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MODELING OF AUTOMOTIVE RECYCLING PLANNING IN THE UNITED STATES

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ABSTRACT−The United States automotive recycling infrastructure has successfully reduced the amount of automotive waste sent to landfills, especially since the introduction of shredders in the late 1950s. Shredders are necessary to process and recycle automotive hulks and other durable goods. However, this industry faces significant challenges as the automotive manufacturers are increasing the use of nonmetallic components which are difficult to recycle. Additionally, it is becoming obvious that automobiles contain hazardous materials which place heavy burdens on the environment. To address this growing concern, we propose a process planning model for automotive shredders to make tactical decisions regarding at what level to process and at what level to reprocess feed stock materials. The purpose of this paper is to test analytical models to help shredders improve the profitability and efficiency of the bulk recycling processes for end of life automobile returns. The work is motivated by an actual recycling problem that was observed at Capitol City Metals shredding facility in Indianapolis, Indiana.

KEY WORDS : Automotive recycling, Landfill fees, Mixed integer program, Sensitivity analysis

NOMENCLATURE

b : number of processing cycles
c_k : processing cost on equipment k
d_{jb} : weight by percentage of j in the b^{th} cycle
f_{ijk} : percentage weight of transit and j from i that can be separated by k
h_t : capital cost for the inventory per time unit
i : group of incoming products
j : type of transit and final output materials
j_k : set of output materials that are processed in k
k : type of equipment and tooling
m_{it} : weight quantity of i in period t
p_{ik} : processing time per weight unit of i on k
q_k : processing capacity of k
r_{jk} : revenue (positive) or cost (negative) per ton of j separated by k
E_{bkt} : weight quantity of material reprocessed in cycle b by k in period t
I_{it} : inventory of incoming product i at the end of time period t
N_{ijkt} : weight quantity of output j from i separated by k after the first cycle in t
S_t : safety inventory level per period
T : time period
X_{it} : weight quantity of incoming product i scheduled to be bulk-recycled in period t
λ_{it} : prices of one ton of incoming product
ρ_{jkbt} : processing time required per ton of j for cycle b on k in period t

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1. INTRODUCTION

Recent consumer trends have been pushing manufacturers to create environment-friendly products than ever. This involves all life-cycle stages of the product including end-of-life disposal. The automotive industry is no exception. Isaacs and Gupta (1998) mentioned that approximately 75% of the materials, in automobiles, mostly metals, are reused or recycled, but the remaining 25% must be disposed. Typically, disposal is to a landfill and there is a growing concern that the available landfill space is rapidly diminishing. It has been estimated that approximately 47% of the current landfills are to be closed over the next ten years (Spengler, 2003). The increasing environmental concerns have caused alarm about the need to recycle a greater percentage of end-of-life vehicles in the immediate future. Meanwhile, the desire for lighter, more fuel efficient vehicles is making it more difficult to recycle greater quantities of nonmetallic materials under the current automotive recycling infrastructure. Automotive manufacturers have modified the design of vehicles in recent years by replacing a percentage of the vehicle weight with lighter materials such as plastic or aluminum. From 1984 to 1993, the usage of cold-rolled steel in vehicles dropped by almost 55 kg (Bhakta, 1994). Design changes like these could be influenced by government regulations for improved environmental product design. The U.S. Energy Policy and Conservation Act of 1975 required automotive manufacturers to produce vehicles with an average fuel efficiency of at least 11.7 kilometers per liter by 1985 (Bhakta, 1994). Manufacturers could have also made the design changes to remain competitive with those manufactures who improved the gas mileage of their vehicles. Although these design changes appear to be only positive, the automotive recyclers have a different perspective. Most of the profits made through automotive recycling are from ferrous metals retrieved by recycling end-of-life vehicles (ELVs). Since the amount of ferrous metals is dropping, the process in which the expired vehicles are recycled is becoming less profitable and generates more automotive shredder residue (ASR) to be disposed of in a landfill. In this paper several alternatives for maintaining or possibly increasing the profitability of automotive shredder recyclers is investigated. The focus is the sensitivity to landfill tipping fees with various input and output factors of the recycling process involving the criteria that the automotive shredder recyclers need to make the important decisions associated with maintaining a profitable shredding operation.

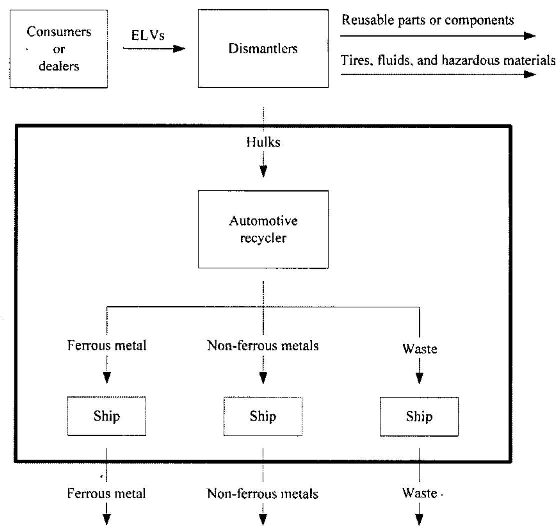

Figure 1. System boundary of automotive recycling.

2. VEHICLE RECYCLING OPERATION

This paper presents short-term planning for automotive recycling by focusing on shredding and separating metallic and non-metallic materials from car hulks through eddy current, magnetic, and air separation. The hulks are purchased from the dismantlers who buy end-of-life vehicles (ELVs) from their consumers or dealers, and disassemble reusable parts or components for resale, such as expensive electronics, engines, transmissions, or gearboxes. They also have to remove fluids and specific hazardous materials and sometimes tires before selling the remaining flattened hulks to the recycler. The hulks are sold at $50 per hulk on average. At this price, the automotive recycler is quite profitable and robust. The net profit of selling materials from a shredded hulk is estimated to be at least $44 (Isaacs,and Gupta, 1998). The system boundary on this paper, as represented by the dark line in Figure 1, begins with arriving hulks transported from the dismantlers by trucks. All dismantlers' operations are excluded in this paper.

2.1. Current Operation

The operations of automotive recycler Capitol City Metals in Indianapolis, Indiana, are typical of industry practice. The process flow, including the inputs and outputs are summarized in Figure 2. After the 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 non-ferrous metals/ASR and mixed metals/ASR. The first flow following the air separator then passes through an eddy current to separate out the light non-ferrous metals, mainly aluminum, from ASR. The ASR is composed of dirt, glass, fabric, foam, gravel, plastics and other non-metallic residue. For the mixed metals flow, a drum magnet separates the ferrous metal from the non-ferrous metals: aluminum, copper, brass and magnesium. Both the ferrous and non-ferrous metals flows are still contaminated with some ASR. Therefore, the non-ferrous metals flow goes through an eddy current to separate the non-ferrous metals from ASR. On the other hand, ASR in the ferrous metal flow is manually separated along a conveyor. After all the separation processes, each of the output groups, ferrous metal, non-ferrous metals, and waste, is directed to a different pile which then is loaded into trucks for resale or transport to further processing. For this automotive recycling operation, we make the following assumptions. Capital cost and shipping cost has not been included on the analysis. The automotive recycler accepts only vehicles. Each vehicle has the same weight and hulk price. Blade changing and all other regular maintenance do not reduce the capacity; they occur on a night shift or on the weekends. Machine start up time is negligible (less than 5 minutes). There is no inventory constraint to accept incoming arrivals. No incoming loads are turned away.

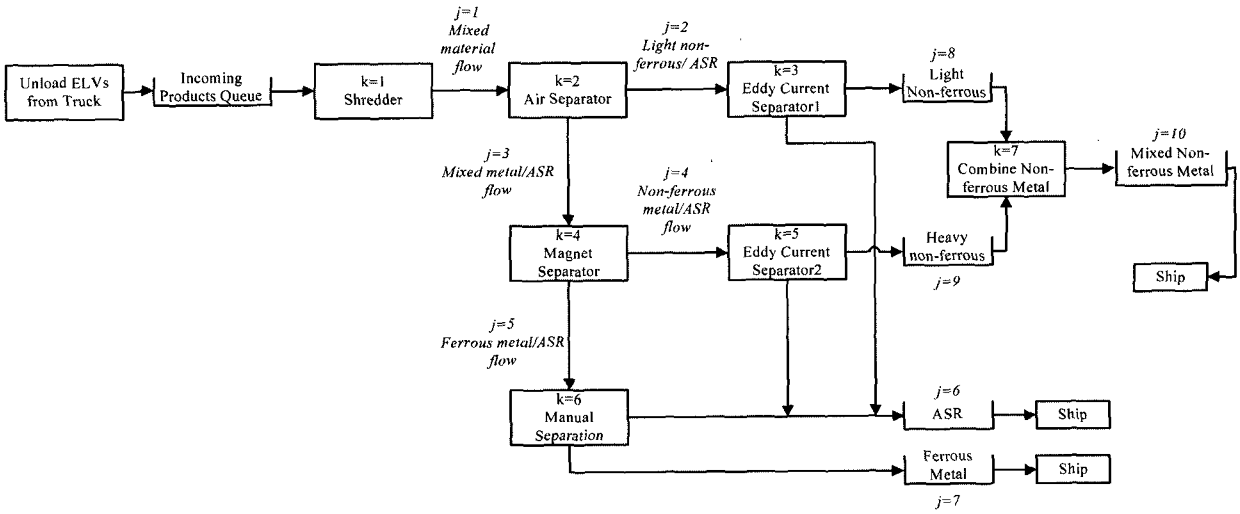

Figure 2. Process flow, processing, inputs and outputs of automotive recycling.

There is no minimum acceptance limit per supplier. Clean-ups are not addressed in the automotive recycling in this paper. The processing costs and time are linear with respect to the quantities of materials processed. Output materials may be positively or negatively valued (positive for metals and negative for waste). Demand for ferrous and non-ferrous metals is infinite with respect to what the recycler can produce, and ASR disposal capability is unlimited. All hazardous items have been removed from the hulks prior to their arrival at the recycling facility.

2.2. Base Model

The base model decision set determines how much material to process by which equipment, in what period to process it, and how much inventory should be held each period. Since the main objective of the automotive recycler is to maximize the profit from selling the output materials separated from the purchased input, this paper investigates the questions to help improve the recycler's efficiency and profitability, especially, How sensitive are the recycling planning decisions including reprocessing with current input to different landfill costs? The model is illustrated in Figure 2. The linear programming model is formulated as follows.

Objective function:

$$\text{Maximize } \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=8}^{10} r_{jk}N_{ijkt} - \sum_{t=1}^{T}\sum_{i=1}^{I}\lambda_{it}m_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K} c_k p_{ik}X_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I} h_t\lambda_i I_{it} \quad (1)$$

Subject to:

$$\sum_{i=1}^{I} p_{ik}X_{it} \le q_k \quad (2)$$

$$f_{ijk}X_{it} - N_{ijkt} = 0 \quad (3)$$

$$I_{i,t-1} + m_{it} - X_{it} = I_{it} \quad (4)$$

$$I_{i,t-1} \ge S_t \quad (5)$$

$$X_{it} \ge 0 \quad (6)$$

$$N_{ijkt} \ge 0 \quad (7)$$

(Here, $i = 1,\ldots, I$; $j \in J_k$; $k = 1,\ldots,K$; $t = 1,\ldots, T$ for equations (1)–(7))

The objective function seeks to maximize the profit of an automotive shredder during a month. In the objective function (1), the first term represents the revenue/cost from final output materials, the second term calculates the cost of incoming products, the third term models the processing cost, and the last term captures capital cost of the inventory of incoming products. Constraints (2) are the capacity limit of equipment. Constraints (3) represent the material flow balances. Constraints (4) enforce the inventory balances. Since Capitol City Metals has not experienced any problems involving storage capacity; there is no constraint to limit the storage space of incoming products. Capitol City Metals is however constrained by the need to protect the shredder from starvation. Therefore constraint (5) enforces the safety stock level. Constraints (6) and (7) ensure non-negativity.

2.3. Reprocessing Model

As an assumption, the reprocessing option has been concentrated on the eddy current separator (k = 3) because of the fact that approximately 90% of the total ASR is generated by the eddy current separator. The land filling cost is set to a high value of $65/ton or a low value of $10/ton. Basically reprocessing model follows base model except the fact that processing cost part are considered different way. Reprocessing model counts weight quantity of material reprocessed in the objective function. Therefore the processing cost part has been divided to base processing cost and reprocessing cost as can be seen in Equation (8). The revised notation to include reprocessing is attached below.

Objective function:

Maximize

$$\text{Maximize} \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=6}^{9} r_{jk}N_{ijkt}-\sum_{t=1}^{T}\sum_{i=1}^{I}\lambda_i m_{it}$$

$$-\sum_{t=1}^{T}\sum_{i=1}^{I} h_i\lambda_i I_{it}-\sum_{t=1}^{T}\sum_{i=1}^{I} (c_3(p_{i3}X_{it}+\rho_{832t}E_t)+ \quad (8)$$

$$\sum_{k=1}^{2} c_k p_{ik}X_{it}+\sum_{k=4}^{6} c_k p_{ik}X_{it})$$

Subject to:

$$\sum_{i=1}^{I} p_{ik}X_{it}+\rho_{jkbt}E_{bkt}\le q_k \quad (j=8;\ k=3;\ b=2) \quad (9)$$

$$d_{jb}N_{i22t}-E_{bkt}=0 \quad (j=6;\ k=3;\ b=1) \quad (10)$$

$$d_{jb}E_{b-1,kt}-E_{ijkt}=0 \quad (j=6;\ k=3;\ b=2) \quad (11)$$

$$N_{ijkt}-(d_{jb}N_{i22t}+d_{j,b+1}E_{bkt})=0 \quad (j=8;\ k=3;\ b=1) \quad (12)$$

$$E_{bkt}\ge 0 \quad (13)$$

(*Here* $i=1,\ldots,I$; $t=1,\ldots,T$ for equations (9)–(13))

$$\sum_{i=1}^{I} p_{ik}X_{it}\le q_k \quad (14)$$

$$f_{ijk}X_{it}-N_{ijkt}=0 \quad (15)$$

(Here, $i=1,\ldots,I; j\ J_k$; and $k=\{1,\ldots,K\}-\{3\}$; $t=1,\ldots,T$ for constraints (14) & (15))

3. EXPERIMENTS

3.1. Experimental Design

To analyze the sensitivity of the reprocessing option to the land filling cost, four different scenarios have been tested as shown in Table 1. Scenario1 and 2 utilize base model scenarios with applying low and high value land filling cost respectively. Base model includes combined light and heavy non-ferrous metal shipment, low plastics content vehicles, low non-ferrous price, no re-processing and no bonuses for purchasing incoming hulks. Scenario 3 and 4 hold same in the base model except the fact that re-processing option has been considered and different value of land filling cost has been applied. The base model (1)–(7) are used in scenarios 1, 2 and reprocessing model (8)–(15) are used in scenarios 3, 4.

Table 1. Experimental design for scenario 1-4.

Scenario	Reprocessing	Landfill fee	Model
1	No	Low	(1)-(7)
2	No	High	(1)-(7)
3	Yes	Low	(8)-(15)
4	Yes	High	(8)-(13)

Table 2. Material Composition of hulks.

		Percentage of output material j recovered on machine k (f_{ijk})			
		Steel-intensive hulks (i = 1)		Polymer-intensive hulks (i = 2)	
Material	Machine	Cycle 1	Cycle 2	Cycle 1	Cycle 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%	

3.2. Data Collection

Two different material compositions for incoming hulks in Table 2 are calculated based on the data from Straudinger and Keoleian (2001), Isaacs and Gupta (1998) and the assumption that eddy current separator 1, eddy current separator 2 and the manual separation contribute 90%, 8% and 2% of the total ASR respectively.

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 Figure 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

Table 3. Processing rates and costs.

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

Table 4. Additional modeling parameters.

Description	Units
Price of hulks	50 $/ton
Weight of incoming hulks per week	2500 ton
Processing capacity	3000 min/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

processing rates for eddy current separators are 18–30 tons per hour (Nijhof, 1997). The processing rates used in this paper are summarized in Table 3.

The remaining modeling parameters for incoming hulks, capacity and inventory are given in Table 4. Automotive shredders purchase hulks by weight. The processing capacity is based on daylight operations.

4. ANALYSIS AND RESULT

The economics of shredding depend upon five factors: the cost of acquiring the hulk; the cost of operating the shredder and material separators; the cost of landfill tipping of the ASR; the price the shredder gets for the shredded ferrous metal; the price the shredder gets for the mixed non-ferrous metal blend (largely aluminum, zinc, and red metals). When discussing recycling, one issue that invariably is raised is the increasing cost of land filling. This paper analyzes the effect of landfill tipping cost and the possible additional profit with reprocessing option. Land fill tipping fee of $30/ton has been used for base model and it reflects the typical cost encountered in the less populated central region of the United States.

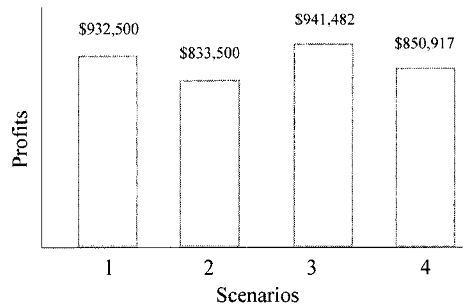

Figure 3. Profit comparison of four different scenarios.

There are also large regional variations in tipping fees from $10/ton to some Northeast facilities at over $65/ton. Therefore, the land filling cost is set to a high value of $65/ton or a low value of $10/ton for this sensitivity analysis. As an assumption, the reprocessing option has been concentrated on the eddy current separator (k=3) because of the fact that approximately 90% of the total ASR is generated by the eddy current separator. It is important to remind that shredder's revenues and costs are based on only the experimental design and data sets previously mentioned in this paper. Shipping cost, capital investment and other costs are not included in this paper. Overall analysis results are found by using GAMS IDE with choosing the CPLEX solver and compared in following Figure 3. In this figure, the profitability of shredder is presented as a function of landfill costs and reprocessing option. Assuming that shipping cost and other costs are constant to the different landfill tipping costs, there are $99,000 difference of profit for no-reprocess and $90.565 difference of profit for reprocess with the landfill tipping cost of low value $10 and high value $65 respectively. This is $9.9/ton and $9/ton difference for each case with two different landfill tipping fees in per ton base.

As can be seen from Figure 3, the results indicate that the impact of landfill cost increases upon shredder profitability is relatively small for both reprocessing and non-reprocessing options. Figure 4 and Figure 5 represent the sensitivity of profit to landfill tipping fee for both no-reprocessing and reprocessing respectively. Both show how much high value of landfill tipping fee can turn the shredders profit to negative for both no-reprocessing and reprocessing cases without considering other revenue and cost factors. Shredder's profit turns to negative with the tipping cost $530/ton for no-reprocessing cost and $585/ton for reprocessing cost. Although, shipping cost and other costs are not included in this analysis, this is fairly large amount of tipping fee and may not be occurred in near future. This result shows that a hulk shredding operation can still achieve profitability at relatively high tipping fees. The crossover

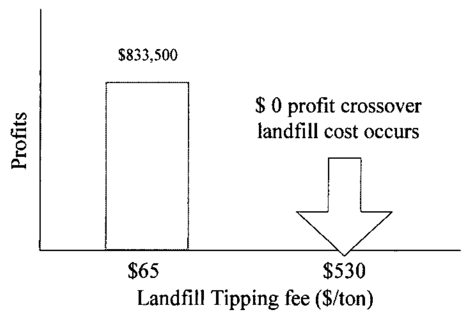

Figure 4. Shredder's Profit for different landfill tipping fees with no reprocessing option.

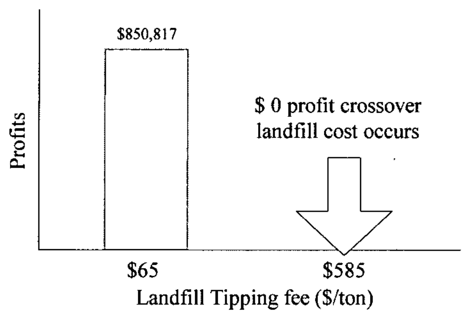

Figure 5. Shredder's Profit for different landfill tipping fees with reprocessing option.

point into loss does not occur until approximately around $550/ton for both case and this value can be obtained with more practical value if we design our model including shipping and capital cost and other costs. And it will obviously give a reduced amount of crossover point.

Figure 6 shows the shredder's overall profit per ton for scenario 1–4. Again, it is important to remind that this profit has been found based on the defined costs structure for the analysis without the consideration of other relevant costs (transportation costs, capital costs, energy costs, etc.). The amount of shredder's profit per ton shown in the Figure 6 will decrease some amount with

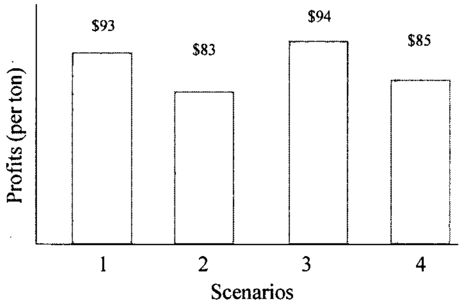

Figure 6. Shredder's overall profit (per ton).

the consideration of these relevant costs and this can be put as extension for the future analysis.

With the downsizing of the automobile, the metallic fraction of the automobile has reduced overall, and the ferrous fraction within that has also reduced. While there currently is a ready market for the ferrous and non-ferrous metallic fractions, there is no demand for the other elements (largely polymers, fabrics and glass) in the form that they emerge from the shredder. Instead, they are disposed of, usually in landfills. However, the contribution of this "automobile shredder residue" (ASR) to overall landfill burden is relatively small. Although about 0.18 tons of ASR is produced for each ton of incoming hulk, the landfill cost is a relatively small fraction of the total operating cost under the assumed basis conditions. The other variable costs are much higher than the landfill cost. The metallic fraction, accounting for approximately 82% by weight of the hulk, has sufficiently high market values to compensate for ASR's relatively small cost liability. In fact, the major cost contributor is the purchase of hulks. Clearly, rising hulk prices are the central factor in shredder profitability. It can be roughly imagined that if landfill costs are low, the costs of the disposal of this ASR is a small fraction of the shredder's operating cost and if the costs of landfill are very high, the shredder may not be able to cover her/his costs. However, the result shows that increase of landfill tipping cost affect relatively less to shredder's business as long as the cost will not reach to the crossover point into net loss which seems not to be occurred in near future.

5. CONCLUSIONS

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 net revenue of shredders. These design changes may also affect their automotive recycling planning decisions when material prices or ASR disposal costs fluctuate. 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. 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 options to products with more widely varying material compositions.

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