Management of Material Flows in Closed-Loop Supply Chains

Decision Support System for Electronic Scrap Recycling Companies

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Abstract

Due to the latest developments in European environmental legislation, producers will be responsible for collecting, sorting and recycling of discarded products at the end of their service life. They will be charged by the total recycling costs which leads to higher lifecycle costs of their products. Therefore, a close cooperation with recycling companies and their integration in producers supply chains, e.g. as suppliers of spare parts and secondary raw materials, will be necessary and leads to so called "closed-loop supply chains". A cost-efficient management of material flows between suppliers, producers, customers and recycling companies requires an integrated information management as well as advanced planning systems. The paper focuses on the design and implementation of a decision support system for electronic scrap recycling companies in closed-loop supply chains. It has been implemented in a major German electronic scrap recycling company and validated by real data.

1. Introduction

High innovation rates and lasting market expansion in electronics industry have led to a steadily increasing number of manufactured electrical and electronic equipment during the last few decades. Due to failures and to rapidly changing technology, it evolves into waste after a few years. 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, and it is forecasted that the amount of electronic scrap will increase 3 – 5 % per year (European Commission 2000). These discarded products should be recovered due to economic and ecological reasons.

Producers of Electrical and Electronic Equipment (EEE) will have the following obligations:

- Financing the collection, treatment, and environmentally sound recovery of WEEE
- Setting up systems for treatment and recovery of WEEE
- Meeting recycling quotas for each device category
- Providing information for treatment facilities about the composition of their products to electronic scrap recycling companies

In order to adopt these obligations economically, producers have to decide strategically on the following questions:

- How to remanufacture used products by refurbishing/upgrading processes
- How to reuse parts and complete modules as substitutes for originally manufactured equipment and spare parts
- How to recycle the non-reusable parts and modules, which consist of a mix of materials, such as heavy metals, ferrous and non-ferrous metals, plastics, wood, glass, etc.

The recovery of electronic scrap is a multistage process. Logistic issues concern collection, grading, transport and allocation of discarded products, reusable parts and modules, as well as of recovered materials. Disassembly in order to remove hazardous substances and reusable parts is often followed by bulk recycling to gain separated material fractions that are sent to metal

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recycling facilities or other recycling specialists (cf. Figure 1).

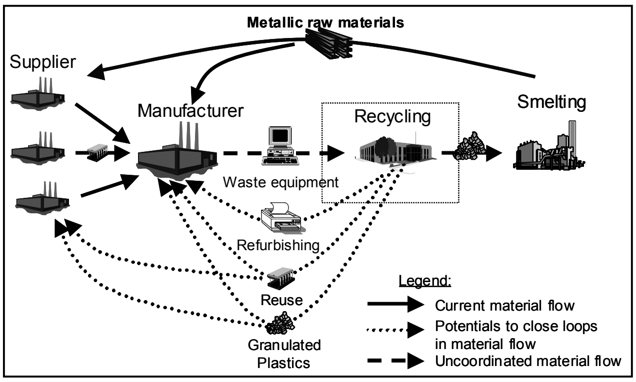


Figure 1. Material flows in closed-loop supply chains [1]

The paper focuses on the design and implementation of a decision support system for electronic scrap recycling companies in closed-loop supply chains. The decision support system consists of a sophisticated techno-economic model of the disassembly and bulk recycling processes. Therefore, a detailed technical analysis of the bulk recycling process is necessary. Based on cooperation between producers and recycling companies, information on product structures, reusable parts and modules, hazardous substances and recoverable materials will be available for all companies participating in the closed loop supply chain. Taking into account detailed information concerning the supply with scrapped products and the demand of reusable parts and modules, recycling companies will be enabled to use the information for the determination of an economically efficient recycling schedule. Due to a low capacity utilization of recycling plants, nowadays, most recycling companies actively require electronic scrap from anonymous markets. Therefore, only a small percentage of the available recycling capacity will be used by scrapped products resulting from long-term contracts with producers or suppliers. Due to high uncertainties in the amount and quality of available WEEE, the long term recycling schedule has to be supplemented by a detailed short term schedule at regular intervals. The recycling company regularly has to decide on the daily recycling schedule of scrapped products, the levels of disassembly, the allocation of reusable parts and modules to producers or suppliers and the further recycling process of recoverable materials.

2. General Problem Description

Decision problems of electronic scrap recycling companies refer to the tasks supply, disassembly and bulk recycling. Other stages like transport, smelting or marketing of reusable parts often are excluded since they are accomplished by external services. The material flow throughout a typical recycling company is shown in Figure 2. Long-term contracts for incurring scrap collected by public and industrial collectors contribute less than 10% of the recovered mass. Thus, the active acquisition of electronic scrap is a necessary task. Since the input storage of recycling enterprises often is a separated profit centre that may acquire and sell scrap on the market, the delivery of scrap to the recovery works is assessed with a given transfer price that is dependent on the scrap market. Therefore, the recovery works manager faces the "acquisition" decision which products from the storage have to be taken and recovered in the considered daily planning period as seen at point (*) in Figure 2. The first recovery step "disassembly" is composed of manual or partly-automated processes. Mechanical assistance concerns only transport and lifting tasks. Planning the disassembly step, the recovery works manager has to determine the disassembly level at point (**) in Figure 2, 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 operations are mandatory in order to eliminate hazardous substances.

The second step "bulk recycling" is designed to gain precious fractions such as ferrous and non-ferrous metals from mixed electronic scrap, using unit operations like crushing and separation steps. When planning the bulk recycling step, the recovery works manager has to decide which scrap types are to be recycled internally or are to be marketed externally as seen at point (***) in Figure 2.

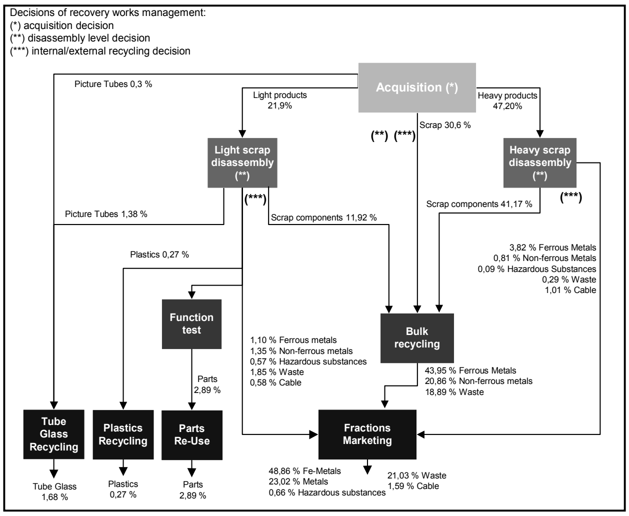


Figure 2. Material flow of a typical electronic scrap recycler [2]

This is a complex problem due to the fact that bottlenecks can appear in different units. Since the long-term capacity of each unit is calculated on the basis of an expected specific input composition, variations from this 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. Thus, a recycling enterprise can benefit from the blended composition of the bulk recycling input adjusted by the feed of different scrap types. The output of the recycling centre is taken to smelting plants (70% metals), chemical industry (>1% plastics), glass industry (>2% tube glass), part traders (3% reusable parts) and waste disposal (22% waste and hazardous substances). A detailed analysis of the disassembly and bulk recycling operations and the relevant planning data is given in chapter 4.

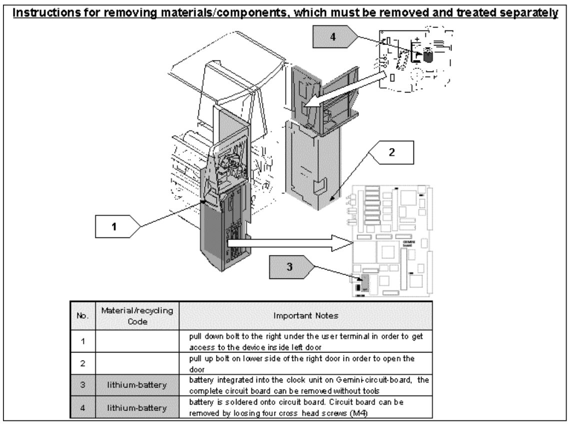
3. Literature Review

General reviews of planning problems in a product life cycle are given by [3], [4] and [5]. According to the chosen system boundary the following literature review is restricted to disassembly levelling and bulk recycling planning problems that occur in the product recovery stage. Penev and de Ron [6] describe a static cost comparison tool to determine an economic disassembly level and sequence of a single product. Krikke et al. [7] use a method on a tactical management level 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. Spengler et al. [8] 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. Lambert [9] develops a linear optimisation model for an optimal disassembly of complex products. A detailed review of disassembly sequencing approaches is given in [10]. Sodhi and Reimers [11] 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 operations research models for the economic assessment of bulk recycling operations. Lund et al. [12] use linear programming in order to analyse the design and the operation of municipal waste material-recovery-facilities. Sodhi et al. [13] present a dynamic programming model for the determination of the operations sequence for float-sink materials separation by density. Stuart and Lu [14], [15] offer decision support for processing and reprocessing options in electronic scrap bulk recycling centres. Rudolph [16] provides an integrated model for disassembly and bulk recycling planning without giving a practicable bulk recycling description. The recent publications that deal with the application of operations research in recovery planning focus on disassembly and bulk recycling aspects. An integrated model of the acquisition, disassembly and bulk recycling problem is not available until now. Therefore, the development of an integrated model for decision support in the three mentioned questions seems to be necessary.

4. Planning Data and Operations Analysis

The application of sophisticated recovery planning models is often obstructed by the lack of data. In this paper, we assume that information is provided by a database that contains product and operations data. Since the composition of discarded electronic products show significant variations, the availability of recycling-relevant information for all partners in the closed-loop supply chain is a complex problem that should be solved by production enterprises and their suppliers, referring to the forthcoming directive of the EU on Waste on Electric and Electronic Equipment [17].



Instructions for removing materials/components, which must be removed and treated separately

No.	Material/recycling Code	Important Notes
1		pull down bolt to the right under the user terminal in order to get access to the device inside left door
2		pull up bolt on lower side of the right door in order to open the door
3	lithium-battery	battery integrated into the clock unit on Gemini-circuit-board, the complete circuit board can be removed without tools
4	lithium-battery	battery is soldered onto circuit board. Circuit board can be removed by loosing four cross head screws (M4)

Figure 3. Sheet of a recycling passport [15]

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 [18] as shown in Figure 3. It can be used to plan recovery operations and to estimate disassembly times. Nowadays, recycling passports exist only as printed versions for selected products, but a possible scenario for the future is the web-based provision of the information from the manufactures to the recycling companies on two different levels. First, the generated recycling passports will be made available in the internet. Thereby it is important to use a format that can not be changed or modified and to permit search-processes to find the recycling passport of a specific device. This level allows the manufacturers to meet the legally required information duties. The second level of information provision goes further and tends to support decision and planning processes within cooperation between manufacturers and recycling companies. This permits the realization of high grade recycling processes like reuse and refurbishing strategies. Thus, it is necessary that a high level of security can be guaranteed since now detailed information will be provided. With support of the internet technology the recycling companies will be enabled to access relevant information by the use of retrieval functions. The recycling company`s browser connects to a web-server and a request form can be filled in. The web-server will then access the recycling data base of the manufacturer by using predefined logics. The requested information will be extracted from this data base and provided to the recycling company by the internet. An example of the disassembly operations structure is depicted in Figure 4.

A personal computer *(i=3)* chosen from the discarded products range *(i=1…6)* must be opened and the harmful part battery *(i=7)* has to be removed *(disassembly activity j=3).*

The resulting by-products are ferrous metals *(i=29)* from casings, which can be recycled in the steel industry and the personal computer without battery *(i=12)*. The disassembly option to gain spare parts *(disassembly activity j=4)* can be exercised if there is a market for the resulting parts CD-drive *(i=11)*, disk-drive *(i=14)*, printed circuit board *(i=22)* and personal computer without drives and boards *(i=13)*. 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 in order to be treated by recycling specialists. Alternatively, the disassembled parts can be recycled internally in a bulk recycling facility where they are mixed with other products and parts. The flowsheet of the bulk recycling step is shown in Figure 5 (a). Figure 5 (b) will be explained in chapter 5.

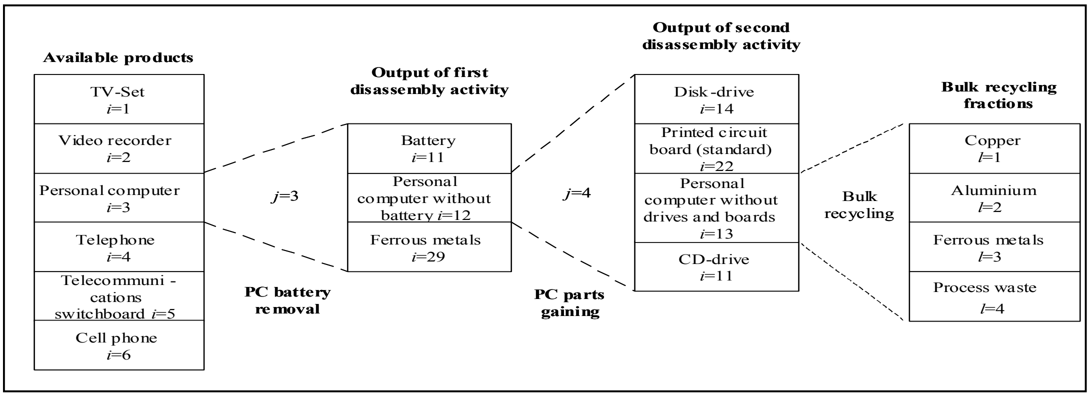


Figure 4. Example of the disassembly operations of a personal computer

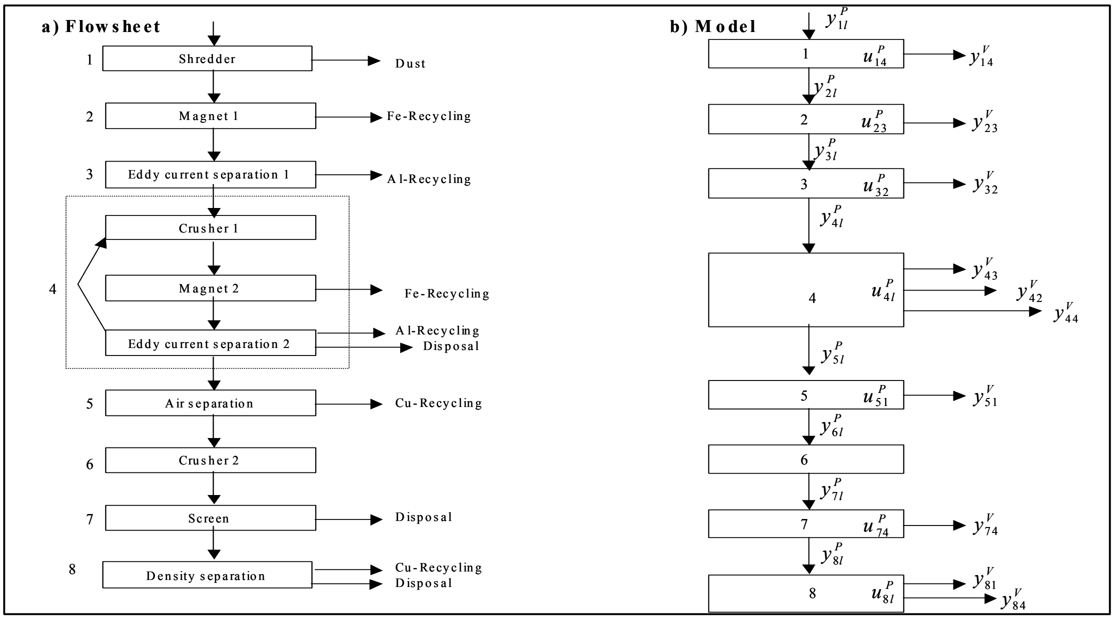


Figure 5. Flowsheet (a) and model (b) of the bulk recycling process

The bulk recycling process consists of size-reduction and separation units. The size-reduction in order to isolate and concentrate the valuable materials is accomplished by several totally automated shredding and crushing units and has decisive importance for the success of the separation. Ferrous metals represent a huge 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 gained by electro- and density-separation processes and classifying stages. 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*. Relevant cost drivers in bulk recycling are maintenance, energy consumption and labour [19].

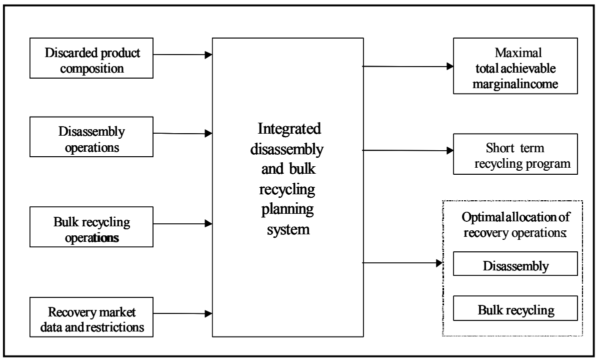


Figure 6. Structure of the considered daily planning problem

The structure of the considered daily planning problem of the recovery works manager is shown in Figure 6. Taking into account the available scrapped products, the feasible disassembly and bulk recycling operations and costs, the market prices of reusable parts and secondary materials as well as capacity and market constraints, the recovery works manager has to determine an optimal short term recycling program and an optimal allocation of disassembly and bulk recycling operations.

5. Formulation of a MILP-Model

The model formulation is based on the linear activity analysis [20] that permits a very simple and appropriate model formulation of recovery planning problems [21], [22]. The modelling approach of the disassembly sector corresponds to the optimisation model that is given by Spengler et al. [8]. The integration of the bulk recycling planning problem and the development of an integrated disassembly and recycling model for short term planning problems is described in [2] and [23]. The activity analysis based model description is shown in Figure 7.

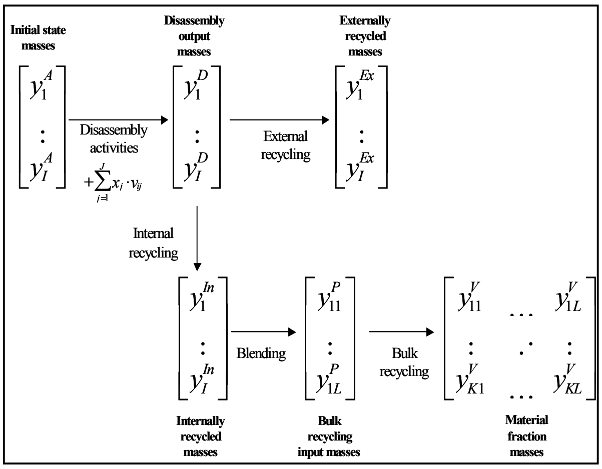


Figure 7. Activity analysis based model description

It is assumed that a number of different discarded products, parts and materials i=*1,...,I* are available in the storage at a given negative or positive transfer price. These *I* scrap types can be disassembled by the application of *j=1,...,J* different disassembly activities and can be processed by a bulk recycling plant using *k=1,...,K* process units. As seen in figure 5b all bulk recycling input masses (*l=1...L*) are allocated to the shredder (*k=1*). Therefore they can be modelled by the vector $(y_{11}^P \ldots y_{1L}^P)^T$ given in Figure 7. The following indices, parameters, coefficients, limits and variables are used:

Indices

i:	Index of scrap types: products, parts, materials $i \in \{1,...,I\}$
j:	Index of disassembly activity $j \in \{1,...,J\}$
k:	Index of unit operation $k \in \{1,...,K\}$
l:	Index of material $l \in \{1,...,L\}$

Parameters and Coefficients

a_{il}:	Composition factor that disposes scrap type *i* composition to material component *l* [kg/kg] $(0 \le a_{il} \le 1)$
c_k^P	Bulk recycling cost factor for unit *k* [€/kg]
c^z	Disassembly labour cost factor [€/h]

e_i^{Ex}	Cost (-) or price (+) factor for scrap type *i* to external recycling [€/kg]
e_i^A	Acceptance cost (-) or price (+) factor for scrap type *i* [€/kg]
e_{kl}^V	Recycling material sale cost (-) or price (+) factor of isolated material fraction *l* separated by separation unit *k* [€/kg]
m_i	Mass of one piece of scrap type *i* [kg] $(m_i > 0)$
t_j^z	Disassembly time needed for one application of activity *j* [h/act]
u_{kl}^P	Transformation coefficient for unit operation *k* and material *l* [kg/kg] $(0 \le u_{kl}^P \le 1)$
v_{ij}	Disassembly activity coefficient for the input (-) or output (+) masses of scrap type *i* caused by one application of activity *j* [kg/act]

Limits

$T^{\max}$	Limit for disassembly labour time [h]
$y_i^{A,\max}$	Limit for masses of scrap type *i* that is available to be taken [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 separation unit *k* [kg]

Variables

x_j	Integer Decision variable for the number of applications of disassembly activity *j*
y_i^A	Decision Variable for the mass of scrap type *i* to be taken for recycling [kg]
y_i^D	Variable for the mass of scrap type *i* after disassembly [kg]
y_i^{Ex}	Variable for the mass of scrap type *i* to external recycling [kg]
y_i^{In}	Decision Variable for the mass of scrap type *i* to internal recycling [kg]
y_{kl}^P	Variable for the mass of material component *l* in the mixture that is treated in separation unit *k* [kg]
y_{kl}^V	Variable for the mass of isolated material fraction *l* separated by separation unit *k* [kg]

The objective function (1) maximises the total achievable marginal income subject to mass balance equations and capacity restrictions. The three short term decision questions are depicted by the decision variables “mass of scrap type *i* to be taken (y_i^A), number of applications of disassembly activity *j* (x_j) and mass of scrap type *i* directed to internal recycling (y_i^{In})”. The values of the other variables are determined by the constraints. The total achievable marginal income results from acceptance revenues/costs, disassembly output revenues/costs, bulk recycling output revenues/costs, variable disassembly costs and variable process costs. Accepted and externally marketed products, parts or materials are accounted with a given price. Acceptance prices e_i^A for delivered material as well as disassembly output sales prices e_i^{Ex} and bulk recycling output sales prices e_{kl}^V refer to the transferred masses[1]. Operations are assessed with a factor representing variable costs. The disassembly cost factor c^z represents labour. The bulk recycling cost factors c_k^P for the unit operations *k* include maintenance, energy, labour and maintenance costs, if not considered as overheads.

$$\underset{\substack{y_1^A,\dots,y_I^A;\\ x_1,\dots,x_J;\\ y_1^{In};\dots;y_I^{In}}}{MAX} \quad \sum_{i=1}^{I}(y_i^A \cdot e_i^A + y_i^{Ex} \cdot e_i^{Ex}) + \sum_{k=1}^{K}\sum_{l=1}^{L} y_{kl}^V \cdot e_{kl}^V$$

$$-\sum_{j=1}^{J} x_j \cdot t_j^Z \cdot c^Z - \sum_{k=1}^{K} c_k^P \cdot \left(\sum_{l=1}^{L} y_{kl}^P \right) \qquad (1)$$

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[1] In reality the fraction may be polluted. That would lead to a price that depends on the composition of these fractions and thus to a price as a function of the decision variables. In the model, these non-linear effects are neglected and constant prices are assumed.

The chosen products, parts and materials can be depicted by an initial state vector $y^A = \lfloor y_1^A \quad \dots \quad y_I^A \rfloor$ that contains the masses y_i^A of every taken scrap type. For every scrap type *i* the material flow throughout the recovery enterprise can be described. Disassembly operations are modelled with linear input-output coefficients v_{ij} that represent the input and output masses of every scrap type in one disassembly activity and the number of applications of the disassembly of this activity x_j (2). The coefficients v_{ij} are given by the input-output-relationships of the disassembly activities.

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

The obtained disassembly output y_i^D has to be directed either to external or to internal treatment (3).

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

The removal of hazardous substances in disassembly is mandatory before the treatment in bulk recycling. In this model, this can be achieved by the setting $y_i^{In} = 0$ initiating external treatment if a scrap type *i* that contains hazardous substances is not disassembled (4).

$$y_i^{In} \begin{cases} = 0 & \text{if i contains hazardous substances} \\ \geq 0 & \text{else} \end{cases}$$
$$i = 1,\dots,I \qquad (4)$$

It is assumed that disassembly output to internal treatment y_i^{In} is completely processed in the bulk recycling units. The input of the bulk recycling process is blended by a mixture of disassembly output parts and/or discarded products in the feed of the process. In the first unit, the input masses y_{kl}^P result from the composition of y_i^{In}. At the moment of destruction in the first unit shredder, the composition coefficients a_{il} dispose the scrap types *i* to a material component *l*. The input masses of the other units can be calculated by the following mass balance equations for each unit (5) (see Figure 5b).

$$y_{kl}^P = \begin{cases} \sum_{i=1}^{I} a_{il} \cdot y_i^{In} & \text{if } k = 1 \\ y_{(k-1)l}^P - y_{(k-1)l}^V & \text{if } k = 2,\dots,K \end{cases}$$
$$l = 1,\dots,L \qquad (5)$$

The transformations in the separation units throughout the flowsheet as seen in Figure 5a are described by linear coefficients u_{kl}^P for the input-output-transformations in separation step *k* as shown in Figure 5b. The coefficient u_{kl}^P represents the share of the available material *l* in the input of the unit *k* that is directed in material fraction *l* of this unit (6). It is determined by empirical data taken from the process diary of the enterprise referred to. The effect of adjustments of the technical shredding and separation parameters in order to improve the process stability is neglected because the range of consequences for the separation coefficients is very small. Due to the availability of empirical data the units Crusher 1, Magnet 2 and Eddy current separator 1 are depicted by just one unit *(k=4)* in the model.

$$y_{kl}^V = u_{kl}^P \cdot y_{kl}^P \qquad k = 1,\dots,K \qquad l = 1,\dots,L \qquad (6)$$

The values of u_{kl}^P as well as price factors e_{kl}^V for the separated fractions are have to be determined empirically. A mass-ratio of 0,75 from the component ferrous metals *(l=3)* that has gone into the unit operation "Magnet 1" *(k=2)* can be found in the separated ferrous metals fraction of the unit. This ratio is based on the share of ferrous metals that has been liberated in the previous size-reduction step. In this unit, only one fraction is gained, but in other units more fractions may be separated as shown in Figure 5.

Capacity restrictions represent input supply capacity (7) as well as output sales capacity (8), (9). Bottlenecks in bulk recycling can appear in every unit due to variations in feed composition. Thus, capacity constraints must be depicted by limits for every unit, too (10). The disassembly capacity restriction refers to a maximum of labour time of the available workers (11).

$$y_i^A \leq y_i^{A,\max} \qquad i = 1,\dots,I \qquad (7)$$

$$y_i^{Ex} \leq y_i^{Ex,Max} \qquad i = 1,\dots,I \qquad (8)$$

$$y_{kl}^V \leq y_{kl}^{V,\max} \qquad k = 1,\dots,K \qquad l = 1,\dots,L \qquad (9)$$

$$\sum_{l=1}^{L} y_{kl}^P \leq y_k^{P,\max} \qquad k = 1,\dots,K \qquad (10)$$

$$\sum_{j=1}^{J} x_j \cdot t_j^Z \leq T^{\max} \qquad (11)$$

Disassembly activities as well as the number of discarded products and parts are modelled as integer variables (12)(13), since the dismantling of a discarded product can not be split.

$$\frac{y_i^A}{m_i}; \frac{y_i^{Ex}}{m_i} \in IN_0 \qquad i = 1,\dots,I \qquad (12)$$

$$x_j \in IN_0 \qquad j = 1,\dots,J \qquad (13)$$

With the given product range that is shown in Figure 4, the MILP consists of 70 Integer Variables, 226 Non-

Integer Variables and 328 Constraints. It can be solved by the application of various kinds of solution procedures for combinatorial optimisation problems. Although mixed-integer linear problems often are NP-hard and lead to exponentially growing solution time due to the complexity of the calculated problem, standard optimisation software packages using Branch-and-Bound Techniques provide a quick solution in case of the given problem complexity.

Therefore, the presented decision support system has been implemented on a personal computer (Pentium III / 600 MHz) referring to EXCEL-spreadsheets that contain the data sets and using commercial solver LINGO optimisation calculations. Using these standard software tools, one takes advantage of their public availability and the absence of additional implementation costs [23].

6. Results and Interpretation

The presented decision support system has been applied to a typical planning situation of electronic scrap recycling companies. A detailed description of the planning data, scenarios and sensitivity analysis is given in [23]. In the following, only a few aspects of the application are mentioned (see Figure 4).

All available "TV-sets" (i=1) are taken and disassembly (j=1) is enforced. The subsequent parts like "picture tubes" (i=10), "housing parts" (i=16) and "cheap circuit boards" (i=21) are marketed externally. A share of the obtained "mixed 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 accepted altogether, are sent to bulk recycling directly. Just a share of available "personal computers" (i=3) is taken. The number is limited by the market restriction for "CD-drives" (i=11). Mandatory disassembly (j=3) is done and the "battery" (i=7) has to be sent to a recycling specialist. The resulting parts of the operation spare part gaining (j=4) – "disk-drives" (i=14), "CD-drives" (i=11) and "standard circuit boards" (i=22) - are marketed externally. "Telephones" (i=4) are accepted in toto and sent to bulk recycling directly (j=5). All "Telecommunication switchboards" (i=5) are taken and disassembled (j=6,7) to gain "precious circuit boards" (i=20) for sale. The "accumulators" (i=9) of taken "cell phones" (i=6) need to be removed (j=9) and treated by specialists. Further disassembly (j=10) of cell phones is not advisable.

The objective function represents a value of about 3000 € per daily planning period. The main contribution to the objective value results from acceptance fee revenues. The disassembly time capacity restriction as well as bulk recycling capacity restrictions are reached. As a result, the feed composition of the bulk recycling plant is adjusted consciously through the choice of taken products and marketed parts. A detailed sensitivity analysis has been carried out [23] and as a result the acceptance prices on the one hand and the metal prices on the other hand have been identified as most important. Furthermore, the result of the presented case study depend on the availability of necessary information concerning the product structure, hazardous substances and reusable parts. The choice of a "representative" product can only be recommended, if not real product data are available.

In order to point out the benefits of the optimisation model, the calculated result should be compared with basic concepts to determine short term recycling programs that already have been used in the past. 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 contain no hazardous substances and that have a negative value are recycled internally. If disassembly and equipment capacity constraints are not reached this way, additionally the products with the highest acceptance prices are treated, in order to maximize the total achievable marginal income. This concept leads to an objective value of about 2400 € per daily planning period. 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 contain no hazardous substances and that have a negative value are recycled internally. This concept is assessed with an objective value of about 2600 €. The success of this concept is impaired by lower bulk recycling output revenues which is 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 optimisation calculation concerning other datasets. Basically, a benefit of at least 10% can be obtained using the optimisation calculation.

7. Conclusions

In this paper, an integrated short term recycling planning problem for electronic scrap has been analysed and formulated as mixed-integer linear programming model, based on the linear activity analysis. The purpose of this daily operational management task is to get an optimal choice of recovered products for disassembly and bulk recycling as well as an optimal allocation of disassembly operations.

Compared with the models found in the literature, the presented model has important specific characteristics: The activity analysis based modelling of material flows throughout the disassembly and muli-stage bulk recycling units, the integration of the acquisition, disassembly and bulk recycling planning problem into one mixed-integer linear programming model and the online-availability of relevant product data via recycling passports. The material with the help of the decision support system, electronic scrap recyclers will be enabled to apply advanced planning systems, which have been implemented in various industrial branches during the last years.. 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 error of the objective value caused by an LP-relaxation of the model is less the 1 % in the considered case study. The possible use of standard sensitivity analysis for linear programs is a strong argument for a relaxation of the integer variables. 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 recycling 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 centred on disassembly and bulk recycling, it becomes obvious that disassembly is only advisable if hazardous or very precious parts are removed. Disassembly in order to gain materials leads to high variable costs. Therefore, rough data are sufficient for a model of scrap recycling if there is no functional value in the recycled parts.

In the future, municipal collection systems with specific scrap categories are expected to be realised in order to comply with regulations like the forthcoming directive on WEEE [17]. The offers on the scrap market and thus the decisions of recovery enterprises will be ruled by this classification. Thus, 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 of the traditional supply chain. Especially the last strategy will lead to closed loop supply chains. Future research is necessary in order to balance demand and supply of the reusable parts and in order to coordinate producers or suppliers demand planning and the recycling program planning of the recycling enterprises.

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