Strategic response to EEE returns: 
Product eco-design or new recovery processes?

Rob Zuidwijk* and Harold Krikke

*corresponding author

a. RSM Erasmus University, 
Department of Decision and Information Sciences, 
PO Box 1738, 3000 DR Rotterdam, The Netherlands, 
rzuidwijk@rsm.nl, Tel: NL +31 104082235, Fax: +31 10 408 9010

b. Tilburg University, Faculty of Economics and Business Administration, 
Department of Organization and Strategy, 
PO Box 90153, 5000 LE Tilburg, The Netherlands, 
krikke@uvt.nl, Tel: NL +31 134663334, Fax: +31 13 466 8354

Abstract – In this paper we study how industry should strategically respond to imposed producer responsibility by regulation such as the WEEE-directive. Product eco-design covers both Design for Disassembly and Recovery (DfX) and Product Data Management (PDM). On the process side, X-ray technologies and Post-shredder Separation Techniques (PST) can also improve the overall efficiency of recovery strategies. We revisit the Roteb case on monitors published in some of our previous work and add characteristics to make it up-to-date. We develop four scenarios with each three different information levels on the disassembly Bill Of Material (dBOM) and on return quality, namely perfect information, partial information, and a scenario with no information. For the three information scenarios, we deploy different decision support models, namely an integer program in case of perfect information, a number of decision rules in case of partial information, and a default strategy in case of no information. Within each scenario, we carry out a sensitivity analysis on those operational parameters affected by the strategic choices mentioned. We conclude with recommendations to OEMs on strategic response related to recovery and elaborate on future research using our modeling approach in the EEE and other types of industry.

Keywords: eco-design, closed loop supply chain, WEEE-directive, product data management, integer program
1. Introduction
Advances in technologies, shortening life cycles and globalization of economies have led to a massive growth of discarded consumer electronics products. In Europe alone, the annual volume of e-waste (i.e., electrical and electronic waste) generated is estimated around 6-7 million tons per year (Van Wassenhove at al., 2004). As a result, industry is facing governmental regulations in Europe but also in parts of Asia.

1.1 The WEEE-directive
The Directive 2002/96/EC (EU, 2003) of the European Union on Waste Electrical and Electronics Equipment (WEEE) imposes on all EU member states to develop legislation based on Extended Producer Responsibility (EPR). EPR makes the Original Equipment Manufacturer responsible for take back and recovery of returned products. Its main aim is to promote reuse and recycling by imposing collection and recovery quota and to reduce e-waste by enhancing the eco-design of products. Also, certain product recycling information must be made public and product marking must be applied to products new on the market.

This so-called WEEE-directive distinguishes ten product categories both concerning B2B and B2C markets. For each category, three recovery options are allowed: component reuse, material recycling and incineration (or energy recovery). There are two types of quota defined: the consumer electronics market has to meet a number of targets that define minimum rates, such as minimum rate of recovery of 70-80%, which includes incineration with energy recovery, and a minimum rate of component, material and substance reuse and recycling (represented by so called weight balances) of 50-70%. In addition, treatment of the collected products is required to remove fractions or groups that contain hazardous materials, such as batteries, printed circuit boards, cathode ray tubes, and external electric cables. The mandatory isolation of (mostly) hazardous contents fixes a minimum degree of disassembly for products containing these substances and also the recovery route is prescribed in detail; see Annex II of the Directive (EU, 2003).

An operational End Of Life (EOL) consumer electronics recovery system should have been ready as of August 13, 2005 (Toffel, 2003; EU, 2003). Although many member states have not met this deadline, there is little doubt that enforcement will become firmer, and that in the long run member states need to comply.
1.2 Industry response to the WEEE-directive and contribution of this paper

Industry faces a set of complex choices that no doubt will result in costs at the short term. However, pioneering companies have shown that with the right choices, reverse logistics systems can be profitable (Krikke et al., 1999). At least a fraction of the materials in EEE returns have an economic value. For example, the increasing scarcity of raw materials in the global economy has boosted the market value of recycled electronic scrap; see e.g. a ferrous market analysis by Nijkerk (2007). Remanufacturing, i.e., the recovery of components and products into ‘as good as new’ condition, is still limited but in some business cases has proven to be very profitable (Krikke et al., 2003b). It therefore deserves exploration.

In order to comply with the directive, industry needs to develop a product recovery strategy. Such a strategy describes the degree of disassembly to be applied as well as the type of recovery to be applied to the product or its released components. Apart from these decisions, which relate to operations, a product recovery strategy needs to address decisions on the strategic level in order to create opportunities.

The type of strategic choices to be made by industry can be roughly divided into two categories: product eco-design, thereby improving take-back and recovery characteristics of the product, or new advanced process technologies to make the reverse channel more robust, thereby accepting existing design characteristics of the product. A review of research on the engineering aspects of product life cycle management, considering amongst others eco-design, disassembly, and product recovery, is given in the survey paper by Gungor and Gupta (1999).

Product eco-design includes Product Data Management (PDM) decisions, where some kind of hardware is built into the product to store critical parameters throughout the lifecycle. Product data management here involves the capture, storage and processing of data relevant to collection, disassembly and recovery. It is common knowledge that the body of products that are sold and that reside in the market, the so-called installed base, is a ‘terra incognita’ due to a lacking of good product PDM systems.

The need for information management in reverse channels, in particular related to product data, has received considerable attention; see for example (Krikke et al., 2003a; Kokkinaki et al., 2004; Van Nunen and Zuidwijk, 2004). The need for (partial) product data relevant to disassembly and recycling is reflected by the development of "recycling passports"; see for example (Spengler et al., 2003). Return
quality can be revealed by monitoring the usage of products. For example, Klausner et al. (1998) describe how a memory chip registers important use related parameters (such as running hours) that are specific for the individual product, and that are used for assessing reparability after return by the customer.

In view of reuse and recycling, products need to be designed such that disassembly and recovery processes are easier to apply. Design for ‘X’ (DfX) stands for reusability at large and focuses on improvements of the product design regarding the end-of-life phase of the product. In view of the WEEE-directive, including potential application of remanufacturing, DfX has a number of aims: (1) to lower disassembly costs, (2) to make material fractions more homogeneous so they can be separated more easily, and (3) design in a modular way and use standardized design.

Recently introduced Post-shredder Separation Technology (PST) no longer requires materials to be separated in uncontaminated material groups so that full disassembly (hence high cost) is not needed. To achieve the highest material recycling rates, full disassembly is often necessary with traditional recycling technology. PST allows products and modules to be shredded as a whole, after which physical separation provides sufficiently pure materials for economically sound reuse. The economic gain is that less disassembly effort is needed, but quality hence revenues may be somewhat less. The key question will be whether or not PST generates sufficiently pure material fractions for recycling as defined by the EU Directive. Interesting from an economic point of view and possibly environment friendly as well, component reuse (as the Directive calls it) is included in the quantitative quota of the EU.

Optimizing product recovery strategies is often hindered by a lack of information on the return flow. New technologies enable efficient information extraction from products such as X-ray equipment that assesses the material composition of returned products (Dalmijn and de Jong, 2006). X-ray primarily focuses on information relevant to disassembly and partially replaces PDM. Using terminology from the survey paper on disassembly sequencing (Lambert, 2003), this paper deals with disassembly on batch or reverse logistics level, and the approach is the hierarchical tree approach. We presume a minimum level of disassembly for the removal of hazardous materials.

In Table 1 we summarize pros and cons of product eco-design and process innovations. Choosing the one or the other or possibly a combination of the two has a
The term dBOM in the table refers to disassembly Bill of Material, to be explained in more detail in Section 2.

<table>
<thead>
<tr>
<th></th>
<th>Pro</th>
<th>Contra</th>
</tr>
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<tbody>
<tr>
<td>Product</td>
<td>DfX</td>
<td>High level recovery options</td>
</tr>
<tr>
<td>PDM</td>
<td></td>
<td>Many parameters recorded</td>
</tr>
<tr>
<td>Process</td>
<td>PST</td>
<td>Directly applicable, robust</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td>Directly applicable</td>
</tr>
</tbody>
</table>

Table 1: Pros and cons of product eco-design versus process improvements

To the knowledge of the authors, product eco-design and new advanced process technologies have barely been studied in an integrated way. Krikke et al. (2003b) are among the few who show how product modularity and the process recovery options should be considered concurrently. This lack of attention may be caused by the fact that product and process improvements are studied in different (academic) disciplines and that they are managed by decision makers that are often found in separate roles in the supply chain. Nevertheless, as this paper shows, an integrated approach is rewarding, as these two types of innovations may interfere.

In this paper, we compare the two types of possible industry responses to the WEEE-directive or similar situations facing massive EEE returns. In Section 2, we develop an integer program and a decision scheme that can be used to determine recovery strategies under different levels of information. In Section 3, we apply the decision models to a case on the recycling and remanufacturing of computer monitors. We develop scenarios taking into account different levels of product information, as obtained by different PDMs or the application of X-ray, and in which we compare the introduction of DfX versus the use of PST. For each scenario, a sensitivity analysis is carried out to test the impact of external factors like return quality and (increasing) EU recovery quota. In Section 4, we discuss the results of the scenario analyses. We also discuss whether or not innovations in product eco-design and recovery process technologies are mutually exclusive. In Section 5, we formulate our conclusions and recommendations, and discuss possibilities to generalize the modeling approach.
2. Modeling Framework

This paper deals with long term decisions concerning the innovations in product design and recovery technologies to improve the product optimal recovery strategy. Our modeling framework aims to support this. In the next few subsections, we consider the economic value of the recovery options, while taking into account the possible impact of innovations. Further, we explore the use of innovations to deal with the WEEE-directive by improving the physical recovery options, both by DfX and new recovery technology. Next, we study the different information levels enabled by information innovations also on the product and process level.

2.1 Economic value of recovery options taking into account PST and DfX

A product recovery strategy determines the degree of disassembly of a product and the assignment of recovery options. Disassembly and recovery is governed by a disassembly Bills Of Materials, in short dBOM. The development of a proper dBOM format is not a trivial matter. For example, Das and Naik (2002) support the planning of disassembly operations by introducing a dBOM format featuring fastener specifications. Moreover, the number of relevant components in a dBOM depends, amongst others, on access topology and the presence of hazardous materials, which can be different from the number of parts in the assembly BOM. The order in which a disassembly sequence can be performed can be optimized; see for example the survey on disassembly sequencing (Lambert, 2003). A simplified dBOM of a computer monitor, relevant to the case discussed in Section 3, is depicted in Figure 6 in Appendix 3 and serves as an illustration. In this figure, one clearly distinguishes the hierarchy of products, modules, and components as well as recovery options.

The disassembly process serves to enable the different recovery options. After disassembly, the released modules are assigned to a recovery option or further disassembled into components. In this paper, we consider the recovery options (1) remanufacturing on the component level after full disassembly, (2) material recycling after full disassembly, (3) material recycling with partial disassembly and the use of Post Shredding Technologies, and (4) disposal.

Note that we basically apply two different approaches of recovery, namely material recycling (two technologies) and remanufacturing. Disposal is only applied when there is no other possibility. We first consider the economic value of these
options and the impact thereon of the aforementioned innovations. In most cases, we model the impact of innovations by more favorable values of parameters in the model.

Material recycling retrieves product value that is permanent, i.e., for which a stable market exists. Although material markets are characterized by price fluctuations, there will always be a demand for materials such as ferrous and non-ferrous metals, and plastics. This option becomes even more attractive with the use of Post-shredder Technology (PST), which prevents full disassembly as a preprocessing step of material recycling. DfX may enhance profitability of recycling, for example by making material fractions more homogeneous.

The value of components, modules and the product as a whole may be high, but will diminish in time, especially in the consumer electronics market; see for example (Guide et al., 2006). Reasons are obsolescence and quality loss, leading to lower yields. In our model, a yield factor is included to represent time-based value. The recovery option considered here is remanufacturing. DfX may help to relax these constraints by increasing modularity or reducing disassembly cost.

2.2 Levels of information and decision support models

Optimizing the recovery strategy occurs from an economical perspective but is constrained by recovery quota and prescribed isolation of hazardous materials. Moreover, the return flows are very heterogeneous and often contaminated or eroded. In the recovery strategy, there are decisions to be made on the degree of disassembly, and the recovery options applied to the released components. We support decision-making using different techniques for different information levels.

No optimization occurs when there is no product information available; then one has to use a conservative default recovery strategy for all products, i.e., full disassembly in order to obtain pure fractions to comply with the WEEE recovery quota. Under perfect information, determining the optimal recovery strategy for individual products results in a combinatorial problem that can be solved using the integer programming model described in Appendix 1.

In the case of partial information, one is able to cluster the heterogeneous flow into semi-homogeneous batches. All products in a single batch are processed by the same recovery option, which might be sub-optimal for some of those products. However, the lack of information prohibits the application of the ILP-model as not all parameters are known.
The clustering of the product inventory into semi-homogeneous batches is a non-trivial step in the planning process. In particular, we use decision rules that are described in detail in Appendix 2 and which are embedded in the decision scheme given in Figure 1. Observe that the decision rules to be used here will make an economic balance but respect an additional constraint related to the WEEE targets.

Figure 1 about here.

We now explain Figure 1 in more detail. Based on (partial) dBOM information, the minimum degree of disassembly in order to remove hazardous materials (hazmat) needs to be determined. Such an activity may come down to a removal of a battery, and may be done beforehand, e.g. in the case of shredding, or as part of a larger disassembly activity, whenever applicable. Based on the reliability of the testing procedure and product characteristics, one needs to decide whether testing and remanufacturing is economically viable. Obviously, products that are designed for remanufacturing should be viable according to Decision Rule 3, which is described in more detail in Appendix 2, and reads: In order to decide between material recycling and performing a quality test for remanufacturing, check whether the adding value of remanufacturing outweighs the misclassification costs and testing costs.

In case remanufacturing is an option, a quality test should select those products that are to be forwarded to the remanufacturing process. Testing requires no additional disassembly compared to mandatory disassembly required for hazmat removal. For products not fit for remanufacturing, the question comes in whether Post-shredder Separation Technology contributes to the WEEE target. In case it doesn’t, we need to make sure that the WEEE targets are satisfied, and we will select products with favorable material groups for full disassembly and recycling into pure fractions. Here Decision Rule 2 is used, which reads: In order to comply with EU directive targets, disassemble those products for which the weight percentage of relevant material groups exceeds a given threshold.

In case that PST contributes to the WEEE target, or the products at hand are not selected to fulfill the target, the primary concern becomes economic feasibility of full disassembly. Here Decision Rule 1 comes into play, which reads: A Product will be fully disassembled when the disassembly costs are outweighed by the adding value of separate recycling compared to co-mingled recycling.
Note that remanufacturing decisions are taken at the product level, when performed at the component level, where some components may be recycled. As can be seen in Appendix 3, the type of recovery applied to components in ‘remanufacturing’ is such that disposal is not necessary even when looked from a pure economic perspective; hence recovery quota are always met for remanufactured products. One type of misclassification referred to in Decision Rule 3 concerns products that are assigned to remanufacturing, but after disassembly it turns out that the components cannot be remanufactured. As full disassembly has already been done, recycling takes place at the component level. Disassembly and testing are incorporated in Decision Rule 3, and repositioning to recycling does not result in additional costs. In the decision flow scheme depicted in Figure 1, Decision Rules 1 and 2 guarantee WEEE-directive compliance. De facto products assigned to remanufacturing and recycling are treated as independent as far as imposed recovery quota are concerned. This may seem rather conservative but does not lead to financial losses for the reasons given above.

3 Case application
In the remainder of this paper we analyze the following monitor recovery case. In 1999, an extensive case study at Roteb, the municipal waste company of the city of Rotterdam and the surrounding area Rijnmond, concerning the collection of household consumer electronics was carried out, including the disassembly of computer monitors (Krikke et al., 1999). Returned through three channels, the inventory of collected monitors is extremely heterogeneous in the sense that product type and material composition vary considerably among the products. Despite proven optimization opportunities for recovery strategies at the time, one decided after the project to install a default ‘full disassembly’ strategy because of practical difficulties.

We again consider the reverse supply chain under the OEMs responsibility including testing and sorting, disassembly, pre-processing, separation and recovery (either material recycling or component reuse through remanufacturing). We need information on the (static) dBOM and sometimes (in case remanufacturing applies) we also need dynamic return quality information. We now explicitly evaluate recovery quota to be achieved. We re-use the data from the monitor case for 48 monitors, related to 44 different types.
We make the following alterations to make the case more up-to-date. An X-ray scan can be used to determine the total weight and the weight fraction of metals. An additional sorting process is installed before the disassembly process which clusters the heterogeneous flow into smaller semi-homogeneous batches, and each batch is treated according to an optimal recovery strategy. Some batches are fully disassembled, others only partially.

In Table 2, we outline the scenarios researched. Base Scenario (A) assumes the WEEE-directive to be in place including mandatory removal of hazardous materials and recycling targets. PST is added as a feasible recovery option in Scenario (B), and DfX has been applied to the products and hence includes remanufacturing as an option in Scenario (C). In Scenario (D), both PST and DfX are available.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Strategic change</th>
<th>Recovery options</th>
<th>Sensitivity analysis on</th>
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<tbody>
<tr>
<td>(A)</td>
<td>EPR assumed</td>
<td>Classic material recycling with prior disassembly</td>
<td>WEEE-directive recovery quota</td>
</tr>
<tr>
<td>(B)</td>
<td>(A) &amp; PST added</td>
<td>Material recycling prior to disassembly and after post shredding</td>
<td>Fee to be received from PST facility</td>
</tr>
<tr>
<td>(C)</td>
<td>(A) &amp; DfX added</td>
<td>Remanufacturing and recycling both prior to disassembly</td>
<td>Return quality</td>
</tr>
<tr>
<td>(D)</td>
<td>(A) &amp; PST &amp; DfX added</td>
<td>All options</td>
<td>Misclassification of return quality</td>
</tr>
</tbody>
</table>

Table 2: Scenario’s researched

To simulate remanufacturing as an option, we select the best-designed subset of 12 from 44 types of monitors. In accordance with our model assumptions, remanufacturing, when applicable, is aimed at component reuse. As mentioned, the partial information scenario, a visual on-off check is done by switching the machine on and off to assess return quality.

For each scenario three information levels are considered. In case the OEM provides product information it is assumed to be a perfect PDM on both dBOM and return quality unless indicated otherwise. The best solution possible is obtained when
we optimize disassembly of each individual monitor by means of the integer program, assuming we have perfect information at our disposal. The worst possible result (from an economic point of view) is full disassembly applied to all monitors, when it will never violate legislative constraints. In situations of partial product information, we optimize using the heuristic rules in Figure 1.

For optimization we use a three-level dBOM, comprising a product level (no disassembly), a module level (partial disassembly) and a component level (full disassembly). Non-modular products have no module level. Product reuse is excluded because of removal of hazardous materials, but co-mingled recycling is possible both on the module and product level. Components are made from one material and can be recycled or remanufactured. Note that in the latter option, some components are still recycled and we ascertained that the products assigned to remanufacturing do meet the WEEE recovery quota, hence this stream can be considered separately. The dBOM and other model data used in our analysis can be found in Appendix 3.

4. Results
In this section, we discuss the results from our analysis of the scenarios explained in Section 3. For each scenario, we present results for perfect product information, i.e., the best possible (ILP-based) solution, denoted by Upper Bound ("UB-ILP"), results for imperfect or partial product information, denoted by "partial", and results with no product information at all, i.e., worst case or Lower Bound solution ("LB"). Altogether, 180 instances are run. It should be noted that calculation times using AIMMS 3.2 with a Cplex 7.1 license are below 0.5 seconds per instance. The heuristic was also implemented in AIMMS 3.2 for convenience but could actually be executed by using MS Excel, for example.

The impact of legislative recovery quota
We optimize scenario (A). We vary the EU recycling quota and calculate the impact on the total revenues (or better: costs since the revenues are negative). As disposal is cheap, the degree of disassembly depends on disassembly cost and the material composition (recycling revenues) of the individual monitors.

Monitors most viable for recycling are selected first when quota are low, and as the quota increases, more and more monitors must be recycled at increasing
marginal cost. As a consequence, increasing quota lead to increasing costs, and even the best possible solution (UB) deteriorates because the solution space is shrinking eventually to the extent that only full disassembly (LB) is allowed; see Figure 2.

Figure 2 about here.

In Scenario (B), PST contributes to the recovery quota due to a liberal interpretation of the WEEE-directive. As a result, revenues are completely insensitive to varying the recovery quota because the application of PST ensures that all recovery strategies comply with EU legislation by default. Increasing material recycling quota with a conservative interpretation of the EU Directive leads to cost increases, similar as in Scenario (A); see Figure 2.

Given the apparent impact of PST, it is necessary to apply sensitivity analysis to this factor. According to (Anonymous et al., 2002; Spengler et al., 2003), the fee of PST is hard to estimate. Note that fee is defined as a payment of the PST facility to the disposer (i.e., OEM). If it has a negative value, the disposer pays the PST facility. Figure 3 shows that with positive fees, or even until –0.15 euro/kg, all monitors are sorted in a co-mingled fraction to be separated by PST. When PST becomes more expensive, monitors that are easy to disassemble are indeed fully disassembled for separate recycling. When the PST fee exceeds –0.25 euro/kg, all monitors are disassembled and the PST option is no longer viable and also reaches the lower bound.

We can also see that the introduction of PST has in fact greater potential than the introduction of PDM for the purpose of efficiency gains: the gap between partial and UB results is small. Only when fees are very negative, i.e., when disposers have to pay say at least 0.25 euro/kg, the PST solution leads to high cost. The take-away here is that with reasonable PST fees and a liberal EU Directive (i.e. allowing PST as a feasible recovery option), we can always reach a good solution.

Figure 3 about here.

The value of dBOM information and return quality
The value of dBOM information is to be derived from the cost per kg product calculated for the entire process. For optimizing Scenarios (A) and (B) under partial
information, while respecting the WEEE targets, Decision Rule 2 requires the frequent re-setting of the threshold value $b^{\prime\prime}$ as described in Appendix 2. This leads to about 20% misclassification of returns. As a result, the difference between the UB value and the value of ‘partial’ in both scenarios (A) and (B) can be seen as the cost of misclassification, due to having only partial information. Analogously, the difference between the LB value and the value of ‘partial’ represents the cost of having no information at all. In scenario (A) increasing legislative recovery quota minimizes the value of information as the values of UB, partial and LB converge.

At first sight, the value of information in scenario (B) is tremendous, when compared with the LB. However, closer examination of the results learns that all products should now be allocated to PST based recycling. This is a lesson learned in retrospect, but it means that in scenario (B) our LB should be the maximum of classic or PST based recycling value. The value of information is lost when both separate and co-mingled recycling options are applied. We may conclude that, with a more liberal interpretation of EU legislation, there is no need for dBOM information.

For scenario (C), we introduce DfX and hence remanufacturing as another recovery option to further increase optimization possibilities. The current WEEE already acknowledges this option as feasible as long as it concerns component reuse. In this scenario we apply the visual “on-off” check for assessing return quality, representing the partial information results in Figure 4. Not all components are fit for remanufacturing due to deterioration of quality. Therefore a visual “on-off” check is performed, representing the partial information results in Figure 4. This information is used to feed Decision Rule 3.

Again the UB - integer program represents the ideal (return quality) information situation optimized by the integer program and the (improved) lower bound LB is again related to full disassembly and material recycling. Classic material recycling becomes more viable due to reduced disassembly cost and more homogeneous materials. Additional testing and sorting cost lead to remanufacturing solutions below the LB solution (provided by full disassembly and material recycling) in case of low or zero return quality. Note that the quality check is done at the product level whilst remanufacturing takes place on the component level. Hence full disassembly is necessary for remanufacturing.
Although PST is not applied in this scenario, for verification purposes we allowed it in some runs, but not a single monitor that was ‘designed for recycling’ was actually allocated to PST.

Most unexpected is that the revenues are not a linear function in return quality, in particular in the case of partial information. The explanation for this is as follows. When the return quality is high, the chances of misclassification are low, even with a simple check. Good monitors will always switch on. Vice versa, bad monitors never switch on. The most uncertainty exists when the odds are 50-50 hence here the value of information is maximal. Then our heuristic makes the most misclassification errors, and the curve is relatively steep between a yield of 40-60%.

Figure 4 about here.

**DfX and information on return quality**

DfX reduces the heterogeneous nature of the return flow and enhances quality classification. Second, due to increased modularity, purer materials and lower disassembly cost improve the viability of both remanufacturing and material recycling.

Calculations show convincingly that remanufacturing is to be preferred and the second best option is material recycling on the lowest disassembly level. PST is no longer necessary since pure fractions can be obtained at low (disassembly) cost. Thus it confirms our conclusion that DfX eliminates the viability of PST. It can also be shown easily that dBOM information for material recycling is of little use, since products have become much simpler in their material composition. The question now is: how good should product information be with respect to return product quality?

Assuming an actual feasibility for remanufacturing of 50% (that is one out of two returned products are good enough to be remanufactured), we now vary the percentage of misclassification. It leads to the loss of revenues because at most 20% of the good products (=10% of total) are assigned to material recycling whilst remanufacturing was possible and vice versa 20% of the products assigned to remanufacturing appear not to be fit once disassembled. We see that with a fixed return quality revenues behave in a linear manner. Figure 5 gives the result of that scenario (D). The results are not surprising given the results of the other three scenarios. It does however bring up the following point. Although product eco-design
may enable the installation of PDMs and the application of remanufacturing, it simultaneously facilitates material recycling and reduces disassembly cost, thereby reducing the viability of remanufacturing and hence the need for PDM. This paradox needs to be considered carefully as – for reasons of market cannibalization – many OEMs prefer material recycling to remanufacturing.

Figure 5 about here.

5. Conclusions and outlook

In this paper we addressed two possible strategic responses to the WEEE-directive by industry: Product eco-design (PDM and DfX) versus new recovery process technologies (X-ray and PST). The overall conclusion is that the first beats the latter but has a delayed effect. This means that the EU policy to make OEMs primarily responsible for recovery, as implemented by the WEEE-directive, is appropriate. But as mentioned in Section 1, the directive aims both to promote the reuse and recycling by imposing collection and recovery quota, and to reduce e-waste by enhancing the eco-design of products. The current directive definitely stimulates collection and recovery but more incentives are needed to reward product eco-design. In its current form the WEEE-directive is more of a waste avoidance act.

From a recovery value standpoint, remanufacturing should be the prime recovery strategy, but it requires a high quality of returns. Moreover, the cost of misclassification can be high, so that for remanufacturing we need a PDM with reliable return quality information.

The impact of DfX lies primarily in enabling remanufacturing, but also very strongly on reducing the heterogeneous nature of return flows, which improves the efficiency of material recycling.

Post Shredding Technologies are useful for recycling historic inventory but once new products are designed for disassembly, remanufacturing and recycling, it becomes obsolete.

The value of information on dBOMs in optimizing recovery strategies is limited, especially in the case of material recycling, due to PST enabling but also due to DfX that reduces the number of materials used in a product.
These conclusions can have a significant impact on the WEEE-directive implementation. We have however ignored a number of issues that deserve further exploration.

First, our approach is not fully life cycle driven. Sometimes environmental issues at other stages than the end-of-life phase may be more important. For example, weight reduction through the application of plastics may reduce the energy use of products but also reduces recycle-ability. Thus we should extend our model with forward processes.

Second, although remarketing of ‘second hand’ products is traditionally difficult, new internet technologies have directed market opportunities towards the development of internet enabled electronic markets that support transactions between consumers and (small) businesses by providing tools that match supply and demand through information exchange and even auctions (Kambil and Heck, 2002). On many such markets, such as www.ebay.com, recovered electronic items are presented. Thus product reuse may become a more viable option than it is today.

Third, although this model was primarily developed for the EEE case, the application of the integer program and the decision rules described in Appendices 1 and 2, respectively, can be extended to other industrial sectors up to a certain extent. The structure of the integer program is rather generic and should have a broad application. As producer responsibility and related recovery quota are to be implemented in various other sectors of industry, the decision modeling is likely to be applicable to e.g. packaging, automotive etc. The development of decision rules in a decision flow scheme as depicted in Figure 1, based on partial availability of information, is more specific. It depends on the type of decisions that can be made under partial information, and on the technologies used. Some technologies such as X-ray units are very specific for the EEE sector and also the mandatory product information (recycling passport) is not incorporated in other EU directives.
Appendix 1: The integer programming model

Index Sets

\( P \) Set of product types;
\( M \) Set of modules;
\( C \) Set of components;
\( F \) Set of material groups or ‘fractions’, including the co-mingled fraction from partial disassembly;
\( R \) Set of recovery options [separate recycling, co-mingled recycling, disassembly, remanufacturing].

Parameters

\( n^p \) number of products (of type) \( p \) returned;
\( n^{p,m} \) number of modules \( m \) in a single product \( p \);
\( n^{p,m,c} \) number of components \( c \) in a single module \( m \) released from product \( p \);
\( G^p \) weight of product \( p \) (in kg);
\( G^{p,m} \) weight of module \( m \) in product \( p \) (in kg);
\( G^{p,c} \) weight of component \( c \) in product \( p \) (in kg);
\( G^{p,c,f} \) weight of material group \( f \) in component \( c \), contained in product \( p \) (in kg);
\( \rho^f \) revenues material group \( f \) in € per kg;
\( \rho^c \) revenues remanufactured component \( c \) in € per kg;
\( \tau^p \) cost of disassembling the product \( p \) expressed in €;
\( \tau^{p,m} \) cost of disassembling the module \( m \) released from product \( p \) expressed in € (cost are set zero when product is non-modular);
\( T^f \) % of the material group \( f \) that must be recycled or remanufactured according to legislation;
\( y^c \) yield factor for remanufacturing component \( c \) depending on return quality.
Decision variables

\( X^{p,r} \) number of products \( p \) that are processed according to recovery option \( r \in \{ \text{co-mingled recycling, disassembly} \} \);

\( Y^{p,m,r} \) number of modules \( m \) released from \( p \) that are processed according to recovery option \( r \in \{ \text{co-mingled recycling, disassembly} \} \);

\( Z^{p,c,r} \) number of components \( c \) released from \( p \) that are processed according to recovery option \( r \in \{ \text{separate recycling, remanufacturing} \} \).

In the following, the super index \( r = \text{'co-mingled'} \) refers to “co-mingled recycling” in the case of number of products \( X^{p,r} \) and number of modules \( Y^{p,m,r} \), and \( r = \text{'recycling'} \) to “separate recycling” in the case of number of components \( Z^{p,c,r} \).

Objective function to be maximized

\[
\begin{align*}
\sum_{p} X_{p,r=\text{co-mingled}} G^p \rho^{f=\text{co-mingled}} & + \text{ (revenues co-mingled recycling for products as a whole)} \\
\sum_{p,m} Y_{p,m,r=\text{co-mingled}} G^{p,m} \rho^{f=\text{co-mingled}} & + \text{ (revenues co-mingled recycling for modules as a whole)} \\
\sum_{p,c,f} Z_{p,c,r=\text{recycling}} G^{p,c,f} \rho^f & + \text{ (revenues separate recycling uncontaminated materials)} \\
\sum_{p,c,f} Z_{p,c,r=\text{remanufactured}} G^{p,c} \rho^c & + \text{ (revenues remanufactured components)} \\
-\sum_{p,m} X_{p,m,r=\text{disassembly}} \tau^p & \text{ (disassembly costs products)} \\
-\sum_{p,m} Y_{p,m,r=\text{disassembly}} \tau_{p,m} & \text{ (disassembly costs modules)}
\end{align*}
\]

(1)

Constraints

\[
\begin{align*}
\sum_{r} X_{p,r} & = n^p \quad \forall p \\
\sum_{r} Y_{p,m,r} & = X_{p,r=\text{disassembly}} n^p m \quad \forall p, m \\
\sum_{r} Z_{p,c,r} & = \sum_{m} Y_{p,m,r=\text{disassembly}} n^p m c \quad \forall p, c \\
\sum_{p} X_{p,r=\text{recycle}} G^p + \sum_{p,m} Y_{p,m,r=\text{recycle}} G^{p,m} + \sum_{p,c,r} Z_{p,c,r} G^{p,c} & = \sum_{p} n^p G^p
\end{align*}
\]

(2) (3) (4) (5)
\[ \frac{T_f}{100} \sum_p n^p G^p \leq \sum_{p,c,f} Z_{p,c,r} G^{p,c,f} \quad \forall f \]  

\[ Z_{p,c,r=\text{remant}} \leq \sum_m n^p n^{p,m,c} G^{p,c} y^c \quad \forall p,c \]  

\[ X_{p,r}, Y_{p,m,r}, Z_{p,c,r} \geq 0 \quad \text{integers} \quad \forall p,m,c,r \]  

Constraints (2) ensures that all products are processed. Constraint (3) ensures that all modules released from disassembling the products are processed. Constraint (4) ensures that all components released from disassembling the modules are processed. Constraint (5) represents the weight balance in the system. Constraint (6) represents the targets set by EU directives. Constraint (7) ensures that the amount of remanufactured components respects the remanufacturing yield. Constraint (8) represents the need that entire products/modules/components are processed and of course negative goods flows do not exist.
Appendix 2: Decision rules

Decision Rule 1

*Product type* $p$ will be fully disassembled when the disassembly costs are outweighed by the adding value of separate recycling compared to co-mingled recycling.

We obtain this decision rule from the integer programming optimization by restricting our decision space. The decisions to be supported are either (A) to scrap the whole product into a co-mingled fraction, or (B) disassemble the product into components (i.e., full disassembly), and recycle the components separately into pure material fractions. The objective value for product type $p$ under decision (A) comes down to

$$n^p G^p \rho^{f=\text{co-mingled}'},$$

and the objective value for product type $p$ under decision (B) reads

$$\sum_{c,m,f \neq \text{co-mingled}'} n^p n^{p,m} n^{p,m,c} G^{p,c,f} \rho^f - \sum_p n^p \tau^p - \sum_{p,m} n^p n^{p,m} \tau^{p,m}. \quad (10)$$

Decision (B) is preferred over decision (A) for product type $p$ when

$$\tau^p + \sum_m n^{p,m} \tau^{p,m} \leq \sum_{c,m,f \neq \text{co-mingled}'} n^p n^{p,m,c} G^{p,c,f} \rho^f - G^p \rho^{f=\text{co-mingled}'}. \quad (11)$$

When we focus on a material group $f$, we may use a more restrictive decision rule

$$\tau^p + \sum_m n^{p,m} \tau^{p,m} \leq \left( \frac{b^{p,f}}{100} \rho^f - \rho^{f=\text{co-mingled}'} \right) G^p, \quad (12)$$

which only requires knowledge of the weight percentage $b^{p,f}$ of material group $f$ in product $p$ (instead of weights of all modules, components, and material groups in all components).

Decision Rule 2

*In order to comply with EU directive targets, disassemble those products for which the weight percentage of relevant material groups exceeds a given threshold.*

As suggested by Decision Rules 1 and 2, in case a material group represents a significant part of the recovery value of a product, it may be sufficient to estimate the relative weight of that material group inside the product in order to make a disassembly decision. In order to comply with the WEEE-directive under partial
information, we will reconsider the relative weight of a material group. In order to assure that recycling targets are met, we will keep track of compliance for the whole batch of products. The following mathematical notion supports this. Let $W_f(b)$ be the total weight of products in the batch with weight percentage of material group $f$ greater than $b$, so that, in particular, $W_f(0)$ denotes the total weight of all products, and $W_f(1) = 0$. If we define the target parameter $T^f$ to be the minimum weight percentage of material group $f$ in products that is recycled within the WEEE target constraints, we arrive at the constraint
\[
\frac{T^f}{100} W_f(0) \leq W_f(b).
\]
(13)

By taking the corresponding (minimum) value of $b$ for which $W_f(b)/W_f(0) \leq T^f/100$, we have obtained a threshold value that we denote by $b^f*$. We comply with the WEEE-directive for the batch if we apply Decision Rule 2 using this threshold.

**Decision Rule 3**

*In order to decide between material recycling and performing a quality test for remanufacturing, check whether the adding value of remanufacturing outweighs the misclassification costs and testing costs.*

The quality assessment states either that a product is fit for remanufacturing $R$ or fit for material recycling $M$. In terms of misclassification, we distinguish four probabilities, i.e., numbers between 0 and 1, that add up to one:
\[
p_{RR} + p_{MR} + p_{RM} + p_{MM} = 1.\]
We explain these probabilities below.

The probability that a product is rightfully classified as being fit for remanufacturing equals $p_{RR}$. The associated profit equals the revenue of a remanufactured product minus remanufacturing costs: $\rho^R - c^R$. The probability that a product is classified as being fit for remanufacturing while it actually is not fit for that purpose is equal to $p_{RM}$. For such a product, additional costs will occur as the product needs to be relocated from the remanufacturing process to the recycling process. We assume that both material recycling and repositioning costs are incurred, while only
material recycling revenues are gained:  \( \rho_M - c_{RM} - c_M \). The repositioning costs \( c_{RM} \) may contain costs of disassembly incurred during the erroneous preparation for remanufacturing, but as mentioned at the end of Section 4, these costs are absorbed in the recycling channel, when full disassembly is economically viable. The probability that a product is classified as being correctly fit for material recycling only equals \( p_{MM} \). The associated profit equals \( \rho_M - c_M \). The probability \( p_{MR} \) relates to products that are fit for remanufacturing but are classified as being fit for material recycling only. The associated profit again is equal to \( \rho_M - c_M \). Since \( \rho_R - c_R > \rho_M - c_M \), there are lost revenues associated with this misclassification.

We distinguish two alternative strategies: (1) recycle all products or (2) use a quality assessment to remanufacture products that are considered fit. If we assume that the costs for the quality assessment (test) equals \( c_T \), we get for strategy (1) an expected profit per product equal to \( \rho_M - c_M \), while the expected profit for strategy (2) is equal to

\[
p_{RR}(\rho_R - c_R) + p_{RM}(\rho_M - c_{RM} - c_M) + (p_{MR} + p_{MM})(\rho_M - c_M) - c_T =
\]

\[
p_{RR}(\rho_R - c_R) + (1 - p_{RR})(\rho_M - c_M) - c_T - p_{RM}c_{RM}.
\]

The decision is based on a comparison of these two profits. One will perform a quality test and forward products to the remanufacturing option when

\[
p_{RR}((\rho_R - c_R) - (\rho_M - c_M)) \geq p_{MR}c_{MR} + c_T,
\]

i.e. when the adding value of remanufacturing outweighs the misclassification costs and testing costs.
## Appendix 3  Data sets of Roteb case revisited

Figure 6 about here.

<table>
<thead>
<tr>
<th>Disassembly level</th>
<th>Name</th>
<th>Number</th>
<th>Recovery option</th>
<th>Material fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Monitor</td>
<td>48 total, 44 types</td>
<td>PST (or disposal)</td>
<td>Co-mingled</td>
</tr>
<tr>
<td></td>
<td>Battery separate</td>
<td>11 in 44</td>
<td>Disposal</td>
<td>Hazmat</td>
</tr>
<tr>
<td>Module</td>
<td>Foot-unit</td>
<td>25 in 44</td>
<td>PST (or disposal)</td>
<td>Co-mingled</td>
</tr>
<tr>
<td></td>
<td>Chassis-unit</td>
<td>25 in 44</td>
<td>PST (or disposal)</td>
<td>Co-mingled</td>
</tr>
<tr>
<td>Component</td>
<td>Casing</td>
<td>44 in 44</td>
<td>Recycle or remanufacturing</td>
<td>Plastics</td>
</tr>
<tr>
<td></td>
<td>Printed Circuit Boards (PCB including motherboards)</td>
<td>115 in 44</td>
<td>Recycle or remanufacturing</td>
<td>PCB, high, low or medium</td>
</tr>
<tr>
<td></td>
<td>Tube</td>
<td>44 in 44</td>
<td>Recycle or remanufacturing</td>
<td>Tube fluff</td>
</tr>
<tr>
<td></td>
<td>Chassis parts</td>
<td>88 in 44</td>
<td>Recycle or remanufacturing</td>
<td>(non-) Ferro</td>
</tr>
<tr>
<td></td>
<td>Wiring, cables and plug</td>
<td>44 in 44</td>
<td>Recycle or remanufacturing</td>
<td>(non-) Ferro</td>
</tr>
<tr>
<td></td>
<td>Spool and electronics</td>
<td>44 in 44</td>
<td>Recycle or remanufacturing</td>
<td>Spool+transformer</td>
</tr>
<tr>
<td></td>
<td>Frame of foot</td>
<td>44 in 44</td>
<td>Recycle or remanufacturing</td>
<td>Plastics</td>
</tr>
<tr>
<td></td>
<td>Transformer</td>
<td>13 in 44</td>
<td>Recycle or remanufacturing</td>
<td>Spool+transformer</td>
</tr>
</tbody>
</table>

**Table 4: dBOM parameters**

If there are no separate batteries or transformers found these are generally mounted on the motherboard and cannot be removed.
<table>
<thead>
<tr>
<th>Product</th>
<th>Average (min)</th>
<th>Variance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module chassis-unit</td>
<td>1.25</td>
<td>0.18</td>
</tr>
<tr>
<td>Module foot-unit</td>
<td>1.00</td>
<td>0.17</td>
</tr>
<tr>
<td>Battery</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5: Disassembly times**

<table>
<thead>
<tr>
<th>Recycling</th>
<th>Revenues 1998 (euro)</th>
<th>Revenues 2004 (euro)</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk plastics</td>
<td>-0.10 per kg</td>
<td>-0.10 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Ferro</td>
<td>0.04 per kg</td>
<td>0.05 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Non ferro</td>
<td>0.56 per kg</td>
<td>1.25 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>PCB-high</td>
<td>2.00 per kg</td>
<td>1.00 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>PCB-medium</td>
<td>0.79 per kg</td>
<td>0.50 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>PCB-low</td>
<td>0.11 per kg</td>
<td>0.00 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Tube fluff</td>
<td>-0.08 per kg</td>
<td>-0.05 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Spool+transformer</td>
<td>0.22 per kg</td>
<td>0.22 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Wiring fluff</td>
<td>0.27 per kg</td>
<td>0.27 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Battery storage</td>
<td>-0.90 per kg</td>
<td>-0.10 per kg</td>
<td>Recycle</td>
</tr>
<tr>
<td>Co-mingled</td>
<td>0.00 per kg</td>
<td>0.00 per kg</td>
<td>Recycle</td>
</tr>
</tbody>
</table>

Disassembly
- 12 per man hour
- 24 per man hour

**Table 6: Costs and revenues**
References


Guide VDR, Souza GC, Van Wassenhove LN, Blackburn JD. Time value of commercial product returns. Management Science 2006; 52(8); 1200-1214.


(Partial) dBOM info
Assess minimum degree of disassembly for hazmat isolation

(Decision Rule 3)
Design for reman
Adding value reman outweighs testing and misclassification cost?

PST contributes to the WEEE target?

Mass ratio fractions
Measure $b^f$ for products and establish $W_f(b)$

(Decision Rule 2)
WEEE recycling target
Compute $b^f$ so that adding value scrap pure fractions outweigh disassembly costs; does $b^f \geq b'^f$ hold?

(Decision Rule 1)
Econ viability disassembly
Compute $b'^f$ to comply with targets: does $b'^f \geq b^f$ hold?

Return quality probabilities
Assess $p_{AA}, p_{AU}, p_{UA}, p_{UU}$

Quality Test
Product fit for remanufacturing?

Disposal

PST & recycling

Full disassembly & recycling

Start here

Figure 1: A decision tree for product recovery

Sensitivity analysis scenario (A) on recovery quota

Figure 2: Scenario (A), EPR assumed
Sensitivity analysis scenario (B) on fee PST

Figure 3: Scenario (B), PST added

Sensitivity analysis scenario (C) on return quality

Figure 4: Scenario (C), DfX added
Sensitivity analysis scenario (D) to distortion of return quality information
(‘Visual check versus perfect’)

Figure 5: Scenario (D), PST and DfX added
Figure 6: Simplified dBOM and recovery options (arrow means ‘allocated to’)

Co-mingled recycling of materials or disposal

Battery (mandatory inspection and if applicable removal)

Chassis-unit (module, sometimes missing)

Foot-unit (module, sometimes missing)

Chassis-unit

Module level

Foot-unit

Foot-unit

Chassis-unit

Module level

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Component level

‘pure’ material recycling based on separate material fractions or in case of application of DfX remanufacturing of components.