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Integrated planning of acquisition, disassembly and bulk recycling: a case study on electronic scrap recovery*

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Abstract. Due to national and supranational legislation activities, the recovery of discarded products will attain an increasing momentum. Electronic equipment consists of many different parts and materials. Therefore, the related recovery process is often divided into disassembly to remove harmful substances or reusable parts and into bulk recycling to recover ferrous and non-ferrous metals. In order to consider the interactions between choice of scrap to be recovered (acquisition problem), disassembly and bulk recycling, a mixed-integer linear programming model for integrated planning of these stages is presented in this case study. It is applied to determine the daily allocation of products to processes for a major electronic scrap recovery centre that faces limited processing capacities and market restrictions. The optimization calculations covering typical discarded electronic products to be recycled in the related centre lead to a relevant improvement of the economic success.

Key words: Reverse logistics – Electronics recovery – Recovery planning

1 Introduction

It is estimated that in the European Union more than 6 million tons of "Waste on Electrical and Electronic Equipment" (WEEE) were generated in 1998. This quantity is predicted to increase by 3–5 % per year (European Commission, 2000).

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These discarded products should be recovered to prevent leachate pollution from landfills caused by substances like heavy metals. The recovery and the reuse of the valuable materials and parts may be another valid reason.

The recovery of electronic scrap is a multistage process. Logistic issues concern collection, grading, transport and allocation of discarded products as well as of recovered materials. Disassembly in order to remove hazardous substances and reusable parts is often followed by bulk recycling to recover separated material fractions that are sent to metal recycling facilities or other recycling specialists. In order to consider the complex interactions between these stages appropriately, the application of mathematical decision support appears promising (Fleischmann, 2000). In this case study, the determination of the daily recovery program concerning processed items and executed processes is examined for a major recovery centre.

The paper is structured as follows. In Section 2 the case is defined. Hence a review of technical processes and material flows, the planning problem and data as well as the related literature are outlined. Based on this, a mixed-integer linear programming model for the considered planning problem is developed and solved in Section 3. The results for the basic data set and the discussion of different solution procedures are presented in subsequent Section 4. Section 5 consists of a detailed interpretation of the numerical results for different scenarios. Conclusions and recommendations for future research are derived in the final Section 6.

2 Problem definition

2.1 Case description

This case study refers to the acquisition, disassembly and bulk recycling planning of the Electrocycling GmbH that recovers industrial and consumer electronics in an integrated recovery centre in Goslar (Germany). The fixed costs represent about a half of the total treatment costs due to the related investments of 15 MEuro. The operating costs result especially from disposal fees, maintenance and labour wages for more than 100 workers. A detailed description of the recovery centre is given by Koch and Kasper (1996).

In the considered planning problem, the system boundary is limited to the recovery works profit centre, not including the input storage. Other stages like transport, smelting or marketing of reusable parts are excluded since they are accomplished by external services. The material flow throughout the enterprise is shown in Figure 1. Long-term contracts for scrap collected by public and industrial collectors contribute less than 10% of the recovered mass. Thus electronic scrap is actively acquired by the input storage of the enterprise. This is a separate profit centre that may sell scrap to external customers as well as to the internal customer recovery works. After the recovery works profit centre has ordered the daily range of scrap types to be processed from the input storage, the delivery to the adjacent recovery works is accomplished immediately. The scrap is assessed with a given transfer price that is dependant on the scrap market. Therefore, the recovery works manager faces the internal "acquisition" decision as to which products have to be taken

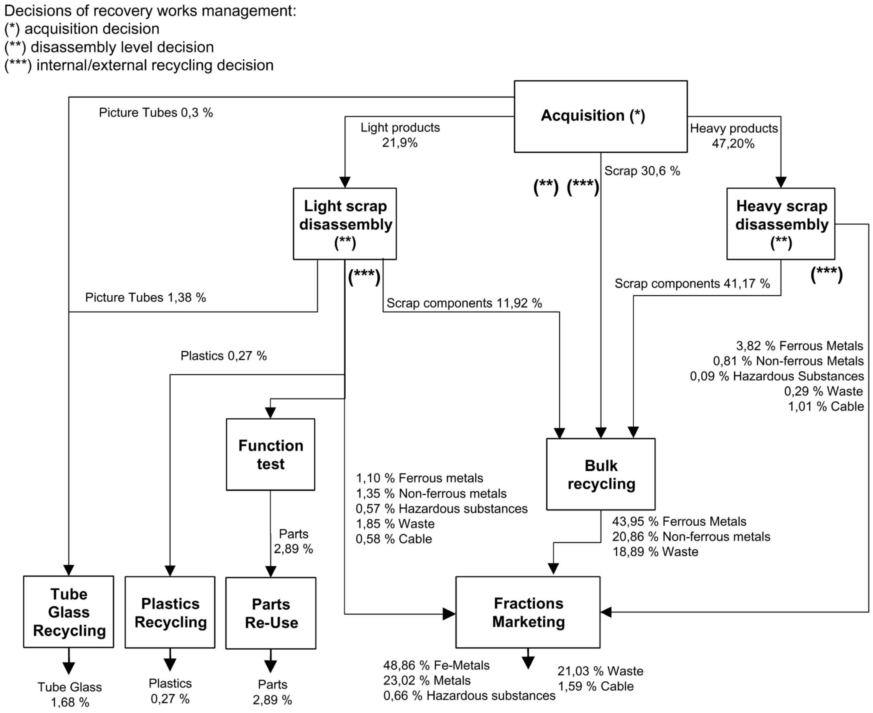

Fig. 1. Material flow of the recovery centre (Mass-%)

from storage and recovered in the considered daily planning period as seen at point (*) in Figure 1.

The first recovery step "disassembly" is composed of manual or partly-automated processes. Mechanical assistance addresses only transport and lifting tasks. In planning the disassembly step, the recovery works manager has to determine the disassembly level at point (**) in Figure 1, taking into account that some products do not have to be disassembled at all, that the reusable part demand as well as prices change daily and that some disassembly activities are mandatory in order to eliminate hazardous substances.

The second step "bulk recycling" is designed to recover precious fractions such as ferrous and non-ferrous metals from mixed electronic scrap, using unit operations like crushing and separation. When planning the bulk recycling step, the recovery works manager has to decide which scrap types are to be recycled internally or marketed externally as seen at point (***) in Figure 1. This is a complex problem due to the fact that bottlenecks can appear in different units. Based on a specific input composition and the expected separation of material fractions, the required capacity for every unit had been calculated in the process design phase. Thus the unit capacities have been fixed for the long term planning horizon. Deviations from the expected composition can lead to bottlenecks in the subsequent units if the components that should be separated in the preceding units of the facility, e.g. ferrous metals, are underrepresented in the feed. In order to balance these deviations, a recycling centre can benefit from the blended composition of the bulk recycling input adjusted by the feed of different scrap types. The output of the recovery centre is taken to smelting plants (70% metals), chemical industry (< 1% plastics), glass industry (< 2% tube glass), part traders (3% reusable parts) and waste incineration (22% waste and hazardous substances).

The work to be completely done on the same day has to be determined daily by the recovery works manager, taking into account the available capacities. Since the three related planning problems choice of "scrap types to recover" (*), "disassembly activities" (**) and "internal/external treatment" (***) have to be solved by the same person, show a complex interaction and are dependant on the daily situation, the application of an integrated short term planning model for the recovery works profit centre is advisable.

2.2 Literature review

General reviews of planning problems in a product life cycle are given by Gungor and Gupta (1999) and Spengler and Schröter (2001). According to the chosen system boundary the following literature review is restricted to disassembly and bulk recycling planning problems that occur in the product recovery stage. Penev and de Ron (1996) describe a static cost comparison tool to determine an economic disassembly level and sequence of a single product. Krikke et al. (1998) develop a method to determine a good product recovery and disposal policy of one product type taking into account technical, economic and ecological criteria. For this purpose a two-phased dynamic programming algorithm is presented. Meacham et al. (1999) provide an optimal disassembly configuration algorithm for single as well as for multiple products. Spengler et al. (1997) develop a mixed-integer linear programming model based on linear activity analysis for integrated dismantling and recycling of buildings. The purpose of the model is to obtain optimal dismantling strategies but also an optimal assignment of components and parts to recycling techniques. A planning tool for integrated planning of recovery and remanufacturing is given by Uzsoy and Venkatachalam (1998). Sodhi and Reimer (2001) describe an integrated disassembly and material recovery model for discarded electronic products. In addition to other works the presented model includes the process stage of metal smelting.

Only a few papers refer to operation research models for the economic assessment of bulk recycling operations. Lund et al. (1994) use linear programming to analyse the design and the operation of municipal waste material-recovery-facilities. Sodhi et al. (1999) present a dynamic programming model for the determination of the unit operations sequence for float-sink materials separation by density. Alternative disposal strategies for cars are assessed using goal programming by Isaacs and Gupta (1998), taking into account the profit for disassembler and shredder. Stuart and Lu (2000a,b) offer decision support for processing and reprocessing options in electronic scrap bulk recycling centres. Rudolph (1999) provides an integrated model for disassembly, remanufacturing and bulk recycling planning without giving a practicable processing description.

The planning situation presented in the preceding subsection differs from the assumptions of these papers concerning two major facets. On the one hand, in this case study scrap has to be acquired actively. The focus in the recent publications is laid rather on the question of how to treat given discarded products (Penev and de Ron, 1996; Krikke et al., 1998; Spengler et al., 1997; Uzsoy and Venkatachalam, 1998), e.g. on the determination of the disassembly level. On the other hand, the recovery centre referred to consists of disassembly and multi-level bulk recycling. The capacity restrictions are given in each processing step and can not be subsumed due to the complex interactions of disassembly activities, unit operations, material composition and chosen products. Since the recycling centre can benefit from the calculated composition of bulk recycling input, the consideration of the impact of input composition in combination with the basic engineering foundations of the processes in individual separation units is advisable. Few models take into account the interaction of subsequent recovery processes (Sodhi and Reimer, 1999; Rudolph, 1999; Isaacs and Gupta, 1998), but the unit capacities are not considered separately. The detailed bulk recycling models (Lund et al., 1994; Stuart and Lu, 1998a,b) neglect the interactions with disassembly. Thus the recent publications that deal with the application of operations research in recovery planning can not be directly applied in the considered case study. The development of an integrated model for the daily planning of acquisition and recovery processes is necessary.

2.3 Planning data

The application of recovery planning models is often obstructed by the lack of data. In this case study, information is provided by a database that contains product and processing data. Since the composition of discarded electronic products shows significant variations, the products have to be classified into different types. Because of the variations within these types, a representative product has to be chosen for each type, and a detailed range of possible disassembly activities as well as an inventory of material composition have to be prepared. The delivery of recovery-relevant information is a complex problem that should be solved by production enterprises, referring to the forthcoming directive of the EU on Waste on Electric and Electronic Equipment (European Commission, 2000). A practical concept seems to be the "recycling passport" of the Belgian-German equipment producer AGFA-Gevaert AG that contains data about hazardous substances, composition and reusable parts (Verein Deutscher Ingenieure, 2000). It can be used to plan recovery processes and to estimate disassembly times. Based on this, the development of a database with recovery data provides necessary information for planning at recycling facilities.

2.4 Recovery process analysis

The input-output-relations throughout the execution of the possible disassembly activities are given in Table 1. The index i ($i = 1, \dots, 29$) describes the scrap types (products, parts, materials). The range of discarded products ($i = 1, \dots, 6$) that is

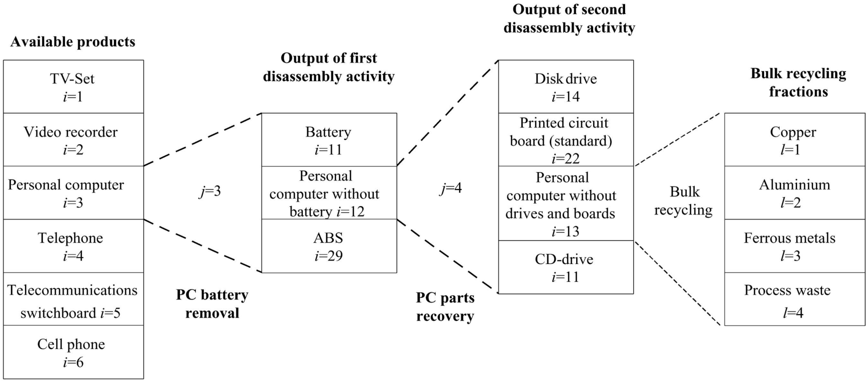

Fig. 2. Model of discarded product recovery (example PC)

available in input storage as well as of subsequent disassembly output materials ($i = 29$) and parts ($i = 7, \ldots, 28$) are shown in Table 1. The column index j ($j = 1, \ldots, 10$) specifies the possible disassembly activities. Each row i describes the result of one execution of a certain disassembly activity j that represents the disassembly of exactly one piece of a defined scrap type. Negative values of the given coefficient v_{ij} represent the mass input of the scrap type to the activity, positive values the mass output. A time factor for the execution of one activity j is presented in the bottom row.

The structure of the product recovery including disassembly activities and bulk recycling is depicted in Figure 2. A "personal computer" chosen from the discarded products range must be opened and the harmful part "battery" has to be removed (disassembly activity $j = 3$). The option to recover spare parts ($j = 4$) can be exercised if there is a market for these parts. Residues can be treated in bulk recycling in order to recover metals or can be marketed externally. As seen in Table 1, one "personal computer" ($i = 3$) of 10 kg is dismantled into one "battery" ($i = 7$) of 0,05 kg, into "ABS" ($i = 29$) from casings of 0,5 kg and into one "personal computer without battery" ($i = 12$) of 9,45 kg. This "personal computer without battery" ($i = 12$) can be disassembled by the activity "personal computer spare parts recovery" ($j = 4$) leading to one "CD-drive" ($i = 11$), one "disk-drive" ($i = 14$), one "printed circuit board (standard)" ($i = 22$) and one "personal computer without drives and boards" ($i = 13$) with the given masses. In Table 1 typical disassembly activities like the required removal of hazardous substances or the recovery of reusable parts are shown. Since these activities are manual work, the relevant cost-driver is labour. Disassembly output has to be directed towards external or internal treatment. In case of external treatment, the output is collected in boxes and marketed externally, e.g. as spare parts or to be treated by recycling specialists. Otherwise, the disassembled parts are discharged by a belt or by gravitation to the input of the bulk recycling facility where they are mixed with other products and parts.

The flowsheet of the bulk recycling step is depicted in Figure 3. The multi-level bulk recycling consists of size-reduction and separation units. The size-reduction to isolate and concentrate the valuable materials is accomplished by several

Table 1. Scrap types and disassembly activities Input-Output-Matrix

	Activity		TV dismantling	Video dismantling	PC battery removal	PC parts recovery	Telephone dismantling	Switch-board opening	Switch-board board removal	Switch-board parts removal	Cellular phone accu removal	Cellular phone board removal
	v_{ij}	$j =$	1	2	3	4	5	6	7	8	9	10
			[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
	Products											
$i = 1$	TV-set		−25	0	0	0	0	0	0	0	0	0
2	Video recorder		0	−4	0	0	0	0	0	0	0	0
3	Personal computer		0	0	−10	0	0	0	0	0	0	0
4	Telephone		0	0	0	0	−1.5	0	0	0	0	0
5	Telecommunication switchboard		0	0	0	0	0	−100	0	0	0	0
6	Cellular phone		0	0	0	0	0	0	0	0	−0.2	0
	Parts											
7	Battery		0	0	0.05	0	0	0	0	0	0	0
8	Coverings		0	0	0	0	0	5	0	0	0	0
9	Accumulator		0	0	0	0	0	0	0	0	0.1	0
10	Cathode ray tube		13.75	0	0	0	0	0	0	0	0	0
11	CD-Drive		0	0	0	0.2	0	0	0	0	0	0
12	Personal computer without battery		0	0	9.45	−9.45	0	0	0	0	0	0
13	Personal computer without drives		0	0	0	8.09	0	0	0	0	0	0
14	Disk-drive and boards		0	0	0	0.2	0	0	0	0	0	0

Table 1 (continued)

	Activity		TV dismantling	Video dismantling	PC battery removal	PC parts recovery	Telephone dismantling	Switch-board opening	Switch-board board removal	Switch-board parts removal	Cellular phone accu removal	Cellular phone board removal
	v_{ij}	$j =$	1	2	3	4	5	6	7	8	9	10
			[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
	Parts											
15	Mixed entertainment electronics parts		6.25	3.2	0	0	0	0	0	0	0	0
16	Housing parts		3.75	0.4	0	0	0	0	0	0	0	0
17	Telephone back		0	0	0	0	0.6	0	0	0	0	0
18	Cellular phone body		0	0	0	0	0	0	0	0	0.1	−0.1
19	Cellular phone waste		0	0	0	0	0	0	0	0	0	0.05
20	Printed circuit board (precious)		0	0	0	0	0	0	4.75	0	0	0
21	Printed circuit board (cheap)		1.25	0.4	0	0	0	0	0	0	0	0
22	Printed circuit board (standard)		0	0	0	0.96	0	0	0	0	0	0.05
23	Switch board parts		0	0	0	0	0	0	0	9.025	0	0
24	Telephone front		0	0	0	0	0.45	0	0	0	0	0
25	Telecommunication switchboard without boards		0	0	0	0	0	0	90.25	−90.25	0	0
26	Telecommunication switchboard (open)		0	0	0	0	0	95	−95	0	0	0

Table 1 (continued)

	Activity		TV dismantling	Video dismantling	PC battery removal	PC parts recovery	Telephone dismantling	Switch-board opening	Switch-board board removal	Switch-board parts removal	Cellular phone accu removal	Cellular phone board removal
	v_{ij}	$j =$	1	2	3	4	5	6	7	8	9	10
			[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
	Parts											
27	Telecommunication switchboard (frame)		0	0	0	0	0	0	0	81.225	0	0
28	Telephone receiver		0	0	0	0	0.45	0	0	0	0	0
	Materials											
29	ABS		0	0	0.5	0	0	0	0	0	0	0
	Time Factor t_j^Z	[h/act]	0.1	0.03	0.03	0.02	0.006	0.01	0.05	0.05	0.005	0.015

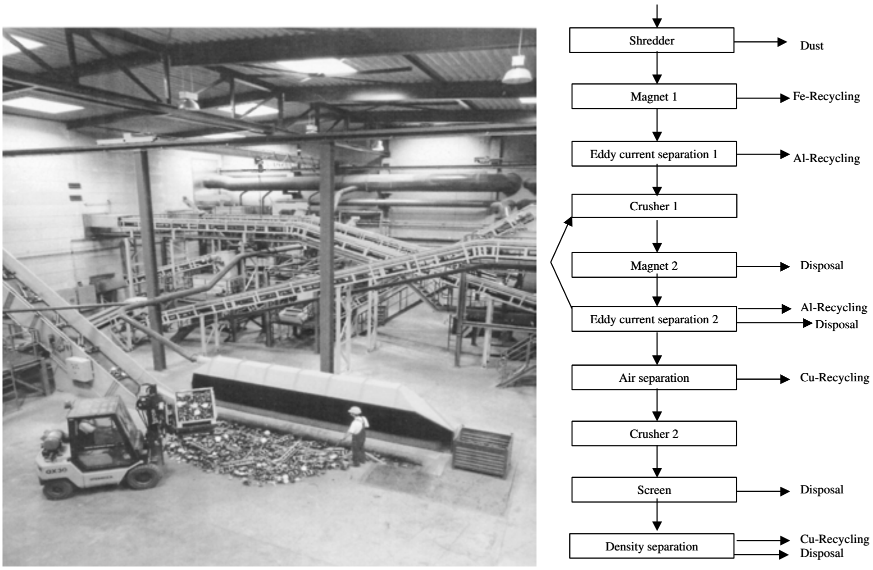

Fig. 3. Bulk recycling picture and flowsheet

totally automated shredding and crushing units and has decisive importance for the success of the separation. Ferrous metals represent a major share of the bulk recycling input. Their removal by magnetic separators takes place after the first shredding step since the size-reduction of ferrous metals is very energy- and wear-intensive. Other valuable materials like aluminium and copper are recovered by eddy-current separators in which metals are isolated due to their electric conductivity (Schubert, 1994), by density-separation processes and by classifying stages. The remaining non-valuable materials like paper or mixed plastics can be found in the process waste that is sent to external incineration. The range of material components in the input of the units as well as of separated material fractions in the output of the units is indicated with the index l as shown in Table 2. Relevant cost drivers in bulk recycling are maintenance, energy consumption and labour (Meier-Staude and Mersmann, 1997).

Table 2. Materials in bulk recycling

l	Material
1	Copper
2	Aluminium
3	Ferrous metals
4	Process waste

2.5 Planning horizon

The acquisition planning in the enterprise is divided into two levels. First, the scrap has to be acquired at the market by the input storage profit centre. For the related tasks like supplier negotiations, forecasting or logistics, the planning horizon ranges from one week to six months. In this case study, however, due to the "recovery works" as the given system boundary, only the daily internal acquisition is considered. Thus acquisition and delivery from the adjacent storage is executed within few minutes, and acquisition capacity constraints are given by the masses available from the input storage of the recovery enterprise. The available disassembly capacity is determined by the maximal number of operators who can be delegated to disassembly that day. In bulk recycling, each unit may treat a defined mass per period. The related time period is influenced by the number of shifts per day and by expected downtimes due to maintenance operations. In the case examined, the daily available unit capacities result from one shift without downtimes. The total time required for internal acquisition and transport as well as for disassembly and bulk recycling is exceeded significantly by the given capacity constraint horizon, and thus the time needed for acquisition and processing can be taken into account using the given capacity restrictions. Based on the analysis of recovery processes, the daily planning problem of determining the short term recovery program becomes apparent: Taking into consideration the structure and composition of these scrap types, the different disassembly activities and unit operations, market prices and costs, the possible reuse options, achievable proceeds as well as capacity and market constraints, the recovery works manager has to determine daily the optimal choice of scrap types to recover, the optimal allocation of disassembly activities and the optimal choice of scrap types input to bulk recycling.

3 Model formulation and solution procedure

In this section, an integrated short term planning model based on the material flows throughout the recovery centre is provided. It leads to an optimal solution of the presented decision problem maximising the total achievable marginal income. The chosen model formulation is based on linear activity analysis (Koopmans, 1951) that permits a very simple and appropriate model formulation of recovery planning problems (Souren, 1996; Spengler, 1998). In the model the depiction of the disassembly sector corresponds to the mixed-integer disassembly optimization model that is given by Spengler et al. (1997). The structure of the material flows is shown in Figure 4.

It is assumed that a number of different discarded products, parts and materials i are available in the input storage at a given negative or positive transfer price. These I scrap types can be disassembled by the execution of J different disassembly activities and can be processed by a bulk recycling plant using K process units. The following notation is used:

Indices

i Scrap types: products ($i \in \{1, \ldots, I_1\}$), parts ($i \in \{I_1 + 1, \ldots, I_2\}$), materials ($i \in \{I_2 + 1, \ldots, I\}$)
j Disassembly activity $j \in \{1, \ldots, J\}$
k Unit operation $k \in \{1, \ldots, K\}$
l Material $l \in \{1, \ldots, L\}$

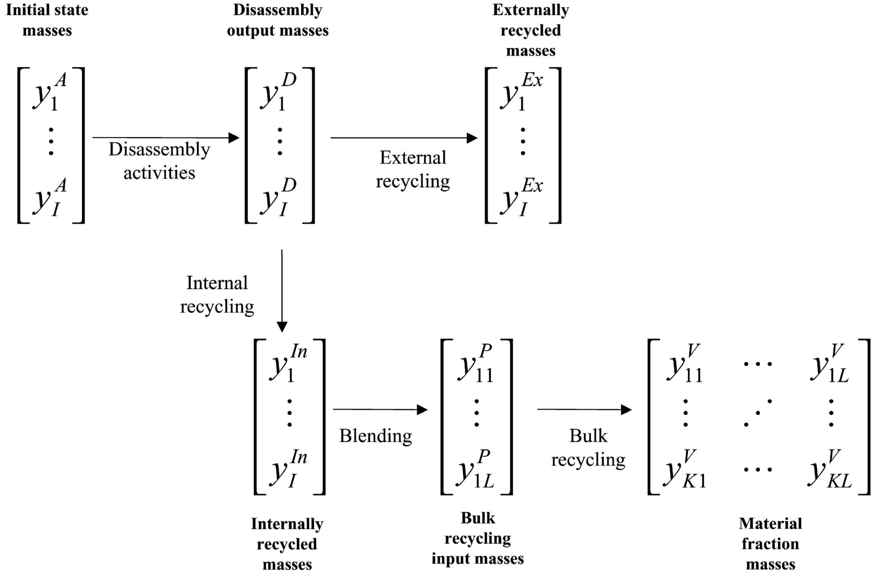

Fig. 4. Model of material flows

Parameters, coefficients and limits

a_{il}	Composition factor that assigns scrap type i composition to material component l [kg/kg] $(0 \leq a_{il} \leq 1)$
c_k^P	Bulk recycling cost factor for unit operation k [Euro/kg]
c^Z	Disassembly labour cost factor [Euro/h]
e_i^{Ex}	Cost $(-)$ or price (+) factor for scrap type i to external recycling [Euro/kg]
e_i^A	Acceptance cost $(-)$ or price $(+)$ factor for scrap type i [Euro/kg]
e_{kl}^V	Recycling material sale cost $(-)$ or price $(+)$ factor of isolated material fraction l separated by separation unit k [Euro/kg]
m_i	Mass of one piece of scrap type i [kg] (m_i is only defined for products and parts if reuse has to be considered)
$T^{\max}$	Limit for disassembly labour time [h]
t_j^Z	Disassembly time needed for one execution of activity j [h/act]
u_{kl}^P	Fraction of material l extracted at unit operation k [kg/kg] $(0 \leq u_{kl}^P \leq 1)$
v_{ij}	Disassembly activity coefficient for the input $(-)$ or output $(+)$ masses of scrap type i caused by one execution of activity j [kg/act]
$y_i^{A,\max}$	Limit for the maximum mass of scrap type i to be obtained from storage [kg]
$y_i^{Ex,\max}$	Limit for sale capacity of scrap type i to external recycling [kg]
$y_k^{P,\max}$	Limit for equipment capacity of separation unit k [kg]
$y_{kl}^{V,\max}$	Limit for sale capacity of isolated material fraction l separated by unit k [kg]

Variables

$x_j \in N_0$	Number of executions of disassembly activity j [act]
$y_i^A \in \left[0; y_i^{A,\max}\right]$	Mass of scrap type i to be taken from storage for processing [kg] with $y_i^A/_{m_i} \in N_0$ if m_i is defined
$y_i^D \in [0; \infty)$	Mass of scrap type i after disassembly [kg]
$y_i^{Ex} \in \left[0; y_i^{Ex,\max}\right]$	Mass of scrap type i to external recycling [kg] with $y_i^{Ex}/_{m_i} \in N_0$ if m_i is defined
$y_i^{In} \in [0; \infty)$	Mass of scrap type i to internal recycling [kg]; $y_i^{In} = 0$ if i contains hazardous substances
$y_{kl}^P \in [0; \infty)$	Mass of material component l in the mixture that is treated in unit operation k [kg]
$y_{kl}^V \in \left[0; y_{kl}^{V,\max}\right]$	Mass of isolated material fraction l separated by unit operation k [kg]

Based on these notations the decision problem can be formulated as a mixed-integer linear programming (MILP) model.

$$MAX \sum_{i=1}^{I} (y_i^A \cdot e_i^A + y_i^{Ex} \cdot e_i^{Ex}) + \sum_{k=1}^{K} \sum_{l=1}^{L} y_{kl}^V \cdot e_{kl}^V - \sum_{j=1}^{J} x_j \cdot t_j^Z \cdot c^Z - \sum_{k=1}^{K} c_k^P \cdot \left(\sum_{l=1}^{L} y_{kl}^P \right) \qquad (1)$$

subject to:

$$y_i^D = y_i^A + \sum_{j=1}^{J} x_j \cdot v_{ij} \qquad i = 1, \ldots, I \qquad (2)$$

$$y_i^D = y_i^{Ex} + y_i^{In} \qquad i = 1, \ldots, I \qquad (3)$$

$$y_{kl}^P = \begin{cases} \sum_{i=1}^{I} a_{il} \cdot y_i^{In} & \text{for } k = 1 \\ y_{(k-1)l}^P - y_{(k-1)l}^V & \text{for } k = 2, \ldots, K \end{cases} \qquad l = 1, \ldots, L \qquad (4)$$

$$y_{kl}^V = u_{kl}^P \cdot y_{kl}^P \qquad k = 1, \ldots, K \; l = 1, \ldots, L \qquad (5)$$

$$\sum_{l=1}^{L} y_{kl}^P \leq y_k^{P,\max} \qquad k = 1, \ldots, K \qquad (6)$$

$$\sum_{j=1}^{J} x_j \cdot t_j^Z \leq T^{\max} \qquad (7)$$

The objective function (1) maximizes the total achievable marginal income resulting from acceptance revenues/costs, disassembly output revenues/costs, bulk recycling output revenues/costs, variable disassembly costs and variable process costs. The three short term decisions are depicted by the decision variables:

- the mass of scrap type i to be taken (y_i^A),
- the number of executions of disassembly activity j (x_j),
- the mass of scrap type i directed to internal recycling (y_i^{In}).

The other variables y_i^D, y_i^{Ex}, y_{kl}^P and y_{kl}^V are not essential due to the fact that they could be expressed by means of the decision variables. However, the explicit consideration of these material flows is a precondition for the detailed interpretation of the solution. Thus the values of y_i^D, y_i^{Ex}, y_{kl}^P and y_{kl}^V are determined by the constraints (2)-(5). Disassembly activities are modelled with the number of executions of the disassembly of this activity x_j and input-output coefficients v_{ij} that represent the input-output-relationships of the disassembly activities seen in Table 1 (2). The obtained disassembly output y_i^D has to be directed either to external or to internal treatment (3). The disassembly output to internal treatment y_i^{In} is completely processed in the bulk recycling units.

It is assumed that the product structure is completely destroyed in the first unit shredder. This simplification is based on the scrap refining studies of Koch and Kasper (1996) who state a liberation degree for ferrous metals of about 90% after shredding and for copper of more than 96% after crushing. At the moment of destruction, the composition coefficients a_{il} assign the scrap types i to a material component l. The input masses of the other units can be calculated by the mass balance equations for each unit (4). The separation units are described by linear coefficients u_{kl}^P representing the share of the available material l in the input of the unit k that is directed into material fraction l of this unit (5). As seen in Figure 5, a share of 0,75 of available "ferrous metals" ($l = 3$) is separated in unit "magnet 1" ($k = 2$). The values of u_{kl}^P have been determined from empirical data and are shown in Table 3. Bottlenecks in bulk recycling can appear at every unit due to variations in feed composition. Thus capacity constraints must be depicted by limits for every unit (6). Disassembly capacity refers to a maximum of labour time (7).

Input supply capacity and output sales capacity are given by the domains of the variables $y_i^A; y_i^{Ex}; y_{kl}^V$. The mandatory removal of hazardous substances before the treatment in bulk recycling is forced by the setting $y_i^{In} = 0$ initiating external treatment for scrap types i that contain hazardous substances. Disassembly activities x_j as well as the number of discarded products and parts y_i^A/m_i; y_i^{Ex}/m_i are modelled as integer variables. This might not be essential if the values of these variables are high enough. In that case the LP-relaxation of the MILP will lead to an acceptable solution quality.

With the product range that is shown in Table 1, the mixed-integer linear optimization model consists of 68 integer variables, 224 non-integer variables and 131 constraints. Standard optimization software packages using Branch-and-Bound techniques provide a quick solution in case of the given problem complexity. Therefore, the presented integrated recovery planning model has been implemented on a personal computer (Pentium III / 600 MHz) referring to EXCEL-spreadsheets that contain the data sets and using the commercial solver LINGO for the optimization calculations. Using these standard software tools, one takes advantage of their public availability and the absence of additional implementation costs. The solution time for the given problem is less than 2s.

Table 3. Linear coefficients u^P_{kl} and prices e^V_{km} in bulk recycling units (other $u^P_{kl} = 0$)

			Dust from shredder	Ferrous metals from magnet 1	Aluminium from Eddy current 1	Aluminium from Eddy current 2	Ferrous metals from magnet 2	Waste from Eddy current 2	Copper from air separation	Waste from Screen	Copper from density separation	Waste from density separation
Unit	$k =$		1	2	3	4	4	4	5	7	8	8
Material	$l =$		4	3	2	2	3	4	1	4	1	4
Separation coefficient	u^P_{kl}	[kg/kg]	0.3	0.75	0.75	1	1	0.45	0.7	0.22	1	1
Unit	$k =$		1	2	3	4	4	4	5	7	8	8
Material	$l =$		4	3	2	2	3	4	1	4	1	4
Material price	e^V_{kl}	[Euro/kg]	−0.15	0.05	1	1	0.04	−0.15	1.5	−0.15	1.5	−0.1

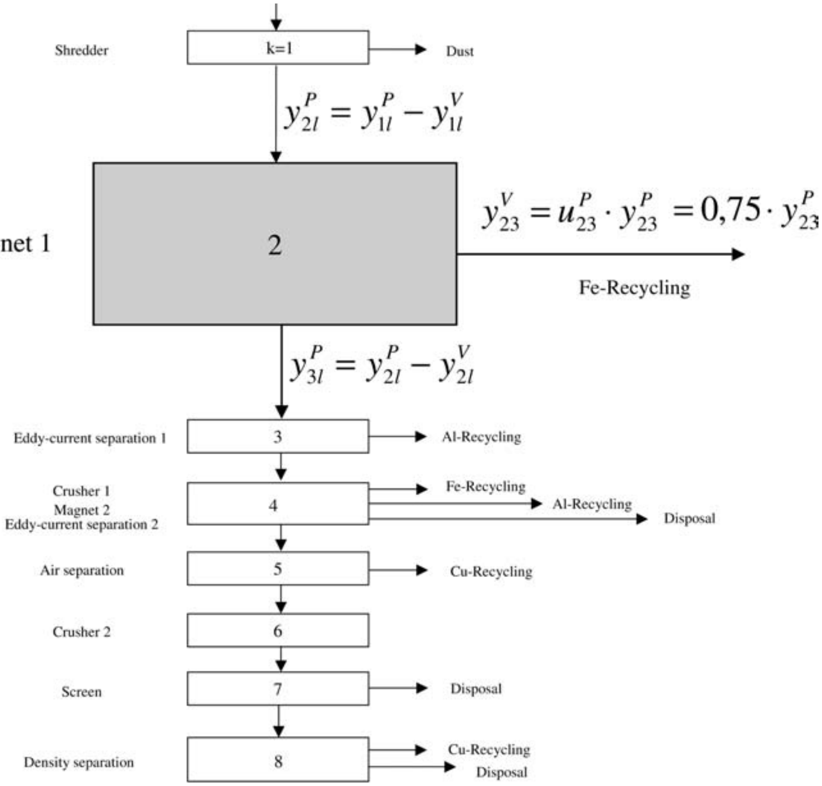

Fig. 5. Bulk recycling model

4 Numerical results

In this section, the complete solution data for one optimization calculation are presented. The impact of different solution procedures for the given planning problem like a non-integer model or intuitive strategies is discussed. The solution to the short term recovery program is shown in Tables 4 and 5. The masses of treated scrap types are given by the values of decision variables y_i^A and y_i^{In} in Table 4. In Table 5 the number of disassembly activities to be executed is stated by the value of decision variable x_j.

All available "TV-sets" ($i = 1$) are taken and disassembly ($j = 1$) is enforced. The subsequent parts like "cathode ray tubes" ($i = 10$), "housing parts" ($i = 16$) and "cheap circuit boards" ($i = 21$) are marketed externally. A share of the obtained "mixed entertainment electronic parts" ($i = 15$) is treated internally, another share of them is treated externally due to the capacity restrictions in the bulk recycling units. "Video recorders" ($i = 2$), which are all accepted, are sent to bulk recycling directly. Only a fraction of available "personal computers" ($i = 3$) is taken. This quantity is limited by the market restriction for "CD-drives" ($i = 11$). Mandatory disassembly ($j = 3$) is done and the "battery" ($i = 7$) is sent to a recycling specialist. The resulting parts from the operation spare part recovery ($j =$

Table 4. Scrap type data and decision variable y_i^A and y_i^{In} results

			Acceptance price	External recycling price	Taken mass	Maximal mass to be processed	Inter-nally recycled mass	Externally recycled mass	Maximum of external recycled mass	Mass per piece	Composition factor Cu	Composition factor Al	Composition factor Fe	Composition factor waste	Contains hazardous substances
i	Name		e_i^A	e_i^{Ex}	y_i^A	$y_i^{A,\max}$	y_i^{In}	y_i^{Ex}	$y_i^{Ex,\max}$	m_i	a_{i1}	a_{i2}	a_{i3}	a_{i4}	
	Unit		[Euro/kg]	[Euro/kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg/piece]	[−]	[−]	[−]	[−]	
1	TV-set	Product	0.625	–	3,000	3,000	0	–	0	25	0,03	0,00	0,13	0,85	yes
2	Video recorder	Product	0.3	–	2,000	2,000	2.000	–	0	4	0,09	0,00	0,40	0,51	no
3	Personal computer	Product	0.1	–	300	2,000	0	–	0	10	0,15	0,00	0,47	0,38	yes
4	Telephone	Product	0.25	–	600	600	600	–	0	1.5	0,09	0,00	0,08	0,84	no
5	Telecommunication switchboard	Product	0	–	2,000	2,000	0	–	0	100	0,11	0,10	0,62	0,17	no
6	Cellular phone	Product	1	–	412	500	0	–	0	0.2	0,05	0,00	0,00	0,95	yes
7	Battery	Part	–	−0.1	–	0	0	1.5	–	–	0,00	0,00	0,00	1,00	yes
8	Coverings	Part	–	−0.1	–	0	0	100	–	–	0,00	0,00	0,90	0,10	no
9	Accumulator	Part	–	−0.25	–	0	0	206	–	–	0,00	0,00	0,00	1,00	yes
10	Cathode ray tube	Part	–	−0.05	–	0	0	1650	–	–	0,00	0,00	0,00	1,00	yes
11	CD−Drive	Part	–	5	–	0	0	6	6	0.2	0,20	0,00	0,30	0,50	no
12	Personal computer without battery	Part	–	−0.1	–	0	0	0	–	–	0,16	0,00	0,44	0,40	no

Table 4 (continued)

			Acceptance price	External recycling price	Taken mass	Maximal mass to be processed	Inter-nally recycled mass	Externally recycled mass	Maximum of external recycled mass	Mass per piece	Composition factor Cu	Composition factor Al	Composition factor Fe	Composition factor waste	Contains hazardous substances
i	Name		e_i^A	e_i^{Ex}	y_i^A	$y_i^{A,\max}$	y_i^{In}	y_i^{Ex}	$y_i^{Ex,\max}$	m_i	a_{i1}	a_{i2}	a_{i3}	a_{i4}	
	Unit		[Euro/kg]	[Euro/kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg/piece]	[−]	[−]	[−]	[−]	
13	Personal computer without drives and boards	Part	–	−0.1	–	0	242	0	–	–	0,15	0,00	0,50	0,35	no
14	Disk-drive	Part	–	1	–	0	1	5	5	0.6	0,20	0,00	0,30	0,50	no
15	Mixed entertainment electronics parts	Part	–	−0.1	–	0	351.3	398.7	–	–	0,10	0,00	0,50	0,40	no
16	Housing parts	Part	–	−0.1	–	0	0	450	–	–	0,00	0,00	0,00	1,00	no
17	Telephone back	Part	–	−0.1	–	0	0	0	–	–	0,10	0,00	0,20	0,70	no
18	Cellular phone body	Part	–	−0.1	–	0	0	206	–	–	0,10	0,00	0,00	0,90	no
19	Cellular phone waste	Part	–	−0.1	–	0	0	0	–	–	0,00	0,00	0,00	1,00	no
20	Printed circuit board (precious)	Part	–	1	–	0	0	95	–	–	0,30	0,00	0,00	0,70	no
21	Printed circuit board (cheap)	Part	–	0	–	0	0	150	–	–	0,10	0,00	0,00	0,90	no

Table 4 (continued)

			Acceptance price	External recycling price	Taken mass	Maximal mass to be processed	Inter-nally recycled mass	Externally recycled mass	Maximum of external recycled mass	Mass per piece	Composition factor Cu	Composition factor Al	Composition factor Fe	Composition factor waste	Contains hazardous substances
i	Name		e_i^A	e_i^{Ex}	y_i^A	$y_i^{A,\max}$	y_i^{In}	y_i^{Ex}	$y_i^{Ex,\max}$	m_i	a_{i1}	a_{i2}	a_{i3}	a_{i4}	
	Unit		[Euro/kg]	[Euro/kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg/piece]	[–]	[–]	[–]	[–]	
22	Printed circuit board (standard)	Part	–	0.5	–	0	0	28.8	–	–	0,20	0,00	0,00	0,80	no
23	Switch board parts	Part	–	0	–	0	0	0	–	–	0,20	0,20	0,50	0,10	no
24	Telephone front	Part	–	−0.1	–	0	0	0	–	–	0,10	0,00	0,00	0,90	no
25	Telecommunication switchboard without boards	Part	–	0	–	0	1805	0	–	–	0,11	0,11	0,64	0,15	no
26	Telecommunication switchboard (open)	Part	–	0	–	0	0	0	–	–	0,12	0,10	0,60	0,17	no
27	Telecommunication switchboard (frame)	Part	–	0	–	0	0	0	–	–	0,10	0,10	0,65	0,15	no
28	Telephone receiver	Part	–	−0.1	–	0	0	0	–	–	0,05	0,00	0,00	0,95	no
29	ABS	Material	–	0.05	–	0	0	15	–	–	0,00	0,00	0,00	1,00	no

Table 5. Number of executions of disassembly activities – decision variable x_j results

Disassembly activity j	Input scrap type	Number of executions of disassembly activity (=disassembled pieces)
		x_j
1	TV-set	120
2	Video recorder	0
3	Personal computer	30
4	Personal computer without battery	30
5	Telephone	0
6	Telecommunication switchboard	20
7	Telecommunication switchboard (open)	20
8	Telecommunication switchboard without boards	0
9	Cellular phone	2060
10	Cellular phone body	0

4) – "disk-drives" ($i = 14$), "CD-drives" ($i = 11$) and "standard circuit boards" ($i = 22$) – are marketed externally. The entire amount of "telephones" ($i = 4$) is also accepted and sent immediately to bulk recycling ($j = 5$). "Telecommunication switchboards" ($i = 5$) are all taken and disassembled ($j = 6, 7$) to recover "precious circuit boards" ($i = 20$) for sale. The "accumulators" ($i = 9$) of taken "cellular phones" ($i = 6$) need to be removed ($j = 9$) and treated by specialists. Further disassembly ($j = 10$) of cellular phones is not recommended. The disassembly time capacity constraint and the capacity restriction of the first unit shredder are reached as seen in Table 6. As a result of bulk recycling capacity restrictions, the feed composition of the bulk recycling plant is adjusted consciously through the choice of taken products and marketed parts. The consequence of mono-treatment would have been a decrease in capacity of up to 40% compared to the unit 1's capacity for some scrap types since bottlenecks can appear in the units 1, 4, 5 or 6 depending on the composition of the scrap types. Thus the blending of different scrap types in the feed of bulk recycling represents an economic value for the recycling centre. The objective function represents a value of 2,906 Euro per daily planning period as seen in Table 7. The main contribution to the objective value results from acceptance fee revenues.

In Table 7 the results of different solution procedures for the basic data set are shown. The integer variables cause exponentially increasing solution time due to the complexity of the optimization problem. When the basic data set has been solved by an optimization model without integer variables, the calculated short term recovery program has not changed at all. Concerning other data sets, there were no changes at all in most of the cases, in some cases there were small deviations. However, the use of integer variables concerning the given problem complexity causes negligible extra solution time and can be justified by the more precise model formulation. In

Table 6. Unit cost factors and capacities

		Process cost factor	Maximum available capacity	Used capacity in basic scenario
		c_k^P	$y_k^{P,\max}$	$\sum_{l=1}^{L} y_{kl}^P$
Unit	k	[Euro/kg]	[kg]	[kg]
Shredder	1	0.02	5,000	5,000
Magnet 1	2	0.005	5,000	4,397
Eddy-current separation 1	3	0.005	4,000	2,697
Crusher 1, Magnet 2, Eddy-current separation 2	4	0.02	3,000	2,530
Air separtion	5	0.005	2,000	1,275
Crusher 2	6	0.02	1,500	924
Screen	7	0.005	2,000	924
Density separation	8	0.005	1,500	754

cases of growing problem complexity, the elimination of integer variables may be advisable to provide a quick solution time.

In order to point out the benefits of the optimization model, the calculated result should be compared with basic concepts to determine short term recovery programs that have been used in the enterprise as seen in Table 7. The first concept, “Re-Use”, aims at high disassembly output revenues and demands the choice and disassembly of products that contain parts with positive market value, e.g. computers with CD-drives. Disassembly is continued until all parts with a positive value are liberated. Parts that do not contain any hazardous substances and that have a negative value are recycled internally. If disassembly and equipment capacity constraints are not reached this way, the products with the highest acceptance prices are treated. As shown in Table 7, this approach leads to an objective value of 2,411 Euro. The lower value is caused mainly by lower acceptance fees due to smaller TV-set ($i = 1$) quantities.

The second concept “Acceptance Fees” determines the choice of discarded products in sequence of acceptance prices. Only mandatory disassembly is done until the constraints are met. Parts that do not contain any hazardous substances and have a negative value are recycled internally. This concept is assessed with an objective value of 2,557 Euro. The success of this concept is impaired by lower bulk recycling output revenues caused by the treatment of less valuable scrap from TV-sets ($i = 1$) and telephones ($i = 4$) in the bulk recycling units. These intuitive strategies have been compared to the optimization concerning other data sets. Basically, a benefit of at least 10% can be obtained using the optimization model proposed in Section 3.

Table 7. Effect of application of different solution procedures for the short term planning problem

Solution procedures		“Optimization”	“Non-integer model”	“Re-use”	“Acceptance fees”
Note		Optimization based on mixed-integer linear programming	Optimization based on linear programming	Intuitive: Choose scrap types that contain parts with positive value!	Intuitive: Choose scrap types that have high acceptance fees!
Acceptance fees		3,067 Euro	3,067 Euro	2,511 Euro	3,141 Euro
Disassembly output revenues		−105 Euro	−105 Euro	15 Euro	−145 Euro
Bulk recycling output revenues		788 Euro	788 Euro	729 Euro	419 Euro
Disassembly costs		625 Euro	625 Euro	625 Euro	625 Euro
Process costs		219 Euro	219 Euro	220 Euro	233 Euro
Objective function value		2,906 Euro	2,906 Euro	2,411 Euro	2,557 Euro
Chosen scrap types		[kg]	[kg]	[kg]	[kg]
TV-set	i=1	3,000	3,000	2,450	3,000
Video recorder	2	2,000	2,000	1,496	2,000
Personal computer	3	300	300	300	160
Telephone	4	600	600	2	600
Telecommunication switchboard	5	2,000	2,000	2,000	600
Cellular phone	6	412	412	500	500
Disassembly activities notes		None	No changes	Disassembly is done until all parts with positive value are gained.	Only mandatory disassembly
Recycling direction notes		None	No changes	Internal recycling of parts with negative value	Internal recycling of parts with negative value

5 Scenario analysis

The interpretation of the solution for the considered short term planning model reveals bottlenecks and risks concerning the presented recovery system. Recommendations for future planning can be derived, including design improvement hints and promising strategic positions for the recycling enterprise. For that purpose, the system behaviour under changing conditions has been analysed by the assessment of different scenarios based on the sensitivity analysis (review of dual prices and reduced costs) for the non-integer solution of the basic data set.

According to the basic scenario in Table 7, the acceptance fees and the bulk recycling output revenues represent a major share of the objective value. Therefore, price variations have been examined as seen in Table 8. With regard to the acquisition of scrap, all acceptance fees are changed to zero and to double value of the basic scenario respectively. The volatility of material markets is considered by changing the prices for copper and aluminium to half and to double value. Changes in cost coefficients have been analysed as well, but the related impacts are very small. The impact of different capacity constraints can be seen in Table 9. Labour capacity is increased to double value due to the option of hiring temporary workers and decreased to half value due to possible sick leaves of operators. Unit capacity may be harmed by failure downtimes. The extension of acceptance constraints leads to the outranking devices “TV-set” and “video recorder”.

The review of dual prices concerning the capacity restrictions of the non-integer solution leads to two bottlenecks and thus to potential improvements for the design of the present recovery system.

On the one hand, one should consider the idea of hiring more workers in the long run. As a result of the sensitivity analysis, 1 Euro that is additionally spent for human work in disassembly would lead to an increasing marginal income of 0.32 Euro. However, this way represents only a small contribution to improve the result. Even if the disassembly capacity is increased up to 150% in the scenario “More Labour Capacity” in Table 9, the benefit for the objective function value amounts to only 1% due to the limited range of attractive disassembly activities. The reduced costs concerning the disassembly activities x_j for $j = 2, 8, 10$ in the basic scenario exceed the value of the objective coefficients $t_j^Z \cdot c^Z$. Therefore, the accomplishment of these activities would not be recommendable even if there were no disassembly capacity restrictions. The main explanation is to be found in the very restricted market for reusable parts, which is also shown through the poor results of the basic “Re-Use” approach. A decrease in disassembly capacity of 50% in the scenario “Less Labour Capacity” leads only to a deviation of the objective function of about 5%.

On the other hand, the sensitivity analysis reveals that every 1 kg additional daily capacity in the shredder ($k = 1$) would improve the objective value by 0.17 Euro. A decreasing unit capacity up to the half in the scenario “Less Unit Capacity” in Table 9 results in a strong reduction of about 17% concerning the objective function value. More scrap types with low material value, such as “mixed entertainment electronic parts” ($i = 15$), are recycled externally. Scrap types that require disproportionate unit capacity, like telecommunication switchboards, are not taken for treatment.

Table 8. Effect of different scenarios concerning prices

Scenarios		Basic scenario	“Metal prices double”	“Metal prices half”	“Acceptance prices double”	“Acceptance prices half”	“Acceptance prices zero”
Assumptions		Basic scenario	The prices for copper and aluminium fractions grow to double value	The prices for copper and aluminium fractions sink to half value	The acceptance prices for all scrap types grow to double value	The acceptance prices for all scrap types sink to half value	The acceptance prices for all scrap types sink to zero
Acceptance fees		3,067 Euro	2,949 Euro	3,067 Euro	6,194 Euro	1,263 Euro	0 Euro
Disassembly output revenues		−105 Euro	−158 Euro	−105 Euro	−140 Euro	11 Euro	149 Euro
Bulk recycling output revenues		788 Euro	1,973 Euro	313 Euro	768 Euro	866 Euro	998 Euro
Disassembly costs		625 Euro	625 Euro	625 Euro	625 Euro	387 Euro	195 Euro
Process costs		219 Euro	215 Euro	219 Euro	219 Euro	214 Euro	214 Euro
Objective function value		2,906 Euro	3,924 Euro	2,431 Euro	5,977 Euro	1,539 Euro	738 Euro
Chosen scrap types	y_i^A	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
TV−set	i=1	3,000	3,000	3,000	3,000	3,000	–
Video recorder	2	2,000	1,996	2,000	2,000	2,000	1,244
Personal computer	3	300	1,310	300	–	520	2,000
Telephone	4	600	600	600	600	–	–
Telecommuication switchboard	5	2,000	2,000	2,000	2,000	2,000	2,000
Cellular phone	6	412	195	412	472	–	–
Disassembly activities notes		None	Telephones are not shredded due to low material value	None	None	PC disassembly is performed more often	PC disassembly is performed more often
Recycling direction notes		None	Scrap types with low material value are recycled externally	None	None	Complete internal recycling of mixed entertainment electronic parts	None

Table 9. Effect of different scenarios concerning restrictions

Scenarios		Basic scenario	"Less labour capacity"	"More labour capacity"	"Less unit capacity"	"Bigger scrap market 1"	"Bigger scrap market 2"
Assumptions		Basic scenario	The disassembly capacity sinks to half value	The disassembly capacity grows to double value	The unit capacity of all units sinks to half value	All acceptance restrictions are extended to 3/2 value	There are no acceptance restrictions
Acceptance fees		3,067 Euro	2,625 Euro	3,267 Euro	3,005 Euro	3,991 Euro	5,406 Euro
Disassembly output revenues		−105 Euro	−126 Euro	−160 Euro	−247 Euro	−277 Euro	−421 Euro
Bulk recycling output revenues		788 Euro	782 Euro	929 Euro	395 Euro	825 Euro	425 Euro
Disassembly costs		625 Euro	313 Euro	880 Euro	625 Euro	625 Euro	625 Euro
Process costs		219 Euro	219 Euro	214 Euro	126 Euro	215 Euro	229 Euro
Objective function value		2,906 Euro	2,749 Euro	2,942 Euro	2,402 Euro	3,699 Euro	4,556 Euro
Chosen scrap types	y_i^A	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
TV-set	i=1	3,000	3,000	3,000	3,000	4,500	6,250
Video recorder	2	2,000	2,000	2,000	2,000	3,000	5,000
Personal computer	3	300	–	1,420	280	300	–
Telephone	4	600	600	600	600	900	–
Telecommunication switchboard	5	2,000	2,000	2,000	700	2,200	–
Cellular phone	6	412	–	500	352	24	–
Disassembly activities notes		None	Mandatory TV-set disassembly and switchboard parts removal	Disassembly of telephone and pc; capacity not reached	None	Disassembly of telephones is done due to low material value	Only mandatory TV-set disassembly
Recycling direction notes		None	None	None	Scrap types with low material value are recycled externally	Scrap types with low material value are recycled externally	Internal video recorder recycling, TV-set parts are marketed externally

Thus a valuable improvement hint for future process design modifications may be raising the capacity of the bottleneck unit 1 in bulk recycling in the long run.

The decision concerning internal or external recycling of scrap types is influenced strongly by the market situation. The variation of prices as seen in Table 8 directs the program depending on the amount of valuable materials. With the growing relevance of bulk recycling output revenues, scrap types with big metal shares should be recycled internally. Higher (lower) acceptance prices, lower (higher) metal prices and bigger (smaller) scrap markets lead to a choice of more (less) low-value scrap types like cellular phones or telephones and of less (more) scrap types with valuable parts like personal computers. Scrap types with low material value, for instance telephone parts, are recycled externally in order to reduce the amount of plastics in bulk recycling. As a result more unit capacity for the more valuable inputs like parts of personal computers is available.

The reduced costs concerning the internally recycled masses y_i^{In} give relevant hints to decide in which cases one should think about external recycling of scrap types. Those parts that contain very high ($i = 20; 22$) shares of valuable metals have the highest reduced costs. As a conclusion, it is difficult to obtain any benefit from trying to improve the purity of nearly pure scrap types by mixing it with other scrap in the feed of the bulk recycling plant.

As a result of the optimization calculations for the present system, disassembly is only advisable if hazardous or very precious parts are removed. Disassembly can not compete with bulk recycling concerning the recovery of valuable materials due to the high variable costs. However, the long-term allocation between manual activities and unit operations may be completely different because of the high impact of fixed cost in bulk recycling that have not to be taken into account in this short term planning calculation.

The data set of this case study refers to a typical, but small range of electronic devices. Classifying the considered products into several groups and taking into account the outcomes of the scenario analyses, one is enabled to generalize a recycling characterization for other products.

- Some devices like “TV-sets” ($i = 1$) or “cellular phones” ($i = 6$) contain harmful substances that require mandatory disassembly activities. The reuse possibilities and the material values are low. This leads to a decreasing share in the short term recovery program when acceptance prices fall, which is shown in the scenarios “Acceptance Prices Zero” and “Acceptance Prices Half” as seen in Table 8. Thus the only reason to treat this group is the acceptance fee revenue. Other devices in that group may be refrigerators or monitors.
- “Video recorders” ($i = 2$) and “telephones” ($i = 4$) can be shredded directly since they do not contain any harmful substances. The motive to treat this group is mainly the acceptance fee, but the material value represents a small contribution as well. Hi-fi devices and some domestic appliances may be characterized in the same way.
- “Personal computers” ($i = 3$) and “telecommunication switchboards” ($i = 5$) as well as lot of other investment goods contain reuse parts and valuable materials. The recovery of these represents a considerable economic value. The

relevance of treating this group increases with sinking acceptance prices as well as growing material and parts prices and market extent.

It becomes obvious that the acceptance fees have the highest impact on the success of the company. The share of the acceptance fees in the overall marginal income is nearly 106% in the basic scenario as seen in Table 4. Hence the "disassembly" and "bulk recycling" steps of the optimal recovery program have a negative value. Furthermore, the objective function value of the basic strategy "Acceptance Fees" touches almost the level of the basic scenario (88%). The scenarios with lower or no acceptance prices reduce the objective value of the basic scenario to 53% and 25% respectively. In comparison, the scenario with lower prices for copper and aluminium leads only to a reduced objective value of about 16%. Basically, it would be very profitable at the moment to try to take more scrap types with high acceptance fees.

Considering these results and ongoing trends in the legal and economic environment such as the forthcoming European directive concerning Waste on Electrical and Electronic Equipment (European Commission, 2000), one can also derive recommendations for strategic planning. Since recycling business depends on two markets that may contribute to success, two strategic positions determining a market focus seem to be promising. Both of them may derive benefit by long-term cooperation with producers of equipment in order to avoid deviations in supply. An important aspect of both strategies is to assure the delivery of the necessary input of discarded products (Guide and van Wassenhove, 2001).

Concentrating on the acceptance fee revenues, one should secure the delivery of scrap through supplier contracts. An important change concerning future scrap markets is the extended producer responsibility in the electronics industry, which will lead to charging producers for collecting, sorting and recovery of WEEE from private households. Producers have to provide systems to assure the treatment of collected WEEE. As a result, producers or consortia of producers will obtain greater importance as customers of the recycling industry. In order to meet fixed recycling quotas, e.g. through the isolation of pure plastic fractions, the high-end disassembly of "low-valued" scrap will obtain an increasing status. The main challenge for the recycling company is to enter these systems by signing long-term-contracts. This will lead to economy-of-scale benefits due to greater quantities of WEEE from private households (TV-sets, video recorders, personal computers) and long-term fixed acceptance fee revenues. The other side of this strategy is characterized by marketing incentives for the incurring recycling output.

A different strategic position focuses on the output side of recycling. Variations in the metal markets can not be avoided by fixed-price contracts because of the small market relevance of recycling enterprises in comparison to smelting plants. However, the delivery of reusable parts for spare parts management and equivalent-to-new-parts for the use in production processes are a practical way to secure output proceeds, especially concerning investment goods. The scrap supply may be accomplished by financial incentives or by cooperation with producers. In the latter case, recycling companies should be integrated into the producers supply chain, e.g. as a supplier of spare parts. In order to support this cooperation, producers and recycling enterprises should use joint information and planning tools.

6 Conclusions and recommendations for future research

In this paper, an integrated short term recovery planning problem for electronic scrap has been analysed and formulated as a mixed-integer linear programming model, based on the linear activity analysis. The purpose of this daily task is to obtain an optimal choice of recovered products for disassembly and bulk recycling as well as an optimal allocation of disassembly activities. Compared with the models found in the literature, the presented model has some specific characteristics, especially the description of material flows throughout the bulk recycling units, the consideration of the choice of taken products in combination with capacity constraints and the explicit modelling of interactions between disassembly and bulk recycling. Though the planning tool refers to electronic scrap recovery, it can also be applied to other recovery planning problems with bulk recycling processes.

The integer constraints in the present model formulation are not essential, but justified by the precise depiction of the reality and the short solution time for the given complexity. The presented model provides practicable decision support concerning the amount and types of discarded products as well as disassembly and bulk recycling activities for recovery facilities. Compared with basic short term recovery programs used in the examined recycling enterprise, a benefit of at least 10% can be obtained. When we model a multistage electronic scrap recovery facility including disassembly and bulk recycling, our results show that disassembly is only advisable if hazardous or very precious parts are removed. Therefore, rough data are sufficient for a model of scrap recycling if there is no functional value in the recycled parts.

Useful insights concerning operation of the recycling system can be given by the analysis of reduced costs, dual prices and scenarios. On the one hand, the share of valuable scrap types treated in the bulk recycling unit should grow with sinking acceptance prices and unit capacities as well as with increasing material prices. On the other hand, using bulk recycling for nearly pure scrap types seems to be questionable.

The data set of this case study consists of a typical range of products that represent major groups of electronic scrap. This classification is not based on standardized collection groups because these groups depend on the collector at present. In the future, municipal collection systems with specific scrap categories are expected to be realized to comply with regulations like the forthcoming directive on WEEE (European Commission, 2000). The scrap market itself and therefore the decisions of recovery enterprises will be affected by this classification. Hence the adaptation of these scrap categories in the planning model will be necessary.

Long-term cooperation between producers of equipment and recycling enterprises will attain an increasing relevance due to the expected benefits for both sides. Two basic strategic positions for recycling enterprises have been presented: on the one hand concentrating on acceptance fee revenues within the scope of implementing take back and recycling-systems and on the other hand intensifying efforts to recover reusable parts which will find a ready market through producers and suppliers in the traditional supply chain. Especially the last strategy will lead to closed loop supply chains. Future research is necessary to balance demand and supply of the reusable parts and to coordinate producers or suppliers demand planning and the recovery program planning of the recycling enterprise.

Since the presented model formulation is limited to one planning period, an enhancement to regard dynamic factors may be promising in order to take inventory decisions into account. Impurities affect the compositions and the prices of externally marketed material fractions. Though the assumption that only target materials are separated by the units is justified by the fact that the separated fractions are nearly pure, the consideration of these impurities in the separated fractions may be beneficial. In addition, the assessment of the derived hints for process improvements should be analysed in the context of a long-term planning period.

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