Available online at www.sciencedirect.com

ScienceDirect

European Journal of Operational Research 177 (2007) 969–981

EUROPEAN JOURNAL OF OPERATIONAL RESEARCH

www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

An automotive bulk recycling planning model

J.A.S. Williams [a,*], S. Wongweragiat [b], X. Qu [b], J.B. McGlinch [c],
W. Bonawi-tan [d], J.K. Choi [b], J. Schiff [e]

[a] Department of Management and MIS, University of West Florida, Pensacola, FL 32514-5752, United States
[b] Purdue University, West Lafayette, IN, United States
[c] John Deere Power Systems, Waterloo, IA, USA
[d] Tranzact Technologies, Elmhurst, IL, United States
[e] Siemens Energy & Automation, Atlanta, GA, United States

Received 14 May 2004; accepted 8 January 2006
Available online 2 May 2006

Abstract

The automotive recycling infrastructure successfully recovers 75% of the material weight in end-of-life vehicles primarily through ferrous metal separation. However, this industry faces significant challenges as automotive manufacturers increase the use of nonferrous and nonmetallic materials. As the nonferrous content in end-of-life vehicles rises, automotive shredders need to evaluate to what extent to separate nonferrous metals. We propose a recycling planning model for automotive shredders to make short-term tactical decisions regarding to what extent to process and to reprocess materials through multiple passes. In addition, the mixed integer programming model determines whether to combine materials for shipment. In a case study for automotive shredding decisions for the current composition and more polymer-intensive end-of-life vehicles, we use our model to show the sensitivity of the decision to reprocess light nonferrous metal to low and high metal prices. Contrary to observations in practice to mix light and heavy nonferrous metals for shipment, we show multiple scenarios where the model chooses to reprocess and ship separated light and heavy nonferrous metals.

Keywords: Environment; Production

1. Introduction

Of the approximately 150,000 cars per year reaching end-of-life in Sweden (Sverige, 1997), 70–75% of each end-of-life vehicle (ELV) was recycled (Borjeson et al., 2000). Likewise, of the 15,000,000 vehicles retired per year in the United States, 15–25% of their total weight is landfilled (Duranceau and Lindell, 1999). A significant fraction of the landfilled portion of ELVs, commonly called automotive shredder residue (ASR), is polymeric (Orr, 2000). The recycling of ELVs begins with parts recovery and proceeds to shredding and then material separation by magnetic and density properties (Phillips, 1996; Dalmijn, 1990). Automotive recycling outputs consist of ferrous metal, nonferrous metals, and ASR (Orr, 2000).

---

[*] Corresponding author. Tel.: +1 850 474 2283; fax: +1 850 474 2314.
E-mail addresses: JAWilliams@uwf.edu (J.A.S. Williams), McGlinchJanetK@JohnDeere.com (J.B. McGlinch).

0377-2217/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.ejor.2006.01.031

Investigations to improve recovered material grades focus on processing parameters. For instance, Aboussouan et al. (1999) analyze the effectiveness of shredding different size, morphology, and metallographic distributions of shredded car fragments, using different sizes of square sieving mesh screens. Reprocessing mixed materials repeatedly through separators to generate purer output streams is investigated in (Nijhof and Rem, 1999; Stuart and Lu, 2000). Another approach to upgrade scrap is selective disassembly and material sorting prior to shredding (Boom and Steffen, 2001). Design for recycling, separation guidelines and processing to improve material output purity are important factors (Coulter et al., 1998; Rios et al., 2003).

Spengler et al. (2003) present a mixed integer linear programming (MILP) model for short-term recovery planning for electronic scrap acquisition, disassembly and bulk recycling. The sensitivity of the solution to the acceptance fees and the prices for copper and aluminum are investigated. The results show that the marginal revenue will decrease with decreasing acceptance fees as well as with decreasing metal prices, and that the decision for internal or external recycling of scrap types is strongly influenced by the acceptance fees and the market prices of materials. Process configurations are assumed fixed; reprocessing and shipment decisions are not included (Spengler et al., 2003). Sodhi and Reimer (2001) decompose the electronics recycling network into three independent mathematical programming models for the collection source, the recycler, and the smelter. The recycler model maximizes profit by choosing what materials to collect for a processing fee and to which smelters to send mixed materials for the highest returns. Lu et al. (2004) present an MILP model to make processing, reprocessing, set-up and storage decisions for electronics recycling planning. Their model does not consider shipment decisions.

Similar to the automotive shredder, the electronics recycler seeks to earn profit from separated materials. While the electronics recycler is paid to receive products and faces higher variability of incoming shipments, the automotive recycler uses purchase price to control incoming shipment quantities. Then they process hulks and sell the nonferrous metals to aluminum, copper, or brass specialized shops for further separation and resale to a secondary market (Isaacs and Gupta, 1998). However, the steel-intensive automotive design has been changing to lighter weight materials, such as aluminum, magnesium, plastics and composites (McAuley, 2003). According to Bhakta (1994), the rise of aluminum usage in automotive production has steadily increased from 43.9 kg to 80.3 kg in the six years following 1977. This triggers further research whether to separate aluminum residue from the nonferrous metals for separate sales. By using eddy current separation, the aluminum may be separated from the mixed nonferrous flow and sold separately for aluminum-to-aluminum recycling (Zhang et al., 1998). Research is needed to determine to what extent the shredder should process the light nonferrous metal to optimize profit.

The nonferrous flow may also be affected by the plastic content in vehicles. Isaacs and Gupta (1998) consider disassembly operations to remove 25% of the high value plastics prior to the shredding operations. Given a fixed shredding process, they analyzed the sensitivity of the profitability of the disassembler and the shredder to the polymer content in the vehicle design, quantity of polymer materials removed, and polymer disposal costs. Because their strategic model is based on a fixed shredding process, the impact of increasing plastic content on the shredder's processing decisions over shorter periods of time are not addressed. For example, as the plastic content in hulks increases, the shredder's ASR disposal costs increase, especially in areas where ASR is defined as hazardous waste (Straudinger and Keoleian, 2001). While polymers separated by a dismantler are not hazardous, those processed through a shredder may become mixed with hazardous materials.

Straudinger and Keoleian (2001) discuss the business economics of dismantlers and shredders. They stress that transportation costs play a large role in dismantler-to-shredding pricing relations. Further, they explain that key factors influencing shredder profitability include scrap metal prices, ELV metal content, and shredder proximity to metal smelters.

In summary, a model that considers processing, reprocessing, storage, and shipment composition decisions is needed for the specific planning requirements of automotive shredders. This recycling planning gap for automotive shredders is addressed in this paper.

2. Automotive recycling

This research studies short-term planning for automotive recycling by focusing on shredding and separating metallic and nonmetallic materials from car hulks through magnetic separation and eddy current separation. The hulks are purchased from scrap metal dealers or dismantlers who buy end-of-life vehicles (ELV) from con-

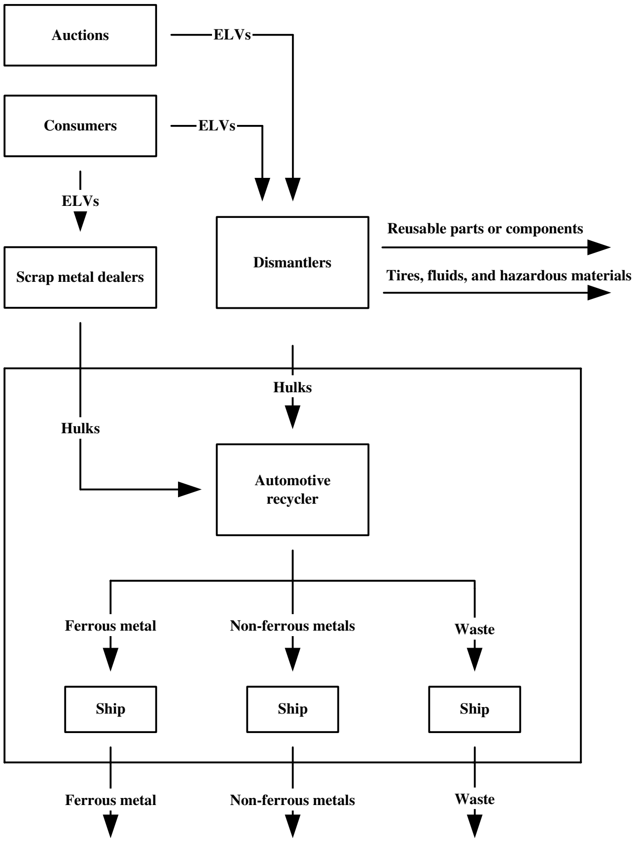

Fig. 1. System boundary of automotive recycling.

sumers or auctions as shown in Fig. 1. The scrap metal dealers remove fluids and batteries, and flatten hulks. Dismantlers disassemble reusable parts or components for resale, such as expensive electronics, engines, transmissions, or gearboxes. The dismantlers also remove fluids and specific hazardous materials and sometimes tires before selling the remaining flattened hulks to the recycler. The system boundary on this study, as represented by the dark line in Fig. 1, begins with flattened hulks arriving at the automotive shredder. The scrap metal dealer and dismantler operations are excluded in this study. The focus of this paper is the planning process at the shredding facility.

2.1. Current operation

Typical operations for an automotive shredder including the inputs and outputs are summarized in Fig. 2 with solid arrows. After car hulks are unloaded from the trucks, they are queued for shredding. Then, the shredded mixed materials flow passes through the air separator after which the material diverges into two different flows: light nonferrous metal/ASR and mixed metals/ASR.

Following the shredder and air separator, the light materials pass through an eddy current separation to sort the light nonferrous metal, mainly aluminum, from ASR. The ASR is composed of dirt, glass, fabric, foam, gravel, plastics, and other nonmetallic residue. For heavy materials flow, a drum magnet separates the ferrous metal from the nonferrous metals which include aluminum, copper, brass, and magnesium. Both the ferrous and nonferrous metal flows are still contaminated with some ASR. Therefore, the nonferrous metals flow proceeds through an eddy current to separate the nonferrous metals from ASR. On the other hand, ASR in the ferrous metal flow is manually removed along a conveyor. After all the separation processes, each of the output groups, ferrous metal, light nonferrous metal, heavy nonferrous metal, and ASR, are directed to a different bin to be loaded into trucks for resale or transport to further processing. The light and heavy

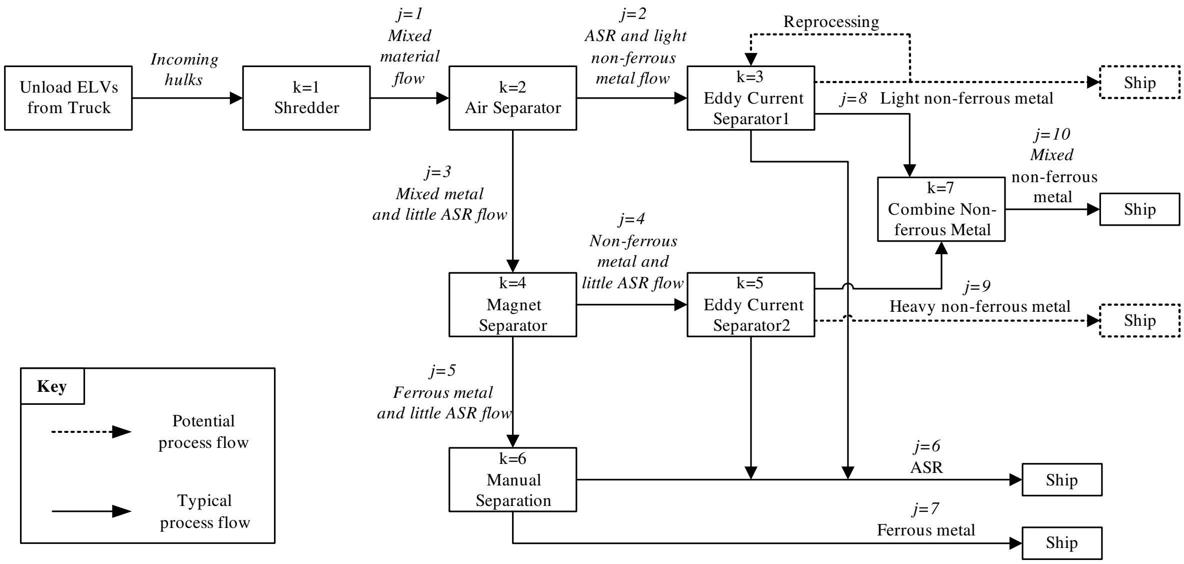

Fig. 2. Process flow, equipment, inputs and outputs for current automotive recycling operation.

nonferrous metals separated by eddy current operations contain mostly aluminum, copper, and brass. When the separate light and heavy nonferrous metals accumulate, the light nonferrous metal is transported and combined with the heavy nonferrous metal for shipment as mixed nonferrous metal. Potential process flow variations to increase output purity are illustrated with dotted arrows. One option to increase the purity of light nonferrous metal output is to reprocess it through the "eddy current separator 1" in Fig. 2 a second time to remove additional ASR. Another option to maintain purer nonferrous metal shipments is to ship light versus heavy nonferrous metals separately.

For this automotive recycling operation, we make the following assumptions. The automotive recycler accepts only vehicle hulks. Hazardous fluids have been removed from the hulks prior to their arrival at the shredding facility. There is no minimum acceptance limit per supplier of hulks. Output materials recovered from these hulks may be positively or negatively valued (positive for metals and negative for ASR). Demand for ferrous and nonferrous metals is infinite with respect to what the recycler can produce, and ASR disposal capability is unlimited. For the recycling process, we assume that blade changing and other regular maintenance do not reduce the processing capacity; they occur on a night shift or during weekends. Machine start up time is negligible. Processing costs and time are linear with respect to the quantities of materials processed.

2.2. Notation

The following notation is used in our model.

Indices, limits, and sets

i	type of incoming product; $i \in \{1,\ldots,I\}$
j	type of output material; $j \in \{1,\ldots,J\}$
k	type of equipment and tooling; $k \in \{1,\ldots,K\}$
t	time period; $t \in \{1,\ldots,T\}$
Φ	set of equipment which separates final outputs
ψ	set of equipment which separates final nonferrous metals
Λ	set of post-shredding equipment with only single-pass processing
J_k	set of output materials processed from equipment k
K_j	set of equipment that process material j
β_{ik}	maximum number of cycles that product i may be processed on equipment k
b	number of processing cycles; $b \in \{1,\ldots,\beta_{ik}\}$

Parameters

a_i	space needed to store one unit weight of incoming product i
c_{kb}	cost of processing for cycle b on equipment k per time unit
f_{ijkb}	percentage weight of final output material j of product i that can be recovered by processing on equipment k after cycle b
h_t	percentage of capital cost for inventory per period t
λ_{it}	price per unit weight of incoming product i in period t
m_{it}	weight of incoming product i in period t
p_{ik}	processing time per unit weight of product i on equipment k
Π_{i0}	initial inventory weight of product i
q_k	effective processing capacity of equipment k in time units per period
r_{jkb}	revenue from each unit weight of output material j by processing on equipment k after cycle b
ρ_{ijkb}	processing time per unit weight of output j from product i for cycle b on equipment k
s	total available storage space for incoming products
σ_{ijkb}	processing time per unit weight of output j from product i on equipment k after being processed on equipment $(k-1)$ for b cycles
z_{jb}	shipment cost per unit weight of output j after being processed for b cycles

Variables

E_{ijkbt}	weight of in-process product of output j from product i by processing on equipment k for cycle b in time period t
F_{ijkbt}	weight of final output material j from product i by processing on equipment k after cycle b in time period t
I_{it}	weight of incoming product i stored in staging inventory at the end of time period t
N_{ijkbt}	weight of in-process product of output j from product i that moves to processing equipment k at the end of cycle b in time period t
X_{it}	weight of product i scheduled for bulk recycling in time period t
Y_t	$\begin{cases} 0, & \text{if outputs 8 and 9 are not mixed in time period } t \\ 1, & \text{if outputs 8 and 9 are mixed in time period } t \end{cases}$

2.3. Automotive bulk recycling planning model

The objective of the automotive recycler's planning model is to maximize the profit from selling the output materials separated from the purchased input. A typical process flow is shown in Fig. 2 with solid arrows while potential modifications to increase the output purity are shown with dotted arrows. For example, the dotted arrow from the "light nonferrous" to the "eddy current separator 1" represents decision variables, E_{i832t}, to further separate ASR from aluminum-rich nonferrous metals. The dotted arrows from "light" and "heavy" nonferrous to "ship" represent decision variables F_{i83bt} and F_{i95bt} respectively, to ship separately. The mixed integer programming model for the planning decisions in Fig. 2 is formulated as follows:

$$\begin{aligned} \text{Maximize:}\quad & \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k\in\Phi}\sum_{j=6}^{10}\sum_{b=1}^{\beta_{ik}} r_{jkb}F_{ijkbt} - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k\in\Phi}\sum_{j=6}^{10}\sum_{b=1}^{\beta_{ik}} z_{jb}F_{ijkbt} - \sum_{t=1}^{T}\sum_{i=1}^{I}\lambda_{it}m_{it} \\ & - \sum_{t=1}^{T}\sum_{i=1}^{I} h_t\lambda_{it}I_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I} c_{11}p_{i1}X_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k\in\Lambda}\sum_{j\in J_k} c_{k1}\sigma_{ijk1}N_{ijk1t} \\ & - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j\in J_3}(c_{31}\sigma_{ij31}N_{ij31t} + c_{32}\rho_{ij32}E_{ij32t}) \end{aligned} \tag{1}$$

$$\text{Subject to:}\quad \sum_{i=1}^{I} p_{ik}X_{it} \leqslant q_k, \quad k = 1;\ t = 1,\ldots,T \tag{2}$$

$$\sum_{i=1}^{I}\sum_{j\in J_k}\sigma_{ijkb}N_{ijkbt}\leqslant q_k,\quad b=1;\ k\in\Lambda;\ t=1,\ldots,T \tag{3}$$

$$\sum_{i=1}^{I}\sum_{j\in J_k}(\sigma_{ijk1}N_{ijk1t}+\rho_{ijk2}E_{ijk2t})\leqslant q_k,\quad k=3;\ t=1,\ldots,T \tag{4}$$

$$I_{i,t-1}+m_{it}-X_{it}=I_{it},\quad i=1,\ldots,I;\ t=1,\ldots,T \tag{5}$$

$$I_{i0}=\Pi_{i0},\quad i=1,\ldots,I \tag{6}$$

$$\sum_{i=1}^{I}a_iI_{it}\leqslant s,\quad t=1,\ldots,T \tag{7}$$

$$f_{ijkb}X_{it}=N_{ij(k+1)bt},\quad k=1;\ b=1;\ j\in J_k;\ i=1,\ldots,I;\ t=1,\ldots,T \tag{8}$$

$$f_{ij'kb}N_{i1kbt}=N_{ij'k'bt},\quad i=1,\ldots,I;\ j'\in J_k;\ b=1;\ k=2;\ k'\in K_{j'};\ t=1,\ldots,T \tag{9}$$

$$f_{i8k1}N_{i2k1t}=F_{i8k1t}+E_{i8k2t}+N_{i871t},\quad i=1,\ldots,I;\ k=3;\ t=1,\ldots,T \tag{10}$$

$$f_{i6k1}N_{i2k1t}=F_{i6k1t},\quad i=1,\ldots,I;\ k=3;\ t=1,\ldots,T \tag{11}$$

$$f_{i8k2}E_{i8k2t}=F_{i8k2t},\quad i=1,\ldots,I;\ k=3;\ t=1,\ldots,T \tag{12}$$

$$f_{i6k2}E_{i8k2t}=F_{i6k2t},\quad i=1,\ldots,I;\ k=3;\ t=1,\ldots,T \tag{13}$$

$$f_{ij'kb}N_{i3kbt}=N_{ij'k'bt},\quad i=1,\ldots,I;\ j'\in J_k;\ b=1;\ k=4;\ k'\in K_{j'};\ t=1,\ldots,T \tag{14}$$

$$f_{i9kb}N_{i4kbt}=F_{i9kbt}+N_{i97bt},\quad i=1,\ldots,I;\ b=1;\ k=5;\ t=1,\ldots,T \tag{15}$$

$$f_{i6kb}N_{i4kbt}=F_{i6kbt},\quad i=1,\ldots,I;\ b=1;\ k=5;\ t=1,\ldots,T \tag{16}$$

$$f_{ijkb}N_{i5kbt}=F_{ijkbt},\quad i=1,\ldots,I;\ j\in J_k;\ b=1;\ k=6;\ t=1,\ldots,T \tag{17}$$

$$N_{i9kbt}+N_{i8kbt}=F_{ijkbt},\quad i=1,\ldots,I;\ j\in J_k;\ b=1;\ k=7;\ t=1,\ldots,T \tag{18}$$

$$\begin{aligned}&\sum_{i=1}^{I}(F_{i831t}+F_{i832t}+F_{i951t})\leqslant(1-y_t)\sum_{i=1}^{I}\sum_{j\in J_k}\left[f_{ijkb}\left(\sum_{t=1}^{T}m_{it}+\Pi_{i0}\right)\right],\\&\quad j\in J_k;\ b=1;\ k=7;\ t=1,\ldots,T\end{aligned} \tag{19}$$

$$\sum_{i=1}^{I}F_{ijkbt}\leqslant y_t\sum_{i=1}^{I}f_{ijkb}\left(\sum_{t=1}^{T}m_{it}+\Pi_{i0}\right),\quad j\in J_k;\ b=1;\ k=7;\ t=1,\ldots,T \tag{20}$$

$$X_{it}\geqslant 0,I_{it}\geqslant 0,\quad i=1,\ldots,I;\ t=1,\ldots,T \tag{21}$$

$$F_{ijkbt}\geqslant 0,\quad i=1,\ldots,I;\ j=1,\ldots,J;\ k\in\Phi;\ b=1,\ldots,\beta_{ik};\ t=1,\ldots,T \tag{22}$$

$$N_{ijkbt}\geqslant 0,\quad i=1,\ldots,I;\ j=1,\ldots,J;\ k=1,\ldots,K;\ b=1;\ t=1,\ldots,T \tag{23}$$

$$E_{ijkbt}\geqslant 0,\quad i=1,\ldots,I;\ j=1,\ldots,J;\ k=3;\ b=2;\ t=1,\ldots,T \tag{24}$$

$$Y_t=0\text{ or }1,\quad t=1,\ldots,T. \tag{25}$$

The objective function seeks to maximize the profit of an automotive shredder over planning horizon T. In the objective function (1), the first term represents the revenue from final output materials, the remaining terms calculate the costs of shipment for final outputs, incoming products, inventory holding of incoming products, and processing, respectively.

Constraints (2)–(4) are the operating capacity limits. Constraints (5) enforce the inventory balance for the incoming hulks. Constraints (6) initialize inventory. Constraints (7) represent storage capacity of incoming products. Constraints (8)–(20) maintain materials flow balances. Constraints (21)–(25) ensure non-negativity.

By extending the electronics recycling planning model in (Lu et al., 2004), this automotive recycling model introduces some innovative features. This model considers the following options for the light nonferrous metal separated after the first cycle: shipping as finished goods, reprocessing, or mixing with heavy nonferrous metal for shipment in constraints (10), (15), (18), (19) and (20). In addition to helping automotive recyclers plan for processing, reprocessing, and staging inventory, our model determines if particular materials should be shipped separate or mixed in order to optimize the objective function.

The complexity of the planning model depends on the process structure, type of incoming hulks, and number of planning periods. For the typical process of an automotive shredder in Fig. 2, the planning model includes $I + 21IT$ continuous decision variables, T integer decision variables, and $I + 10T + 15IT$ constraints. For the two types of incoming hulks differentiated by plastic content and four planning periods evaluated in the experiments in the next section, 170 continuous decision variables, four integer decision variables, and 162 constraints are modeled.

3. Experiments with the model

To test the model, we visited actual automotive shredders and collected data from published studies. Due to higher quality of reprocessed light nonferrous metal which may be sold at a more attractive price, the main interest for this paper is to study how the recycler's profitability is sensitive to reprocessing and shipment decisions under different ferrous and nonferrous metal prices and different ELV compositions. Since we observed recyclers mixing and shipping heavy and light nonferrous metals, a goal of this research is to determine if the recycler should ship materials mixed or separate to maximize the net revenue.

We ran our model with different sets of material price parameters and quantities of polymer-intensive hulks. For the first and second data set scenarios, we identified the lowest and highest ferrous metals prices during the period January 2000 to June 2005 in (*American Metal Market*, 2000–2005). We tested increasing the light nonferrous metal second cycle reprocessing value from 110% to 120% of the light nonferrous metal first cycle processing value. We evaluated the sensitivity of the arrival percentage of polymer-intensive hulks by examining scenarios where incoming hulks were composed of 25% polymer-intensive hulks and 75% steel-intensive hulks. We also evaluated 50% of each type of incoming hulk as well as 75% incoming polymer-intensive hulks and 25% incoming steel-intensive hulks. Table 1 summarizes the scenarios tested with our model. Because the nonferrous mixed metal price impacts whether a light nonferrous metal second cycle is profitable, we checked the price point at which the decision to mix nonferrous metals is made for each scenario that the light nonferrous metal second cycle price is fixed. Similarly, we checked the price point at which the decision to reprocess for a second cycle light nonferrous metal for a fixed mixed nonferrous metal price. The price point search is indicated by an asterisk in Table 1. Our experiments were solved with GAMS 2.50 on a Sun Microsystems Ultra-450 in less than 1 minute per run (GAMS Development Corporation, 2003).

3.1. Data collection

The main parameters needed in the automotive planning recycling model include the composition of hulks, the processing rate, the processing cost, the shipping cost, and the prices for recycled materials. We analyzed two different material compositions for incoming hulks in Table 2: steel-intensive and polymer-intensive hulks. In Table 2, the outputs for ASR, ferrous, light nonferrous, and heavy nonferrous recovered are from (Straudinger and Keoleian, 2001; Isaacs and Gupta, 1998). We assume that eddy current separator 1, eddy current separator 2, and the manual separation contribute 90%, 8%, and 2% of the total ASR, respectively. The remaining percentages were calculated from the process flow diagram in Fig. 2.

The processing rates used in our case study are summarized in Table 3. The processing rates of a shredder and an air separator are usually 60–80 tons per hour (Straudinger and Keoleian, 2001). Since the process in Fig. 2 is continuous, the processing rates of the magnetic separator, the manual separation, and the optional shipment combinations are calculated based on the processing rate of the shredder and the material composition of the hulks. Typical processing rates for eddy current separators are 18–30 tons per hour (Nijhof, 1997).

Nijhof and Rem (1999) estimate the processing cost of an eddy current separator to be $250,000 per year, including energy, labor, and maintenance costs. Isaacs and Gupta (1998) estimate that the total cost of automotive shredding is $18.80 per ton. We divide the total cost into the processing costs for seven machines in Table 3 based on the energy consumption, the number of operators, and maintenance cost for each machine.

The transportation costs of output materials are a significant element in an automotive shredder's cost structure. We estimate costs by considering the densities of materials, the maximum weight and volume per truckload, and the transportation distances between the shredder and the metal processors. In Table 4, the transportation cost of ASR is lowest since the transportation distance of ASR is much shorter than the other

Table 1
Scenarios

Scenario[a] No.	Hulk[b] price ($ton)	Metal selling price ($/ton)						% Polymer-intensive hulks $m_{2t}/(m_{1t}+m_{2t})$
		Ferrous scrap $j=7$	Heavy nonferrous[c] $j=9$	1st cycle light nonferrous[d] $j=8$; $b=1$	Increase in 2nd cycle light nonferrous[e]	2nd cycle light nonferrous[e] $j=8$; $b=2$	Mixed nonferrous[f] $j=10$	
1	43	81	400	560	10%	616	*	25%
2	43	81	400	560	20%	672	*	25%
3	43	81	400	560	10%	616	*	50%
4	43	81	400	560	20%	672	*	50%
5	43	81	400	560	10%	616	*	75%
6	43	81	400	560	20%	672	*	75%
7	43	81	400	560	*	*	360	25%
8	43	81	400	560	*	*	360	50%
9	43	81	400	560	*	*	360	75%
10	135	305	580	540	10%	594	*	25%
11	135	305	580	540	20%	648	*	25%
12	135	305	580	540	10%	594	*	50%
13	135	305	580	540	20%	648	*	50%
14	135	305	580	540	10%	594	*	75%
15	135	305	580	540	20%	648	*	75%
16	135	305	580	540	*	*	486	25%
17	135	305	580	540	*	*	486	50%
18	135	305	580	540	*	*	486	75%

[a] Scenarios 1–9 refer to a low ferrous metal price scenario that corresponds to the metal prices in the November 16, 2001 issue while scenarios 10–18 refer to a high ferrous metal price scenario that corresponds to the metal prices in the November 12, 2004 issue of *American Metal Market*.

[b] Hulk is labeled "autobody" in *American Metal Market*.

[c] Heavy nonferrous is priced according to "mixed yellow brass turnings, borings copper scrap" in *American Metal Market* since the majority of heavy nonferrous automotive metal consists of mixed copper (Straudinger and Keoleian, 2001).

[d] 1st cycle light nonferrous is priced according to "old aluminum sheet & cast, aluminum scrap" in *American Metal Market*.

[e] 2nd cycle light nonferrous is priced at 110% of the 1st cycle light nonferrous price for scenarios 1, 3, 5, 10, 12 and 14, 120% for scenarios 2, 4, 6, 11, 13 and 15. In scenarios 7–9 and 16–18, an "*" rather than a price is shown in Table 1 which indicates a search for price point at which the decision to reprocess changes.

[f] Mixed nonferrous is priced at 90% of the minimum of the heavy and 1st cycle light nonferrous metal prices for scenarios 7–9 and16–18. In scenarios 1–6 and 11–15, an "*" rather than a price is shown in Table 1 which indicates a search for price point at which the decision to ship separate changes.

Table 2
Material composition of hulks

Material	Machine	Percentage of output material j recovered on machine k (f_{ijkb})			
		Steel-intensive hulks ($i=1$)		Polymer-intensive hulks ($i=2$)	
		Cycle 1 ($b=1$)	Cycle 2 ($b=2$)	Cycle 1 ($b=1$)	Cycle 2 ($b=2$)
$j=1$	$k=1$	100.0%	–	100.0%	–
$j=2$	$k=2$	21.12%	–	25.26%	–
$j=3$	$k=2$	78.88%	–	74.74%	–
$j=4$	$k=4$	5.66%	–	6.03%	–
$j=5$	$k=4$	73.22%	–	68.72%	–
$j=6$	$k=3$	15.21%	0.59%	19.35%	0.59%
	$k=5$	1.40%	–	1.77%	–
	$k=6$	0.35%	–	0.44%	–
$j=7$	$k=6$	72.87%	–	68.27%	–
$j=8$	$k=3$	5.91%	5.32%	5.91%	5.32%
$j=9$	$k=5$	4.26%	–	4.26%	–
$j=10$	$k=7$	10.17%	–	10.17%	–

Table 3
Processing rates and costs

Machine		Processing rate (ton/hour)		Processing cost ($/minute)	
No.	Description	Steel-intensive hulks	Polymer-intensive hulks	Cycle 1	Cycle 2
$k = 1$	Shredder	65	65	8.2	–
$k = 2$	Air separator	65	65	1.6	–
$k = 3$	Eddy current separator 1	25	25	1.6	1.6
$k = 4$	Magnet separator	51	49	1.6	–
$k = 5$	Eddy current separator 2	25	25	1.6	–
$k = 6$	Manual separation	48	45	1.4	–
$k = 7$	Shipment combination	6.6	6.6	1.2	–

Table 4
Transportation costs of final output materials

Material		Transportation cost ($/ton)
No.	Description	
$j = 6$	ASR	20
$j = 7$	Ferrous metal	28
$j = 8$	Light nonferrous metal	35
$j = 9$	Heavy nonferrous metal	25
$j = 10$	Mixed nonferrous metals	30

Table 5
Additional modeling parameters

Description	Units
Weight of incoming hulks per week	2500 ton
Processing capacity	3000 minutes/week
Initial inventory	2500 ton
Space needed to store hulks	6 m^3/ton
Total available storage space for incoming products	20000 m^3
Percentage of capital cost for inventory	0.48%/week
ASR	50$/ton

material transportation distances. Since the transportation distances of ferrous metal and nonferrous metals are assumed equal, the differences between their transportation costs mainly result from their different densities. Lighter materials result in lower truckload weights which correspond to more expensive transportation cost.

The remaining modeling parameters for incoming hulks, capacity, inventory, and costs are given in Table 5. Automotive shredders purchase hulks by weight. The processing capacity is based on daylight operations. The typical landfill tip for ASR in the United States is assumed to be $50 per ton (Kanari et al., 2003).

4. Results

Figs. 3 and 4 indicate the decisions for the low ferrous metal price scenarios 1–9 while Figs. 5 and 6 indicate the decisions for the high ferrous metal price scenarios 10–18. In scenarios 1–9, the model may choose to ship and sell light nonferrous metal separate from heavy nonferrous metal for the light nonferrous metal prices indicated by "Ship separate" in Figs. 3 and 4. Also indicated in Fig. 3 on each "Ship separate" bar is the reprocess versus process once decision. Whenever the model chooses to ship mixed nonferrous metals, processing capacity is not used for reprocessing.

In Fig. 3 the second cycle light nonferrous metals price is fixed at either 110% or 120% of the first cycle value. In Fig. 3, for scenarios 1, 3, and 5, the model makes the same reprocessing and shipping decisions,

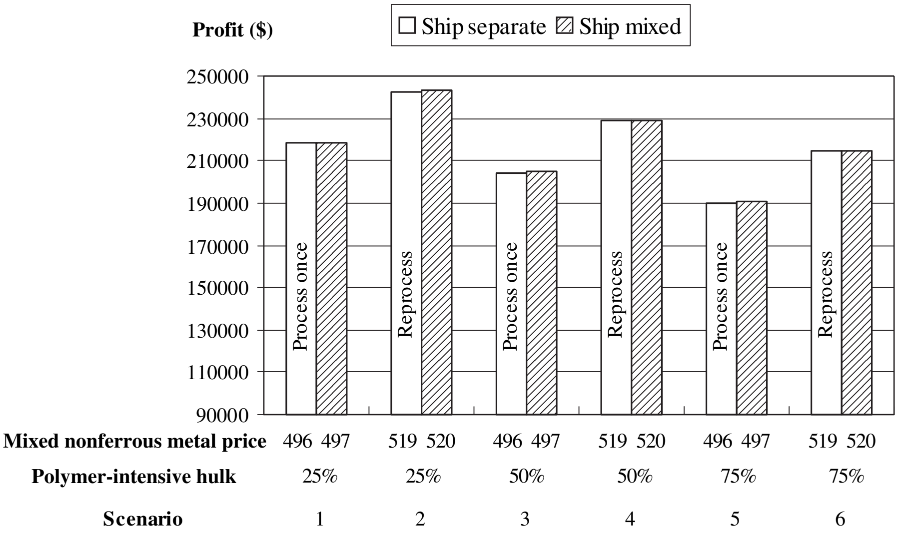

Fig. 3. Decisions and profits for scenarios 1–6 with low ferrous metal price.

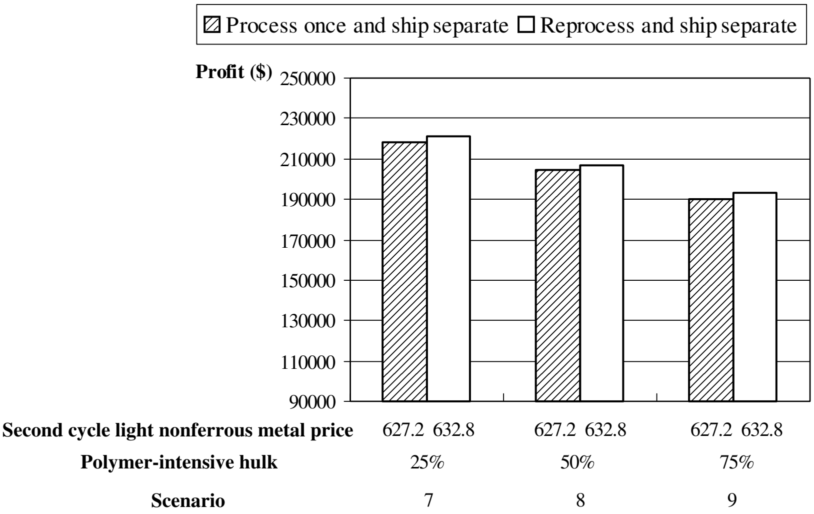

Fig. 4. Decisions and profits for scenarios 7–9 with low ferrous metal price.

indicating that these decisions were insensitive to the percentage of hulk arrivals that are polymer-intensive. However, the profit decreases as the arrival percentage of polymer-intensive hulks increases from 25% to 75%. When the price of reprocessing light nonferrous for a second cycle is raised from 110% to 120% of the first cycle price, the price for nonferrous at which the decision to ship mixed rises from $497/ton to $520/ton.

In Fig. 4, the mixed nonferrous metals price is fixed at $360/ton. The profit decreases significantly as the arrival percentage of polymer-intensive hulks increases in Fig. 4. In scenarios 7, 8, and 9, the price of second cycle light nonferrous at which the decision to reprocess light nonferrous metals occurs at $632.8/ton, regardless of the tested percentage of hulk arrivals that are polymer-intensive. The complexity of the recycling planning problem indicates that the model is helpful in determining when it is more profitable to allocate processing capacity to reprocessing.

In the optimistic scenarios in Fig. 5, the second cycle light nonferrous metals price is fixed at either 110% or 120% of the first cycle value. In Fig. 5, for scenarios 10–15, the model determines not only when to ship mixed

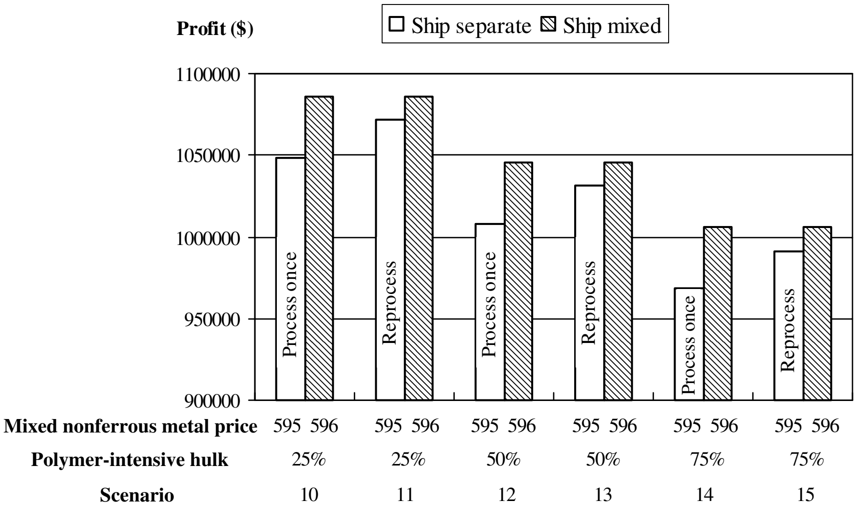

Fig. 5. Decisions and profits for scenarios 10–15 with high ferrous metal price.

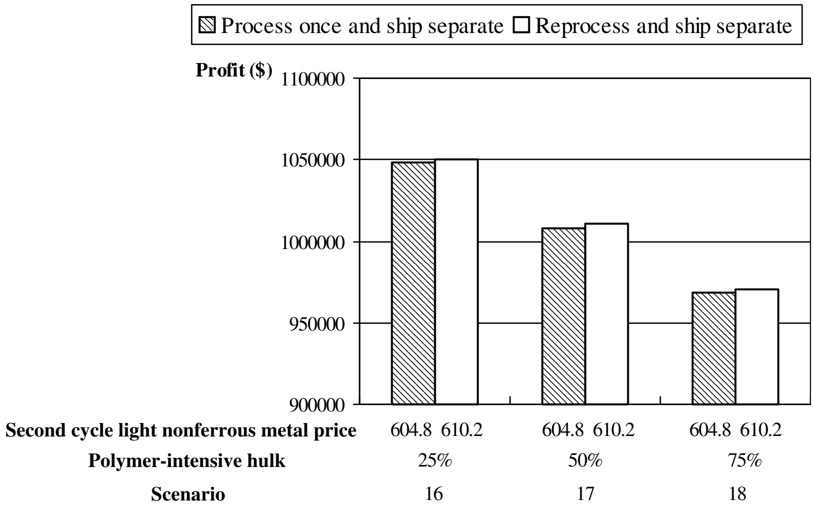

Fig. 6. Decisions and profits for Scenarios 16–18 with high ferrous metal price.

but also when to reprocess. Processing only one cycle versus reprocessing for a second cycle decisions are indicated when the model chooses to ship light nonferrous metal separate from heavy nonferrous metals. In scenarios 10, 12, and 14, despite the wide range of percentages for polymer-intensive vehicle hulks, the decisions are the same to ship separate light single cycle-processed and heavy nonferrous metals or mixed metals. In scenarios 11, 13, and 15, however, the higher price for reprocessed light nonferrous metals results in a decision to ship separate light reprocessed and heavy nonferrous metals or mixed metals as indicated in Fig. 5. These results indicate that the shipping and processing decisions are sensitive to the second cycle light nonferrous metal prices tested but insensitive to the percentage of hulk arrivals that are polymer-intensive. The decision to ship mixed nonferrous metals occurs at the mixed nonferrous metals price of $596/ton.

When the mixed nonferrous metals price is fixed optimistically at $486/ton, Fig. 6 illustrates that the profit decreases significantly as the arrival percentage of polymer-intensive hulks increases. In scenarios 16–18, the price of second cycle light nonferrous at which the decision to ship reprocessed light nonferrous metals occurs at $610/ton, regardless of the tested percentage of hulk arrivals that are polymer-intensive. With the optimistic pricing, the recycling planning problem model is again helpful in determining when it is more profitable to allocate processing capacity to reprocessing.

5. Conclusion

As fuel consumption efficiency and emission concerns have prompted automobile manufacturers to change the composition of automobiles to utilize lighter weight materials than steel, these design changes affect the profits of shredders. Our model may help automotive recyclers to improve their efficiency and profitability for processing hulks. For example, if recyclers do not consider reprocessing light nonferrous output, they may miss higher value material sales opportunities. Furthermore, the model determines when to ship light nonferrous metal separate from heavy nonferrous metal. Our model demonstrates that for recent mixed, light, and heavy nonferrous metals prices, there are instances when the recycler should reprocess light nonferrous metals and ship them separately from heavy nonferrous metals to maximize net revenue.

In conclusion, as the automotive industry continues to modify vehicle designs, the model presented in this paper can help automotive recyclers plan for their recycling operation accordingly. The model is designed for sensitivity analysis of the material composition of the vehicle and of the market prices for associated recovered materials that are processed at different levels.

Future research directions include analyzing set-ups between shredding ELVs, appliances, or other scrap. Although the mix of steel and polymer-intensive vehicles did not significantly alter recycling processing decisions in the ELV case, the model proposed in this paper could be used to determine the sensitivity of reprocessing and shipment composition options to products with more widely varying material diversity.

Acknowledgements

This research was supported by National Science Foundation grants DMII-0049074 and BES-0124761. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

Aboussouan, L., Russo, Ph., Pons, M.N., Thomas, D., Birat, J.P., Leclerc, D., 1999. Steel scrap fragmentation by shredders. Powder Technology 105, 288–294.

American Metal Market, January 2000–January 2005.

Bhakta, P.N.H., 1994. Recent technology and trends in automotive recycling. Journal of Materials 46 (2), 36–39.

Boom, R., Steffen, R., 2001. Recycling of scrap for high quality steel products. Steel Research 72 (3), 91–96.

Borjeson, L., Lofvenius, G., Hjelt, M., Johansson, S., Marklund, S., 2000. Characterization of automotive shredder residues from two shredding facilities with different refining processes in Sweden. Waste Management & Research 18, 358–366.

Coulter, S., Bras, B., Winslow, G., Yester, S., 1998. Designing for material separation: Lessons from automotive recycling. Journal of Mechanical Design 120, 501–509.

Dalmijn, W.L., 1990. Practical applications of eddy current separators in the scrap recycling industry. In: van Linden, J.H.I., Stewart, Jr., D.L., Sahai, Y. (Eds.) Proceedings of the Second International Symposium on Recycling of Metals and Engineered Materials, pp. 303–314.

Duranceau, C., Lindell, T., 1999. Automotive recycling as reuse: Investigation to establish the contribution of reuse on recyclability. SAE 1999-01-0987.

GAMS Development Corporation, 2003, GAMS 2.5, Washington, DC 20007, USA.

Isaacs, J.A., Gupta, S.M., 1998. Economic consequences of increasing polymer content for the US automobile recycling infrastructure. Journal of Industrial Ecology 1 (4), 19–33.

Kanari, N., Pineau, J.L., Shallari, S., 2003. End-of-life vehicle recycling in the European Union. Journal of Materials 55 (8), 15–19.

Lu, Q., Stuart, J.A., Posner, M.E., Bonawi-tan, W., Qu, X., 2004. Modeling short-term planning for bulk recycling of electronics equipment, Purdue University, Report 2004-07.

McAuley, J.W., 2003. Global sustainability and key needs in future automotive design. Environmental Science & Technology 37 (23), 5414–5416.

Nijhof, G.H., 1997. Automatic sorting of aluminium packaging from domestic refuse. In: Proceedings of the sessions of the Aluminium Committee at the 126th TMS Annual Meeting, Code: 47830, Orlando, FL, TMS.

Nijhof, G.H., Rem, P.C., 1999. Upgrading nonferrous metal scrap for recycling purposes. Journal of Materials 51 (8), 20–23.

Orr, W.W., 2000. USCAR US field trial for automotive polymers recycling: Interim findings. SAE 2000-01-0735.

Phillips, M., 1996. Magentic separation basics. Recycling Today (November), 68–78.

Rios, P., Stuart, J.A., Grant, E., 2003. Plastics disassembly versus bulk recycling: Engineering design for end-of-life electronics resource recovery. Environmental Science and Technology 37, 5463–5470.

Sodhi, M.S., Reimer, B., 2001. Models for recycling electronics end-of-life products. OR Spectrum 23, 97–115.

Spengler, T., Ploog, M., Schroter, M., 2003. Integrated planning of acquisition, disassembly and bulk recycling: A case study on electronic scrap recovery. OR Spectrum 25, 413–442.

Straudinger, J., Keoleian, G.A., 2001. Management of end-of-life vehicles (ELVs) in the US, Center for Sustainable Systems, University of Michigan Report No. CSS01-01.

Stuart, J.A., Lu, Q., 2000. A model for discrete processing decisions for bulk recycling of electronics equipment. IEEE Transactions on Electronics Packaging Manufacturing 23 (4), 314–320.

Sverige, B.I., 1997. The Association of Swedish Car Manufacturers and Wholesalers, Annual Report, Sweden, Stockholm.

Zhang, S., Forssberg, E., Arvidson, B.R., 1998. The current status of eddy current separation. Erzmetall 51 (12), 829–836.