TOTAL QUALITY AND ENERGY
IN AUTOMOBILE MATERIALS RECYCLING PROCEDURES.

Evangelos P. Koltsakis, Hariton M. Polatoglou
Physics Dept, Aristotle University of Thessaloniki, Thessaloniki, Greece, 54124.
vangelis@auth.gr, hariton@auth.gr

ABSTRACT
In the present work we model procedures of an end-of-life vehicle (ELV) recycling plant. Material transformations and energy consumption / transformation are accounted. Variations and total changes in energy quality are calculated. Critical control points (CCP) are detected and taken under special consideration.

INTRODUCTION
The increase of the automobile industry over the last years by developing a mass consumer market and the shortening of products life circle[1] has created a lot of concern[2] for the management of the waste[3] of withdrawn automobiles because of the possible environmental physical and chemical hazardous substances[4] contained and of the environmental and energy costs[5] and benefits of materials recycling. As quality in waste management procedures has to be assured, a detailed study of each crucial parameter is essential. Energy[6] consumption and transformation is another crucial parameter.

Facts
Nearly all of the 27 million cars around the world that reach the end of their useful life are recovered for recycling each year. Automotive recyclers now can recover nearly 80% of the total materials by weight from a vehicle. The remaining 20% of vehicle materials that cannot be recycled is called auto shredder residue (ASR). ASR includes plastics, rubber, wood, paper, fabric, glass, sand, dirt, and ferrous and nonferrous metal pieces. Five million tons of ASR are disposed of in landfills each year.

Consumers purchasing used or reconditioned parts save 50 percent or more compared to the cost of purchasing new parts.

More than 25 million tons of materials are recycled from vehicles each year. Nearly 90% of automotive aluminum is recovered and recycled. Although this aluminum represents less than 10% of the average motor vehicle by weight, it accounts for roughly half of the vehicle's value as scrap.

Auto recyclers supply more than one-third of all ferrous scrap (iron and steel) to the scrap processing industry. When manufacturers use scrap iron and steel instead of virgin ore, they reduce air and water pollution by more than half during the manufacturing process.

Car recycling description
Cars are recycled in four steps:

- dismantling,
- crushing,
- shredding, and
- resource recovery.

In the dismantling stage, processors recover the fluids and take apart the usable parts and components. These include batteries, wheels and tires, steering columns, fenders, radios, engines, starters, transmissions, alternators, select plastic parts and components, glass, foams, catalytic converters, and other components, based on aftermarket demand. The processor then crushes the vehicle and loads it onto the vehicle shredder. The shredder grinds the vehicle into fist-sized pieces, which are then separated into ferrous and non-ferrous (aluminum) metals, as well as ASR (Fig. 1). After separation, the recovered metals are remelted at the mills, and the ASR is land filled.

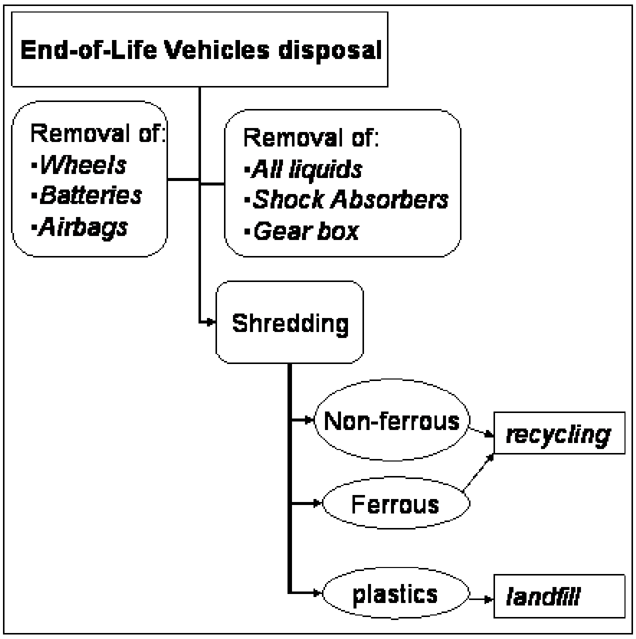

Fig. 1. The disposal route for end-of-life vehicles in an operational ELV site.

Our work

In the present work we model procedures of an end of life car recycling plant. Also, we observe, describe and record the workings in an existing car recycling plant as they are actually achieved through official legislated procedures[7] that recently have been started. Observational data are used to adjust the model parameters and are also used to determine the effectiveness of the model. Material transformations and energy consumption / transformation are accounted. Variations and total changes in energy quality (entropy, exergy) are calculated and compared to those of the corresponding model. This leads to the determination of the model parameters and the assessment of the suitability of the model. CCPs are detected and taken under special consideration.

The recorded data analysis is significant for the improvement of stages of the procedures and for the improvement of the whole plan in the recycling plant, for the minimization of energy loss and for the improvement of the recovery of the re-usable materials.

The aim of the work is the waste reduction through maximization of recycling degree, the stabilization of the hazardous materials and the improvement of the procedures by developing more thermodynamically efficient processes balanced with the environmental requirements.

MODELING

We develop a model for the study of the procedures of the processing of ELVs from the viewpoint of energy and entropy.

The aim of the model planning

The model aims at the study of:

- the amount of energy which is consumed during the processing
- the energy transformations that are taking place during the processing
- the changes in the entropy during the processing
- the energetic content of the final products
- the possibility of minimizing the consumed energy during the processing
- the maximization to the useful energy of the final products
- the application of more environmental-friendly technologies
- the critical control points during the whole procedure

Quality consideration

Critical control points (Table 1) are of a great significance in the model, as recycling methods all ready applied have a big margin for improvement, in various sectors, like as: handpicking and / or automated picking, energy amount consumed, energy amount reusable, toxic metals in materials etc.

Table 1. Critical control points taken under consideration

1	Energy waste (amount and quality)
2	Material waste
3	Toxic materials driven to landfill or to recycling
4	Staff health and safety

The minimization of the energy consumed in the processing and the maximization of the recovered energy from recycling are today subjects of special interest in the context of industrial ecology, and for this reason they are one of the CCPs of our model.

The management of the disposable materials requires more analytical separation, with the search for new separation techniques for the salvage of re-usable materials and the detection and stabilization and the control of some possibly existing toxic materials, which at present they are dumped to the landfills or are incinerated.

Staff health and safety matters also are of great concern as another CCP in our model, because of the possibly dangerous materials mentioned above and of the possibly risky working conditions.

Description of the model

In this section we shall introduce the definitions of the model quantities. For the purpose of having a tractable model simplifications will be introduced. First of all we confine the material fractions into four, denoted by f_i, i.e ferrous, non-ferrous, plastic and glass. If m_{car} denotes the mass of the car then the mass of each fraction is given by $m_i = m_{car} f_i$.

As the empirical findings indicate, most of the energy in processing ELVs goes to the shredding step. To estimate this energy we must find in how many pieces each material fraction is expected to be broken to. We must use the fact that the components of the car come in different sizes and therefore each component results a different number of pieces and a different amount of energy is needed to do so. Ideally one can use the information for each component to obtain both the number of pieces and the energy. Instead we simplify the estimation considering that the parts fall into some size categories denoted by α. If $\mu_{\alpha i}$ is the average mass of the α size category and ith fraction, then the number of parts each size category and material fraction can produce after the shredder is given by $\nu^{\gamma}_{\alpha i} = m_i / \mu_{\alpha i}$. In addition we denote with $\mathrm{E}^{\gamma}_{\alpha i}$ as the energy to cut a piece from the α-size category and the ith material or to separate it from the rest. Now we have all the necessary quantities to calculate the energy and the entropy of the processing of EVLs.

$$E = \sum \nu^{\gamma}_{\alpha i} \mathrm{E}^{\gamma}_{\alpha i} \qquad (1)$$

To define the entropy we make the assumption that all the pieces are randomly mixed. If the number of pieces of each material fraction is $N_i = \Sigma\, v_{\alpha i}$ and $p_i = N_i / \Sigma\, N_i$ is the probability of finding a piece from a given material then the entropy is given by

$$S = -kN \sum p_i \ln p_i \qquad (2)$$

Process Modeling

Here we describe the modeling for the time evolution of the process to include the idle periods of the plant, the feeding speed, the number of incoming cars per day and the time constants for the different processes. This can help us find the optimum conditions for the operation of the plant (example in Fig. 2).

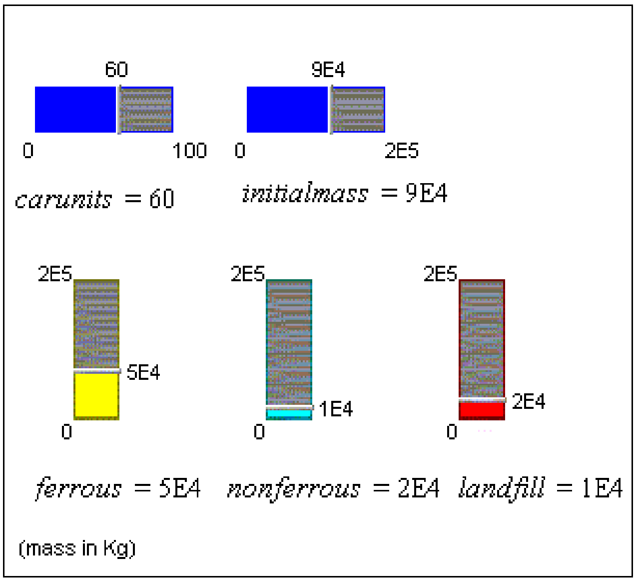

Fig. 2. Modeling application graph.

More specifically, the model aims at the documentation, study and analysis of:

- the quantities of the incoming materials and the separated output materials
- the procedures and methods that are employed in relation to:
    - the degree of the material separation
    - the energy that is consumed or recovered
    - the recovery of useful materials
    - the possibility of applying more efficient methods
    - the time that the materials remain in the plant
    - the environment
    - the stuff health and safety

In addition the model would allow the study of different scenarios and determine their outcome.

CASE STUDY

For the application of the model in realistic processes, we observe and document the procedures followed by a plant for ELVs. This plant is one of the two in Greece that are officially commissioned to process ELVs.

Table 2. Experimental data.

	ferrous	**non ferrous**	**plastic**	**glass**
mass %	65	10	10	15
sizes distribution (%)				
small	20	90	80	95
medium	30	10	10	5
large	50	0	10	0
m_i	975	150	150	225
$\mu_{\alpha i}$ (kg)				
small	3,2	1	0,2	1
medium	12,8	4	0,8	4
large	51,8	16	3,2	16
$v_{\alpha i}$				
Small	61	135	600	214
medium	23	4	19	3
Large	9	0	5	0
$N_{i\ (shredder)}$	93	139	623	217
ΣN_i	1072			
$p_{i\ (shredder)}$	0,087	0,129	0,582	0,202
	-0,212	-0,265	-0,315	-0,323
ΔS/k (shredder)		***1196***		
$N_{i\ (ferrous)}$	0	139	623	217
ΣN_i	979			
$p_{i\ (ferrous)}$	0,000	0,142	0,637	0,221
	0,000	-0,277	-0,287	-0,334
ΔS/k (ferrous)		***879***		
$N_{i\ (non\ ferrous)}$	0	0	623	217
ΣN_i	840			
$p_{i\ (non\ ferrous)}$	0,000	0,000	0,742	0,258
	0,000	0,000	-0,221	-0,349
ΔS/k (non ferrous)		***479***		

The diagram (Fig. 1) shows the different stages of processing. By observing the actual working of the plant we arrive to the values of the various quantities defined above. These values are displayed in Table 2 for a 1500 kg average mass vehicle.

Using these values and the formulas (1) and (2) we calculate the energy needed to complete each stage of processing and the accompanied entropy change. In figure 3 we present the energy and the entropy change compared to the energy and the entropy of the initial state of the car.

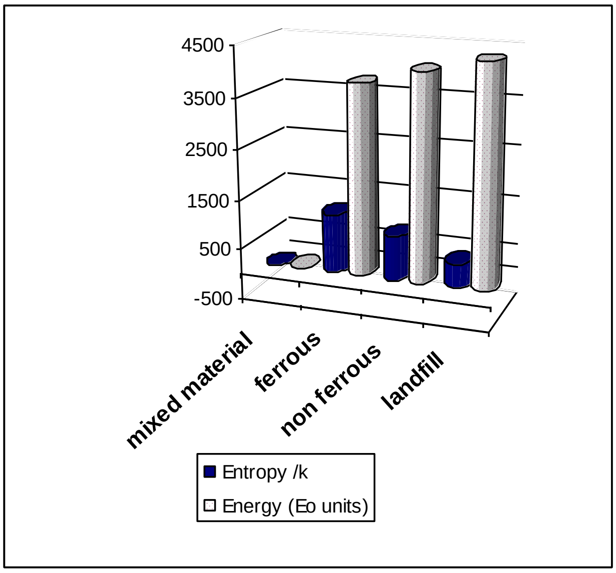

Fig. 3. Entropy and energy modeling.

RESULTS AND DISCUSSION

We have introduced several quantities in order to facilitate the quantitatively description of the processes. The determination of these quantities has led to the calculation of properties such as the required energy at each step and the accompanied change in entropy.

We notice that most of the energy goes to the shredder and ways to improve this should be sought. In addition the entropy shows a large change at the shredder stage and takes lower values as the separation proceeds. While the separation stages use some knowledge about the material, which makes it more targeted, the shredder stage is not material specific and that explains both the change in the entropy and the energy required. We have not analyzed the sensitivity of the above conclusion on the values of the quantities we have used but we don't expect any significant deviation. Currently we study the merit of the values we have picked.

By analyzing the different issues of EVL processing we find that there are several critical control points which must be considered in order to remove possible malfunctions of the procedures. The establishment of such CCPs in actual practice will help to monitor their effectiveness and also to show ways of improvement.

There are some additional aspects which are under investigation such as: the preparation of different scenarios and their merit through the time modeling of the procedures, and analysis of the materials to determine with analytical methods their chemical composition.

CONCLUSIONS

The processing of ELVs, with the new and under consideration requirements, is a novel and relatively large scale industrial function. A lot of study is needed in order to access the impact of the various parameters and to optimize many procedures and methods as there already exist strict environmental standards and need for control in the disposal chain. We have approached this problem by developing models for the qualitative and quantitative transformations of the energy and the changes of the entropy during the processing of the EVLs. We have applied the models for one of the two officially commissioned and operational ELV sites in Greece.

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