $BSVAg$ = Gross smelter value for silver
- $BSVPd$ = Gross smelter value for palladium

The smelter values for copper, gold, silver and palladium are calculated as given below:

$$BSVCu = (McCu - UDCu)*PrCu$$  \hspace{1cm} (11)

$$MeCu = RecCu*\frac{PercCu}{Tail}$$  \hspace{1cm} (12)

The term MeCu refers to the weight of the amount of copper in the rest fraction. When the unit deduction is subtracted and the total is multiplied with the price that can be obtained for copper, the gross smelter value for copper is calculated.

The same calculation is made for determining the gross smelter values for the precious metals gold, silver and palladium. Dividing by 1000000 is necessary to determine the weight of the fractions as these are given in parts per million. For the three precious metals we have:

$$BSVAu = MAX(0, \frac{RecAu*ppmAu - UDAu}{1000000})*PrAu)$$  \hspace{1cm} (13)

$$BSVAg = MAX(0, \frac{RecAg*ppmAg - UDAg}{1000000})*PrAg)$$  \hspace{1cm} (14)
\[
\text{BSVPd} = \text{MAX}(0, \frac{\text{Tail} - \text{UDPd}}{1000000} \cdot \text{PrPd})
\]

Finally, the total refining charges are calculated as:

\[
\text{TotRef} = (\text{MeCu} - \text{UDCu}) \cdot (1 - \text{Tail}) + \text{TRCAu} + \text{TRCAg} + \text{TRCPd}
\]

Here, the total refining charges are determined as the weights of the precious metals containing fractions times the refining charges per kg that are applicable for the respective precious metals.

\[
\text{TRCAg} = \text{MAX}(0, \frac{\text{RecAg} \cdot \text{ppmAg} - \text{UDAg}}{1000000} \cdot \text{RefAg})
\]

\[
\text{TRCAu} = \text{MAX}(0, \frac{\text{RecAu} \cdot \text{ppmAu} - \text{UDAu}}{1000000} \cdot \text{RefAu})
\]

\[
\text{TRCPd} = \text{MAX}(0, \frac{\text{RecPd} \cdot \text{ppmPd} - \text{UDPd}}{1000000} \cdot \text{RefPd})
\]
The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios
Appendix 2: Scenario Analysis Results in Graphs and Tables

In Chapter 6 the scenario analysis that constitutes the main body of this dissertation was reported on. In Chapter 7, the results of the scenario analysis have been presented. In this appendix, these results have been displayed graphically to support and facilitate the interpretation of the results given in Chapter 7.

2.1 Scenario analysis results for metals dominated products

The results displayed in this section belong to section 7.1, in which an overview and interpretation of results for the metals dominated product category is given.
Scenario analysis results, ranked according to size of effects
Effects: only positive effects are ranked
Performance indicator: End-of-life revenues
Category: Metals dominated products
Three largest effects omitted from graph

Figure 37: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Palladium and gold concentration scenarios</td>
<td>115.3%</td>
<td>43.7%</td>
</tr>
<tr>
<td>B Average to progressive palladium price scenarios 3</td>
<td>4.2%</td>
<td>10.3%</td>
</tr>
<tr>
<td>C Progressive economies of scale scenarios with type 3 substitution</td>
<td>22.2%</td>
<td>22.2%</td>
</tr>
<tr>
<td>D Average economies of scale scenarios with progressive component +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>type 3 substitution</td>
<td>12.8%</td>
<td>0.1%</td>
</tr>
<tr>
<td>E Conservative to average palladium price scenarios</td>
<td>10.3%</td>
<td>3.4%</td>
</tr>
<tr>
<td>F Average economies of scale with type 3 substitution</td>
<td>7.1%</td>
<td>7.1%</td>
</tr>
<tr>
<td>G (Predominantly) progressive bottom-up legislative scenarios</td>
<td>5.7%</td>
<td>5.2%</td>
</tr>
<tr>
<td>H Average to progressive economies of scale scenarios</td>
<td>5.5%</td>
<td>2.3%</td>
</tr>
<tr>
<td>I Average economies of scale scenarios with progressive component</td>
<td>5.3%</td>
<td>2.3%</td>
</tr>
<tr>
<td>J Conserv. bottom-up legislative scenario but with progressive processing</td>
<td>5.1%</td>
<td>5.1%</td>
</tr>
<tr>
<td>K Average to progressive end-of-life cost scenarios</td>
<td>5.1%</td>
<td>2.0%</td>
</tr>
<tr>
<td>L Copper related material substitution scenarios</td>
<td>2.7%</td>
<td>1.2%</td>
</tr>
<tr>
<td>M Average bottom-up legislative scenario</td>
<td>2.3%</td>
<td>2.3%</td>
</tr>
<tr>
<td>N Progressive gold price scenario</td>
<td>2.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>O Silver concentration scenario</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>P Average to progressive palladium recovery % scenarios</td>
<td>1.5%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Q Progressive copper price scenarios</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>R Average to progressive gold recovery % scenarios</td>
<td>0.9%</td>
<td>0.5%</td>
</tr>
<tr>
<td>S Progressive aluminium price scenarios</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>T Ferrous metals recovery percentage scenario</td>
<td>0.7%</td>
<td>0.4%</td>
</tr>
<tr>
<td>U Average to progressive type 1 and 2 plastics recovery percentage scenarios</td>
<td>0.4%</td>
<td>0.2%</td>
</tr>
<tr>
<td>V Average to progressive aluminium recovery percentage scenarios</td>
<td>0.3%</td>
<td>0.1%</td>
</tr>
<tr>
<td>W Average to progressive type 1 plastics price scenarios</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>X Average to progressive silver price scenarios</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Table S7: Legend for Figure 37
Scenario analysis results, ranked according to size of effects
Effects: only negative effects are ranked
Performance indicator: End-of-life revenues
Category: Metals dominated products

Figure 38: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  Aluminium recovery grade change scenario</td>
<td>-0.1%</td>
<td>-0.1%</td>
</tr>
<tr>
<td>B  Conservative to average ferrous metals recovery grade scenario</td>
<td>-0.3%</td>
<td>-0.1%</td>
</tr>
<tr>
<td>C  Conservative to average aluminium price scenarios</td>
<td>-0.7%</td>
<td>-0.1%</td>
</tr>
<tr>
<td>D  Progressive economies of scale scenario but with conservative processing costs</td>
<td>-0.9%</td>
<td>-0.9%</td>
</tr>
<tr>
<td>E  Conservative to average copper price scenarios</td>
<td>-1.4%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>F  Conservative bottom-up legislation scenario with progressive plastics</td>
<td>-1.4%</td>
<td>-1.1%</td>
</tr>
<tr>
<td>prices/recovery rates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G  Conservative end-of-life processing cost scenario</td>
<td>-1.5%</td>
<td>-1.5%</td>
</tr>
<tr>
<td>H  Conservative bottom-up legislation scenario</td>
<td>-1.5%</td>
<td>-1.5%</td>
</tr>
<tr>
<td>I  Conservative economies of scale scenario</td>
<td>-1.5%</td>
<td>-1.5%</td>
</tr>
<tr>
<td>J  Reduct. of ferrous metals content scenarios, substitution with high-yield plastics</td>
<td>-2.7%</td>
<td>-1.6%</td>
</tr>
<tr>
<td>K  Conservative to average gold price scenarios</td>
<td>-6.5%</td>
<td>-2.2%</td>
</tr>
<tr>
<td>L  Reduction of ferrous metals content scenarios</td>
<td>-7.4%</td>
<td>-3.6%</td>
</tr>
</tbody>
</table>

Table 58: Legend for Figure 38

254
The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios

Scenario analysis results, ranked according to size of effects
Effects: only positive effects are ranked
Performance indicator: Recyclability
Category: Metals dominated products

![Bar chart showing relative effect on performance indicator (%) for different scenarios.]

Figure 39: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Economies of scale scenarios with type 3 substitution</td>
<td>12.4%</td>
<td>5.6%</td>
</tr>
<tr>
<td>B. Copper related material substitution scenarios</td>
<td>4.0%</td>
<td>0.3%</td>
</tr>
<tr>
<td>C. Ferrous metals recovery percentage scenario</td>
<td>1.8%</td>
<td>0.9%</td>
</tr>
<tr>
<td>D. Average to progressive economies of scale scenarios</td>
<td>1.1%</td>
<td>0.6%</td>
</tr>
<tr>
<td>E. Progressive economies of scale scenario</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>F. Progressive economies of scale scenario but with conservative processing costs</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
<tr>
<td>G. Conservative bottom-up legislation scenario with progressive plastics</td>
<td>1.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>prices/recovery rates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. Average to progressive type 1 and 2 plastics recovery percentage scenarios</td>
<td>1.1%</td>
<td>0.6%</td>
</tr>
<tr>
<td>I. Average to progressive bottom-up legislation scenarios</td>
<td>1.1%</td>
<td>0.6%</td>
</tr>
<tr>
<td>J. Average economies of scale scenario</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>K. Average to progressive aluminium recovery percentage scenario</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>L. Average to progressive copper recovery percentage change scenario</td>
<td>0.2%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Table 59: Legend for Figure 39
Scenario analysis results, ranked according to size of effects
Effects: only negative effects are ranked
Performance indicator: Recyclability
Category: Metals dominated products

<table>
<thead>
<tr>
<th>Scenario Type</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-5.9%</td>
<td>-3.1%</td>
</tr>
<tr>
<td>Reduction of ferrous metals content scenarios, substitution with high-yield plastics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>-18.8%</td>
<td>-8.3%</td>
</tr>
<tr>
<td>Reduction of ferrous metals content scenarios</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 40: See graph header

Table 60: Legend for Figure 40
2.2 Scenario analysis results for plastics dominated products

The results displayed in this section belong to section 7.2, in which an overview and interpretation of results for the plastics dominated product category is given.

### Figure 41: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>203.9%</td>
<td>203.9%</td>
</tr>
<tr>
<td>B</td>
<td>109.4%</td>
<td>64.1%</td>
</tr>
<tr>
<td>C</td>
<td>102.4%</td>
<td>27.4%</td>
</tr>
<tr>
<td>D</td>
<td>50.8%</td>
<td>18.5%</td>
</tr>
<tr>
<td>E</td>
<td>38.6%</td>
<td>38.6%</td>
</tr>
<tr>
<td>F</td>
<td>37.6%</td>
<td>37.6%</td>
</tr>
<tr>
<td>G</td>
<td>36.7%</td>
<td>36.7%</td>
</tr>
<tr>
<td>H</td>
<td>36.7%</td>
<td>14.7%</td>
</tr>
<tr>
<td>I</td>
<td>35.8%</td>
<td>35.8%</td>
</tr>
<tr>
<td>J</td>
<td>35.6%</td>
<td>35.6%</td>
</tr>
<tr>
<td>K</td>
<td>25.2%</td>
<td>18.6%</td>
</tr>
<tr>
<td>L</td>
<td>14.5%</td>
<td>14.5%</td>
</tr>
<tr>
<td>M</td>
<td>8.6%</td>
<td>4.3%</td>
</tr>
<tr>
<td>N</td>
<td>7.1%</td>
<td>7.1%</td>
</tr>
</tbody>
</table>

Table 61: Legend for Figure 41
Scenario analysis results, ranked according to size of effects
Effects: only negative effects are ranked
Performance indicator: End-of-life revenues
Category: Plastics dominated products

Figure 42: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Scenarios with a progressive plastics price increasing component</td>
<td>40.6%</td>
<td>29.6%</td>
</tr>
<tr>
<td>B Scenarios with an average plastics price increasing component</td>
<td>24.7%</td>
<td>20.4%</td>
</tr>
<tr>
<td>C Material substitution scenario with a reduced ferrous metals content</td>
<td>13.2%</td>
<td>13.2%</td>
</tr>
<tr>
<td>D Selected bottom-up legislative scenarios with conservative effects on</td>
<td>11.9%</td>
<td>10.1%</td>
</tr>
<tr>
<td>processing costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E Conservative end-of-life processing cost scenario</td>
<td>11.0%</td>
<td>11.0%</td>
</tr>
<tr>
<td>F Conservative economies of scale scenario</td>
<td>11.0%</td>
<td>11.0%</td>
</tr>
<tr>
<td>G Economies of scale scenarios with average effect on processing costs</td>
<td>5.4%</td>
<td>2.1%</td>
</tr>
<tr>
<td>(no substitution)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 62: Legend for Figure 42
Figure 43: See graph header.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Top-down legislative scenarios</td>
<td>37.0%</td>
<td>34.7%</td>
</tr>
<tr>
<td>B Progressive to average economies of scale scenarios with type 3 substitution</td>
<td>36.9%</td>
<td>15.8%</td>
</tr>
<tr>
<td>C Progressive to average scenarios for increasing plastics recovery rates</td>
<td>13.5%</td>
<td>6.7%</td>
</tr>
<tr>
<td>D Progressive to average bottom-up legislative scenarios</td>
<td>13.5%</td>
<td>13.5%</td>
</tr>
<tr>
<td>E Progressive to average economies of scale scenarios, no substitution</td>
<td>13.5%</td>
<td>6.7%</td>
</tr>
<tr>
<td>F Progressive to average improved ferrous metals recovery percentage scenarios</td>
<td>1.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>G Progressive to average improved copper recovery percentage scenarios</td>
<td>0.2%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Table 63: Legend for Figure 43
2.3 Scenario analysis results for precious metals dominated products

The results displayed in this section belong to section 7.3, in which an overview and interpretation of results for the precious metals dominated product category is given.

Scenario analysis results, ranked according to size of effects
Effects: only positive effects are ranked
Performance indicator: End-of-life revenues
Category: Precious metals dominated products

Figure 44: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>102.5%</td>
<td>102.5%</td>
</tr>
<tr>
<td>B</td>
<td>53.4%</td>
<td>53.4%</td>
</tr>
<tr>
<td>C</td>
<td>46.8%</td>
<td>46.8%</td>
</tr>
<tr>
<td>D</td>
<td>23.7%</td>
<td>23.7%</td>
</tr>
<tr>
<td>E</td>
<td>7.1%</td>
<td>2.4%</td>
</tr>
<tr>
<td>F</td>
<td>5.3%</td>
<td>1.6%</td>
</tr>
<tr>
<td>G</td>
<td>2.7%</td>
<td>2.7%</td>
</tr>
<tr>
<td>H</td>
<td>2.3%</td>
<td>2.3%</td>
</tr>
<tr>
<td>I</td>
<td>1.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>J</td>
<td>0.9%</td>
<td>0.9%</td>
</tr>
<tr>
<td>K</td>
<td>0.8%</td>
<td>0.3%</td>
</tr>
<tr>
<td>L</td>
<td>0.7%</td>
<td>0.8%</td>
</tr>
<tr>
<td>M</td>
<td>0.7%</td>
<td>0.3%</td>
</tr>
<tr>
<td>N</td>
<td>0.6%</td>
<td>0.5%</td>
</tr>
<tr>
<td>O</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>P</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Table 64: Legend for Figure 44
Scenario analysis results, ranked according to size of effects  
Effects: only negative effects are ranked  
Performance indicator: End-of-life revenues  
Category: Precious metals dominated products

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Average to conservative gold price scenarios</td>
<td>8.1%</td>
<td>2.7%</td>
</tr>
<tr>
<td>B Average to conservative copper price scenario</td>
<td>0.9%</td>
<td>0.2%</td>
</tr>
<tr>
<td>C Material substitution scenario with reduction of ferrous metals content</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>D Bottom-up legislative scenarios with conservative processing cost component</td>
<td>0.2%</td>
<td>0.1%</td>
</tr>
<tr>
<td>E Conservative economies of scale scenarios</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>F Conservative processing cost scenario</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>G Conservative silver price scenario</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Figure 45: See graph header  
Table 65: Legend for Figure 45
### 2.4 Scenario analysis results for CRT based products

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Progressive to average economies of scale scenarios with type 3 plastics substitution</td>
<td>26.9</td>
<td>13.23</td>
</tr>
<tr>
<td>B. Material substitution scenario with increased w% recoverable plastics</td>
<td>14.9</td>
<td>4.9</td>
</tr>
<tr>
<td>C. Various scenarios with progressive effects on plastics recovery percentages (incl. EOS, Legislative)</td>
<td>2.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>
The results displayed in this section belong to section 7.4, in which an overview and interpretation of results for the CRT based product category is given.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>360.4%</td>
<td>360.4%</td>
</tr>
<tr>
<td>B</td>
<td>350.0%</td>
<td>333.2%</td>
</tr>
<tr>
<td>C</td>
<td>332.0%</td>
<td>332.0%</td>
</tr>
<tr>
<td>D</td>
<td>310.3%</td>
<td>239.1%</td>
</tr>
<tr>
<td>E</td>
<td>252.9%</td>
<td>252.9%</td>
</tr>
<tr>
<td>F</td>
<td>204.6%</td>
<td>133.9%</td>
</tr>
<tr>
<td>G</td>
<td>109.0%</td>
<td>109.0%</td>
</tr>
<tr>
<td>H</td>
<td>99.5%</td>
<td>99.5%</td>
</tr>
<tr>
<td>I</td>
<td>89.4%</td>
<td>89.4%</td>
</tr>
<tr>
<td>J</td>
<td>75.8%</td>
<td>75.8%</td>
</tr>
<tr>
<td>K</td>
<td>74.2%</td>
<td>74.2%</td>
</tr>
<tr>
<td>L</td>
<td>66.8%</td>
<td>66.8%</td>
</tr>
<tr>
<td>M</td>
<td>58.6%</td>
<td>33.7%</td>
</tr>
<tr>
<td>N</td>
<td>52.5%</td>
<td>52.5%</td>
</tr>
<tr>
<td>O</td>
<td>41.6%</td>
<td>41.6%</td>
</tr>
<tr>
<td>P</td>
<td>41.6%</td>
<td>16.6%</td>
</tr>
<tr>
<td>Q</td>
<td>40.8%</td>
<td>40.8%</td>
</tr>
<tr>
<td>R</td>
<td>40.7%</td>
<td>16.3%</td>
</tr>
<tr>
<td>S</td>
<td>39.5%</td>
<td>39.5%</td>
</tr>
<tr>
<td>T</td>
<td>35.4%</td>
<td>35.4%</td>
</tr>
<tr>
<td>U</td>
<td>29.8%</td>
<td>9.9%</td>
</tr>
<tr>
<td>V</td>
<td>20.5%</td>
<td>7.8%</td>
</tr>
<tr>
<td>W</td>
<td>20.1%</td>
<td>20.1%</td>
</tr>
</tbody>
</table>

Table 67: Legend for Figure 47
Scenario analysis results, ranked according to size of effects
Effects: only negative effects are ranked
Performance indicator: End-of-life revenues
Category: CRT based products

Figure 48: See graph header

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Conservative copper price scenario</td>
<td>14.5%</td>
<td>14.5%</td>
</tr>
<tr>
<td>B Conservative economies of scale scenario</td>
<td>12.5%</td>
<td>12.5%</td>
</tr>
<tr>
<td>C Conservative processing cost scenario</td>
<td>12.5%</td>
<td>12.5%</td>
</tr>
<tr>
<td>D Conservative legislative bottom-up scenario</td>
<td>12.5%</td>
<td>12.5%</td>
</tr>
<tr>
<td>E Material substitution scenarios with a reduction of copper content</td>
<td>10.3%</td>
<td>9.5%</td>
</tr>
<tr>
<td>F Conservative gold price scenario</td>
<td>8.0%</td>
<td>8.0%</td>
</tr>
</tbody>
</table>

Table 68: Legend for Figure 48
### Scenario analysis results, ranked according to size of effects

**Effects:** only positive effects are ranked  
**Performance indicator:** Recyclability  
**Category:** CRT based products

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Max. effect</th>
<th>Min. effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  Top-down legislative scenarios</td>
<td>68.1%</td>
<td>67.7%</td>
</tr>
<tr>
<td>B  Progressive to average economies of scale scenarios with type 3 substitution</td>
<td>52.6%</td>
<td>52.6%</td>
</tr>
<tr>
<td>C  Average economies of scale scenarios with progressive effects on processing</td>
<td>22.2%</td>
<td>8.9%</td>
</tr>
<tr>
<td>D  Progressive to average type 1 and 2 plastics recovery percentage scenarios</td>
<td>24.4%</td>
<td>24.4%</td>
</tr>
<tr>
<td>E  Progressive to average legislative bottom-up scenarios</td>
<td>17.8%</td>
<td>8.9%</td>
</tr>
<tr>
<td>F  Progressive to average economies of scale scenarios, no substitution</td>
<td>17.8%</td>
<td>8.9%</td>
</tr>
<tr>
<td>G  Material substitution scenarios with increase in copper or ferrous metals</td>
<td>4.1%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

*Figure 49: See graph header*

*Table 69: Legend for Figure 49*
Appendix 3: A Delphi Study on Future Recycling Technology

This appendix gives some of the background behind the Delphi study discussed in Chapter 3.

3.1 General description of the Delphi Study

The importance of taking end-of-life issues into account during products has become obvious in recent years. However, nowadays an overview of what future end-of-life technology could look like is not available. This causes products to be designed with current recycling and/or disassembly technologies kept in mind. Since consumer electronics can last for 15 to 25 years, these technologies will have changed by the time these products are discarded. There is therefore a clear need to gain insights in what future recycling and disassembly technology could be like.

Moreover, on several universities and other research institutes, extensive research projects have been defined to look into these future technologies. The opinions of researchers that work here, for example about the feasibility of their prototype technologies, are often not shared by others in the field, but outside these projects. Especially within companies there is skepticism when it comes to implementing new elements into the design practice, keeping in mind future technologies. This is not necessarily the result of short-sightedness or ignorance, but is caused by the lack of evidence or reassurance that these technologies will indeed be available years or decades from now.

After having several times been confronted with these kinds of remarks and situations it decided to perform a Delphi study on the subject, with the main objective to chart the technical feasibility, as well as the economic attractiveness, of technologies that are currently under development. To this end, a large number of specialists in the field of disassembly and recycling of electronic consumer goods and automobiles was impaneled. By using the Delphi technique it was tried to reach consensus among these specialists on the future developments of issues such as automated/robotized disassembly, material separation and sorting techniques, as well as on several related subjects.

Recycling and disassembly in general can no longer be considered separate. Developments in the first field are highly relevant in the second and vice versa. For these reasons, it was decided to combine an investigation into the fields of cars and electronics end-of-life management, considering recycling and disassembly techniques, in one Delphi study.

The main issues that were addressed in this study are automated disassembly and sorting of plastics and metals streams. In the process of drawing up the first-round ques-
tionnaires certain related issues arose that were added to the study. As a result, the final first-round questionnaire comprised about 70 questions on 10 issues, all related somehow to future end-of-life scenarios of products and the technologies that will or will not make these scenarios possible.

3.2 The Delphi Technique

The Delphi method is used to facilitate communication on a specific task. The method involves anonymity of responses and feedback to the group as a whole or to individuals. Every respondent has the opportunity to modify an earlier judgment. The method is usually conducted via paper and mail and was originally developed at the RAND Corporation by Olaf Helmer and Norman Dalkey. Used as a technique to arrive at a group position regarding an issue under investigation, the Delphi method consists of repeated interrogations, by means of questionnaires, of a group of individuals whose opinions or judgments are of interest. After the initial interrogation of each individual, each subsequent interrogation is accompanied by information about the preceding round of replies, usually presented anonymously. The individuals are thus encouraged to reconsider and, if appropriate, to change their earlier replies in the light of the replies of other members of the panel. After two or three rounds, the group position is determined by averaging.

3.3 The panel

The specialists that participated in this specific Delphi Survey work in the industry, at universities, consultancies and research institutes throughout Europe, North America and the Far East. There were also delegates from governments and several branch organizations. In the figures below the panel compositions are shown.

Fig 1: Panel composition (geographical background)  Fig 2 Panel composition (professional background)

3.4 Panel responses

3.4.1 First round responses

For the first round, 217 individuals were invited to participate in this Delphi study. Initially, individual invitations were based on one or more of the following grounds:

- The invited panel member has a record of relevant publications in the field of disassembly and/or recycling related research.
- The invited panel is known to the authors of this study as being active in the field of disassembly and/or recycling related research.
- The invited panel member was suggested by someone else in the field who felt he or she was more appropriate to be invited.

Additional panel members were added because they appeared to be active in the field also, for example based on internet pages. A few invitations were sent to panel members based in countries that are not yet widely known as being proactive in recycling matters. However, the vast majority of the actual panel that participated eventually, consisted of people that were selected based on the grounds stated above.

In total, 68 specialists responded to the first round questionnaires, which corresponds with a percentage of 31.3%. Considering that most of the respondents that ‘just had to be in the panel’ responded, this was a satisfactory result. Actually, for an independent Delphi study like the underlying one, this is percentage is above expectations.

It should be noted that not every panel member responded to every question in the questionnaire. Nevertheless, every question was answered by at least 65%, and on average by about 75% of the panel members.

3.4.2 Second round responses

In the second round, questionnaires were sent to all 68 panel members who responded in the first round. Of these 68 individuals, 55 responded in the second round, which corresponds with a percentage of just over 80%. To reach this response rate, a reminder had to be sent out to several panel members. A considerable part of these panel members responded that they did not want to change their predictions, which lead to the decision that the first-round answers of the 13 non-respondents were considered to be second-round answers too. It was checked if this had a significant influence on the second-round results, which was not the case.

For all second round questions, on average 19% of the initial predictions were changed. This figure could be regarded as a measure for the level of uncertainty the panel members gave their answers with. There is some variance among the questions: for example, with question 16 (take back of old cars), 28% and 34% of the panel respectively changed their second round answers to the first and second part of that question respectively. High percentages (>25%) were also found for question 11 (on automated
sorting of non-ferrous metal waste streams), and for the economical attractiveness parts of question 9 (on automated sorting of mixed plastics waste streams).

Less prediction alterations (<15%) were made for questions 6 (active disassembly), and 8 (governments stimulating recycling). This mainly seems to be due mainly to the significant number of answers in the ‘later’ category for these questions.

Level of expertise
The panel members were asked to indicate their level of expertise regarding these to four areas:
1. Automotive industry
2. Electronics industry
3. Disassembly practice
4. Recycling practice

These three categories were possible:
1. I consider myself a specialist
2. I have considerable knowledge, but I am no specialist
3. I have general knowledge in this field

This gave the authors the ability to evaluate afterwards whether the (supposed) level of expertise of the panel members had any significant influence on the results.

The distribution of the panel regarding this issue is:

<table>
<thead>
<tr>
<th></th>
<th>Automotive</th>
<th>Electronics</th>
<th>Disassembly</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>I consider myself a specialist</td>
<td>19%</td>
<td>12%</td>
<td>32%</td>
<td>35%</td>
</tr>
<tr>
<td>I have considerable knowledge, but</td>
<td>24%</td>
<td>44%</td>
<td>37%</td>
<td>46%</td>
</tr>
<tr>
<td>I am no specialist</td>
<td>57%</td>
<td>40%</td>
<td>31%</td>
<td>19%</td>
</tr>
</tbody>
</table>

With a simple measure, using the values 1, 2 and 3 for the respective descriptions, the relative levels of expertise for the whole panel can be shown:

<table>
<thead>
<tr>
<th></th>
<th>Automotive</th>
<th>Electronics</th>
<th>Disassembly</th>
<th>Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative measure of expertise</td>
<td>2.38</td>
<td>2.28</td>
<td>1.99</td>
<td>1.84</td>
</tr>
</tbody>
</table>

Although for every question it was indeed analysed whether the levels of expertise were of any influence on the answers, in general there was not enough evidence that this was the case in a significant way.
Appendix 4: More on Active Disassembly

For the purpose of explaining more about the assessment of active disassembly technology, use is made of an article written for the 1999 Life Cycle Engineering conference. Where applicable, the article is “shrunk to fit” this dissertation.

4.1 General description of active disassembly technology

The smart materials used for active disassembly technology include Shape Memory Alloys (SMA) for actuator devices and Shape Memory Polymers (SMP) for releasable fastener devices. In both cases, shape recovery is possible in different manners. Actuation of the SMAs and SMPs would happen just outside of world ambient temperatures for safety and practical reasons and would only change shape under the predetermined temperature. This ‘predetermined’ temperature is based on material composition and is therefore consistent and stable.

Using SMAs, it is possible to effectively force the fastening elements of the product apart. This is essentially due to the material’s ability to be stable in two different temperature states. SMAs are force providers when triggered by a very narrow temperature bandwidth. SMPs act differently as they immediately lose shape integrity over a small temperature band and are therefore useful in the design of fasteners/defasteners capable of a dual shape existence that can be ‘called’ when triggered with a specific temperature exposure. SMPs can also act as shape changing devices without force provision. This also allows for effective disassembly, as a gripping portion of the fastener would lose any gripping ability.

To date, with ADSM it is possible to disassemble sub-assemblies, unbonded components and constituent assemblies including the housing, PCB, LCD, antenna, shielding, transformer, mechanical components, hard and disc drives, buttons, plates, fittings, peripheral connections and various screwed or fastened components.

Earlier SMP active disassembly experiments revealed disassembly times of 10-30 sec-


onds. Most recent developments are approaching 1–2 seconds and it is these figures that are used as a basis for this paper. This marked improvement was made with the latest devices consisting of novel SMP ‘thread loosing’ devices. These exhibited non-destructive active disassembly of a Nokia 6110 cellular phone within a time of 1.5 seconds. Other cellular phones were experimented on using similar SMP devices revealed a mean time of just over 8 seconds. Remarkably, these SMP releasable fastener screws returned to their originally trained shapes without any evidence of having been put through the ADSM procedure. In all cases, active disassembly using these types of SMDs provided the self-dismantling of product housing without any destruction to the host products.

It is imaginable that ultimately a varied waste or product stream can be processed into the same disassembly facility as long as they have SMA or SMP fastener/defasteners. This non-specific reclaimation would bring down the accumulated costs of disassembly, as the different products would share the same disassembly facility. Brand or product specific dismantling lines or facilities would not be necessary. Therefore, one of the advantages of ADSM is the fact that the variety of end-of-life products does not pose a serious problem. This in contradiction with for example automated disassembly, where product variety is often regarded as a bottleneck. It should be noted however, that it is in no way a problem to process products containing SMA or SMP fasteners in an existing facility.

Using smart materials in the design of releasable fasteners and actuators to be introduced at the manufacturing stage, disassembly is possible to effectively split products’ assemblies. This disassembly technique is novel with a variety of potential applications and is known as Eco-Design for Active Disassembly using Smart Materials (ADSM). In several recent publications that critically assessed the concept of active disassembly, and stated that the technology would be promising as long as the cost and safety issues would be overcome.

4.2 Economical assessment of active disassembly technology

In modern recycling practice, basically three scenarios are possible, depending on the product categories they are used on.

- **Scenario 1**: a manual disassembly oriented scenario
- **Scenario 2**: a shredding and separation scenario with minor prior manual disassembly
- **Scenario 3**: a shredding and separation only scenario.

There are two principal ways in which ADSM could be integrated in these scenarios. The first one is to replace manual disassembly in scenarios 1 and 2. This would be done if ADSM turns out to be cheaper than the conventional manual disassembly. A second way is to add ADSM as an additional process in the third scenario. This would be done when it turns out that a prior separation in fractions would result in less contaminant-ed material streams before these streams are shredded and separated and that the costs of doing so would be less the benefits.

In short, ADSM is to be regarded as a “competing technology” compared to manual disassembly, not when compared to shredding and separation. Instead, it is believed that shredding and separation and ADSM should be regarded as complementary, even synergetic technologies.

4.3 Determination of appropriate product categories for ADSM

In this chapter it is considered which product categories are likely to benefit most from the application of ADSM technology during their end-of-life stage. For this purpose, Table 40 illustrates a product category subdivision according to end-of-life product characteristics. This figure is based on research described in Boks et al.\(^{221}\)

Based on the characteristics of ADSM, the use of this technology would be especially beneficial in the following cases:

- When applied instead of manual disassembly, reducing the disassembly time and hence reducing the end-of-life costs,
- When applied instead of or prior to shredding and separation, increasing the material recycling efficiency.

In the following sections it is determined for which product categories these conditions apply.

4.3.1 CRT containing products

Products in this category have already a relatively high material recycling efficiency. End-of-life costs are relatively high however, mainly due to high disassembly costs. Products

with picture tubes are not candidates for shredding and separation because in general more than 50% of the product weight consists of glass, which cannot be processed in a shredder satisfactorily. CRT containing products are therefore usually processed according to scenario 1 as discussed in 4.2. This leads to the hypothesis that with ADSM, the disassembly costs could be brought down considerably. However, no tests have been done yet for applying ADSM to this product category. Therefore there is no data yet to base rejection or acceptance of this hypothesis on.

4.3.2 Metal dominated products

Because of their high metal content, these products have a relatively high material recycling efficiency. By magnetic separation the metals are easily retrieved and the remaining plastics content is low. Also, the end-of-life costs are relatively low. Hence, compared to other product categories, there would be less incentive to focus on the application of ADSM on metal dominated products, and therefore it is not further discussed in this paper.

4.3.3 Plastics dominated products

Products in this category exhibit both a low material recycling efficiency as well as high recycling costs. This leads to the hypothesis that there would be ample room for improvement in this category. It was therefore examined in what way ADSM could contribute to this. Theoretically, by using ADSM, constituent components including plastic (cover) parts could be separated from the inside of the product in a more cost effective way compared to conventional disassembly. This would enable the processing of the inside parts with a lower plastics content, which in theory, could significantly raise the material recycling efficiency score. However, this would also make further processing and even reuse of the plastic parts possible, given the fact that they meet certain prior specifications (such as not being contaminated with flame retardants).

Legislative developments such as the pending EU law on smelting being incompatible with plastics and many take back legislatures world wide like those in the EU and Japan are now closer to coming into effect. These could mean alternatives to end-of-life strategies such as ADSM to provide potentially profitable recycling. Introducing product levies with partial levy return to the party returning the product at end-of-life continues to be a potential way forward to producer responsibility making an opportunity for more recycling scenarios. This would be especially true for the plastics dominated product category. Since 2-5% of manufactured products turns out to be pre-consumer waste, there lies a potentially valuable and high quality resource largely due to incorrect estimations in manufacture, demand and lack of demand as new products are phased in.

At present, several experiments have been conducted for determining the feasibility of ADSM on plastics dominated products. Tests include products such as audio equipment and playstations.
4.3.4 Precious metal dominated products

These products are generally small or miniaturized sophisticated products. Because of their high content of valuable precious metals (found primarily in surface mounted devices on PWBS), products in this category exhibit generally a positive recycling yield. However, they also exhibit a low material recycling efficiency. Based on this, in theory ADSM could be an excellent way to improve the material recycling efficiency because in a stage prior to shredding and separation, the parts containing a low amount of precious metals could be separated in advance. This would only be beneficial in the case that the value of product that still contain their covers is (considerably) less than of the precious metals containing PWBS only. For the most recent generation of cellular phones, this might not be so since because of the high degree of miniaturization the weight of the plastics covers is relatively low. But for less sophisticated products such as the handpieces of cordless phones this is generally not true and therefore these products are definitely candidates for further research and calculations. However, in the case of cellular phones, upcoming EU laws indicate a target of 80% plus recycling for these products. This would indicate clean separation of top and bottom covers.

If indeed legislation is implemented demanding the separate processing of the LCD screens in these products, ADSM could again be extremely beneficial in this case. For this issue, further testing of fastening and separating LCD screens by smart material devices is needed.

4.4 Costs of Active Disassembly using Smart Materials.

The costs incurred by an end-of-life scenario with ADSM can be divided in three categories:

• the cost of inclusion of smart material fasteners into products
• the cost of the actual disassembly process, i.e. preparing a batch of end-of-life appliances, heating up the batch, and unloading that batch to make further processing possible
• the (additional) costs of setting up an ADSM line in a recycling facility.

4.4.1 Category 1 costs:

In volume purchasing, costs of SMP releasable fasteners are the same as traditional metal and polymer fasteners. Therefore, there is no added cost to such an ADSM candidate product. Additionally, there exists the potential to reuse the SMP devices to a cycle value over 10000 times. Purchasing new fasteners for new products would not be required and there lies the potential for lower cost manufacturing. Collection would be in the established separating process and looped back into the manufacturing facility in the same way fasteners are purchased and included in current manufacturing logistics.

In the case of SMA actuator devices, shape reconfiguration would be automatic (due to Shape Memory Effect [SME] properties) depending on devices specified. If reconfigura-
tion were required, this would cost the same as a new traditional fastener. CuZnAl devices do not require reconfiguration whilst NiTi devices may depending on specific requirements. All SMA devices have reuse potential with cycle values also over 10000 times. Purchasing new actuators for new products therefore, would not be required.

Current prices of Shape Memory Alloys are US$ 0.20 per gram for NiTi actuators, and US$ 0.04 per gram for CuZnAl actuators. However, these prices are only temporary as prices continue to drop with time. Increasing manufacturing volumes are expected to lead to a price drop by at least 50% of those quoted.

With high cost actuators (worst case scenario), one device has a weight of 0.5 grams (= US$ 0.10). Additional cost would require primary shape training at only a few cents each. Only one is required per small hand held electronic product. The total cost of the Shape Memory Device (SMD) in this scenario might be US$ 0.15 but all traditional fasteners could be eliminated with some minor design changes eliminating US$ 0.05 to US$ 0.10 leaving a total cost addition of US$ 0.05 to US$ 0.10. For actuators not requiring reconfiguration, there would not be any subsequent costs and the devices would potentially reduce manufacturing costs if they were collected and reused as in a similar fashion described for the SMP devices.

4.4.2 Category 2 costs:

To compare ADSM costs with conventional disassembly costs as done in the case studies further on in this chapter, it needs to be established what the ADSM cost of a single product is. Since in this process costs are incurred by a batch of products rather than per individual product, it has been decided to base comparison on the amount of fasteners in a product. ADSM costs of unjoining a fastener are therefore defined as the ADSM costs for the total batch divided by the total amount of fasteners to be unfastened in the whole batch. For example, if product A has 4 fasteners, and if a 500 product A batch is considered, and if the total ADSM running costs of processing that batch would be $1, then the ADSM costs of product A would be $1 divided by 2000 times 4 equals $0.002.

It can be argued that running costs for ADSM are very low. Running costs essentially consist of heating up a batch of appliances. The energy costs per product of doing so are assumed to be no higher than the energy costs required to have the pneumatic tools used for conventional disassembly operational. In fact, energy costs could be an extremely small fraction of that for manual disassembly due to efficiency of an optimised heated dismantling chamber. Additional running cost are incurred by having for example one person operating the system, but since the labour costs of having that would be divided by the large amount of products processed simultaneously, these would be negligible. The following argumentation supports that hypothesis. In a best case, highly automated scenario, the process of heating up a batch of 100 up to 1000 products would take no more than 10 seconds, consisting of 1 or 2 seconds of actually separating joints and the remaining time for loading and unloading the batch. This would mean that perhaps five batches per minute could be processed, which equals 500 to even 5000 products per minute. At a labour rate of US$ 0.50 per minute that would
result in a labour cost of US$ 0.001 to US$ 0.0001 per product. Even in a worst-case scenario, where the processing of one batch would take, say, 5 minutes (25 times slower), this would still result in very low labour costs of US$ 0.025 to US$ 0.0025 per product. Compared to a conventional disassembly scenario, these costs are very low. Depending on the product category, the cost of manual disassembly for a product can be up to several dollars.

An example from the plastics dominated product category: a Sony playstation would take about 2.5 minutes to disassemble manually, resulting in a cost of about US$1.30. Compared to the worst-case scenario described above the difference is a factor 50 in favour of active disassembly. In less pessimistic scenarios this factor increases easily to 500 or higher. Note: in this case it is assumed that loading and unloading a batch will not incur additional costs since in a conventional disassembly scenario similar handling activities have to be carried out. But because of the high amount of products processed simultaneously, and the fast disassembly times, even additional costs are negligible.

4.4.3 Category 3 costs

Setting up an ADSM facility would likely cost the same or more than setting up a non-robotic or traditional dismantling facility. It is anticipated that the costs of a large conveyor system, thermal zone, product receptacle and dumping mechanisms would be at least US$ 30,000. These costs would not include items already required for a traditional dismantling facility including a building, loading dock and mechanical sorting technologies and machinery. Mechanical separation would need a likely investment of at least US$ 20,000 to 50,000 depending on size and 'completeness' of the system. Alternatively, these procedures could be done without such equipment by hand whereby mean disassembly times may require 2 to 5 seconds in addition per product for disassembly times. The running costs here would more, as labour would have to be factored in (see category 2 remarks).

4.4.4 Remarks on the life cycle perspective

Before passing final judgement on the ecological feasibility of using ADSM as an option in end-of-life processing of consumer electronic goods, either as replacement of conventional disassembly or as addition to existing shredding and separation processes, it needs to be established from a life cycle perspective if ADSM is an environmentally wise thing to do. If energy consumption of an ADSM process is out of proportion, from an ecological viewpoint ADSM could never be justified. Although research on this particular issue is still in progress, it is believed that the running costs and energy requirements for the process are less than was originally assessed. Preliminary results indicate that:

- an ADSM line would require at least 50°-60°C temperature raising;
- a relatively high efficiency heated chamber (water or air). A water-heated chamber could be easier to control and potentially less messy;
- as on a mass dismantling system disassembly times would have a mean average of far less than a second (see 4.4) each, the unit cost per product in energy consumption would be very minimal.
4.5 Impact on product design

After experiments were conducted, examinations were made for necessary design modifications. Besides accepted design for end-of-life, improved incorporation of ADSM would include:

- 'Smart Material Devices' (SMDs) proximity by temperature increase/ hierarchy/ 'break' passage.
- Location specific force provision surpassing tensile force of fastening/product enclosure
- Controlled trigger temperature/time balance affects on structural integrity of product relative to disassembly procedure with tight tolerances for SMD and product enclosure
- SMD design depends on product applications for best results; standardization can be achieved for applications requiring specific execution
- Controlled break points, over-specification reduction, general simplification, hierarchy of subassemblies and vinculum (weakest strength point in product) strength reduction improve the ADSM procedure.

Although ADSM could be implemented without any added costs, very minor initial cost increases would be evident in many applications. New product design must include some changes to the housing of the candidate products if ADSM were to take place if the near minimum energy is to be consumed in the ADSM process. One of the greatest advantages of ADSM is the versatility in cost, design changes and potential implementations. Further work currently under way, demonstrates the principles of these parameters.

This section has compared the attributes of an active disassembly scenario with conventional end-of-life scenarios such as manual disassembly and shredding and separation. ADSM has revealed exciting possibilities particularly with plastics dominated products and precious metal dominated products categories. Although ADSM seems a likely candidate for CRT product dismantling, little work has bee done to verify this. From a cost perspective it has been made clear that an ADSM scenario could potentially be much cheaper than a conventional scenario. From an ecological perspective, it is expected that ADSM can contribute to higher material recycling efficiencies. For these reasons, ADSM is, although in its infancy, a potentially very powerful technology. As smart materials develop and prices drop, non-destructive dismantling for yet smaller components is highly probable. There are no volume non-destructive, nor generic applications known other than ADSM.

With producer responsibility laws become a real including 80% recyclability and clean LCD removal from mobile phones and a demand for more recyclability in other products like cordless phones etc., ADSM feasibility and corporate interest for ADSM increases. Generic cost effective non-destructive dismantling could be the way forward for a large number of product categories for the consumer electronics industry within the near future, either as main strategy or as a complementary strategy to shredding and separation.
4.6 Delphi results on active disassembly

In the aforementioned Delphi study (see section 3.4 of this dissertation) the issue of active disassembly was also addressed. The panel was asked to estimate when active disassembly could account for more than 10% of all disassembly operations for a certain product category. Two different product categories were defined, namely:

- Common white and brown goods
- More expensive or valuable goods like late model computers, palm tops, computer note pads, et cetera.

In the first round of the study the answers showed less consensus, and therefore it was decided that a second round was necessary. The panel was asked to reconsider their predictions assuming that safety would not be compromised by using this technology. In Figure 50 the results of the question are given.

![Bar chart showing Delphi results for active disassembly](image)

*Figure 50 Delphi results for active disassembly*

It is clear that after the second round, the panel is still divided into one group that thinks it will not be until after 2020 before this technique will be used, and another group that thinks that by 2005-2010 this technique may indeed be used on a significant scale. The latter part of the panel predicts that the technique will be applied earlier for the more valuable goods than for the common black and white goods.
The Relative Importance of Uncertainty Factors in Product End of Life Scenarios
Appendix 5: Environmentally Weighted Recycling Quotes in detail

For the purpose of explaining about Environmentally Weighted Recycling Quotes in detail, as started in section 5.4, use is made of the full text of an article to be published in the International Journal of Production Research. The cross references made in this appendix refer to sections in this paper only.

5.1 Introduction

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 is it scientifically very inaccurate. Moreover, calculations based on weight-based recyclability are likely to lead to incorrect decisions. At Delft University of Technology, 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 draft (Waste of Electric and Electronic Equipment), (Commission of the European Communities 2000) (Commission of the European Communities 2000), 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. Following this preposition, a number of items should be covered with an accurate measure of this performance:

1. The measure should describe to what extent material loops can be closed, that is to describe on a material basis how much environmental resource value can be conserved.
2. The measure 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 measure should indicate and prioritise from an environmental perspective the avenues for product (re)design for end-of-life treatment.
4. The measure should give a proper description of the environmental performance of end-of-life treatment systems including the environmental load of logistics, processing and upgrading of materials.

The QWERTY concept, as explained in this article is capable to cover all these issues. In three recent publications (Huisman et al. 2000a,b, Huisman and Stevels 2001a), the concept has been applied to several case studies, enabling for example comparison with the application of the traditional weight-based Material Recycling Efficiency (MRE). Results
show that the conventional MRE does not reflect the real environmental performance of a product's end-of-life treatment (Kalisvaart et al. 2000). In principle, this would mean that targets set in proposed take-back schemes, as stated in the draft WEEE Directive should be revised. In this article all underlying equations and basic assumptions of the QWERTY approach are comprehensively presented for the first time.

A substantial amount of previous research has been conducted on mass balancing of disposed electronic equipment in end-of-life and the environmental consequences (f.i. in 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 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 detailed environmental evaluation of the end-of-life phase of consumer electronic products. With the 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 et. al. 2001, Stobbe 2001). 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.

In this article, environmental value is defined as the value or load that is calculated for a certain material or material processing using an environmental assessment model, such as Life Cycle Assessment (LCA). End-of-life routes are defined as the additional processes after disassembly or shredding and separation as mentioned before. End-of-life treatment scenarios are defined as a set of (different) end-of-life routes for the material fractions resulting from shredding and separation and/ or disassembly. The theoretical framework, including all equations to calculate QWERTY scores is presented in Section 2. All requirements, and further assumptions and underlying data needed to conduct environmental assessment on discarded products are presented in Section 3. Practical application of QWERTY is explained further in Section 4 with a few examples. Conclusions are drawn in Section 5.

5.2 The QWERTY concept, basic equations and assumptions

5.2.1 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). 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 a product. As every end-of-life scenario has an (positive or negative) environmental impact, the aim of the QWERTY concept is to relate the score to realistic best and worst-case scenarios. To do this, a QWERTY score is always determined in relation to a well-defined theoretical minimum environmental impact, 'lower boundary', and maximum environmental impact, 'upper boundary'. 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 a disposed product, economically or technically so old that higher levels of reuse options are not attractive. As is illustrated in (Rose and Stevels 2001), 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 and Stevels, 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.

![Figure 1: Simplified end-of-life treatment structure](image)

Figure 1 illustrates the starting point for the further explanation of the QWERTY context. Here, it is shown that material fractions leaving the pre-treatment and shredding and separation stage can for instance end up as materials either to be landfilled, 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 while on a weight basis it is suggested that a good end-of-life performance is obtained.
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. Especially the replacement of primary materials can vary substantially for different materials because of differences in the prevented environmental load. This is due to substituting for the environmental load of the corresponding primary material production. Notice that the 'order of preferences' in Figure 1 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 1 as will be explained further in Section 2.3.

To calculate QWERTY scores, first the lower boundary or minimum environmental impact 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 upper boundary, for the same product is determined. Then the relevant actual end-of-life treatment is determined and the distances between this scenario and the lower and upper boundaries is measured. As the upper boundary is set at the 0% level and the lower boundary at the 100% level, consequently the actual environmental impact is a percentage in between (see figure 2).

![Diagram showing QWERTY calculation](image)

*Figure 2: 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.

### 5.2.2 Definition of the lower boundary

The lower boundary or minimum environmental impact as depicted in figure 2, 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 1a and 1b describe this definition of the lower boundary.
\[ EVW_{\text{min},i} = m_i \times EV_{\text{subst},i} \]  

(1a)

\[ EVW_{\text{min}} = \sum_{i=1}^{n} (m_i \times EV_{\text{subst},i}) \]  

(1b)

With:
- \( EVW_{\text{min},i} \) is the defined lower boundary/ minimum environmental value for the weight of material \( i \);
- \( EV_{\text{subst},i} \) 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;
- \( EVW_{\text{min}} \) is the total defined lower boundary minimum environmental value for the complete product.

The environmental substitution values in equation 1 can be measured with any suitable environmental assessment method (as further explained in Section 3). Equation 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 may 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 \( EV_{\text{subst},i} \) and \( EV_{\text{min}} \) are usually negative values.

The basis for the lower boundary is subject to choice, but there is substantial reason for choosing the situation sketched above. Any choice based on other scenarios requires additional arbitrary choices to be made regarding the level of environmental impact that must be assumed. The currently chosen boundary only depends on the product’s material composition and is independent of the many possible treatment scenarios. Still, the QWERTY concept is not limited to the above choice for the lower boundary. If a strong preference exists for assuming other definitions, which is definitely not recommended, these can easily be implemented.

5.2.3 Definition of the upper boundary

The definition of the upper boundary 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 pre-treatment: 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 product as a whole, is that some materials have very high environmental impacts on land-fill 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 transfers to the gas-phase in incineration processes, combined with relatively low capturing percentages within the flue gas cleaning system and thus 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 Vogtlaender 2001).

Calculations have shown for this definition that the highest environmental impacts for most materials occur in two routes, or uncontrolled landfilling with maximum leaching to water and soil over a 100 year time period (which is a common worst case assumption in this field), or incineration, without energy recovery and limited traditional wet flue gas cleaning, including all leaching from slag from residues. In some cases, materials can have high environmental impacts in one of the other 'realistic' scenarios (like metal smelting, controlled land-fill, plastic recycling or glass oven). As a mathematical consequence, in the formulas 2a and 2b, the highest 'worst case' maximum environmental impact will be determined by taking the maximum environmental impact value for material i out of the all "realistic" end-of-life routes.

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 (in examples like Table 2, Section 4.1, no negative QWERTY or QWERTYloss values occur for any of the materials). 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). Scenarios like this are in practice 'falling off' the scale. The definitions of the upper boundary are given in equations 2a and 2b.

\[
EVW_{\text{max},i} = m_i \times (EV_{\text{max,eol},i} + EV_{\text{pre,tr},i}) \tag{2a}
\]

\[
EVW_{\text{max}} = \sum_{i=1} \left( m_i \times (EV_{\text{max,eol},i} + EV_{\text{pre,tr},i}) \right) \tag{2b}
\]

With:

- \(EVW_{\text{max},i}\) is the defined upper boundary/maximum environmental value for the weight of material i;
- \(EV_{\text{max,eol},i}\) 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 landfiling);
- \(EV_{\text{pre,tr}}\) 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 upper boundary 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 is relatively high. For the current definition where the part of the upper boundary depending on certain processing steps, the assumed pre-treatment is dominated by the energy to shred the disposed products into small pieces. This energy consumption is rather independent of the product composition and a relatively stable value. If a strong preference exists for assuming other definitions for the upper boundary, which is definitely not recommended, these can easily be implemented.

5.2.4 Determining the actual environmental impact
The actual environmental impact of a certain product (see also figure 2) in a certain end-of-life scenario is represented by equations 3a and 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 1, 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.

\[ EVW_{\text{actual,}i} = m_i \times \left( EV_{\text{pre,}i} \times x_i + rec_i \times grade_i \times EV_{\text{subt,}i} + \sum_{j=1}^{\infty} (EV_{\text{eol,}ij} \times y_{ij}) \right) \]  
(3a)

\[ EVW_{\text{actual}} = \sum_{i=1}^{n} \left( m_i \times \left( EV_{\text{pre,}i} \times x_i + rec_i \times grade_i \times EV_{\text{subt,}i} + \sum_{j=1}^{\infty} (EV_{\text{eol,}ij} \times y_{ij}) \right) \right) \]  
(3b)

With:
• EVW_{actual,i} is the defined actual environmental value for the weight of material i for the EOL 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);
• 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 EOL scenario under consideration.

In equation 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 $EV_{eol,i}$ 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 4. Usually the $EV_{pretri}$ and the $EV_{eol,i}$ are positive values, the $EV_{subsi}$ is a negative value.

$$\sum_{i=1}^{n} y_i = 100\% - rv c_i$$

(4)

In equation 3, 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. 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 environmental value of the secondary material over the environmental value of primary material.

### 5.2.5 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 5. Similarly, the $QWERTY_{loss}$ is the distance of the actual environmental impact from the minimum environmental impact, as represented by equation 6.

$$QWERTY_i = \frac{(EVW_{actual,i} - EVW_{max})}{(EVW_{min} - EVW_{max})}$$  \hspace{1cm} (5a)

$$QWERTY = \sum_{i=1}^{n} \left( \frac{(EVW_{actual,i} - EVW_{max})}{(EVW_{min} - EVW_{max})} \right)$$  \hspace{1cm} (5b)

And:

$$QWERTY_{loss,i} = \frac{(EVW_{max,i} - EVW_{actual,i})}{(EVW_{min} - EVW_{max})}$$  \hspace{1cm} (6a)

$$QWERTY_{loss} = \sum_{i=1}^{n} \left( \frac{(EVW_{max,i} - EVW_{actual,i})}{(EVW_{min} - EVW_{max})} \right)$$  \hspace{1cm} (6b)
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.

\[ QWERTY + QWERTY_{loss} = 100\% \]  \hspace{1cm} (7)

In addition, equation 7 is always valid. The QWERTY score expresses the environmentally weighted recyclability of a product under 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 material present in the product, which is exactly one of the main strengths of this concept. (In practice, equation 7 also helps to check whether the assessments made with the QWERTY score were consistent).

### 5.3 Requirements and assumptions

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

1. Quantified environmental values based on environmental assessment models (paragraph 3.1);
2. The product's material composition (paragraph 3.2);
3. Description of end-of-life scenarios (paragraph 3.3).

In the remainder of this section these issues are further highlighted.

#### 5.3.1 Quantified environmental values based on environmental assessment models

The basic QWERTY concept described in Section 2 uses 'environmental values' (see equation 1-3). These values can be derived from any comprehensive method that produces these scores, but also methods focusing on a single environmental effect, like, for instance, eco toxicity or resource depletion, can be used. Recently, two Life Cycle Assessment (LCA) methods and one method focusing on a single environmental theme were integrated in the QWERTY concept: The Eco-Indicator '95 (Goedkoop 1995), its successor, the Eco-Indicator '99 (Goedkoop and Spriensma, 1999) and the EPS 2000 method (Steen 1999).

1. The Eco-Indicator '95 is a classical, so-called Problem Oriented Approach, LCA-method. The method addresses eleven environmental themes from, nine of which
are included in the normalisation and evaluation steps, leading to a single environmental score. This method has been widely used and is especially preferred by product designers and companies because of the resulting end-point scores.

2. The Eco-Indicator '99 is a new, so called Damage Oriented, LCA-method. The approach is also called a top-down LCA-method since all contributions to all environmental effects are translated to actual damage inflicted to eco-system quality, human health and resource depletion. Thus, this method is very different from its predecessor. It can also be regarded as more transparent, while at the same time different perspectives towards the environment are taken into account and quantified.

3. The EPS 2000 method, which stands for Environmental Priority Strategies in product design. The method is adjusted for damage assessment and also a top-down approach. The EPS system is mainly aimed to be a tool for a company's internal product development process.

In addition to these three methods, other alternative methods like the German TPI Toxic Potential Indicator (Nissen 2000), the Swiss Ecopoints '97 (Braunschweig 1998), the Dutch CML method (Heijungs et al. 1992) and the Danish EDIP (Wenzel et al. 1997) can be integrated as well, to check the consistency of QWERTY scores obtained. In the remainder of this article, the Eco-Indicator '99 method will be used as a default, as it is the most modern method available.

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 and Tillman 1997).

3. An important requirement is an environmental database providing environmental values for all relevant end-of-life processing steps and materials. 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. For QWERTY assessments, the Philips internal LCA-database is used (Van der Wel 2000), as this database contains a sufficient amount of data on materials, components, end-of-life processing steps, energy consumption, emissions and contribution of related processes. In the examples of Section 4, the standard available databases within the LCA software tool SIMAPRO are used (Pré consultants 2002).

5.3.2 Product composition 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 be assumed 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 2001) and the distribution of materials over the relevant end-of-life routes (Huisman and Stevels 2001a). In practice this means that rough QWERTY assessments can be made, based on the six aforementioned materials alone. Exceptions are single products with, in comparison to their product category, high amount 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. 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 QWERTY value. In practice this means an extra loss due to materials ending up in the 'wrong' fraction, which can be quite substantial. The data behind this level of detail will be further explained in Section 3.3.

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 2 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 on 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 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 level 2.
5.3.3 Description of end-of-life scenarios and data

The distribution percentages, mass and energy balances of the end-of-life processing of disposed consumer electronic products that belong to the previously indicated level 2, have been described in literature. Many data is available from one of the subprojects of the Dutch SENTER - IOP Heavy Metals – Consumer Electronics research. This data, published in (Ansems et al. 2002) is obtained from many literature sources and from contacts with Dutch and German recyclers. Out of these literature sources, three calculation modules were derived describing the distribution of all environmentally relevant materials over all fractions and end-of-life routes. Three types of treatments, with process-step sequences representing the European situation, are implemented in the QWERTY approach. The three modules are:

1. Shredding and separation of non-CRT browngoods;
2. Disassembly of housings and CRTs, followed by shredding and separation of the remaining, for CRT-containing browngoods;
3. Separate collection from the non-CRT stream of cellular phones by shredding and separation.

In (Huisman et al., 2001b) these three calculation modules have been introduced. In the next section these data and the implementation of them into the QWERTY concept will be highlighted using examples, which are representative for the issues mentioned in the introduction about the roles of policy, technology and design.

5.4 End-of-life scenarios and examples

5.4.1 Product composition versus fraction composition, CRT based appliances

To exemplify how the QWERTY approach works, the calculation module referring to the treatment of CRT-containing browngoods, will be used. In this case processing starts with a disassembly step. Housings are removed, resulting in a plastic fraction. Picture tubes are also treated in a separate process and are mainly converted to a glass fraction. The remaining parts, including PCBs, are converted to a copper, ferro, aluminium and a residue fraction. In figure 3 this process sequence is illustrated.
The calculation module corresponding with figure 3, estimates the average distribution percentages of the original materials over all fractions being created as well as for the further processing of these fractions. When a specific (ingoing) product composition is entered, the module calculates estimates for the amounts of all relevant materials for all (outgoing) fractions. In the connected LCA-database the corresponding environmental data for a number of subsequent end-of-life routes are known and the equations of Section 2 are applied. In table 1, the result for a typical material composition is given (a 1 kg CRT containing appliance).

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight in (g)</th>
<th>Fraction out (g)</th>
<th>% of original material in the 'right' fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferro</td>
<td>169.6</td>
<td>182.1</td>
<td>95.7%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>29.5</td>
<td>13.8</td>
<td>42.6%</td>
</tr>
<tr>
<td>Copper</td>
<td>34.7</td>
<td>39.5</td>
<td>80.1%</td>
</tr>
<tr>
<td>Plastic</td>
<td>210.6</td>
<td>155.4</td>
<td>73.7%</td>
</tr>
<tr>
<td>Glass</td>
<td>548.7</td>
<td>539.6</td>
<td>95.7%</td>
</tr>
<tr>
<td>Other</td>
<td>7.1</td>
<td>69.5</td>
<td>95.0%</td>
</tr>
</tbody>
</table>

Table 1. Product vs. fraction composition for an average CRT containing appliances

Table 1 shows that, for instance for the copper in the product, approximately 80% of the original copper ends up in the copper fraction, a little under 10% in the ferro fraction and almost all of the remainder in the residue fraction. Out of this 80% copper ending up in the copper fraction, approximately 95% is recovered at a copper smelter. The copper in the other fractions usually ends up in slag. Leaching from slag is included in the relevant environmental scores for (in this case) the ferro fraction and the residue fraction. The loss due to the copper not being recovered and the final copper emissions due to leaching from slag are both allocated to the total copper amount of the product. Note also that the disassembly of the CRT-glass and plastic housings aims at a better separation, not at collection parts for reuse.

In order to make comparisons with the traditional way of addressing recyclability, the most common equation for material recycling efficiency is given in equations 8a and 8b. As stated before, the definition of MRE in many legislative documents is not a very
unambiguous one. 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 et al. 2000).

\[ MRE_i = m_i \times rec_i \]  

(8a)

\[ MRE = \sum_{i=1} (m_i \times rec_i) \]  

(8b)

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 EOL scenario under consideration.

For the example of table 1, the resulting Material Recycling Efficiency (MRE) and the QWERTY scores and losses (based on Eco-Indicator '99) are presented in table 2 and figure 5. They show the contribution of every material to the total QWERTY score plus the QWERTY\(_{loss}\) value as can be calculated with the equations 5 and 6.

<table>
<thead>
<tr>
<th></th>
<th>MRE</th>
<th>QWERTY</th>
<th>QWERTY(_{loss})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferro</td>
<td>15.3%</td>
<td>4.0%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.4%</td>
<td>2.1%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Copper</td>
<td>3.3%</td>
<td>14.0%</td>
<td>6.3%</td>
</tr>
<tr>
<td>Plastic</td>
<td>0.0%</td>
<td>3.3%</td>
<td>31.6%</td>
</tr>
<tr>
<td>Glass</td>
<td>43.9%</td>
<td>12.7%</td>
<td>15.7%</td>
</tr>
<tr>
<td>Other</td>
<td>0.0%</td>
<td>0.3%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Total</td>
<td>64.8%</td>
<td>36.4%</td>
<td>63.6%</td>
</tr>
</tbody>
</table>

Table 2. QWERTY results CRT containing appliance

The contribution of materials to the total QWERTY score is completely different form the contribution to the total MRE score, as materials are not contributing according to their 'weight', but rather their 'environmental weight'. Moreover, for plastic dominated products this effect is even greater, because the relative importance of the copper content is much higher compared to the plastic content (under the assumption that the plastics do not contain flame-retardants). The relative contributions of materials, calculated with the QWERTY concept are therefore likely to lead to different priorities for Design for End-of-life activities, while the conclusions from figures like figure 5 can lead to different priorities for primary material selection and can show, for instance, the relevance of addressing unlocking properties for copper containing components. The unlocking properties of those components can be altered by both appropriate design on one hand, and by optimising shredding and separation process settings on the other hand.
5.4.2 Separate collection of cellular phones

An example of the influence of logistics is the optional treatment of cellular phones. They can be collected separately or as part of a stream of non-CRT containing appliances. For separate treatment, which is, if the numbers of disposed cellular phones are sufficient, in fact the best choice from both an environmental as an economic perspective, because in this way precious metals are recovered to the highest extend, a calculation module similar to that of figure 3 is used, with only two separation steps, using an Eddy Current process and a magnetic separation process. Subsequently, only two fractions are created, a relatively pure ferro fraction and a copper fraction containing all plastics and precious metals.

Figure 5. QWERTY results for an average cellular phone, separate treatment versus treatment as a part of the non-CRT appliances stream

Figure 6 shows the difference in QWERTY scores for the same average cellular phone in the two end-of-life treatment scenarios. The results are shown for three different
environmental assessment models already included in the QWERTY concept (see also 3.3). Assuming that a substantial amount of discarded cellular phones can be collected, it is shown that it is indeed better to treat them separately and not as part of the regular product stream with non-CRT containing appliances. The reason is that with more than one separation step, which means increasing the copper percentage of the copper fraction, too much of the precious metal content is lost (together with an amount of copper) to other fractions. In contrary to the QWERTY score, the MRE values would drop for the above example from 34% for treatment with non-CRT appliances to 31% for separate treatment. This is showing again that environmental policies should focus more on collection rates and optimised logistics than on the importance of weight based recyclability targets.

5.5 Conclusions

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 potential 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 a research community, in which still 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 are. It has been explained that even with limited product and process data, very meaningful results can be generated.

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. From a chain perspective, application of the QWERTY concept has been used to validate current draft legislation and the end-of-life processing practice. It has been shown, for example in the cellular phone processing case study, that separate processing of products or product categories is to be preferred over combined processing. If such results were to be acknowledged, this would imply resetting targets for recyclability as done in WEEE (draft) legislation. This clearly shows that the QWERTY concept could also be useful as a tool for policy makers.

In the near future the current research will be extended to include the following topics:
1. Further development and implementation of new end-of-life scenario modules, for instance pyrolysis of disposed products and of specific fractions;
2. Development of more case specific environmental indicators;
3. More accurate descriptions of the leakage of heavy metals and other environment-
ally relevant materials to the environment, resulting in more accurate environmen-
tal data on further process steps like incineration and landfill of remaining fractions;
4. Quantification of the effects of initial design decisions, for instance the use of lead-
free interconnection techniques rather than traditional techniques;
5. Evaluation of the eco-efficiency of take-back and recycling policies.

5.6 Acknowledgements

The authors wish to thank SENTER – IOP for sponsoring this research and Philips
Consumer Electronics and TNO Environment, Energy and Process Innovation for pro-
viding environmental data and analysis results.

5.7 References

ANSEMS, A.M.M., FEENSTRA, L., 2002, Ontwikkeling verwerking afgedankte electronica, sluiten van
zware metalen kringlopen, Draft report, TNO Environment, Energy and Process Innovation (in Dutch),
Apeldoorn, The Netherlands
BRAUNSCHWEIG, A., 1998, Bewertung in Ökobilanzen mit der Methode der ökologischen Knappheit
Ökofaktoren 1997, Methodik Für Oekobilanzen, Buwal Schriftenreihe Umwelt Nr 297, Bern,
Switzerland, 1998
Proposal 4, May 10, 2000, Brussels
EKVALL, T., TILLMAN, A. M., Open-loop recycling: criteria for allocation procedures, International Journal
European Trade Organisation for the Telecommunication and Professional Electronics Industry, 1997, End-
Cellular Phone Working Group, Swindon, United Kingdom, 1997.
Report 9523, Amersfoort, The Netherlands
Impact Assessment. Final Report, National Reuse of Waste Research Program. Pré consultants,
Amersfoort, The Netherlands
Environmental Life Cycle Assessment of Products: Guide and Backgrounds. Internal report. CML
University Leiden, The Netherlands
Electronics and the Environment, San Francisco, CA, pp. 105-111
Weighted Recycling Quotes in assessing environmental effects in the end-of-life of consumer electronics.
Proceedings of Electronics Goes Green, Berlin, Germany, pp. 453-459
HUISMAN, J., STEVELS, A.L.N., 2001a, Calculating environmentally weighted recyclability of consumer
electronic products using different environmental assessment models. Proceedings of the 2001 IEEE
International Symposium on Electronics and the Environment, Denver, CO, pp. 88-93


In this dissertation it was chosen to provide literature references in the form of footnotes as well as by separately listing them alphabetically, which is done below.


The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios


The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios


Langerak, M. (1997). The waste of audio products; are there alternatives or is it a dead end? Graduation report. Delft University of Technology, Faculty of Industrial Design Engineering, 1997.


The Relative Importance of Uncertainty Factors in Product Life End of Life Scenarios


The Relative Importance of Uncertainty Factors in Product End of Life Scenarios


312


# Tables used in this dissertation

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Incentives for recycling</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>A guide to cross-referenced sections in this dissertation</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>Influence of cornerstones on internal and external factors</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>Market prices for materials found in consumer electronics (Nov. 2000)</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>Grams of material that need to be separated to work on a cost neutral basis</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>Disposal levies for WEEE in the Netherlands</td>
<td>58</td>
</tr>
<tr>
<td>7</td>
<td>Examples of average standard disassembly times</td>
<td>64</td>
</tr>
<tr>
<td>8</td>
<td>Additional waste charges for various substances</td>
<td>70</td>
</tr>
<tr>
<td>9</td>
<td>Main end-of-life processing strategies for brown goods category</td>
<td>73</td>
</tr>
<tr>
<td>10</td>
<td>Disassembly scenario for CRT based products, including outlets for different parts</td>
<td>75</td>
</tr>
<tr>
<td>11</td>
<td>Seven archetypes of environmental consumer orientation</td>
<td>80</td>
</tr>
<tr>
<td>12</td>
<td>Areas where technological developments can cause uncertainty</td>
<td>92</td>
</tr>
<tr>
<td>13</td>
<td>Panel responses on technical feasibility of automated disassembly</td>
<td>95</td>
</tr>
<tr>
<td>14</td>
<td>Panel responses on economical feasibility of automated disassembly</td>
<td>95</td>
</tr>
<tr>
<td>15</td>
<td>Numerical results for electrical and electronical goods</td>
<td>96</td>
</tr>
<tr>
<td>16</td>
<td>Obstacles for automated disassembly</td>
<td>97</td>
</tr>
<tr>
<td>17</td>
<td>Delphi panel results addressing automated sorting of mixed plastics waste streams</td>
<td>100</td>
</tr>
<tr>
<td>18</td>
<td>Ranking of sorting techniques</td>
<td>101</td>
</tr>
<tr>
<td>19</td>
<td>Feasibility of an automated, input-independent sorting machine</td>
<td>101</td>
</tr>
<tr>
<td>20</td>
<td>Fluctuation count for gold prices 1992-2000, monthly and yearly</td>
<td>115</td>
</tr>
<tr>
<td>21</td>
<td>Fluctuation count for silver prices 1992-2000, monthly and yearly</td>
<td>116</td>
</tr>
<tr>
<td>22</td>
<td>Fluctuation count for palladium prices 1992-2000, monthly and yearly</td>
<td>118</td>
</tr>
<tr>
<td>23</td>
<td>Fluctuation count for copper prices 1992-2000, monthly and yearly</td>
<td>119</td>
</tr>
<tr>
<td>24</td>
<td>Fluctuation count for aluminium prices 1992-2000, monthly and yearly</td>
<td>119</td>
</tr>
<tr>
<td>25</td>
<td>Structural effects of developments on processing costs</td>
<td>122</td>
</tr>
<tr>
<td>26</td>
<td>Qualitative overview of likely end-of-life scenarios developments</td>
<td>124</td>
</tr>
<tr>
<td>27</td>
<td>Relevant questions for a second-generation end-of-life evaluation tool</td>
<td>138</td>
</tr>
<tr>
<td>28</td>
<td>Input parameters for the PMRCM</td>
<td>142</td>
</tr>
<tr>
<td>29</td>
<td>Input process parameters for the PMRCM</td>
<td>142</td>
</tr>
<tr>
<td>30</td>
<td>Input market parameters for the PMRCM</td>
<td>143</td>
</tr>
<tr>
<td>31</td>
<td>Input values for the example metals dominated product</td>
<td>147</td>
</tr>
<tr>
<td>32</td>
<td>Default PMRCM results for the example metals dominated product</td>
<td>147</td>
</tr>
<tr>
<td>33</td>
<td>Input values for the example plastics dominated product</td>
<td>148</td>
</tr>
<tr>
<td>34</td>
<td>Default PMRCM results for example plastics dominated product</td>
<td>148</td>
</tr>
<tr>
<td>35</td>
<td>Input values for the example precious metals dominated product</td>
<td>149</td>
</tr>
<tr>
<td>36</td>
<td>Default PMRCM results for the example precious metals dominated product</td>
<td>149</td>
</tr>
<tr>
<td>37</td>
<td>Weight percentages example CRT containing product, including glass</td>
<td>150</td>
</tr>
<tr>
<td>38</td>
<td>Input values for the example CRT containing product, without glass</td>
<td>150</td>
</tr>
<tr>
<td>39</td>
<td>Default PMRCM results for the example CRT containing product</td>
<td>151</td>
</tr>
<tr>
<td>40</td>
<td>Overview of MRE and end-of-life yields for different product categories</td>
<td>152</td>
</tr>
<tr>
<td>41</td>
<td>Division in scenarios</td>
<td>160</td>
</tr>
</tbody>
</table>
Figures used in this dissertation

Figure 1: Three cornerstones of end-of-life management ........................................... 15
Figure 2: The product life cycle .................................................................................. 19
Figure 3: The product end-of-life cycle ................................................................. 19
Figure 4: Lack of methodological description of end-of-life issues in a business context 21
Figure 5: Three cornerstones reflected in the structure of the dissertation .................. 26
Figure 6: Average life-cycle environmental impact per life-cycle stage for consumer electronics 29
Figure 7: Overview of this dissertation ..................................................................... 33
Figure 8: Factors influencing product end-of-life scenarios ....................................... 36
Figure 9: External factors influencing the product's end-of-life stage ......................... 43
Figure 10: Ensemble issue ......................................................................................... 46
Figure 11: Sample taking process to assess material content ..................................... 47
Figure 12: Collection rates up to August 2000 ......................................................... 50
Figure 13: Stepwise correlation between Cu concentration and price paid and asked .... 55
Figure 14: An example of a processing line for miniaturnisation and separation of consumer electronics 67
Figure 15: Hierarchy of end-of-life destinations ....................................................... 71
Figure 16: The outlet specifications determine recycling strategy for WEEE ................. 73
Figure 17: Uncertainty factors influencing scenario uncertainty ............................... 85
Figure 18: From volumes produced to volumes processed ....................................... 106
Figure 19: Correlation between concentration of metals and their environmental impact 113
Figure 20: Correlation between concentration of metals and their market value .......... 113
Figure 21: Correlation between the environmental impact of metals and their market value 114
Figure 22: Gold prices 1992-2000 ............................................................................ 115
Figure 23: Silver prices 1992-2000 ............................................................................ 116
Figure 24: Palladium prices 1992-2000 .................................................................. 117
Figure 25: Palladium price development until November 2001 ............................... 118
Figure 26: Copper prices 1992-2000 ...................................................................... 118
Figure 27: Aluminium prices 1992-2000 .................................................................. 119
Figure 28: ELDA technical product characteristics .................................................. 133
Figure 29: Simplified schematic representation of the PMRCM ................................ 146
Figure 30: Overview of the qualitative and quantitative analysis aspects .................... 156
Figure 31: Cumulative probability for a change the size of $\Delta x$ ............................. 158
Figure 32: End-of-Life revenues for metal dominated products .................................. 192
Figure 33: End-of-Life revenues for plastics dominated products ............................. 195
Figure 34: End-of-Life revenues for precious metals dominated products ................. 197
Figure 35: End-of-Life revenues for CRT based products ........................................ 199
Figure 36: Range of absolute positive effects from economies of scale scenarios per product category 203
Figure 37: See graph header ................................................................................. 253
Figure 38: See graph header ................................................................................. 254
Figure 39: See graph header ................................................................................. 255
Figure 40: See graph header ................................................................................. 256
Figure 41: See graph header ................................................................................. 257
Figure 42: See graph header
Figure 43: See graph header
Figure 44: See graph header
Figure 45: See graph header
Figure 46: See graph header
Figure 47: See graph header
Figure 48: See graph header
Figure 49: See graph header
Figure 46: Delphi results for active disassembly
Samenvatting

Na decennia van met name procesgerichte en afvalzuiveringsgerichte verbeteringen om schade aan het milieu te reduceren, heeft in de afgelopen tien jaar het begrip milieukundige produktontwikkeling of milieukundig ontwerpen, (ecodesign in het jargon) steeds meer opvang gevonden. Binnen de discipline milieukundig ontwerpen is er tevens steeds meer aandacht ontstaan voor de einde-levensduurfase van consumenten electronica. Hoewel vanuit een levensduurperspectief de einde-levensduurfase relatief geringe schade aan het milieu toebrengt, met name in vergelijking met de gebruiksfase van veel produkten, zijn er een aantal belangrijke redenen aan te dragen om onderzoek te doen op dit gebied. Een aantal van deze redenen heeft te maken met emotie en de verschillen in beleving van het onderwerp tussen bedrijven, overheden, belangenorganisaties en consumenten. Vanuit dit perspectief gaan steeds meer bedrijven zich met de einde-levensduur aspecten van produktontwerp bezig te houden. De stimuli hiervoor laten zich uiteindelijk allemal vertalen naar financiële motivaties, hetzij via het behouden of verbeteren van imago en marktaandeel of bijvoorbeeld via het vermijden van kosten door te voldoen aan terughuwetegving.

Onderzoek op het raakvlak van produktontwerp en einde-levensduur heeft zich in het afgelopen decennium voornamelijk proberen bezig te houden met het opstellen van ontwerprichtlijnen en het ontwikkelen van methodes om de verschillende relevante aspecten van milieukundig produktontwerp binnen een bedrijfscontext tegen elkaar af te wegen. Waar vele, voornamelijk kwalitatieve richtlijnen gepubliceerd zijn, is de ontwikkeling van kwantitatieve methoden die gebruik maken van gegevens uit de praktijk sterk achtergebleven. Dit is mede veroorzaakt door enerzijds een beperkte beschikbaarheid van systematisch verzamelde bruikbare data, en anderzijds door de vertrouwelijkheid van data uit de wel aanwezige bronnen. Tegelijkertijd bestaat er ten aanzien van einde-levensduur aspecten nog volop onzekerheid, met name met betrekking tot toekomstige einde-levensduurscenario's is er nog weinig bekend hoe en in welke mate deze effecten financiële consequenties zullen hebben voor producenten op het gebied van ontwerp, technologie en strategie.

In dit proefschrift worden de meest relevante externe factoren die voor onzekerheid zorgen op een rijtje gezet. Met name de factoren welke gerelateerd zijn aan economische, technologische en juridische aspecten worden besproken, zowel vanuit de huidige situatie als vanuit een toekomstig perspectief. Met behulp van deze inzichten zijn scenario's gemanageerd die mogelijke ontwikkelingen weergeven op deze gebieden. Met behulp van een rekenmodule waarin een representatief recyclingproces gemodelleerd is worden de effecten van deze verschillende scenario's met elkaar vergeleken met als voornaamste criteria de einde-levensduurkosten danwel –opbrengsten en het gewichts gewogen recyclingpercentage. Tevens zijn in de analyse scenario's meegenomen die mogelijke alternatieve materiaaltoepassingen weergeven, welke zijn verkregen uit zoge-
The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios

naamde benchmarkstudies die uitgevoerd zijn bij Philips Consumer Electronics. Uitgaande van vergelijkingen met huidige einde-levensduurscenario's voor produkten uit de vier voornaamste produktcategorieën van consumentenelectronica (metaalgedomineerde, kunststofgedomineerde en edelmetaalgedomineerde produkten alsmede produkten met een beeldbuis) kunnen een aantal conclusies getrokken worden.

Het is gebleken dat ontwikkelingen die gerelateerd zijn aan fluctuaties in de prijzen en concentraties van edelmetalen, met name goud en palladium, voor de meeste produktcategorieën tot de grootste effecten voor de einde-levensduurkosten danwel -opbrengsten leiden. Dit is met name het geval voor geminuitariseerde produkten met relatief hoge edelmetaalconcentraties zoals draagbare telefoons. Voor produkten met een hoog gehalte aan kunststoffen zullen ontwikkelingen met betrekking tot schaaleffecten potentieel tot de grootste effecten leiden. Met name scenario's waarin aangenomen wordt dat schaalvergroting binnen einde-levensduursinfrastructuren zal leiden tot het opbloeiien van markten voor gerecyclede kunststoffen (met als gevolg hogere prijzen en verbeterde terugwinningpercentages) leiden potentieel tot zeer gunstige resultaten, zowel vanuit financieel oogpunt als voor potentieel gerealiseerde recyclingpercentages. Ten derde, scenario's die uitgaan van door wetgeving stimuleerde ontwikkelingen leiden eveneens tot aanzienlijke doch over de gehele breedte tot relatief iets minder grote effecten. Voor produkten met aanzienlijke hoeveelheden kunststof echter hebben wetgevingsscenario's die geforceerde oplossingen aandragen om aan in de toekomst geëiste recyclingpercentages te voldoen (bijvoorbeeld door het toepassen van aluminium behuizingen bij televisies), relatief gezien eveneens grote effecten. Hierbij echter zijn (tegendestelde) effecten die optreden tijdens eerdere stadia van de levenscyclus tevens van groot belang, en dienen op een juiste wijze geïnterpreteerd te worden.

Tot de scenario's die leiden tot derde of vierde orde grootte effecten behoren scenario's die uitgaan van koperprijsschommelingen, fluctuaties in proceskosten en wetgevings- of schaalsgrootte scenario's die uitgaan van minder sterke ontwikkelingen. Over het algemeen hebben de effecten van technologische veranderingen op het gebied van bijvoorbeeld recyclingtechnologie in verhouding met andere scenario's slechts geringe effecten. De scenario's die uitgaan van alternatieve materiaaltoepassingen hebben uiteenlopende effecten, met name afhankelijk van de mate waarin substitutie tussen magnetische fricties en (niet recycleerbare) kunststoffen worden geanalyseerd.

Prioriteiten en aanbevelingen die in dit proefschrift gedaan worden hebben betrekking op produktontwerp, technologie en strategie. Wat betreft produktontwerp wordt benadrukt dat plastics een relatief grote rol spelen in relatie met de einde-levensduur fase. De applicatie daarvan valt uiteen in verschillende overwegingen, waarvan de meeste tevens betrekking hebben op zowel andere levenscyclusfasen alsook traditionele zakelijke criteria zoals geld en kwaliteit. Wat betreft technologie wordt de belangrijkste van electronica ontwerp in relatie tot product ontwerp aangegeven. Tevens wordt duidelijk gemaakt dat investeringen in technologie waarschijnlijk in verhouding met andere investeringen weinig effect zullen sorteren, zeker vanuit een economisch perspectief. Aanbevelingen van een strategisch karakter betreffen het betrekken van
zogenaamde "value chain" overwegingen bij het ontwikkelen van een eindelevensduurstrategie, de relevantie van milieukundig supply management, alsmede het belang van het sluiten van overeenkomsten met concurrenten, recyclers en brancheorganisaties. Op die manier kunnen de voorwaarden gecreëerd worden voor gunstige schaaleffecten, bijvoorbeeld door middel van merkspécifieke verwerking. Ook kan op die manier enige invloed uitgeoefend worden op het wetgevingsproces.

Aan het einde van dit proefschrift wordt een relatief groot aantal suggesties voor verder onderzoek in dit vakgebied gedaan. Dit is een consequentie van het verleggen van de systeemgrenzen ten opzichte van eerder onderzoek in dit vakgebied. Een aantal onderwerpen zal verder onderzocht moeten worden om in de toekomst minder speculatieve scenario's te hoeven trekken. Echter, er wordt tevens gesuggereerd dat het vanuit het levenscyclusperspectief wellicht effectiever is om een relatief groter percentage van de beschikbare onderzoekscapaciteit aan andere (ecodesign) disciplines, hoewel omgeven door minder onderzekerheid, te wijden. Te denken valt met name aan het terugdringen van energiegebruik en het optimaliseren van transport, beide ook in samenhang met verbeterd produktontwerp.
The Relative Importance of Uncertainty Factors in Product End-of-Life Scenarios
Curriculum Vitae

Full name: Casparus Burghardus Boks Vlemmix

Place and date of birth: Veldhoven, August 28, 1970

Civil status: Married with Juliette, two beautiful daughters named Ebbe and Marijs

After finishing his atheneum studies in 1988 at the RSG in Eindhoven, Casper graduated at the Econometrics Institute of the Erasmus University Rotterdam in 1995. His graduation project involved a study at the Philips Consumer Electronics TV Lab in Eindhoven on modelling production and end-of-life costs for TVs. Next, he stayed on for half a year as a researcher at Philips' Environmental Competence Center. As of May 1996, he became a Ph.D. candidate with Professor Ab Stevels at the Faculty of Industrial Design Engineering at Delft University of Technology, in the Engineering Design department. By the end of 1999 they were relocated to the Design for Sustainability Program at the now-called Faculty of Design, Engineering and Production, where Casper became an assistant professor in Applied Ecodesign in December 2000. Since then he enjoys both teaching and researching various subjects in (applied) ecodesign.
1. Een generieke methode voor einde-levensduurmanagement die zowel productontwerp, inzameling, retourlogistiek en verwerking omvat zal nooit, waar dan ook, succesvol geïmplementeerd kunnen worden.

A generic method for product end-of-life management, which encompasses design, collection, return logistics and end-of-life processing, will never be successfully implemented anywhere.

2. Een duidelijke waarschuwing dat het volledige levensduurperspectief niet in gedachten gehouden is, is vaak de enige manier om te laten zien dat het volledige levensduurperspectief in gedachten is gehouden.

A clear warning that the full life cycle perspective has not been taken into account is often the only way to show that the full life cycle perspective has been taken into account.

3. De economische voordelen van milieukundig ontwerpen dat specifiek op de eind-levensduurfase is gericht kunnen door de producent vrijwel uitsluitend op indirecte wijze geïncasseerd worden.

Original equipment manufacturers will reap the economic benefits of incremental improvements in end-of-life-oriented ecodesign almost only through indirect effects.
4. De drukke agenda van de president van Rusland had tot voor kort, net zoals de toename van strikte wetgeving op het gebied van emissies van auto's, een significant effect op de winst- en verliesrekening van sommige elektronicareyclers.

The busy agenda of Russia's prime minister as well as the increase in strict legislation for vehicle emissions both, until recently, had a significant effect on the profit and loss account of a number of electronics recyclers.

5. Een eco-efficiency score die betrekking heeft op een situatie waarbij een relevante actor geen invloed heeft op de onderliggende parameters heeft voor deze actor slechts een beperkte waarde.

An eco-efficiency score applicable to a situation where a relevant actor cannot influence the underlying parameters has only limited value for the actor in question.

6. Bij het inschatten van schaaleffecten in relatie tot einde-levensduurscenario's is niet het extrapoleren uit het verleden het grootste probleem, maar het inschatten van de discontinuïteiten.

Extrapolation from past data is not the main problem for the assessment of economies-of-scale in relation to end-of-life scenarios. The main problem is the assessment of discontinuities.

7. Het onderkennen van deelproblemen bij het doen van promotieonderzoek raakt in extrema aan het ontkennen van dezelfde deelproblemen. Overigens is dit niet van toepassing op het wereldwijde milieuprobleem: wereldwijde ontkening is waarschijnlijk een snellere, goedkopere en daardoor meer efficiënte "oplossing" dan de onderkenning ervan.

The recognition of problematic research issues when doing Ph.D. research touches in extremis the denial of those very issues. This does not, for that matter, apply to worldwide environmental problems: as worldwide denial is probably a faster, cheaper and therefore more efficient "solution" than recognition.
8.
Methodologisch verantwoord onderzoek stimuleert het beschrijven van bedrijfskundige problemen maar heeft een remmende werking op het oplossen ervan: oplossingen lossen problemen op, niet methodologieën.

Methodologically justified research stimulates the description of business problems, but has a hindering effect solving them; solutions solve problems, not methodologies.

9.
Het doen van wetenschappelijk onderzoek valt meestal in één de volgende drie categorieën: 1) tellen, 2) puzzelen, of 3) alles opschrijven wat je over een onderwerp weet.

Doing scientific research usually involves one of the following categories: 1) counting, 2) solving puzzles, or 3) writing down everything you know about a subject.

10.
De roep om meer speculatieve stellingen in plaats van stellingen die 'slechts' op basis van observatie geponeerd worden impliceert dat vaker falsificatie door de opponent in plaats van bewijs door de promotiekandidaat op zijn plaats zal zijn. Vandaar de volgende stelling: Het is uiterst onwaarschijnlijk dat koeien die geboren wordt met drie koppen én loeiend Fries spreken, geen agorafobie en/of dyslexie ontwikkelen.

The call for more speculative propositions instead of propositions that are merely posed on the basis of observations implies that more often, falsification by the opponent is called for, rather than proof by the candidate. Hence the following proposition: It is extremely unlikely that cows born with three heads, and which are fluent in Frisian, will not develop agoraphobia and/or dyslexia.

11.
Godsbesef is uitsluitend opvoedkundig bepaald – de standaard notie in het menselijk wezen bevat geen besef van een hogere macht zoals die binnen religies omschreven wordt.

A notion of God is solely pedagogically determined. The default setting of the human being is unaware of any higher spirits as they are portrayed in religions.
12.
Verstokte automobilisten die wegens omstandigheden een doodenneke keer op de trein aangewezen zijn, hebben naar hun eigen zeggen vreemd genoeg altijd nê dan meer dan een half uur vertraging.

Inveterate car drivers who have to rely on public transport once in a blue moon, strangely enough appear to always have an over-30-minute delay.

13.
Alles wat je ruikt krijg je ook daadwerkelijk binnen. Helaas is het omgekeerde niet waar.

Everything you smell, you actually inhale. Unfortunately the reverse is not true.

14.
Je weet pas zeker of je moet afvegen wanneer je al afgeveegd hebt.

You don’t know for sure whether to wipe until after you wiped.

15.
Het is zeer goed mogelijk dat het wegvallen van inkomsten uit de palladiummarkt de uitgave van niet door de wereldpostunie erkende postzegeluitgiften (zoals voor Kalmukkië, Abchazië, Karakalpakië en Noord-Ingoetsjetsjië) in de na het uiteenvallen van de USSR ontstane Sovjetrepublieken gestimuleerd.

Lost revenues from the palladium market have very well have stimulated the issues of stamps that are not recognized by the World Postal Union (as for Kalmukia, Abchasia, Karakalpakia and Northern Inguchetia) in the newly emerged Soviet Republics after the disintegration of the USSR.

Casper Boks, April 2002
Delft University of Technology
Design for Sustainability program

For example by assuming the various factors that are strongly external to a company as constants. Using scenario analysis, the research presented in this dissertation examines such technological, economical, legislative and societal developments in a quantitative way, from a chemical and an environmental perspective. Various factors according to their size, can be drawn where focal attention within management should be directed to become or stay facing the often turbulent developments in life management.