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Mixed Policies for Recovery and Disposal of Multiple Type Assembly Products: Commercial Exploitation of Compulsory Return Flows

H.R. Krikke. P.C. Schuur and A. van Harten

School of Technology and Management Studies, University of Twente
P.O. Box 217, 7500 AE Enschede, The Netherlands
e-mail: H.R.Krikke@sms.utwente.nl

Abstract- New government policies aim at the closure of material flows as part of Integrated Chain Management (ICM). One of the main implementation instruments is extended producer responsibility, which makes Original Equipment Manufacturers (OEMs) formally responsible for take-back, recovery and reuse of discarded products. One of the key problems for OEMs is to determine to what extent return products must be disassembled and which Recovery and Disposal (RD-) options should be applied. On a tactical management level, this involves anticipation to problems like meeting legislation, limited volumes of secondary end markets, bad quality of return products and facility investments in recycling infrastructure. In this paper, a model is described, that can be used to find such a Recovery and Disposal Policy for multiple product types. The objective function incorporates technical, ecological and commercial decision criteria and optimisation occurs using a two-level optimisation procedure. First, a set of potential Product Recovery and Disposal Strategies is generated for each separate product type. Secondly, optimal PRD-strategies are assigned to the products within the context of a coherent product group. The aim is to find an optimal balance between maximising net profit and meeting constraints like recovery targets, limited market volumes and processing capacities. A TV-case is worked out to illustrate the working of the model.

Key words: reverse logistics/ product recovery strategy/ reuse/ recycling/ disassembly/ disposal/ waste-management/ durable products/ Mixed Integer Linear Programming

1 Introduction

In this section we introduce the concept of a recovery strategy and discuss its role within the broader picture of Integrated Chain Management and producer responsibility. Also, an outline is given of models found in the literature, which deal with determining recovery strategies for (urban) waste streams.

1.1 Recovery strategies, Integrated Chain Management and producer responsibility

Traditionally manufacturers only took back discarded products and components selectively, if at all. Products were usually returned to the Original Equipment Manufacturer (OEM), due to contractual obligations (lease products), technical failure etc. However, the growing public interest in environmental issues causes customer demand for recycling and the implementation of new government policies, which aim at the closure of material flows as part of Integrated Chain Management (ICM). As a result, many industrial businesses will compulsorily be confronted with large volumes of discarded products within foreseeable time. Although many OEMs at first react rather reserved to the concept of extended **producer responsibility**, opportunities do exist for commercial exploitation of return flows. However, a number of managerial problems of an entirely new nature will have to be solved. Some critical problem areas are:

- Design For Recycling: product design must enable cost effective disassembly and processing as well as high quality recovery
- the development of secondary end markets in order to sell the recovered waste
- the set up of collection systems: products must be returned in sufficient quantity and quality
- data acquisition: relevant information must be available to decision makers

- taking make or buy decisions and establishing strategic alliances
- choosing optimal Recovery and Disposal (RD-)options.

For more details we refer to e.g. Thierry et al [1] and Pohlen and Farris [2].
The problem we study in this paper concerns the formulation of a **tactical recovery plan**. In such a plan, decision rules are formulated on the handling of return products in terms of disassembly, recovery and disposal. A recovery plan is determined for a tactical planning period, because it serves as a basis for other tactical decisions like facility investments, buy-back agreements with suppliers and negotiations with the government with respect to environmental legislation. We focus on OEMs who produce durable assembly products of multiple types and who are confronted with legislative take-back and recovery obligations. We assume that the various types of return products belong to one product group, e.g. electronic products or cars. The problem situation at hand is reflected in Figure 1.
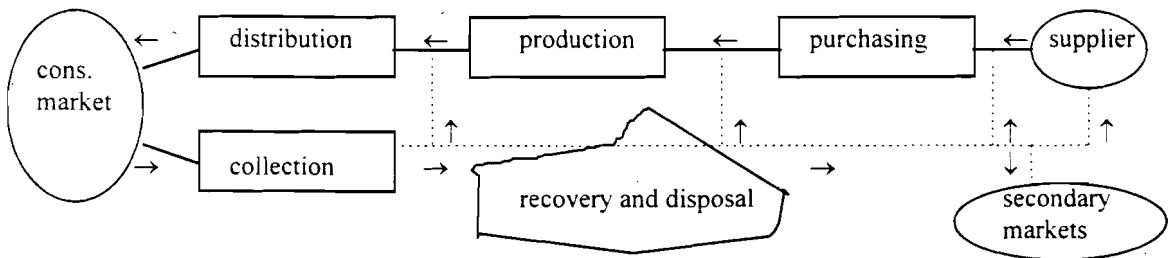

Figure 1 Basic problem situation

Formulating a recovery plan means formulating decision rules with respect to:

(i) determining an optimal level of disassembly for return products and
(ii) assigning optimal **Recovery** and **Disposal** (RD-) options to the product or its released components.

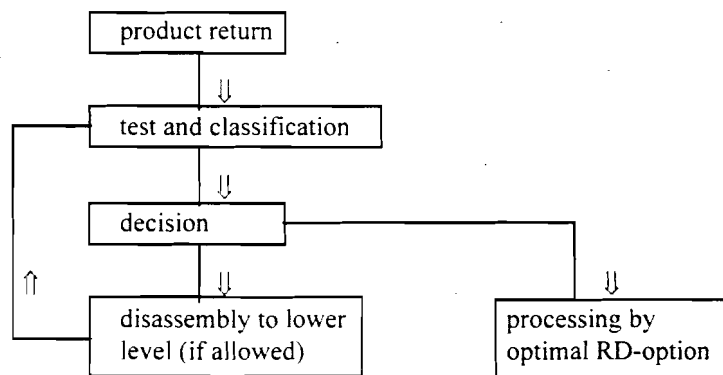The recovery-decision process is reflected in Figure 2.

Figure 2 Structure of the recovery-decision process

Although legislation is the initial driving force behind the return flows, the main goal is to exploit commercial opportunities, i.e., maximise net profit from recovery. However, many constraints may obstruct this endeavour, for example environmental laws. In general, the formulation of a recovery strategy is based on technical, commercial and ecological decision or **feasibility** criteria, which express the technical, commercial and environmental feasibility for application of RD-options. The feasibility of RD-options is assessed per **assembly** (which refers to both products and parts). Examples of these criteria are:

Technical feasibility criteria
- processability of an assembly
- the technical state of an assembly
- separability of materials

- processing properties of materials
- the presence and removability of hazardous contents in assemblies
- capacities of transportation, recovery and disposal facilities.

Commercial feasibility criteria
- technological status of an assembly
- perception of consumers according to secondary products, components and materials
- recovery costs
- secondary market prices
- lost sales in primary markets
- quality of (recovered) secondary assemblies and materials
- limited volumes of secondary end markets.

Ecological feasibility criteria
- disposal bans
- obligatory removal of hazardous contents
- legislative recovery targets.

It should be noticed that these feasibility criteria are applicable at two levels: the **product** level and the **product group** level. cf. Krikke et al [10]. For example, the technical state of a return assembly is a factor to be considered at the product level, because it determines the feasibility of reuse options for that particular product (or parts released from it after disassembly). On the other hand, criteria like legislative recovery targets are defined for entire product groups, e.g. electronics. The main difference between the two levels lies in the possible compensation or substitution effects at the group level. Hence, if one type of product fails to meet certain recovery targets, it can be compensated by another product. Similarly, two different types of cars may have been equipped with the same type of motor. If the PRD-strategy for both cars implies revision of the motor, then they compete in the same (secondary) market. Also in processing capacity, optimisation at the product group level is required, because reverse logistic facilities may be used for multiple product types. The distinction of two decision levels for product type and product group is therefore quite natural as a form of hierarchical decomposition. For that reason, the optimisation is performed in a two-phase procedure. Let us describe the two steps in the procedure.

In the first step, we determine a **Product Recovery and Disposal (PRD-) Strategy** at the product level. In Krikke et al [8], a model is developed which determines a PRD-strategy for **one** product type with maximal net profit, taking into account all relevant technical, ecological and commercial feasibility criteria at the product level. As a case example, we determined a profit optimal strategy for a TV, named TV-X, of which the disassembly tree is reflected in Figure 3.
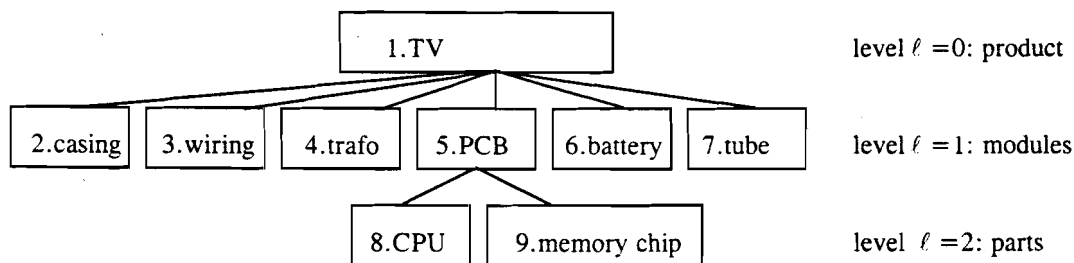

Figure 3   Disassembly tree of TV-X with nine assemblies and three levels

This disassembly tree consists of 9 assemblies in 3 layers, where each layer reflects a disassembly level. Each assembly, which refers to the product as well as its parts, can be found in quality class $q=1$ (good) or $q=2$ (poor) with a certain probability. These probabilities are conditional, i.e., the chance of finding an assembly in a certain class q depends on the class of the parent assembly. For instance, if the parent assembly is returned in good quality, one is more likely to find the children of this assembly in good quality than when the parent has a bad quality. Thus, the model requires a disassembly tree, a quality classification scheme and conditional probabilities as an input. Moreover, disassembly costs and recovery revenues (both also conditional on classes q) are additional input parameters. In the optimisation, the assignment of optimal disassembly and RD-options is now dependent on the quality

classes, hence a PRD-strategy is formulated as a set of **conditional assignment rules** to support disassembly and RD-decisions. Besides an expected net profit, the output consists of an expected rate of disassembly, recovery and disposal operations. A profit optimal PRD-strategy for our case example is shown in Figure 4.
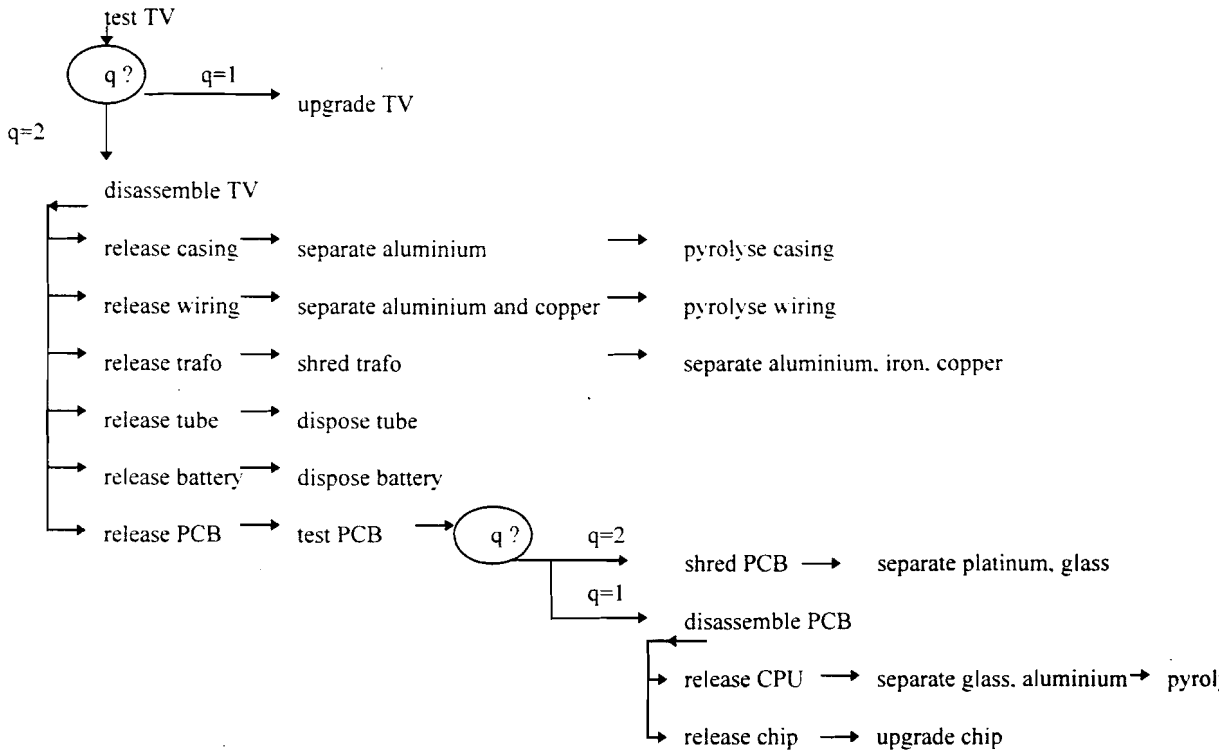

Figure 4 Flow chart of the profit optimal PRD-strategy

Although the PRD-strategy of Figure 4 optimises net profit, it may be less preferable in view of other criteria, like e.g. environmental recovery targets. Therefore, an alternative strategy, with a higher recovery score -and probably less profit- may be desirable. In addition, limited volumes of secondary end markets or restricted capacity of recycling and disposal facilities may also require alternative strategies. Note that alternative strategies at the product level are needed to deal with feasibility criteria at the product group level! The overall idea is to determine multiple PRD-strategies for every product type returned to the OEM. The resulting set of strategies forms the input for the second optimisation step, where mixed policies are determined for an entire product group. Some product types will be processed by the profit optimal PRD-strategy, others by some alternative strategy. This way, compensation or substitution effects are taken into account. Decision support is provided by quantitatively analysing the trade-off between net profit and scores on the above mentioned group level criteria. The aim is to find a balance in -what will be referred to as- the (mixed) **Group Recovery and Disposal (GRD-) policy.** In Figure 5, we summarise the two-phase procedure.
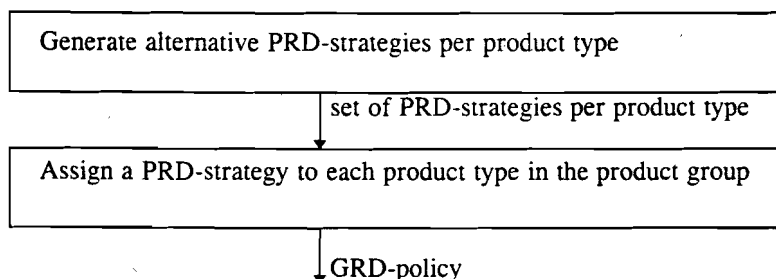

Figure 5 Two-phase optimisation procedure to determine the GRD-policy

In this paper, we present a combination of two models, that was developed to determine an optimal GRD-policy for a product group. First, a heuristic procedure that generates alternative PRD-strategies at the product level is described in Section 2. Subsequently, a MILP model that assigns the PRD-strategies at the group level is the subject of Section 3. Cases are included in both of these sections. The models and case results are discussed in Section 4, where also conclusions are drawn. However, in order to position our research, we first continue this section with a review of the relevant literature.

1.2 Literature review

Relevant literature can be classified in two classes: scheduling models and physical network models. These are discussed in Subsection 2.1 and 2.2 respectively. In Subsection 2.3, we make some notes on the literature in relation to our research.

1.2.1 Scheduling models

Lund [6] developed an LP-model to find the least cost schedule of solid waste recycling and disposal for multiple planning periods. The decision variables are R_{ijt}, which is the number of waste generators of class i (e.g. households in a certain area), to be subjected to recycling option j (e.g. newspaper recycling) in period t. Waste volumes y_t, coming from generators not assigned to recycling, are disposed of to some landfill with capacity X (there is only one landfill in the model). The model is used to determine the least costly assignment of recycling options and landfill operations, given a lifespan T of the landfill. At the end of its lifespan, the landfill is closed and replaced by another one at a certain cost. By varying the landfills economic lifetime T -of course within a range of possible lifetimes- the cost optimal lifespan of the landfill and corresponding assignment of recycling options can be found. Jacobs and Everett [4] developed an extented version of this model that allows for multiple landfills and they investigate additional aspects like e.g. the appropriate service life of consecutive (future) landfills and the effects of landfill (tipping) fees.

1.2.2 Physical network models

Caruso et al [5] consider an Urban Solid Waste Management System (USWMS), which is structured into four phases, namely collection, transportation, processing and landfill. They developed a location-allocation model to find the number and location of the processing plants, given the location of the waste generators and landfills. For each processing plant, the technology -incineration, composting or recycling-, the amount of waste processed as well as the allocation of service users (waste sources) and landfills (waste sinks) are determined. No more than one facility may be located in one geographic zone and there are maximum capacities for all facilities and landfills. The model is single period and has a multi-criteria objective function, with components for economic cost, waste of resources and ecological impact. Efficient heuristics are developed to solve the problem.

In [3], Ossenbruggen and Ossenbruggen describe a computer package for solid waste management (SWAP) and the underlying LP-model. The model describes a waste management district as a network, where nodes represent waste sources, intermediate (capacitated) processing facilities and destinations (sinks) on given locations. Sources, sinks and intermediate stations can be of multiple (technology) types. Decision variables are the amount of waste to be processed by each facility and the magnitude of flows between the facilities. Implicitly, the applied technologies are determined. Constraints follow from technically allowed processing sequences and capacity limitations. The algorithm finds the cost optimal solution, where the cost function only includes variable costs per waste unit, e.g. kg. These unit costs incorporates tipping fees, shipping costs and revenues from reuse.

Pugh [7], describes the HARBINGER model, which gives decision support in the long term waste management planning of a city or county. The waste management system involves collection, transportation, treatment and disposal or reuse of a communities waste stream. These systems tend to be very complicated, which explains the need for mathematical analysis. The heart of HARBINGER lies in the multiperiod allocation submodel, which determines the cost-optimal assignment of wastes from the sources to treatment and disposal facilities on given locations, within constraints set by the user (e.g. for capacity). Optimisation occurs on least cost. Other submodels of HARBINGER are used to specify the input for the allocation submodel and for post-optimality analysis.

1.2.3 Notes on the literature

The two kinds of models have clearly different approaches. The scheduling models determine optimal recovery and disposal options for a waste stream, without considering the physical network, while the physical network models focus on location-allocation aspects, thereby implicitly determining optimal recycling technologies.

Both kinds of models are in line with the second step of our optimisation procedure, especially the scheduling models which deal with the assignment of recycling options within linear constraints. They give us valuable insight in the inevitable trade-offs between various criteria, relevant in assigning recovery and disposal options to waste streams. LP-models prove to be very suitable for determining a recovery and disposal plan, because they are relatively easy to model and solve and give possibilities for sensitivity analysis. However, the above models do not fit our problem definition for two major reasons.

First, a distinction lies in the definition of waste. Both the scheduling - and the physical network models deal with a mixed (urban) waste stream and not with durable assembly products. Therefore, no distinction is made between optimisation at the product level and the product group level nor does one allow for product and component reuse and disassembly aspects. Second, the definition of recycling options is different. In the scheduling models, recycling options are coupled to identified substreams: one can only assign one recycling option to each waste substream for each class of waste generators. The physical network models combine the assignment of recovery options with the design of the physical network. This may lead to great modelling and computational complexity in a GRD-policy situation. In our view, the problems of recovery planning and physical network design should be decoupled and the GRD-policy should be seen as one of the input parameters of the physical network design. Hence, we propose a stronger use of decomposition here, which results in higher simplicity.

In our model, we identify multiple product types and per product type we allow for various disassembly levels and recovery options. Within a PRD-strategy, assignment rules are formulated for disassembly, reuse, recycling or disposal of the product or its released components and materials. We think the above elements make our model more realistic for assembly products. For the same reason, we made some simplifications on other aspects. To avoid high uncertainty in parameter values, we do not use a multi period planning approach, but restrict ourselves to one (tactical) planning period. Moreover, we do not distinguish between different classes of waste generators at the GRD-level, but instead quality classes are incorporated in the alternatives at the product level already. Operations management of the reverse logistics is also considered as a decoupled problem which can be addressed after the network design. As a consequence, the GRD-policy is determined on a market level, i.e., we neglect the physical design aspects of the reverse logistic system. The main underlying assumption is that cost and revenue functions are the same for all locations. This may not always be the case. For example, the profitability of applying an RD-option might partly depend on transportation costs. However, regional differences between various sources of return products can easily be captured in our model by considering them as different products. We come back to this in Section 4.

2 Generating a set of PRD-strategies at the product level

This section is organised as follows. In Subsection 2.1 the need for alternative strategies will be illustrated with an example of TV-X. In 2.2 a heuristic procedure is developed, which can determine such an alternative strategy. In 2.3 this procedure is applied to the same example as the one used in 2.1. We shall not repeat the full sets of data of the TV-X case, for this we refer to Krikke et al [8].

2.1 The need for alternative PRD-strategies

As we explained in Section 1, the PRD-strategy is determined at the product level and may be suboptimal with respect to feasibility criteria at the product group level, such as environmental impact, market aspects and needed processing capacity. In this subsection, we consider situations where the profit optimal strategy falls short on some of these criteria. Before we start the discussion however, we introduce some notation, which will be used throughout the remainder of the paper.

- n   number of products of the product type under consideration

- j   assembly of the product, j=1..J
- q   quality class that assemblies can be found in. q=1..Q
- r   RD-option by which assemblies can be recovered. r=1..R
- s_0 (original) profit optimal PRD-strategy
- $R_0(j,q)$ original set of feasible RD-options r for assembly j in class q for profit optimal PRD-strategy
- $R(j,q)$ set of feasible RD-options r for assembly j in class q for alternative PRD-strategy
- c   feasibility criterion at product group level. c=1..C
- T(c)   targets set on c
- mf(c)   the mass fraction of the total return flow associated with c
- J(c)   set of relevant assemblies j for criterion c
- R(c)   set of relevant RD-options r for criterion c
- g_c weight assigned to c. reflecting its relative importance
- $\varphi(c,s)$ the physical flow bearing on criterion c, resulting from applying PRD-strategy s to one product, e.g. for c='recycling': the amount of recycled materials in KGs
- CL(k)   a cluster (=set of) criteria c with index k, k=1..K
- O(k)   priority ordering of clusters CL(k)
- $\phi_k(r)$ total improvement on CL(k) as a result of removing r from R(j,q), where the total improvement is the sum of improvements on all $c \in CL(k)$
- r_k^{rem} RD-option to be removed from R(j,q) $\forall j \forall q$ to improve scores on CL(k)
- r_0 dummy RD-option, indicating no feasible r_k^{rem} exists
- s_{alt}^k alternative PRD-strategy with improved score on CL(k)
- S   set of PRD-strategies
- TM   mass of the total return flow
- TM(j)   mass of assembly j

Now let us start with an elaborate example. Consider the PRD-strategy s_0 for TV-X in Figure 5. It results in a net profit of 218 per TV. see Krikke et al [8]. However, net profit is not the only criterion that determines whether a PRD-strategy is feasible. As we mentioned before, important additional group level criteria that determine the overall feasibility of a PRD-strategy are:

- the extent to which reuse and recycling options are applied (to meet legislative recovery targets)
- needed capacity (because processing capacity may be a critical constraint)
- resulting secondary products (because sales volumes of secondary markets may be restricted).

In an optimisation procedure at the group level, one has to take these aspects into account. To illustrate the need for alternative PRD-strategies, we take a closer look at legislative recovery targets for reuse and recycling.

The amount of reuse in PRD-strategy s shall be indicated by $\varphi(e1,s)$, overall material recycling by $\varphi(e2,s)$ and metal recycling by $\varphi(e3,s)$ hence c=e1,e2.e3. If we apply s_0 to TV-X, 53% of the return flow is reused. Of the **remaining** 47%, a major part is recycled. The amounts material recycling are summarised per material in Table 1.

	plastics	iron	copper	aluminium	platinum	glass	toxins	total
present in TV (kg)	1.6	1.25	0.8	0.7	0.7	3.0	0.15	8.2
recycled amount (kg)	0.05	0.5	0.8	0.6	0.525	0.2	0	2.7
contributes to	e2	e2/e3	e2/e3	e2/e3	e2/e3	e2	e2	

Table 1 Weights of the materials in TV-X and amounts of recycled materials

The physical flows become:

- $\varphi(e1,s_0)$= 0.53*TM(1)= 4.3 kg product and part reuse (TV and chip)
- $\varphi(e2,s_0)$= 0.47*(0.05+0.5+0.8+0.6+0.525+0.2)=1.3 kg for materials all together
- $\varphi(e3,s_0)$ = 0.47*(0.5+0.8+0.6+0.525)=1.1 kg for metals

The relative **recovery scores** are calculated as follows:

- for product/part reuse: 0.53 or 53% (e1)
- for material recycling: $n*1.3/0n*0.47*8.2=0.34$ or 34% (e2)
- for metal recycling: $n*1.1/n*0.47*8.2*0.4=0.71$ or 71% (e3).

In our case, legislative targets are set T(e1)=25%, T(e2)=70% and T(3)=95%. Hence, we fall short on the targets T(e2) and T(e3). Therefore, an alternative strategy is required.

We would like to stress again, that alternative strategies are generated at the product level in order to comply better with criteria at the product group level. Recovery targets are only one example of these criteria. We may include any feasibility criterion c analogously to the ones above, for example for market or capacity reasons. Alternative strategies are generated for each product type part of the product group!

Note that $\varphi(c,s)$ can be negative. This may e.g. occur when applying a certain RD-option generates a market demand for another RD-option. An example. In the PRD-strategy s_0 in Figure 5, second hand TVs are reused. Suppose that the TVs are sold at the second hand market m1, then $\varphi(m1,s_0)=0.50$ TVs. Now, let us assume the repair of the TVs requires a certain (refurbished) part, which was also recovered after return and for which an external market m2 exists independent from m1. Then, this part is withdrawn from the external market m2 for the benefit of m1 and we set $\varphi(m2,s_0) = -0.50$. Hence, if a constraint T(m2) is imposed on the refurbished parts market (because of a restricted market volume), this constraint is relaxed by applying s_0 to TV-X. In Thierry et al [1], it is discussed how product recovery options are interrelated.

In conclusion, alternative strategies are generated on a number of (combinations of) criteria c. It is logical to formulate **one** alternative strategy for a combination of group level criteria of which synergy is to be expected in generating an alternative strategy. For example, improving the metal recycling score of TV-X also improves the overall material recycling score, which justifies the clustering of criteria c in a cluster CL(k). This is done for all products i. The ultimate result is I sets S_i, where $S_i = (s_0, s^1_{alt} .. s^K_{alt})$, with K the number of clusters of group level criteria c that require the generation of alternative strategies. The sets S_i form the input for the second optimisation step: assigning the PRD-strategies to each product type in a GRD-policy. This will be discussed in Section 3. First, we shall describe a heuristic procedure to generate an alternative strategy at the product level in the next subsection.

2.2   A procedure for generating alternative PRD-strategies

In this subsection, we describe a general procedure for generating a set of alternative PRD-strategies, which is reflected in Figure 6. The core of the procedure is a heuristic algorithm. The heuristic algorithm works basically as follows.

Starting point is the profit optimal PRD-strategy s_0 with an expected net profit and expected scores on group level criteria c. We wish to improve the scores on criteria of some cluster CL(k). Let us assume that this cluster concerns the recovery scores. We now remove environment unfriendly alternatives from the set of RD-options. Hence, the recovery scores are increased by favourably modifying the sets of feasible RD-options $R_0(j,q)$. If we do not harm the recovery improvements, we also remove options in favour of other criteria clusters, which are given less priority. After modification of the set $R_0(j,q)$, the PRD-strategy is recalculated according to Krikke et al [8]. Analogously, we can determine alternative strategies for other clusters, where the recovery cluster is given a lower priority. This way, for every cluster CL(k) an alternative PRD-strategy s^k_{alt} is determined. These alternative PRD-strategies also consist of conditional assignment rules. Before this heuristic can be applied however, some steps must be undertaken.

First, all RD-options that can potentially improve the score on any criterion c must be added to the set of feasible RD-options $R_0(j,q)$ $\forall j \forall q$. For example, in the original stochastic DP-model of Krikke et al [8], it is only allowed for one recycling option per assembly j per class q, where a subprocedure determines which recycling option is optimal. Here, all recycling options that are applicable must be taken into account, even the most non-profitable ones. Second, the criteria must be clustered in K sets CL(k).

The procedure in Figure 6 iteratively generates alternative PRD-strategies with increasing performance on group level criteria. However, also the mass and number of the product as well as the scores and masses of other products are relevant. For example, a light product which is returned in small quantities, does not contribute a lot to the realisation of recovery targets, even though it has a high

recovery score. This has to be taken into account when the GRD-policy is determined. We will come back to this in Section 3.

product level   **product group level**
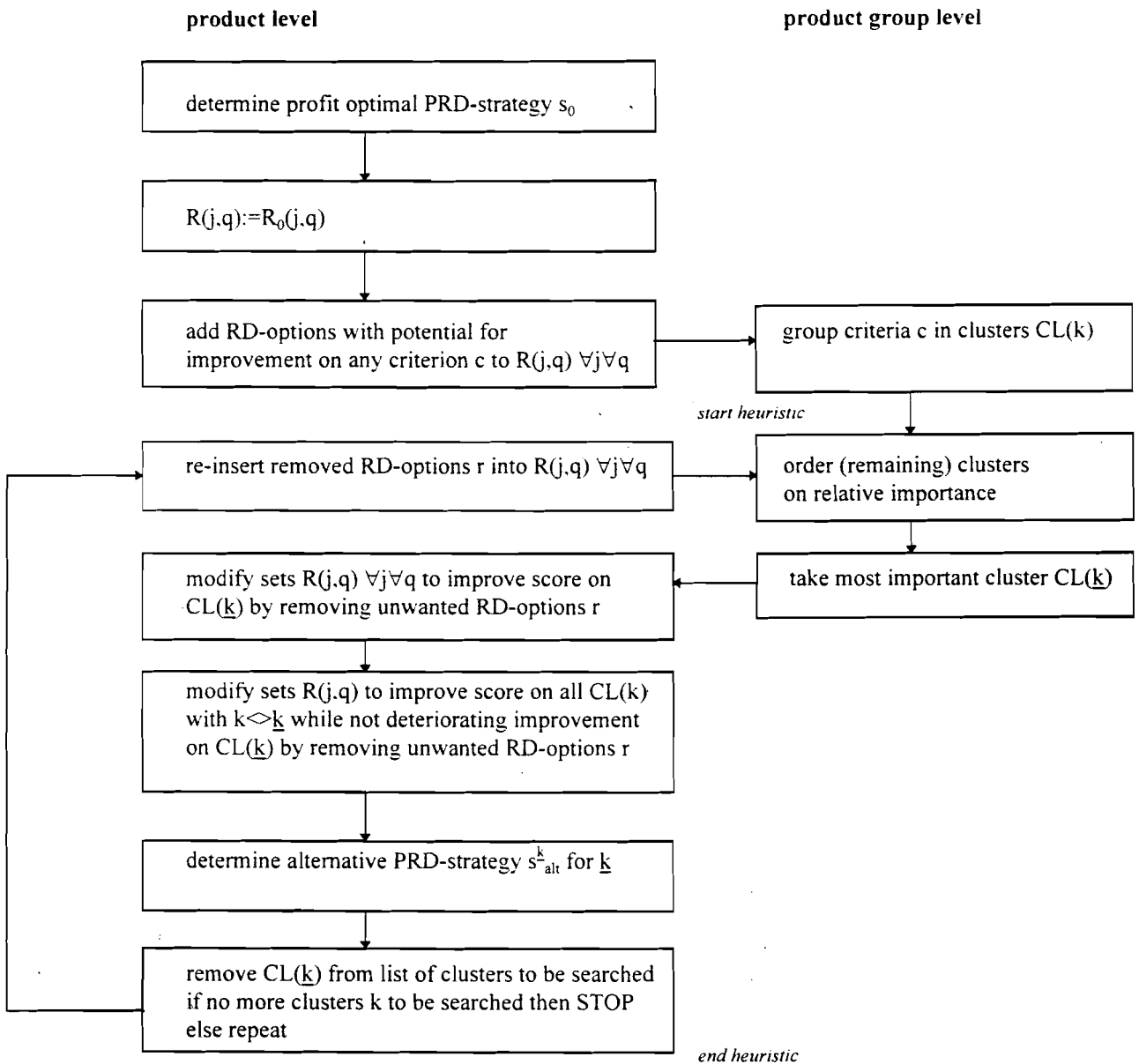
Figure 6   Full optimisation procedure for determining a set of alternative PRD-strategies

Let us now describe the heuristic algorithm in detail:

i.   Order[1] all clusters $CL(k)$ by: $\displaystyle\sum_{c \in CL(k)} g_c*(T(c)-n*\varphi(c,s_0)/TM*mf(c))$. Set $O(k)=<k_1..k_K>$

ii.   Set $\underline{k}:=k_1$ and $k:=\underline{k}$

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[1]   In case of $<$ constraint. In case of $>$ constraint, the ordering is done by $\displaystyle\sum_{c \in k} g_c*(n*\varphi(c,s)/TM*mf(c)-T(c))$

iii.   Select RD-option r_k^{rem} to be removed

for r:=1 to R do $\phi_k(r):=0$

for all j, j $\in \underset{c \in CL(k)}{\cup}$ J(c), do

for all q do

for all r, r$\in$R(j,q) and r $\notin \underset{c \in CL(k)}{\cup}$ R(c), do

$\phi_k(r):= \phi_k(r)+TM(j)*p(j,q)$

$r_k^{rem}:=$ ARGMAX $\phi_k(r)$

$r \notin \underset{c \in CL(k)}{\cup}$ R(c)

if $\phi_k(r)=0 \ \forall r$ then $r_k^{rem}:=r_0$

iv.   If $r_k^{rem} \in$ R(j,q) then remove r_k^{rem} from R(j,q) $\forall j \forall q$ unless a set becomes void. It that case do nothing.

v.   If no changes have been made in R(j,q) for any (j,q) then goto vi. else goto iii.

vi.   Set k:=k+1. If k<=K then goto iii. else goto vii.

vii.   Determine PRD-strategy for $\underline{k}$. The resulting strategy is s_{alt}^k. Set $g_c:=0 \ \forall c \in \underline{k}$. If $\underset{c \in CL(k)}{\sum} g_c >0$

for any k, then re-insert removed RD-options into R(j,q) $\forall j \forall q$ and goto i. else STOP.

2.3 An alternative PRD-strategy for TV-X

Now, we continue the case and determine alternative PRD-strategies in which we improve the scores on e2 (material recycling) and e3 (metal recycling). Reuse (e1) should not get worse. Also, the market volume m1 for second hand TVs is restricted. Only one out of four TVs can be upgraded for sale, while in the PRD-strategy of Figure 5 one out of two TVs is assigned to this option.

<u>Full procedure applied to TV-X</u>

First, we cluster criteria c, then we apply the heuristic algorithm. Two clusters k are formed. In the first cluster, the recovery criteria e1, e2 and e3 are grouped. Inclusion of e1 is allowed, because only scores on reuse are dependent on quality class q. Hence, no improvement on e2 and e3 can be realised by changing the amount of product or part reuse (e1). In other words: maximising reuse of the 'good' assemblies does not harm the recycling scores of the remaining 'bad' assemblies, since recycling feasibility is not quality dependent. The second cluster consists of only one criterion, namely market volume for 2nd hand TVs. The data are summarised in Table 2. Again, for the full sets of data, we refer to Krikke et al [8].

parameter	parameter value
RD-options	r= 1 (upgrade), 2 (restore), 3 (recycling), 4 (disposal)
cluster k=1	e1, e2, e3
cluster k=2	m1
R(k=1)	r=1..4
R(k=2)	r=1
J(k=1)	j=1..9
J(k=2)	j=1
$\phi(e,s_0)$ for e1,e2,e3 in kg	4.3/2.7/2.4
$\phi(m1,s_0)$ in numbers	0.5

Table 2 Parameter settings for alternative PRD-strategies for TV-X

The heuristic algorithm is used to generate two alternative PRD-strategies for TV-X, one for cluster CL(1) with improved recovery scores and one for cluster CL(2) with less TVs to be sold at the 2nd hand market. This goes as follows:

i. $\sum_{e} g_e*(T_e-n*\varphi(e,s_0)/TM*mf(e)) = 1.18$ and $g_{m1}*(n*\varphi(m1,s_0)/TM*mf(m1)-T(m1)) = 0.25$

   hence $k_1 = 1$ and $k_2 = 2$

ii.   Set $\underline{k} := 1$ and $k:=1$

iii. $r_k^{rem} := 4$ (disposal)

iv.   Remove $r=4$ from $R(j,q)$ $\forall j \forall q$

v.   Goto iii.

iii. $r_k^{rem} := r_0$

iv.   No changes in $R(j,q)$ $\forall j \forall q$

v.   Goto vi.

vi.   Set $k:=2$, goto iii.

iii. $r_k^{rem} := r_0$, the only candidate $(r=1)$ is not feasible because $r \in \bigcup_{c \in CL(\underline{k})} R(c)$

iv.   No changes in $R(j,q)$ $\forall j \forall q$

v.   Goto vi.

vi. $k=3>K$, goto vii.

vii.   Determine PRD-strategy for $\underline{k}=1$, see Krikke et al [8].
        The resulting strategy is s^1_{alt} , set $g_e:=0$ $\forall e \in CL(\underline{k})$, goto i.

i. $\sum_{e} g_e*(T_e-n*\varphi(e,s_0)/TM*mf(e)) = 0$ and $g_{m1}*(n*\varphi(m1,s_0)/TM*mf(m1)-T(m1)) = 0.25$

   hence $k_1 = 2$ and $k_2 = 1$

ii-vii {the algorithm is repeated for $\underline{k}=2$, resulting in s^2_{alt}}.
        Because no more cluster CL(k) can be searched, the algorithm STOPS

The ultimate result is a set of alternative strategies $S=\{s_0, s^1_{alt}, s^2_{alt}\}$. In Figure 7, s^1_{alt} is depicted. The main difference compared to the profit optimal strategy is, that disposal is replaced by recycling as optimal RD-option for both the assemblies 5 and 6. In this option, these assemblies are shredded and the materials are separated for recycling and sales, including the toxins. The scores on e2 and e3 are improved to 0.76 and 0.88 respectively, while the targets were 0.70 and 0.95. Net profit has sunk from 218 to 201.

Now that we have developed a procedure to generate a set of PRD-strategies, we continue with determining a GRD-policy in the next section.
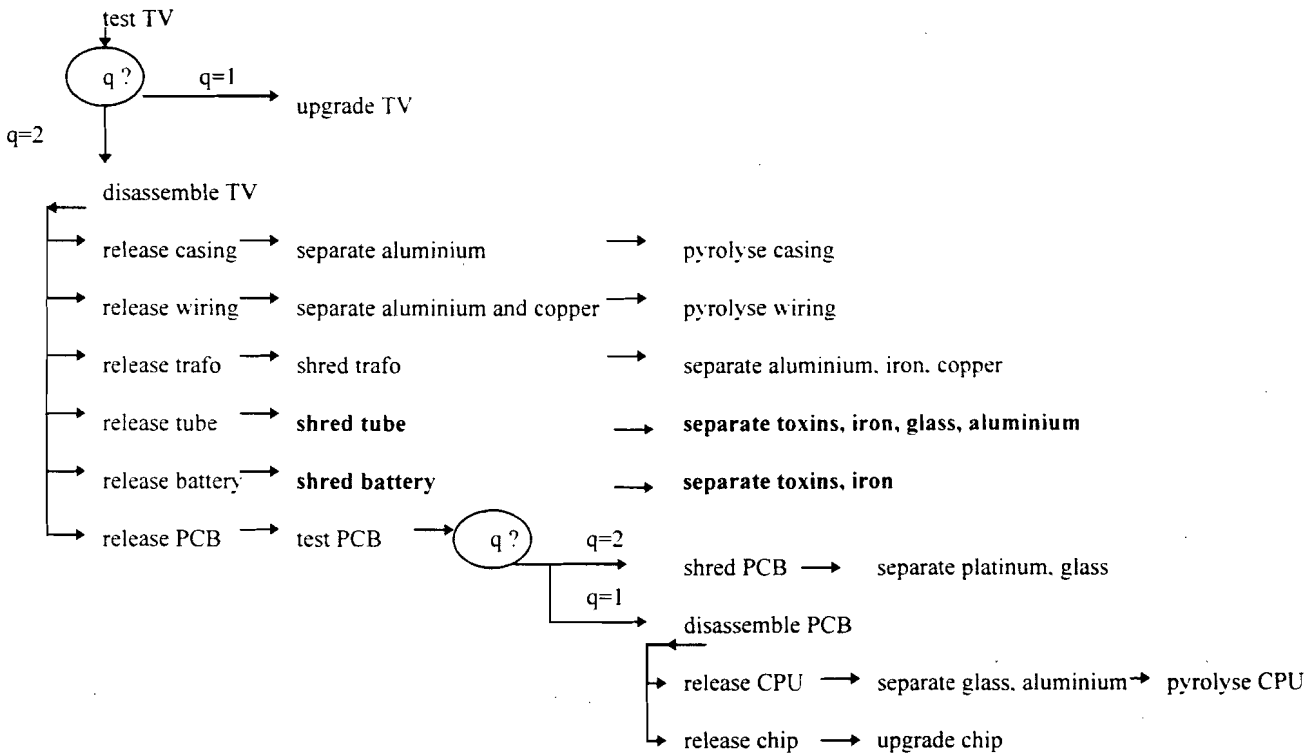
test TV

q ?   q=1   → upgrade TV

q=2

disassemble TV

release casing → separate aluminium → pyrolyse casing

release wiring → separate aluminium and copper → pyrolyse wiring

release trafo → shred trafo → separate aluminium. iron. copper

release tube → **shred tube** → **separate toxins, iron, glass, aluminium**

release battery → **shred battery** → **separate toxins, iron**

release PCB → test PCB → q ?   q=2 → shred PCB → separate platinum. glass

q=1 → disassemble PCB

release CPU → separate glass. aluminium → pyrolyse CPU

release chip → upgrade chip

Figure 7   Flow chart of the alternative PRD-strategy s^1_{alt} (changes in bold)

3 A MILP-model for determining the GRD-policy at the group level

After generating a set of alternative PRD-strategies for each product type, we have to assign an optimal strategy to each product type. This is done by a MILP-model, which is described in Subsection 3.2. In Subsection 3.3, a TV-case is discussed as an example using the model. First, we formulate the problem in Subsection 3.1. The notation used is the same as in the previous sections, except that we add an i for identifying separate product types in a multi-product situation.

3.1 Problem formulation

The problem situation at hand is the following. It is forecast that in the next planning period I types of products i are returned in quantities n_i. The total number of products is N, with $\sum_i n_i = N$. At the product level, for each product type i, a set S_i of alternative PRD-strategies s is available. All strategies have a certain expected net profit w_{is} and an expected rate of applied disassembly, reuse, recycling and disposal operations: each combination (i,s) results in a flow $\varphi(c,i,s)$ per single product i for relevant criteria c at the product group level.

The aim of the MILP-model is to find an optimal assignment f_{is} $\forall i \forall s$ that balances between net profit and complying with constraints T(c) imposed on group level criteria. These criteria are of entirely different nature and can be incompatible. To avoid infeasibility, we consider the constraints as soft and we strive for minimising the deficit with respect to the constraints. We distinguish for three categories of criteria c: environmental criteria e (e=1..E), market criteria m (m=1..M) and capacity criteria p (p=1..P). The relative importance or weight of the decision criteria can vary, depending on several factors. For example, the market weight may depend on price-elasticity of the market, or buy-back contracts with suppliers or possibilities for market expansion. Weights for recovery targets may depend on e.g. consumer behaviour and penalties to be expected from the government. In practical situations, it may be necessary to distinguish for additional categories of criteria c.

All N return products must be processed for disposal or reapplication within the planning period. Every product type can only be processed by only one PRD-strategy. It is assumed that all parameters remain constant within the planning period and that the required data or reliable estimates are available.

3.2 Model construction

Because in a GRD-policy it is aimed to balance between net profit and group level feasibility criteria, we specify the minimal net profit (target) level TP and the **deficit variables** d_e, d_m and d_p, which reflect the deviation to the group level constraints. Weights g_e, g_m, and g_p are assigned to the variables to reflect their importance. We only whish to penalise violations to the targets $T(e)$, $T(m)$ and $T(p)$, so we formulate z_e, z_m and z_p. Now, we construct the following MILP-model:

$$\text{MIN} \quad \sum_e g_e * z_e + \sum_m g_m * z_m + \sum_p g_p * z_p \qquad \{\text{minimise deficit variables}\} \qquad (3\text{-}1)$$

subject to

$$\sum_i \sum_s f_{is} * w_{is} * n_i >= TP \qquad \{\text{net profit target}\}$$

$$\sum_i \sum_s f_{is} * \varphi(e,i,s) * n_i = T(e)*TM*mf(e)*(1-d_e) \; \forall \; e \qquad (\text{recovery targets})$$

$$\sum_i \sum_s f_{is} * \varphi(m,i,s) * n_i = T(m)*TM*mf(m)*(1+d_m) \; \forall \; m \quad \{\text{market volumes}\}$$

$$\sum_i \sum_s f_{is} * \varphi(p,i,s) * n_i = T(p)*TM*mf(p)*(1+d_p) \; \forall \; p \qquad \{\text{capacity constraints}\}$$

$z_e >= d_e$ {logical constraints}
$z_e >= 0$
$z_m >= d_m$
$z_m >= 0$
$z_p >= d_p$
$z_p >= 0$

$$\sum_s f_{is} = 1 \; \forall \; i \qquad\qquad\qquad\qquad\qquad \{\text{entire flow should be processed}\}$$

$f_{is} = 0,1 \;\; \forall i \; \forall s$ {one strategy per product type}

Some comments need to be made:

- Our model has similarities with on the one hand a knap-sack problem and on the other hand a product-mix or blending problem. But there are some differences. Compared to a knap-sack problem there is not one, but a number of constraints. This makes it a generalised knap-sack problem. Compared to a product-mix problem, the decision variable is a boolean and not a continuous variable. Of course, as a variant of the problem, the decision maker may wish to assign mixed strategies to one product type i. Then, f_{is} becomes a fraction and the problem is now solved as an LP-problem. In Subsection 4.2 we will come back to this subject.
- Other relevant decision criteria may be included in the model if necessary. For example, besides a maximum capacity, also a minimum level of turnover may be required for certain processing capacities. Any general feasibility criterion c can be fitted into the model, as we shall see in the discussion of the case in 3.3.
- Because the group level constraints are defined softly, one can always find a feasible solution by properly manipulating TP. We choose this way of modelling, because in practical situations it may be hard to meet all constraints $T(c)$ fully. However, if desired one can define some decision criterion as a hard constraint and remove the deviation variable from the objective function. One could also formulate the objective function as maximisation of net profit, subjected to the hard

constraints T(e), T(m) and T(p), but again we emphasise the risk that no feasible solution can be found.
- The general model is formulated such, that all constraints are linear (except for the 0,1-constraint). However, in practical situations non-linear constraints may occur, as we shall in the next subsection.

3.3 Case: determining an GRD-policy mix for three TVs

In this subsection we describe a TV-case for three different types of TVs and work out the assignment of PRD-strategies in an GRD-policy at the product group level. Calculations were made with the help of the solver LINGO on a Switch 486 computer. Data are derived from Bink [11].

3.3.1 Description

Suppose an OEM takes back three types of TVs: A, B and C. Now, we have to determine an GRD-policy for these products for the coming planning period. Relevant data with respect to the composition of the return flow are reflected in Table 2. Note that none of the TVs resembles TV-X.

i	product type	number n_i	mass
1	A	1000	8.2
2	B	1500	18
3	C	500	12
TOTAL		3000 (N)	41.200 (TM)

Table 2   Composition return flow

The overall material composition of the products is reflected in Table 3. Note that the material composition is the same for all three types of TVs.

material	mass percentage
glass	30
metals	40
plastics	15
toxins	15

Table 3   Material composition of products

At the product level, an optimal PRD-strategy s1 has been determined for three types of TV. At the product group level, the following constraints must be taken into account:

- Recovery targets, formulated similarly but not equivalent to Dutch regulation, are as follows.
  T(e1): at least 25 mass % should be reused as product/component,
  and of the **remaining** return flow
      T(e2): at least 70 mass % of all materials should be recycled,
      T(e3): at least 95 mass % of the metals should be recycled.
- The market volume T(m1) for second hand TVs is limited to 500 TVs.
- The disposal capacity for landfill T(p1) is limited to 7500 kg.

Note that three kinds of group level constraints c are present in this case. They have been clustered in three clusters k. Therefore, three alternative PRD-strategies have been determined for each product type. Hence, we have four strategies for each type of TV, of which the net profits are given in Table 3.

	s1	s2	s3	s4
A	215	201	201	176
B	30	0	10	-100
C	75	0	0	-200

Table 4   Net profits of PRD-strategies per product

The physical output is relevant for recovery targets T(e1), T(e2) and T(e3), the secondary TV-market T(m1) and disposal capacity T(p1). Table 5 summarises the physical flows φ(c,i,s) per product per PRD-strategy for c=e1, c=e2, c=e3, c=m1 and c=p1. Note that flow φ(p1,i,s) is zero in case incineration is applied as disposal option and that market volumes are here expressed in numbers.

	s1	s2	s3	s4
e1 (kg)	4.1/9/6	4.1/9/6	4.1/9/6	0/7.2/5.4
e2 (kg)	1.3/2.9/3.4	3.1/6.7/5.1	3.1/5.9/5.1	5.9/5.9/5.1
e3 (kg)	1.2/2.9/2.4	1.5/3.6/2.4	1.5/2.5/2.4	2.9/2.5/2.4
m1 (numbers)	0.5/0.5/0.5	0.5/0.5/0.5	0.5/0.5/0.5	0/0.4/0.4
p1 (kg)	1.8/6.1/2.6	0/2.3/0.9	0/3.1/0.9	0/4.9/1.5

Table 5 Physical output φ(c,i,s) of processing one TV of type A/B/C

Finally, weights are assigned. This is a management decision itself. In this case, the management wants to put emphasis on the recovery targets, because it fears repercussions of the government and customers. Therefore, a weight of 3 is assigned to z_{e1}, z_{e2} and z_{e3}. The market and disposal constraints are taken less seriously, so a weight of 1 is assigned to z_{m1} and z_{p1}.

3.3.2 Case model construction

The general model of Subsection 3.2. is now tailor made for this problem. The critical reader may have observed that the linearity of the case problem is troublesome. Let us explain the complications in more detail.

The cause of the complications lies in the formulation of the recovery targets for metal recycling (e3) and overall material recycling (e2). These targets are defined for the return flow resulting after reuse (e1). As a result, the constraints for T(e2) and T(e3) become non-linear. We introduce l_0 as the amount of return flow assigned to reuse, with $l_0 = \sum_{i=1}^{3} \sum_{s=1}^{4} \varphi(e1,i,s)*n_i*f_{is}$, and construct the following model for the case problem:

$$\text{MIN} \quad 3z_{e1}+3z_{e2}+3z_{e3}+z_{m1}+z_{p1} \qquad (3\text{-}2)$$

subject to

$$\sum_{i=1}^{3} \sum_{s=1}^{4} f_{is}*n_i*w_{is} >= TP \qquad (3\text{-}2\text{-}1)$$

$$\sum_{i=1}^{3} \sum_{s=1}^{4} f_{is}*n_i*\varphi(e1,i,s) = 0.25*TM*(1-d_{e1}) \qquad (3\text{-}2\text{-}2)$$

$$\sum_{i=1}^{3} \sum_{s=1}^{4} f_{is}*n_i*\varphi(e2,i,s) = 0.70*(TM-l_0)*(1-d_{e2}) \qquad (3\text{-}2\text{-}3)$$

$$\sum_{i=1}^{3} \sum_{s=1}^{4} f_{is}*n_i*\varphi(e3,i,s) = 0.95*0.4*(TM-l_0)*(1-d_{e3}) \qquad (3\text{-}2\text{-}4)$$

$$\sum_{i=1}^{3} \sum_{s=1}^{4} f_{is}*n_i*\varphi(m1,i,s) = 500*(1+d_{m1}) \qquad (3\text{-}2\text{-}5)$$

$$\sum_{i=1}^{3} \sum_{s=1}^{4} f_{is}*n_i*\varphi(p1,i,s) = 7500*(1+d_{p1}) \qquad (3\text{-}2\text{-}6)$$

$$z_{e1} >= d_{e1} \qquad (3\text{-}2\text{-}7)$$
$$z_{e1} >= 0 \qquad (3\text{-}2\text{-}8)$$
$$z_{e2} >= d_{e2} \qquad (3\text{-}2\text{-}9)$$
$$z_{e2} >= 0 \qquad (3\text{-}2\text{-}10)$$

$$z_{e3} >= d_{e3} \qquad (3\text{-}2\text{-}11)$$
$$z_{e3} >= 0 \qquad (3\text{-}2\text{-}12)$$
$$z_{m1} >= d_{m1} \qquad (3\text{-}2\text{-}13)$$
$$z_{m1} >= 0 \qquad (3\text{-}2\text{-}14)$$
$$z_{p1} >= d_{p1} \qquad (3\text{-}2\text{-}15)$$
$$z_{p1} >= 0 \qquad (3\text{-}2\text{-}16)$$

$$\sum_{s=1}^{4} f_{is} = 1 \qquad \forall\ i=1,2,3 \qquad (3\text{-}2\text{-}17)$$

$$f_{is} = 0,1 \qquad \forall i=1,2,3 \quad \forall\ s=1,2,3,4 \qquad (3\text{-}2\text{-}18)$$

As we can see, the constraints 3-2-3 and 3-2-4 are quadratic. To eliminate the term with e1 from the constraints, we have to estimate the amount of reuse l_0 **in advance** of the optimisation. Therefore, we estimate that a fraction C of the total return flow will be reused in an optimal solution. We substitute $l_0 = C*TM$ in the constraints 3-2-3 and 3-2-4, as a result of which the constraints become linear. However, the deviation variables d_{e2} and d_{e3} no longer reflect the **real** deviation to the targets T(e2) and T(e3), because the amount of reuse l_0 is prefixed while it is actually an outcome of the optimisation. As a consequence, the values of z_{e2} and z_{e3} may become too large or too small, depending on the choice of C, which has an effect on the objective function value and thus eventually on the assignment of PRD-strategies. Therefore, it is of paramount importance to make a good choice for C, resulting in a substituation for l_0 that comes close to the actual amount of reuse. For this optimisation, we choose C=0.25, based on the data of Table 4 and 5. After the optimisation, we can retrieve the real deviation to the targets, denoted as $\underline{d}_{e2}$ and $\underline{d}_{e3}$, as follows:

$$\underline{d}_e = 1 - \frac{(TM-l_0)*(1-d_e)}{TM-(1-d_{e1})*l_0} \qquad \text{for } e=e2,e3 \qquad (3\text{-}3)$$

Of course, linearisation can also be achieved by defining the deviation variables as the absolute deviation to the recovery targets. This way, one would avoid the use of l_0. However, since it is impossible to know the absolute magnitude of the flows for e1,e2 and e3 as well as for m1 and p1 in advance of the optimisation, we now have a problem of choosing the right weighing factors g_{e1}, g_{e2}, g_{e3}, g_{m1} and g_{p1}. Moreover, we like to **compare** the deviation to all five constraints, hence we prefer the relative definition of the deviation variables.

In the next subsection, we analyse the behaviour of the deficits as a function of the total net profit.

3.3.3 Case results

The case is worked out in two steps. First, we analyse the situation with the parameter settings described in the previous subsection. We do so, by varying the **minimal** required net profit TP, which results in different scores for the deviaton variables as well as the **actual** net profit. Let us take a look at the results in Table 6.

TP	assignment A/B/C	d_{e1}	$\underline{d}_{e2}$	$\underline{d}_{e3}$	d_{m1}	d_{p1}	profit
0	s4 s2 s4	-0.57	-0.06	0	0.9	-0.44	76000
80000	s4 s2 s2	-0.60	-0.08	-0.01	1	-0.48	176000
180000	s4 s2 s1	-0.60	-0.02	-0.01	1	-0.37	213500
220000	s4 s3 s1	-0.60	0.05	0.17	1	-0.21	228500
230000	s4 s1 s1	-0.60	0.32	0.10	1	0.39	258500
260000	s1 s3 s1	-1.00	0.17	0.22	2	-0.03	267500
270000	s3 s1 s1	-1.00	0.37	0.10	2	0.39	283500
285000	s1 s1 s1	-1.00	0.49	0.14	2	0.63	297500

Table 6 GRD-policies for various TP, $g_e=3\ \forall e$, $g_{m1}=1$, $g_{p1}=1$

The variables d_{e1}, $\underline{d}_{e2}$, $\underline{d}_{e3}$, d_{m1} and d_{p1} reflect the relative deficit to the constraints T(e1), T(e2), T(e3), T(m1) and T(p1). As long as they are **non positive**, the constraint is **satisfied**. A value lower than zero reflects the relative slack. A **positive** value implies that the constraint is **violated**. This is penalised in

the objective function by z_c. We observe that most group level constraints are met if TP=180.000, since the deficit variables are non positive. The real profit is then 213.500. There is one exception to this: the secondary TV-market, which is overflown by a 100 percent. Therefore, we now vary the weight g_{m1} with steady TP= -100.000 and g_e remains 3 $\forall$ e, g_{p1} remains 1. The results of this scenario are reflected in Table 7.

g_{m1}	assignment A/B/C	d_{e1}	$\underline{d}_{e2}$	$\underline{d}_{e3}$	d_{m1}	d_{p1}	profit
1	s4 s4 s2	-0.34	0.11	0.24	0.7	0.04	26.000
100	s4 s4 s2	-0.34	0.11	0.24	0.7	0.04	26.000
1000000	s4 s4 s2	-0.34	0.11	0.24	0.7	0.04	26.000

Table 7 GRD-policies for various g_{m1}, TP=-100.000, g_e=3 $\forall$e, g_{p1}=1

As we can see, it is very difficult to decrease the overload on the secondary TV-market. This means that it is worthwhile to make a marketing effort, in order to expand the market. If one would succeed in doubling the market volume, an optimal GRD-policy would be an assignment of (s4, s2, s1) to the products A, B and C with a total profit of 213.500. If no market expansion can be realised, one will have to go back to the product level and remove 'upgrade' from the set of feasible RD-options R(j,q) for at least one of the products A, B or C. An alternative PRD-strategy with no product reuse will be generated, after which the assignment optimisation is repeated.

We summarise the results in Figure 8. On the x-axis, we depict the total net profit of the GRD-policies involved. On the y-axis, we depict the corresponding values for the deviation variables. Thus, we obtain the function of the (dependent) deviation variables and the (independent variable) net profit. Next, we discuss our model and the case results in Section 4.
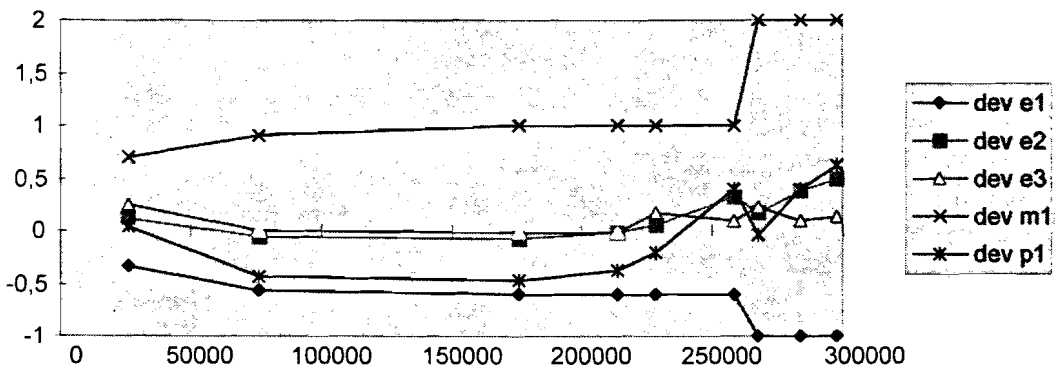

Figure 8 Deviation variables as function of net profit

4 Discussion and Conclusions

The discussion falls apart in three subsections. In Subsection 4.1 the models validity is discussed, in Subsection 4.2 we present the results of LP-relaxation of the MILP-model in which case results are used. In 4.3, conclusions are drawn.

4.1 Validity of the model

In this subsection we shall discuss the reality of our main implicit assumptions.
(i) The length of the planning period mainly depends on the availability of data and stability of the parameter settings. In principle, the model is developed for the tactical management level, which implies a planning horizon of approximately 1-3 years. In our view, it is not very realistic to extend the planning horizon to multiple periods, because this requires data on all future parameter settings. For example, if a multi-period problem with 4 periods of 3 years were to be solved, this would require estimates for a timespan of 12 years on the number, types and quality of the products/components returned, volume and prices in secondary markets, cost prices for recovery and disposal, availability of (new) recovery/disposal techniques, legislation an so on. This may be very difficult. Therefore, we take

a more practical approach which, in short, boils down to 'look where we stand now' and 'see where we should be heading to'. Of course, a decision maker may wish to include the effects of historic decisions. For example, if a facility, established in a former period, is available in the coming planning period, then the costprices of RD-options using this facility might be lower than RD-options requiring new facilities. Also, a certain processing capacity is available to these RD-options, which is a group level criterion. In general, effects of historic decisions should be incorporated in the cost and revenue functions at the product level and the constraints at the group level.

(ii) The model does not distinguish between different parameter settings for products of one type, returned from different geographic areas. This can be easily repaired, if necessary. For example, the profitability of RD-options might partly depend on transportation costs, hence on the physical distance between supply points, facility locations and demand points. We can solve this by defining product subtypes i on the basis of regions -e.g. TVs X from France- and RD-suboptions by market locations - e.g. TV reuse for second hand markets in Nigeria- and adapt net profits accordingly. Again, differences are incorporated in the cost and revenue functions and this may lead to considering different options.

(iii) The GRD-policy serves as an input for the physical design of the reverse logistic network. The basic idea behind this, is to decouple the problems of 'what to do with return products' and 'how to build the logistic system for it'. Here the design of the logistic network is tuned on the GRD-policy, hence it should provide sufficient capacity to realise the assigned PRD-strategies. However, the logistic network also has on influence on the parameter settings of the GRD-policy, especially the cost functions. Therefore, some kind of feed back loop may be fruitful.

(iv) A major assumption in our research, is that only one decision maker determines the GRD-policy. We believe this is the best approach for analytical purposes, but it is also applicable in practical situations. Even if responsibility is scattered all over the reverse chain, it is useful to determine the GRD-policy that is globally optimal as a starting point for discussions or negotiations. If this GRD-policy prejudices some channel members, a compensation scheme should be established. Although this is a very interesting subject, it is beyond the scope of our present research.

4.2 LP-relaxation

In the MILP-formulation only one PRD-strategy is assigned to each product type. This is not the case when an LP-formulation is used, which is in fact a relaxation of the MILP-formulation. For example, if we solve the LP-model for the parameters as given in the first scenario of Subsection 3.3, then an optimal assignment is: (i1,s1), (i2,0.1 s1/0.9 s2) and (i3,s1), with a net profit is 218.000 and deviation variables values d_{e1}= -0.6, d_{e2}=0, d_{e3}=0.01, d_m=1 and d_p=-0.29.

Concluding, there are no important changes in results due to LP-relaxation in this case. However, differences strongly depend on the parameter settings, hence this kind of analysis can certainly be worthwhile. One should be aware of the fact that modelling the problem as an LP-problem requires fractional assignments of PRD-strategies. This complicates the implementation, because multiple strategies are assigned to one product type. There are several ways to deal with this:

- Establishing 'turn-by-turn' processing rules, but presumably this does not work in practice.
- Assigning PRD-strategies to geographically distinct supply points, such that the overall assignment within the GRD-policy must be realised. For example, return products of type i2 from supply point II are processed by s2, return products i2 from the other supply points I, III and IV are processed by s1.
- Establishing operational decision rules, in which fluctuations in inventory level, demand and supply, available resources etc. determine the actual assignment of PRD-strategies **in time**. Of course, in the end the tactical assignment should be realised.
- Reformulate the PRD-strategies. For example, try to generate an alternative strategy, that leads to a mixture of s1 and s2.

The formulation as an LP-problem also enables sensitivity analysis, which can be very useful in testing the robustness of solutions. However, these issues need further exploration.

4.3 Conclusions

The introduction of extended producer responsibility confronts OEMs with entirely new managerial problems, among which the determination of recovery strategies for return flows. This paper discusses the determination of an optimal Group Recovery and Disposal (GRD-) Policy for compulsorily returned (discarded) durable assembly products of multiple types. It deals with the question, how to handle this return flow in terms of disassembly, recovery and disposal. The problem is dealt with on a tactical management level, because it involves anticipation to management issues like environmental legislation, buy-back agreements with suppliers, developing secondary end markets and investments in recycling infrastructure. Some interesting models were found in the literature, but none of them fits our problem definition, which includes aspects like multi-level assembly structures, recovery targets, limited market volumes and interrelated RD-options. Therefore, we present a new combination of two models, which enables us to economically exploit compulsorily return flows as much as possible, within commercial, environmental and technical constraints. In this approach, we first generate a set of alternative PRD-strategies at the product level for each product type. For this, we use a heuristic algorithm in combination with one of our previous models. Subsequently, a MILP-model is used to assign these strategies into a mixed GRD-policy. The output is an assignment of a strategy s* to each product type i, where each assigned PRD-strategy consists of conditional assignment rules for disassembly and RD-options to assembly j in class q, $\forall j \forall q$. Due to the soft formulation of constraints, a feasible solution can always be found. In practical situations, some variation of the MILP-model may be required, in order to deal with e.g. non-linear constraints. Reformulation as an LP-model enables slightly better results, but also requires the implementation of mixed strategies per product type. A case was worked out to illustrate the applicability of the model. Subjects for further research include analysing the robustness with respect to uncertainty in parameters, the operational managment of implementing PRD-strategies, situations of shared decision responsibilities in the reverse chain and the mutual impact of GRD-policies and physical network design. In our future research, we shall particularly focus on the latter aspect.

Literature

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