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Models for recycling electronics end-of-life products*

Modelle zum Recycling von Altprodukten aus dem Elektronikbereich

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Abstract. Increasing environmental concerns about the disposal of mass produced products have resulted in efforts to take back end-of-life consumer products. Legislation aimed at forcing manufacturers to take back electronics products at the end of their useful lives has either been adopted or is impending in many countries. This, along with shrinking landfill capacity and the reluctance of communities to open new waste sinks underscores the importance of developing methods and models for the management of end-of-life materials and products.

This paper reports a study of the reverse channels for recycling of electronics products. The economics of electronics recycling are modeled from the viewpoints of the generators, recyclers, and material processors separately. A variety of mathematical programming models, representative of the many ways in which the recycling industry currently operates, have been proposed along with numerical illustrations. Models integrating disassembly and material recovery decisions are also presented. These models can be used by recyclers and processors for optimizing recycling operations and thus contribute towards the economic sustainability of electronics recycling.

Zusammenfassung. Zunehmende Berücksichtigung von Umweltgesichtspunkten bei der Abfallbehandlung hat zu einer Verstärkung der Bedeutung der Rücknahme von Altprodukten nach Ablauf ihrer Gebrauchsphase geführt. So wird in vielen Ländern durch gesetzgeberische Maßnahmen ein immer größerer Druck auf die Hersteller von Elektro- und Elektronikgeräten ausgeübt, ihre Erzeugnisse nach Ende ihrer Nutzungsdauer wieder zurück zu nehmen. Zugleich nehmen vorhandene Deponiekapazitäten zur Beseitigung solcher Produkte ab und es verringert

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sich die Neigung seitens der Gebietskörperschaften, neue Deponien zu eröffnen. Damit nimmt die Bedeutung der Entwicklung von Methoden und Modellen zum Management der Verwertung von Altprodukten in diesem Bereich immer mehr zu.

Der vorliegende Beitrag befaßt ich mit der Untersuchung entsorgungslogistischer Aktivitäten im Rahmen des Recyclings von Elektronikschrott. Dabei werden die Planungsprobleme für ein ökonomisch vorteilhaftes Recycling getrennt aus der Sicht der Erzeuger, Entsorger und Verwerter der Altprodukte modelliert. Zur Darstellung der Entscheidungsprobleme im Recyclingbereich wird eine Reihe von Modellen der Mathematischen Optimierung vorgestellt und mit numerischen Beispielen untermalt. Hierbei werden auch Modelle zur Integration von Demontage- und Verwertungsplanung präsentiert. Solche Modelle können ebenso von Entsorgern wie von Verwertern zur Optimierung ihrer Recyclingaktivitäten genutzt werden.

Key words: Electronics recycling – End-of-life models – Material recovery – Reverse logistics

Schlüsselwörter: Elektronikschrott – Altprodukt-Recycling – Recyclingmodelle – Entsorgungslogistik

Introduction

Producers of electronics goods are increasingly facing pressure from users and by government mandates to recycle end-of-life products. One recent example of a government mandate to force electronics recycling is in Massachusetts, where a ban on CRT disposal in landfills has been enacted in 1998 to reduce the amount of lead contamination in runoff from landfills [1]. The law, which focuses only on banning the landfilling of Cathode Ray Tubes (CRTs), does not specify who has the responsibility for recycling. While this is a ground breaking law in the United States, many European countries have already gone one step further and started focusing on a system of Extended Producer Responsibility (EPR). EPR is “the extension of the responsibility of producers for the environmental impacts of their products to the entire product life cycle”[2]. Consequently producers are now responsible for the take-back, recycling and disposal of their products and packaging, shifting the end-of-life responsibilities to private industries and away form the public sector. EPR originated in the “German Packaging Ordinance of 1991,” which was the first law requiring producer responsibility for taking back and recycling sales packaging ([2] and [3]). After Germany, 27 other European countries have started producer responsibility systems for packaging as of May 1998, and 16 have started programs for batteries [4]. In April of 1998 the first draft of a directive on EPR for end-of-life electronics was being looked at by the EU, while Switzerland, the Netherlands, Italy, and Norway have already adopted some form of EPR for end-of-life electronics [2]. While a number of studies on the collection and disposal of packaging in the form of household recyclables have been reported in the literature ([5], [6] and [7]), recycling end-of-life electronic products and waste differs from household recycling in two significant ways. First, household recyclables are usually composed of single material packaging, whereas

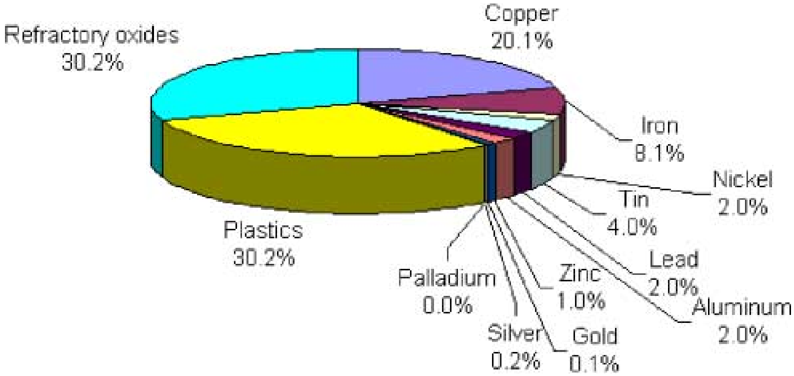

Fig. 1. Typical material composition of electronic scrap

electronic waste is a composite of several materials, some of which are considered hazardous. Second, household recyclables are usually made of low value materials, thus limiting the amount of additional processing that can be done to separate "clean" streams economically. On the other hand electronics waste and end-of-life goods have small quantities of both precious and non-precious metals, as well as easily re-usable components, which sometimes makes it feasible to collect and process small quantities from widely distributed sources.

A certain amount of material recovery is possible from most electronics waste. An optimal level can be determined by balancing the cost involved in material recovery against the revenue that can be gained from the removed components/parts [8], and the metals [9]. For example when parts such as memory chips, CPUs, and hard drives are removed from old 386 and 486 computers, the profit from component recovery is low because of the high cost of manual labor for disassembly and the low value of these components. However, the profit generated from the sale of precious metals concentrated in electronics components can sometimes exceed the cost of collection and processing. Consequently, there may be a financial advantage in collecting and recycling high value electronics. However, some electronics waste contains hazardous materials, such as batteries and CRTs, that require complex and expensive processing for elimination. In such cases there may not be any recoverable profit from recycling, and an additional fee is usually charged for collection.

Electronics scrap is composed of a ratio of approximately 40:30:30 of metal, plastics and refractory oxides respectively. As shown in Figure 1, the typical metal scrap consists of copper (20%), iron (8%), tin (4%), nickel (2%), lead (2%), Zinc (1%), silver (0.2%), gold (0.1%), and palladium (0.005%) [10]. Polyethylene, polypropylene, polyesters, polycarbonates, and phenolformaldehyde are the typical plastic components. Using this material composition, one ton of electronic waste in June 1999 , processed efficiently, could yield upto U.S. $9193.46 if the metals were sold at market prices obtained from (www.recycle.net) and (www.grn.com). Table 1 shows the detailed calculation of this total value, which is diagrammed in Figure 2.

The principal methods for recycling electronics scrap efficiently are disassembly, bulk recycling and smelting. Disassembly involves the removal of components

Table 1. Typical recovery values from 1 T of electronic waste

Material	Percentage	Quantity	Value ($ per lb)	Total Value ($)
Copper	20.000%	400	0.98	392
Iron	8.000%	160	0.045	7.2
Nickel	2.000%	40	2.23	89.2
Tin	4.000%	80	2.35	188
Lead	2.000%	40	0.21	8.4
Aluminum	2.000%	40	0.71	28.4
Zinc	1.000%	20	0.48	9.6
Gold	0.100%	2	3885.57	7771.14
Silver	0.200%	4	34.4	137.6
Palladium	0.005%	0.1	5019.16	501.916
Plastics	30%	600	0.1	60

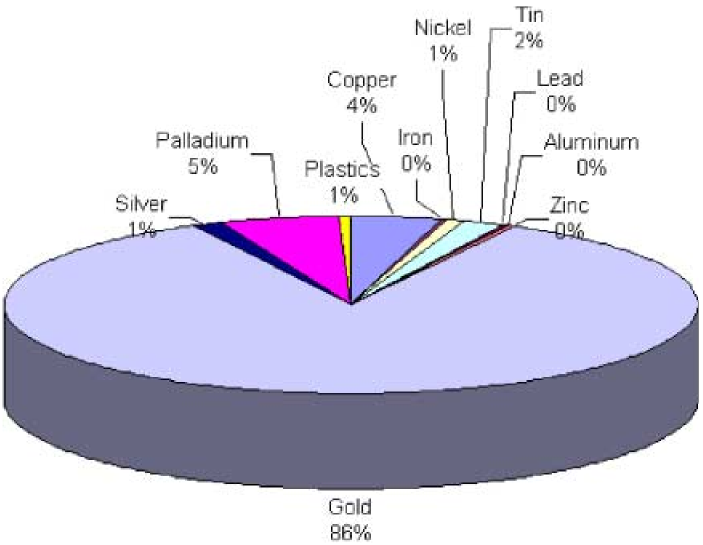

Fig. 2. Revenue breakdown by material from electronic waste

and specific materials from products. A product can be disassembled either completely or partially to remove some targeted materials [11]. Dissembly is a labor intensive task, and the cost of disassembly is proportional to the effort that must be expended to remove components. The optimal disassembly decision balances the cost of disassembling a product against the value of components removed, environmental liabilities, and the residual material value in the product ([11], [12], [13], [14] and [15]). ([16]) gives an overview of disassembly models as well. Environmental consequences of disposal are usually computed by methods such as Life Cycle Analysis [17] or single figure environmental indicators [18]. The residual value of a product which has been disassembled can be computed from the value of the material content and the weight of the item. In most situations bulk recycling is used in conjunction with disassembly – after a certain subset of hazardous and valuable parts are removed, the remaining parts can be efficiently bulk recycled.

Bulk recycling

Bulk recycling is the wholesale processing of recyclables, mostly for material recovery. In most cases some disassembly is done, primarily to remove hazardous materials or valuable parts. The remainder of the product is then shredded into flakes. Separation methods based on physical properties of materials can be used to separate these flakes into four categories: ferrous metals, nonferrous metals, plastics and a composite residual mixture [19]. The first three groups can then be further refined into pure streams for resale. Metals are removed from the composite mixture by magnets and eddy currents. Plastic separation is not as simple. Plastics can be further separated based upon different physical properties such as mass, density, or particle size. Techniques such as sink-float separation, air classification [20], and ultrasonic methods [21] take advantage of physical properties in separating plastics into pure streams. Methods for optimizing sink float separation sequences can be found in [22]. However, high value metals that are layered onto ceramics and plastics cannot be removed by physical separation methods. These are usually found in the composite residual mixture, and material recovery is typically effected by smelting and refining.

Various smelting methods can be used to separate lower value materials such as Copper, Aluminum, Zinc, Lead, Tin, Titanium and high value precious metals such as Gold, Silver, and Platinum group metals [23, 24]. Precious metals are processed using a pyrometallurgical recovery process, where products containing the desired metals are first smelted in a blast furnace with litharge, coke, and pyrites. The precious metals are mostly collected in a lead bullion created by the litharge [24]. Silver can then be recovered from the bullion using a cupelation process, in which the Pb-Ag bullion is melted in a hearth furnace where Pb and other impurities are removed by preferential oxidation effected by air blowing. This results in a semi-pure silver that is cast into anodes, and this is further processed by electrorefining. Gold can be easily recovered using a chlorination process. Platinum group metals however, can be complicated to refine. While a chemical treatment plant can process out the six metals in the platinum group (PT, Rh, Ru, Ir, Os, and Pd), separating these metals requires a significantly greater degree of processing than for gold or silver since all six metals are usually present simultaneously [24].

In this paper the reverse channels for the recycling of electronics products are represented as a network of flows between generators, recyclers and material processors. While this is similar to the approach presented in [25], the models presented do not integrate the entire reverse production system (RPS). Rather, mathematical programming models, representative of the many ways in which the recycling industry currently operates in the U.S., detail the interactions between different components of the network. Since it is at the recyclers' level that most product disposal options are considered, models integrating material recovery and disassembly decisions for electronics recycling by recyclers have been developed.

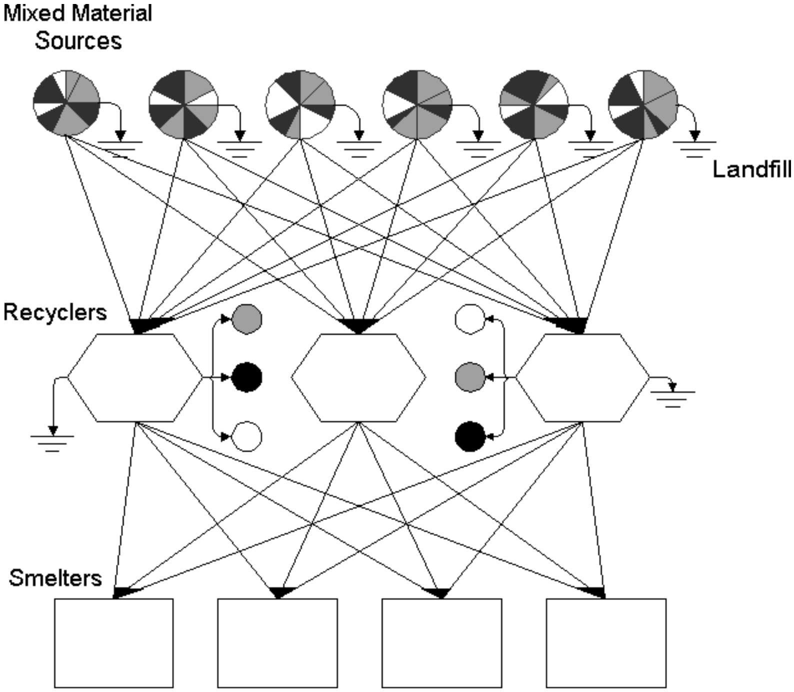

Fig. 3. The flow of a electronics recycling system

The electronics recycling network

A typical electronics recycling network is shown in Figure 3. Recyclers collect electronics waste from sources such as, cities, schools, office buildings, and manufacturers. The recyclers may then add some value by disassembly and processing to separate components and materials as previously discussed. These are then forwarded either to various processers/smelters for further processing into pure metal streams or for plastics recovery, or both. The entire system functions as a complex integrated economic entity, making monolithic representations large and intractable. In the discussion that follows, individual portions of the system have been modeled separately in relation to their specific goals. Although this decomposition may lead to suboptimal solutions for the total system, it facilitates the modeling effort and a detailed representation of the scope of decisions faced by individual components of the recycling system.

Source models

Sources of electronics waste can be organized into three categories. These are: (i) mixed groups of items in one location, (ii) a single item type spread over many locations, and, (iii) and various groups of items spread over many locations [26]. Examples of the first category include individual consumers, universities, offices, collection centers that serve individual consumers etc. The second category is representative of manufacturers or intermediate agencies such as municipalities or collection centers, who collect a particular product type at different locations for disposal. The last category may represent one or more manufacturers cooperating to share economies of scale for product disposal. The decision makers at this level do not involve themselves in detailed issues such as product disassembly, bulk recycling or material recovery from product disposal. In some cases they may participate fiscally through cost/profit sharing agreements with recyclers. In general, they are merely interested in the disposal of potentially hazardous materials, and may also pay for the convenience of having the material disposed with no residual liability. Other motivations for recycling may be environmental preservation, waste reduction or product end-of-life recycling mandates. The source problem is then identified as the decision problem for the generators of end-of-life products. It focuses on a waste generator who is selecting one or more recyclers to collect electronics waste from different locations, where each recycler charges different rates for collecting different materials/items. With an increasing number of recyclers willing to collect material, the goal of any source becomes one of minimizing the cost or, if possible, maximizing profit from recycling. While recycling at the source level is also motivated by environmental concerns, these are hard to measure, and this effect is not quantified by recycling service providers. Any negotiations are usually limited to the cost of the service. An additional option is landfilling - however this is limited only to non-hazardous materials and has an associated tipping fee (typically \$40–\$70 /T in the U.S.). A simple formulation of the source problem is:

$$Min\ z = \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{j=0}^{J}(SR_{ij} + TC_{ipj})V_{ipj} \tag{1}$$

$$s.t.\ \sum_{j=0}^{J} V_{ipj} = W_{ip}\ \forall\,(i,p) \tag{2}$$

$$V_{ip0} = 0\ \forall\, i\ \in h \tag{3}$$

$$V_{ipj} \in R^{+}\ \forall\,(i,p,j) \tag{4}$$

This formulation focuses on minimizing each source's net cost for material removal. The revenue from recycling each item i at a location p can be determined by adding the transportation cost to recycler j, TC_{ipj} to the cost a source pays the recycler to recycle an item (SR_{ij}). As indicated earlier, recyclers sometimes pay to remove items such as PC's and must be paid to remove items such as CRTs. Thus, this cost is negative if the recycler pays the source for the item and is positive if the source pays the recycler. Constraints (2) are material balance enforcements that ensures the aggregate quantity of each item at each location, W_{ip}, is sent either to a recycler or a landfill. V_{ipj}, the volume of item i that is transferred from source, p to recycler, j is the decision variable used to calculate the total disposal cost for all items. Landfilling too is easily accommodated by considering the landfill as a recycler, with appropriate tipping costs. Constraints, (3), are added to ensure only benign items are sent to the landfill ($j = 0$).

In this form, the solution of the source problem is trivially determined by assigning each item to the recycler who gives the highest return. Complications such as quantity discount, multi-item discounts and periodic pickup schedules can be easily included in extensions of this model.

Recycler models

Given that there are many different sources of electronics waste, electronics scrap recyclers have to make critical decisions on how to acquire material for optimizing operating costs, which include transportation, disassembly and material recovery costs. To acquire high value material, a recycler will usually need to pay some compensation to the source. This amount is based directly upon the composition of the material. As an example, printed circuit boards are known to have small amounts of precious metals and recyclers sometimes pay to pick up such items. In contrast, situations where the source will pay for collection and processing of electronics waste to comply with regulations also exist. One such example is that of computer monitors, where the sources pay the recycler for disposal because of the high processing cost to eliminate hazardous coated CRT glass.

A limited survey conducted with ten of the larger electronics scrap recyclers in the U.S. has found that a wide variety of schemes are currently being used for payment and compensation for collection and processing of electronic waste. In general, recyclers will pay for computer scrap without monitors. This payment is not always set in advance, although dealers of used computers do offer fixed prices for newer, working computers. The recycler collects the material, processes it and then returns some fraction of the profit to the supplier. Small electronics items such as telephones do not usually yield positive returns to the sources. The recycler may take these products for nothing, or charge a small fee for the service. As mentioned earlier monitors present a completely different situation. All recyclers surveyed charged a fee for picking up monitors. These charges range from $ 5.50 to $ 15.00 per unit in addition to any transportation cost.

In addition to deciding what materials to collect, the recycler also needs to decide where to send material for further processing for metal extraction. Different refiners/smelters specialize in the recovery of specific materials. To maximize return, the recycler needs to choose the smelter that returns the highest revenue for a given batch of materials. A related decision is that of determining an appropriate level of disassembly. It is often possible to disassemble products so that the concentration of a particular set of materials is increased, while either discarding materials or subassemblies that have little recovery value, or can be sold directly in an untreated form. This issue is dealt with in more detail later in this paper

Metal separation is usually done by a process where the smelter melts out all but the target materials. As stated earlier, end-of-life electronics products typically contain a mixture of precious metals in low concentrations. Since even small amounts of precious metal can be very valuable, different choices on how best to process a batch of electronics waste can yeild significantly dissimilar returns. Different processors have different setup fees, processing fees, transportation fees, minimum metal recovery stipulations and are capable of recovering different fractions of material from the metal mix. Smelters charge for material processing in many different ways. In some cases, they can charge a variable cost for each ton of dry input. A variable fee per ton for each material recovered is also typical. Additionally, setup fees for each metal recovered may also be levied. Another method of compensation is for smelters to retain a minimum amount of each metal they process. When long term relationships are established, contracts can be set up between the recycler and smelter for fixed quantities of material to be processed. These contracts stipulate minimum metal contents in the raw materials and aggregate quantities to be supplied over a certain time period. In most cases, penalties can be levied if toxic or undesirable elements are present in the mixture since these must be isolated prior to any recovery. Smelters can also generate profits for themselves if the recovery from materials processed exceeds the assayed values agreed upon with the suppliers. Given the combination of issues involved, selecting the best set of smelters for a given input material stream is not always an obvious decision.

Each smelter (l) can be characterized by a technological coefficient, T_{kl}, which is a fraction representing the amount of input metal (k) that the processor is capable of recovering. This recovery fraction is less than unity because material recovery processes are not perfect. Some small amounts of material may be economically impossible to recover. The variable cost charged for each unit processed can be incorporated into this recovery fraction. The additional setup cost is a fixed charge (S_{kl}), applied for each metal type recovered by the processor. Costs can also include transportation fees that are proportional to the distance between the recycler and processor (CS_l). Extra costs that should be considered relate to costs the collector will incur if the processor requires some special delivery needs. These might include items such as special bins, irregular labeling, extra unloading costs, or special trucking needs. Furthermore, acquisition costs can be assessed for each unit of a material acquired. Different models can be developed for different combinations of costs.

In many situations electronics recyclers collect pre-separated or partially manufactured electronics waste that does not require further disassembly. In these situations recyclers accrue a profit in two ways. First they can charge a fee for their services as described earlier, and second, they can make a profit from selling the materials they collect to different smelters. To generate revenue, the recycler is faced with two operating decisions. The first is a decision on what materials to collect, and the second is to decide on which smelter to send the material to. A model that handles both issues concurrently, thus maximizing the recyclers total revenue can be formulated as:

$$Max\ z = \sum_{k=1}^{K} \sum_{l=1}^{L} ((G_{kl}\ R_k) - (Y_{kl}\ S_{kl})) - \sum_{i=1}^{I} \sum_{l=1}^{L} (C_i + CS_l) X_{il} \tag{5}$$

$$\text{s.t.} \sum_{i=1}^{I} X_{il}\ A_{ik}\ T_{kl} \geq G_{kl} \quad \forall\,(k,l) \tag{6}$$

$$M\ Y_{kl} \geq G_{kl} \quad \forall\,(k,l) \tag{7}$$

$$\frac{\sum_{i=1}^{I} X_{il}\, A_{ik}}{\sum_{i=1}^{I} X_{il}} \quad \geq \quad B_{kl}\, Y_{kl} \quad \forall\,(k,l) \tag{8}$$

$$\sum_{l=1}^{L} X_{il} \quad \leq \quad W_i \quad \forall i \tag{9}$$

$$Y_{kl} \in \ [0,1] \ \forall(k,l);\ X_{il}, G_{kl} \in R^{+} \ \forall\,(i,k,l) \tag{10}$$

In the model (5–10), the objective, (5), maximizes the recyclers profit after subtracting the cost of acquiring item i, C_i, as well as the cost of transporting the item to smelter l, CS_l. The recycler's revenue is calculated by subtracting the cost of setups from the profit received for recovered metals. This profit is calculated by multiplying G_{kl}, the amount of metal k recovered at smelter l with the unit selling price of metal k, R_k. In (6), G_{kl} is calculated as the amount of metal k that can be recovered from all the items sent to smelter l. In this constraint, A_{ik} is the coefficient representing the amount of metal k in item i. Constraints (7) trigger the binary decision variable Y_{kl} if metal k is recovered at smelter l. Constraints (8) are blending constraints that produce a mixture with the minimum concentration requirement (B_{kl}) for metal k at smelter l. However, this constraint is active only if metal k is recovered at smelter l. Finally, (9) requires the amount of item i shipped to smelter l, represented by the decision variable X_{il}, to be less than the weight of item i available for shipment W_i.

The formulation (5–10) is a non-linear, mixed integer formulation. While general approaches based on Benders decomposition [27] and outer approximations [28] may be used to solve this model, a branch and bound scheme is preferred since since fixing Y_{kl} gives a linear formulation which is easy to solve. This is further developed in [29].

As an illustration of this model, assume three items (computers, Video Casssette Recorders (VCRs), and televisions) containing different amounts of Gold, Silver, and other grouped metals, are available to a recycler for collection. Furthermore, two smelters are available to process the items. The cost of transportation to the smelters are 0.025 and 0.015 ($ per lb.) respectivly, and the value of the metals is: gold 3885.57, silver 34.4 and other metals 60.0 ($ per lb.). The example is solved by enumerating on Y_{kl} and solving the remaining linar model using CPLEX and GAMS. These data and the solution are shown in Figure 4 below.

Recycler models with product disassembly

In many cases recyclers recover value by performing some disassembly operations on end-of-life electronics items prior to processing for material recovery. The disassembly step can enhance value in several ways. First, removed components might be worth more sold directly than as contributions to the material recovery revenue. Second, additional materials not recoverable from the original product because of concentration limitations might now be recoverable from disassembled subassemblies. Lastly, separated subassemblies can be sent to different smelters for a more profitable material recovery than the entire product being sent to a single smelter.

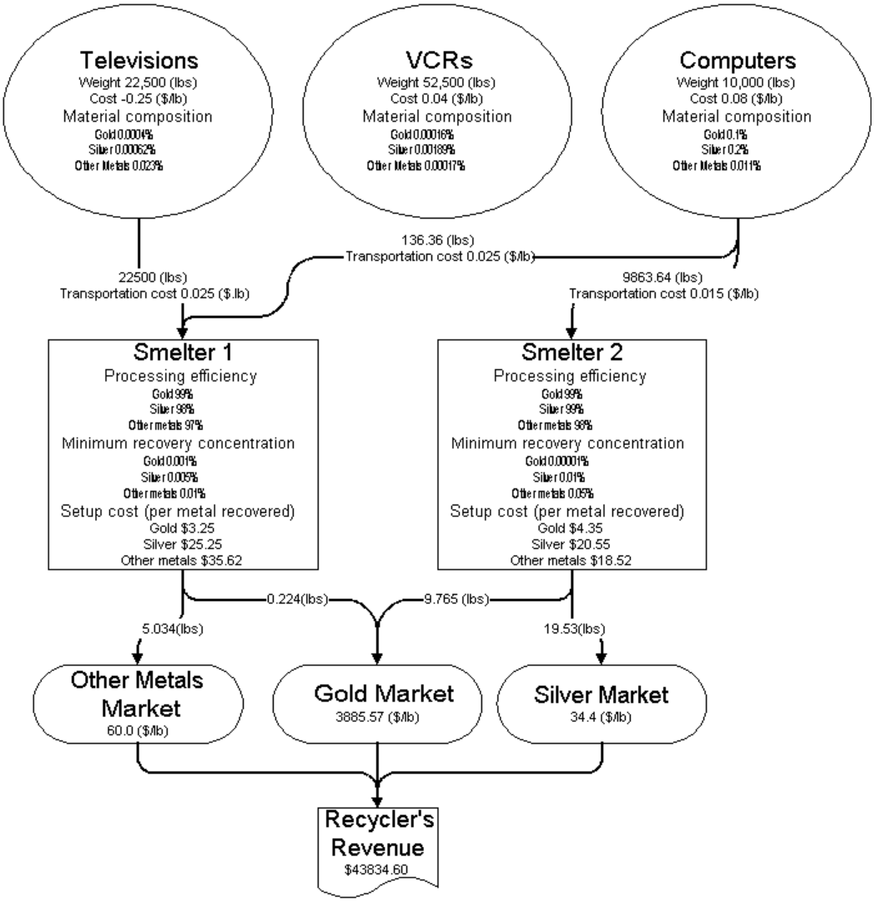

Fig. 4. Illustration of recycler's model (5)–(10)

Although several different models of the disassembly problem have been reported in the literature, ([13, 14] and [30]), a process for integrated consideration of material and component/subassembly recovery is difficult to develop because of the large number of component/subassembly subsets possible by disassembly. This is also consistent with the discussion in [15]. However, it is possible to limit consideration to a smaller set of possible disassembly subsets with associated disassembly costs, by investigating candidate subsets for material recovery. These can then be included in a material recovery formulation, prescribing the best combined disassembly and material recovery decision.

As an illustration, consider the data for a personal computer in Table 2. If the entire P.C. is processed for metal recovery, the gold content is 0.005%. However, the motherboard has a gold concentration ten times higher. Using these data, subsets of components can be grouped and proposed as candidates for metal recovery evaluation. This is illustrated in Table 3.

Table 2. Metal composition of items in a P.C.

Component	Weight (lbs)	Percent of metal in component: Gold	Silver	Copper	Iron	Pt. Group	Wt Fraction
Motherboard	1.430	0.05	0.1	0.8	0	0.001	0.06
Daughter boards	0.95	0.05	0.1	1	0	0.005	0.04
Case	14	0	0	0	95	0	0.61
Floppy drive	1.12	0.0001	0	5	12	0	0.05
Hard drive	1.03	0.0005	0.001	2	9	0.0001	0.05
Power supply	4.3	0	0	35	25	0	0.19
Total	22.83	0.005	0.01047	7.019	63.960	0.0003	1

Table 3. Metal composition of items grouped together

Row	Items grouped together	Weight (lbs)	Percent of metal in component: Gold	Silver	Copper	Iron	Pt. group	Fraction of P.C. wt.
1	PC	22.83	0.005	0.01047	7.019	63.960	0.0003	100
2	Mother board, Daughter board	2.38	0.05	0.1	0.88	0	0.0026	0.104
3	Case, Power supply	18.3	0	0	8.22	78.552	0	0.802
4	Mother-board, Daughter-board, Case	16.38	0.0073	0.0145	0.13	81.197	0.0004	0.717
5	Mother-board, Daughter-board, Case, Power supply	20.68	0.0058	0.0115	7.38	69.512	0.0003	0.906
6	Mother-board, Daughter-board, Hard drive, Floppy drive	4.53	0.0264	0.0528	2.15	5.013	0.0014	0.198

The problem of simultaneous determination of optimal component disassembly and material recovery can now be formulated by using the disassembly cost for obtaining each proposed subset of materials of item i, D_{is}, which is the net cost or revenue after factoring in any value recovered from components sold directly. This will be negative if there is a profit - i.e. the cost of disassembly is less than the revenue returned from the sale of components. However, if the levels of disassembly described by each subset of parts, is predetermined and therefore, not optimized. Thus, model (5) - (10) can be extended as:

$$\max z = \sum_{k=1}^{K}\sum_{l=1}^{L}((G_{kl}R_k) - (Y_{kl}S_{kl})) - \sum_{l=1}^{L} CS_l \sum_{i=1}^{I}\sum_{s\in S_i} X_{ils}$$
$$-\sum_{i=1}^{I}\sum_{s\in S_i}\frac{D_{is}}{f_{is}}\sum_{l=1}^{L} X_{ils} \tag{11}$$

$$\text{s.t.} \sum_{i=1}^{I}\sum_{s\in S_i} X_{ils}\, A_{iks}\, T_{kl} \quad \geq \quad G_{kl} \quad \forall\,(k,l) \tag{12}$$
$$M\, Y_{kl} \quad \geq \quad G_{kl} \quad \forall\,(k,l) \tag{13}$$
$$\frac{\sum_{i=1}^{I}\sum_{s\in S_i} X_{ils}\, A_{iks}}{\sum_{i=1}^{I}\sum_{s\in S_i} X_{ils}} \quad \geq \quad B_{kl}\, Y_{kl} \quad \forall\,(k,l) \tag{14}$$
$$\sum_{s\in S_i}\frac{1}{f_{is}}\sum_{l=1}^{L} X_{ils} \quad = \quad W_i \quad \forall i \tag{15}$$
$$Y_{kl} \in \ [0,1]\ \forall(k,l);\ X_{ils}, G_{kl} \in R^{+}\ \forall\,(i,k,s,l) \tag{16}$$

This model is similar to (5)–(10), except for the disassembly cost of selected subsets which is subtracted from the objective, and the fractional weight material balance in (15). The decision variables in this model are X_{ils}, which represents the amount of subset s of item i sent to smelter l. $B_{kl}, CS_l, G_{kl}, R_k, S_{kl}, Y_{kl}$ all have the same definition as in (5) – (10). The coefficient A_{ik} is replaced here by A_{iks}, and this can now be interpreted as the amount of metal k in subset s of item i. The cost of acquiring item i, C_i is not factored into the objective function because it is assumed that this model is solved by the recycler who has a certain quantity of items in inventory, and has to determine optimal disassembly and dispersal strategies. However, acquisition costs can be easily accommodated if necessary. In this model, several candidate plans for disassembly of the product are first generated. Corresponding to each disassembly plan, there is a set of disassembled components that can be sold directly, and a residual set intended for material recovery. There is also a cost, D_{is}, associated with each plan, which represents the revenue from the disassembled compoments reduced by the cost of disassembly. Because of the direct disposal of components, a reduction factor, f_{is} is computed as:

$$f_{is} = \frac{\text{Weight of residual set in plan} s}{\text{Original weight of assembly}}.$$

As an example, the data in Table 3 shows the approximate material content and several candidate disassembly plans for a personal computer. Although the PC consists of several smaller components, such as connectors and wires in addition to those shown, for the discussion that follows we limit our attention to the major components only. Thus, if the computer is sold without any processing (disassembly), the fraction of gold recoverable from the shredded mixture is 0.005%. However, if the power supply, case and drives are removed by disassembly (as shown in Row 2), and the remaining fraction is processed for metal recovery, the concentration of gold increases to 0.05%, almost a ten fold increase. This is approximately true for silver and platinum as well. Thus, the cost of separating the case and power supply can now be compared with the savings in processing the higher concentration motherboard and daughter-board scrap, and an economically optimal decision can be made. Thus, several candidate disassembly sets can be generated a-priori for each product type in the recycler's inventory, and the model selects the optimal level of each candidate plan that must be used. Several disassembly plans may be selected for the same product type, because of the varying contributions of different plans to different metal concentrations. The requirement that the disassembly plans be generated manually is not considered to be excessively limiting since there will usually be only a few dominant disassembly plans for electronics products. Also, although a bipartite paprtition of each disassembled subset has been considered here, a multipartite separation of each subset can also be accommodated without any change in the structure of the model. Landfilling options can also be included by representing the landfill as a (dummy) smelter, from whom no metal is recovered and a charge is applied for any amount shipped. Plastics recovery can also be addressed by designating a smelter as specializing in the recovery of plastics. However this model does not optimize pastics separation and related issues explicitly.

As an illustration of the application of this model, a hypothetical scenario is represented in Figure 5 below, where two products are being evaluated for recycling. Two smelters are available, both capable of processing all metals (metal 1 and 2) in these products. Product 1 can be processed either as-is, or can be further disassembled (at a cost of $0.40/item). The quantities and other model specific parameters are shown in the figure. Solving (11)–(16) with this data results in an optimal solution where 5200 pounds of product 1 is sent to smelter 1 for processing after disassembly, and the rest of product 1 is sent to smelter 2 for metal recovery. All of product 2 is sent to smelter 2 for processing. The split in Product 1 allows metal 2 to be recovered from product 2 by raising the composite concentration to a level above the minimum required.

This example helps illustrate the complexity of decisions that arise when recycling electronics for material recovery, and the utility of models such as (11) – (16) in facilitating the economic sustainability of electronics recycling.

Smelter model

Smelters receive items or parts from recyclers for processing. In some cases, smelters are required by contract to accept many of the items sent for metal recovery, but non-contract materials may also be processed to fill the smelters remaining capacity. When the smelter acquires items to recover metals for profit, a variable cost per unit of recovered metal and a fixed cost for extracting metal is incurred.

A model that allows the smelter to maximize profit (17) subject to a material balance constraint (20), a minimum required material content for recovery (21), and a capacity limitation (22) is:

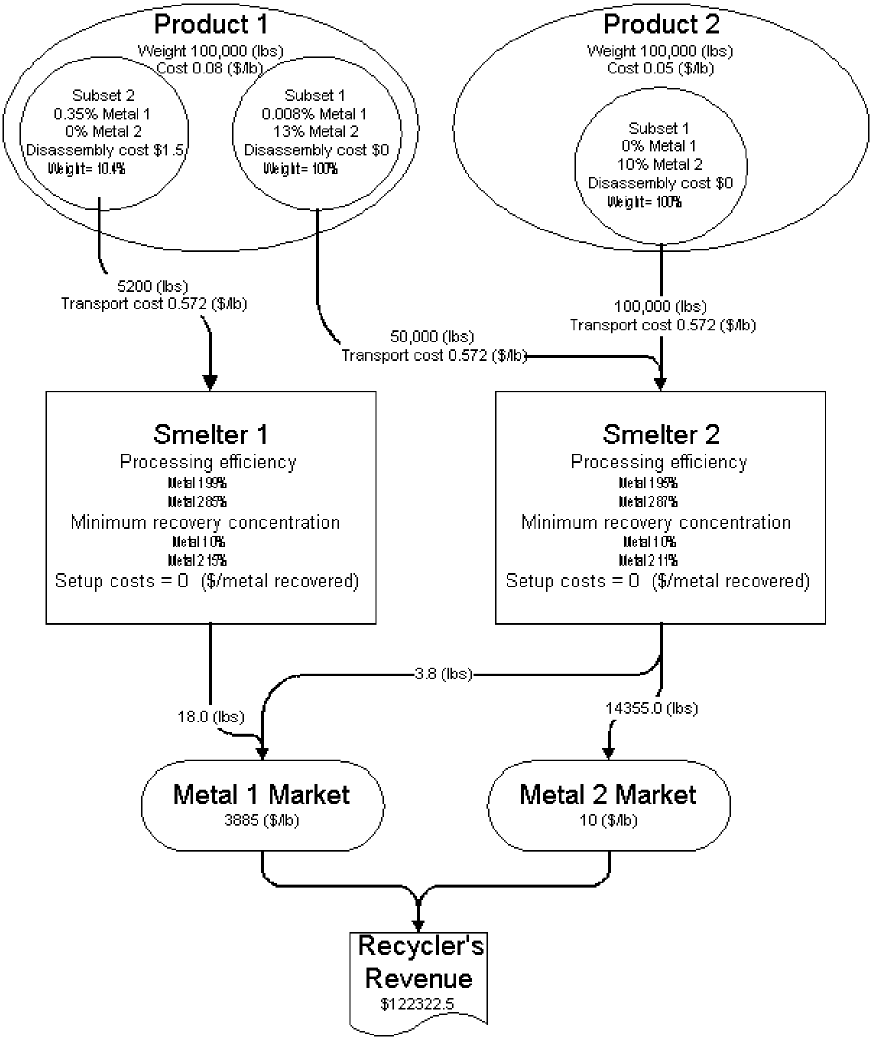

Fig. 5. Illustration of recycler's model (11)–(16)

$$Max\ z = \sum_{k=1}^{K}\sum_{j=1}^{J}(R_k G_{kj} - F_k\, Y_{kj} - \pi \sum_{i=1}^{I} X_{ij}) \tag{17}$$

s.t.

$$G_{kj} \le \sum_{i=1}^{I} X_{ij}\, A_{ik}\, T_k \quad \forall\,(k,j) \tag{18}$$

$$M\, Y_{kj} \ge G_{kj} \quad \forall\,(k,j) \tag{19}$$

$$X_{ij} \le W_{ij} \quad \forall\,(i,j) \tag{20}$$

$$\frac{\sum_{i=1}^{I} X_{ij}\, A_{ik}}{\sum_{i=1}^{I} X_{ij}} \ge Y_{kj}\, B_k \quad \forall\,(k,j) \tag{21}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij} \;\leq\; Cap \tag{22}$$

$$X_{ij}, G_{kj} \in R^{+}\,\forall\,(i,j,k);\; Y_{kj} \in [0,1]\,\forall\,(k,j) \tag{23}$$

The objective (17), maximizes the profit after deducting setup and processing charges. Here, R_k is the per unit revenue from metal k. F_k is the fixed cost of processing metal k. π is the per unit cost of processing at the smelter, which is assumed to be independent of the item type processed. However, if this is not the case, the corresponding term would be $\sum_{j=1}^{J}\sum_{i=1}^{I}\pi_i X_{ij}$. The first constraint (18), calculates G_{kj}, the amount of metal k recovered from recycler j and limits this quantity to be less than the amount of metal recoverable from the material sent from recycler j. Constraint (19), requires Y_{kj} to be one if metal k is recovered from the material sent by smelter j, i.e. G_{kj} is greater than zero. The quantity constraint, (20) requires the amount of item i sent from recycler j, X_{ij} to be less than the amount of item i available for processing from recycler j, W_{ij}. The blending constraint (21) requires that the concentration of metal k, in the items sent for processing from recycler j, $(\sum_{i=1}^{I} X_{ij}\,A_{ik})/(\sum_{i=1}^{I} X_{ij})$ to be greater than B_k, the minimum concentration requirement for metal k, if metal k is to be recovered from the material sent from recycler j, if the variable Y_{kj} is set to one. The capacity limitation (22), requires the total number of items sent for processing $\sum_{i=1}^{I}\sum_{j=1}^{J} X_{ij}$ to be less than the smelters capacity Cap. Finally, (23), requires Y_{kj} to be binary and G_{kj} and X_{ij} to be positive.

This model is also non-linear, because of constraints (21). Here too a branch-and-bound scheme by fixing the binary variables may be preferred to general approaches such as benders decomposition [27], outer approximations [28] because of the linear nature of the problem once the binary variables are fixed.

Conclusion

In this paper, a study of reverse channels for end-of-life electronics products is presented in a framework similar to that developed by [15]. The economics of electronics recycling have been modeled from the viewpoints of the generators, recyclers, and material processors separately. A variety of mathematical programming models, representative of the many ways in which the recycling industry currently operates, have been proposed, along with a discussion of solution techniques. A numerical illustration has been included for the recycler model. In addition, an integrated consideration of the disassembly and material recovery problem has been formulated at the recycler's level. Although an intergrated model representing the entire system would result in lower costs than those obtained using the models that separately address the decisions at each level, it is unlikely that the actual execution of decisions would be guided towards such an idealized goal. The models proposed here depict the generators, the recyclers and the processors/smelters of end-of-life electronics products each acting in their best interests, which is perhaps a more accurate representation of the actual behavior of these players in reality. The models set up in this paper can be used by recyclers and processors for optimizing recycling operations, and can also be used to study decisions such as pooling recycling efforts at the generators level, subsidizing takeback for recyclers etc.

Nomenclature
Source model (1–4)

i = item
j = recycler
p = location
SR_{ij} = per unit cost of sending item i to recycler j
TC_{ipj} = per unit transportation cost to send item i from location p to recycler j
V_{ipj} = volume of item i sent from location p to recycler j
W_{ip} = weight of item i available for pickup at location p

Recycler model (5–10)

A_{ik} = amount of metal k in item i
B_{kl} = minimum concentration of metal k for processing at smelter l
C_i = per unit acquisition cost of item i
CS_l = per unit transportation cost to smelter l
G_{kl} = amount of metal k processed at smelter l
i = item
k = metal
l = smelter
M = a large number
R_k = per unit revenue from metal k
S_i = subsets (disassembly) plans for part i
S_{kl} = setup cost for metal k at smelter l
T_{kl} = transformation coefficient of metal k at smelter l
W_i = weight of item i available for processing
X_{il} = amount of item i sent to smelter l
Y_{kl} = assignment variable for metal k at smelter l

Recycler model with product disassembly (11–16)

A_{iks} = amount of metal k in subset s of item i
B_{kl} = minimum concentration of metal k for processing at smelter l
CS_l = per unit transportation cost to smelter l
D_{is} = cost to disassemble subset s from item i
f_{is} = fraction of total weight of item i in subset s
G_{kl} = amount of metal k processed at smelter l
i = item
k = metal
l = smelter
M = a large number

R_k = per unit revenue from metal k
s = subset of parts
S_{kl} = setup cost for metal k at smelter l
T_{kl} = transformation coefficient of metal k at smelter l
W_i = weight of item i available for processing
X_{ils} = amount of subsets s from item i sent to smelter l
Y_{kl} = assignment variable for metal k at smelter l

Smelter model (17–23)

A_{ik} = amount of metal k in item i
B_k = minimum concentration of metal k for processing
Cap = capacity of smelter
F_k = fixed charge for processing metal k
G_{kj} = amount of metal k processed from items sent from recycler j
i = item
j = recycler
k = metal
M = a large number
π = per unit cost of processing an item
R_k = per unit revenue from metal k
T_k = transformation coefficient of metal k
W_{ij} = amount of item i available for processing from recycler j
X_{ij} = amount of item i processed from recycler j
Y_{kj} = assignment variable for processing metal k from recycler j

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