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SUSTAINABLE PRODUCTION RESEARCH - OPTIMIZATION MODEL FOR PROCESSING END-OF-LIFE VEHICLES

Abstract: *This paper focuses on the production process in the vehicle recycling factory. It presents a tactical production planning problem for vehicle recycling factory in the EU legislative environment as well as global business environment. The problem is formulated as a linear program, which provides optimal storage, processing and recovery, recycling and landfill disposal route decisions. The proposed model can help vehicle recycling factories improve their eco-efficiency and profitability, but also give answers to many important and current issues. Moreover, this paper deals with the question of which prices should be set in EU member states for landfill disposal, combustion in municipal solid waste incinerator (MSWI) and processing in advanced thermal treatment (ATT) plant in order that End-of-life vehicle Directive can have the most positive environmental effect on the vehicle recycling factory business.*

Keywords: *End-of-Life Vehicles, ELV Directive, Production Planning*

1. INTRODUCTION

The treatment of End-of-Life Vehicles (ELVs) and the environmental impact of discarding the resulting residues are subjects of worldwide concern (Simic and Dimitrijevic, 2010). ELVs are the priority in the EU waste flow. The latest data shows that 6.34 million ELVs were processed in 2008, with the average weight of 949.38 kg (Eurostat, 2010). Particularly in an attempt to reduce waste that originates from ELVs, in 2000 the EU enforced the ELV Directive (2000/53/EC). It aims at preventing waste from ELVs and protecting the environment through promoting the collection, reuse and recycling of their components (EU, 2000). According to the Directive, beginning on the 1st of January 2006, vehicle recovery must reach a minimum of 85% by weight per vehicle (with energy recovery maximum 5%), of which a minimum of 80% will have to be reuse and material recycling. By the 1st of January 2015, recovery will rise to a minimum of 95% (with energy recovery maximum raised to 10%), of which minimum 85% will have to be reuse and material recycling.

Efficient processing of automobile shredder residue (ASR) or auto fluff fraction represents a major concern for vehicle recycling factory. ASR is the waste generated during the shredding process. It is a by-product of the recycling procedure and makes up 20-25% weight of the average ELV, i.e. approximately 200kg. Vigano et al. (2010) estimated that the total ASR production in the EU can be in the range of 1.93–2.34 million tonnes per year. Moreover, this type of waste represents up to 10% of the whole amount of hazardous wastes produced per year in the EU, and about 60% of the total shredding wastes (Rossetti et al., 2006).

This paper focuses on the production process in the vehicle recycling factory. It presents a tactical production planning problem for vehicle recycling factory in the EU legislative environment as well as global business environment. The problem is formulated as a linear program, which provides optimal storage, processing, and recovery, recycling and landfill disposal route decisions.

This paper is organized as follows. Section two gives comprehensive literature review. Section 3 presents the vehicle recycling factory model. Case study is placed in the Section 4, and the Last section presents the main conclusions of the paper.

2. LITERATURE REVIEW

Literature provides a significant number of different mathematical models. Their detailed analysis is more than necessary in a need to identify the key directions of the further development of this very important and dynamic research area. Isaacs and Gupta (1997) were the first researchers to model automotive recycling infrastructure using the Goal Programming (GP) method. They analysed profitability of dismantlers and recyclers in the following cases of polymer-intensive (PI) vehicles processing: polymer share increase in the automobile material composition, mandatory plastics dismantling (25%) and increase in the price for plastics landfill disposal. Boon et al. (2003) expand Isaacs and Gupta's (1997) mathematical formulation for the recycling infrastructure to assess the materials streams and process profitability for several clean vehicles cases. Results indicate that although these vehicles may not garner the same profit levels as conventional internal combustion engine vehicles, they are profitable for the process if there are markets for parts and if there are sufficient quantities of non-ferrous materials. Gupta and Isaac (1997) solved ELV recovery planning problem using GP. Individual models were created for PI and aluminium-intensive (AI) vehicles. They reached the conclusion that the polymer share increase in the automobile material composition will not jeopardize existence of the ELV processing industry, but will deteriorate results of its business. Boon et al. (2001) use GP to model the auto recycling infrastructure and investigate materials streams and process profitability for the following AI vehicle processing scenarios: price raise of isolated non-ferrous metals, more detailed dismantling, increase in processing costs and change in AI vehicles design. They emphasized that the existing infrastructure is in most cases able to process these vehicles with making profit. Sodhi et al. (1999) investigate cases of single and all target material(s) sorting of the sequencing problem and present a solution procedure based on dynamic programming. Johnson and Wang (2002) created two types of optimisation models: American, the only one that is focused on profit, and EU model in which optimisation depends on the defined vehicle recovery rate. According to the American model of processing, recovery rates are 89.4 and 75.1% for premature and true ELV respectively. In case of the EU model of processing without energy recovery, 85.0% of recovery was possible only if recycling tires and remanufacturing more valuable parts. In case of EU model of processing with energy recovery, recovery rates are 96.1 and 85.0% for premature and true ELV respectively. Consequently, they were able to conclude that it was not possible to renew 95% weight of average ELV with the existing equipment. Kumar and Sutherland (2008) provide an overview of studies on automotive recovery infrastructure and identify following limitations of available models: inadequate description of the complex material flows and economic transactions within the infrastructure, minimal consideration of market factors (such as scrap metal prices), lack of consideration for government policies and limited variety of examined future scenarios. Chen et al. (2010) thoroughly described principles and characteristics of the ELV processing system in Taiwan and concluded that improving and optimising the process of tactical and operational planning of ELV processing is necessary in order to make recycled materials more competitive. Coates and Rahimifard (2006) present a holistic end-of-life cost model for the vehicle recovery sector and focus on the potential applications of this model to support both high and low level decisions. Coates and Rahimifard (2009) develop a post-fragmentation separation model, capable of simulating the value-added processing that a piece of automated separation equipment can have on a fragmented ELV waste stream. The model takes the input composition of the ELV waste stream and determines the most likely route of each material flow. Williams et al. (2007) 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. Qu and Williams (2008) formulate the automotive reverse production planning and pricing problem in a nonlinear programming model, develop an approximate supply function for hulks when adjacent shredders price independently, and compare Market with Optimized pricing strategy in three trends for ferrous metal and hulk prices: constant, increasing and decreasing. Proposed model is solved using the MINOS solver of the commercial software GAMS Distribution 21.3.

3. VEHICLE RECYCLING FACTORY PLANNING PROBLEM

Modelling of separation processes can provide foundation for facility optimisation, where waste flows are assessed for their value and recoverability (Coates and Rahimifard, 2009), and optimal processing route is selected based on environmental and economic drivers. A detailed flow sheet is the starting point for the formulation of the vehicle recycling factory planning model, and it is depicted in Figure 1. Presented flow sheet contains a network of various unit operations necessary for processing numerous material flows, ranging from shredding to metal producing processes and therefore gives configuration of the contemporary vehicle recycling factory. In addition, any possible route can be viewed and assessed as a potential solution of the analysed planning problem.

When the procured hulks arrive, they are unloaded from transportation vehicles and forwarded to storage. Hulks planned for recycling are successively taken over from there and transported to shredder which is the core of the vehicle recycling factory. It is a giant, 3000–8000 hp hammer mill that shreds vehicle hulks into mostly fist-size chunks to liberate the metals from everything else (Jody and Daniels, 2006). A heavy duty cyclone is usually installed on top of the shredder to vacuum the light ASR fraction. This fraction can be further sorted or shipped to selected advanced thermal treatment (ATT) plant. If the first option is chosen, then the second magnetic sorter separates this material flow to ferrous metals 2 and non-ferrous (NF) mix fractions. NF mix can also be further sorted to isolate non-ferrous metals from it, sent to selected ATT plant or disposed on landfill. If the first option is chosen, then the second eddy current sorter separates this material flow to non-ferrous metals 2 and second fraction of non metals, which will then be routed to the optimal destination.

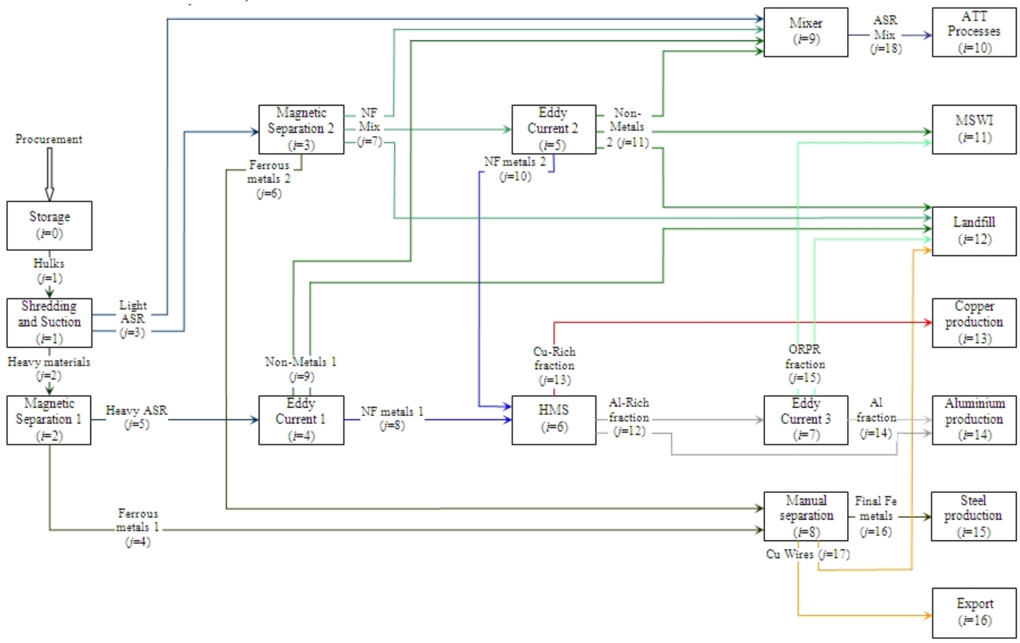

Figure 1 – Flow sheet of the contemporary vehicle recycling factory

Heavy materials fraction passes through the first magnetic sorter which diverts the ferrous metals 1 from the heavy ASR fraction. Market requirements dictate that both fractions of ferrous metals are firstly manually treated along a conveyor for possible impurities (above all, for insulated Cu wires), and only then sold to steel industry. As for the fraction of insulated Cu wires, two routes are possible, export and (manual) recycling in low cost labour countries, and landfill disposal. Incineration of this fraction in municipal solid waste incinerator (MSWI) has not been taken into consideration for the reasons of financial unfeasibility (Bellmann and Khare, 1999) and ecological unacceptability. Heavy ASR fraction is forwarded to the first eddy current sorter which separates it to non-ferrous metals 1 and the first fraction of non-metals. As shown in Figure 1, the first and the second fraction of non-ferrous metals are then routed to heavy media sorter (HMS). HMS is filled with medium of specific gravity equals to 3.5 tonnes/m3 and separates Al-rich and Cu-Rich fractions. Alternatively, it is common for HMS to utilise heavy liquids such as Magnetite and Ferro-silicate solutions having specific densities of 1.5 and 3.5 tonnes/m3 respectively (Coates and Rahimifard, 2009). Al-rich fraction can be sold as is, or routed on the third eddy current sorter for further refinement from organics, rubber, plastics and rest fraction (ORPR). Isolated ORPR fraction can be either incinerated in MSWI or landfilled. In addition, more detailed description of processing and cost features of sorting equipment, MSWI and ATT processes can be found in the Case study section.

3.1. Notation

The following notation is used.

Indices and sets

- i – Index of entity; $i \in \{0,\ldots,I\text{-}1\}$
- j – Index of material flow; $j \in \{1,\ldots,J\}$
- t – Index of time period; $t \in \{1,\ldots,T\}$

- A_i – Set of material flows isolated with sorting entity (i.e., sorting equipment and manual processes) i; $i \in \{1,\ldots,I\text{-}I'\text{-}2\}$
- Ψ_j – Set of sorting equipment and manual processes, and/or (pre)destination(s) for material flow j; $j \in \{2,\ldots,J\}$
- Ω_i – Set of entities which route materials to entity i; $i \in \{1,\ldots,I\text{-}1\}$
- Φ_i – Set of entities on which materials are routed from entity i; $i \in \{1,\ldots,I\text{-}I'\text{-}1\}$
- F – Set of destinations where material recycling take place
- M – Set of various metal producers in EU member state or other country
- D – Set of destinations where energy recovery takes place

Parameters

- I – Number of entities, where entities of analysed flow sheet are sorting equipment and manual processes, mixer or predestination, destination and storage
- J – Number of material flows
- T – Number of analysed time periods
- I' – Number of destinations
- S_0 – Initial inventory weight of hulks
- S_{min} – Safety inventory level
- C_i – Processing capacity of sorting equipment or process i per time period
- E_{ij} – Efficiency of sorting entity i in the case of material flow j in percents
- E_i^R – Recycling efficiency of destination i in percents
- E_i^E – Energy efficiency of destination i in percents
- Q_R – Recycling quota
- $Q_{R'}$ – Recovery quota
- Q_E – Energy quota
- $R_{i'it}$ – Sale price of metal sorted on entity i' to destination i per weight unit in period t
- C_i^A – (Advanced) thermal treatment cost in destination facility i per weight unit
- C_i^L – Landfill disposal cost of ASR sorted on entity i per weight unit
- C_t^P – Procurement cost price per weight unit in period t
- C^I – Inventory holding cost rate per time period
- C_i^S – Sorting cost of material flow on sorting entity i per unit weight
- $C_{i'i}^T$ – Transportation cost per weight unit of material sorted or mixed on entity i' to destination i per weight unit

Variables

- S_t – Weight of hulks in storage at the end of time period t
- P_t – Weight of incoming procurement in period t
- $X_{ii't}$ – Weight of material flow routed from entity i to entity i' in time period t

3.2. Model formulation

Based on these notations, the production planning problem for vehicle recycling factory can be formulated as a linear programming model.

$$\begin{aligned} \text{MAX} \quad & \sum_{t=1}^{T}\sum_{i=13}^{I-1}\sum_{i'\in\Omega_i} X_{i'it}R_{i'it} \\ & - \sum_{t=1}^{T}\sum_{i=I-I'}^{11} C_i^A \sum_{i'\in\Omega_i} X_{i'it} \\ & - \sum_{t=1}^{T}\sum_{i\in\Omega_{12}} X_{i12t}C_i^L - \sum_{t=1}^{T} C_t^P P_t \\ & - C^I \sum_{t=1}^{T} S_t - \sum_{t=1}^{T}\sum_{i=1}^{I-I'-2} C_i^S \sum_{i'\in\Omega_i} X_{i'it} \\ & - \sum_{t=1}^{T}\sum_{i=I-I'}^{I}\sum_{i'\in\Omega_i} X_{i'it}C_{i'i}^T \end{aligned} \qquad (1)$$

Subject to:

$$S_t = \begin{cases} P_t + S_0 - X_{01\,t} & \text{if } t=1 \\ P_t + S_{t-1} - X_{01\,t} & \text{if } t=2,\ldots,T \end{cases} \quad (2)$$

$$S_t \geq S_{min} \qquad \forall\, t \; (3)$$

$$\sum_{i' \in \Omega_i} X_{i'\,i\,t} \leq C_i \quad i=1,\ldots,I\text{-}I'\text{-}2; \qquad \forall\, t \; (4)$$

$$\sum_{j' \in \Psi_j} X_{i\,j'\,t} = E_{i\,j} \sum_{i' \in \Omega_i} X_{i'\,i\,t} \quad i=1,\ldots,I\text{-}I'\text{-}2;$$

$j \in \mathrm{A}_i$; $\forall\, t$ (5)

$$X_{i\,j\,t} = \sum_{i' \in \Omega_i} X_{i'\,i\,t} \quad i=9; j=10; \; \forall\, t \qquad (6)$$

$$\sum_{i \in \mathrm{M}} \sum_{i' \in \Omega_i} X_{i'\,i\,t} + \sum_{i \in \mathrm{F}} E_i^R \sum_{i' \in \Omega_i} X_{i'\,i\,t} \geq Q_R X_{01t}$$

$\forall\, t$ (7)

$$\sum_{i \in \mathrm{M}} \sum_{i' \in \Omega_i} X_{i'\,i\,t} + \sum_{i \in \mathrm{F}} E_i^R \sum_{i' \in \Omega_i} X_{i'\,i\,t} + \sum_{i \in \mathrm{D}} E_i^E \sum_{i' \in \Omega_i} X_{i'\,i\,t} \geq Q_{R'} X_{01t} \qquad \forall\, t \; (8)$$

$$\sum_{i \in \mathrm{D}} E_i^E \sum_{i' \in \Omega_i} X_{i'\,i\,t} \leq Q_E X_{01t} \qquad \forall\, t \; (9)$$

$$P_t \geq 0, S_t \geq 0 \qquad \forall\, t \; (10)$$

$$X_{i\,j\,t} \geq 0 \qquad i=0,\ldots,I\text{-}I'\text{-}1; j \in \Phi_i; \; \forall\, t \; (11)$$

The objective function (1) seeks to maximize the profit of the vehicle recycling facility over planning horizon. In the objective function, the first term represents income from the isolated metals sale, the second term represents costs for (advanced) thermal treatment of ASR, the third term relates to ASR landfill disposal costs, the fourth term calculates the procurement costs, the fifth term represents storage costs for hulks that have not been assigned for recycling, the sixth term presents material sorting costs and the last term presents costs for material transport to the final destination.

Constraints (2) enforce the inventory balances, i.e. weight of the stored hulks at the end of t period is determined when the total quantity of procured and available hulks is reduced by the weight of hulks planned for recycling in the analysed period. Since the shipping of procured vehicle hulks depends on transportation congestion and weather (Qu and Williams, 2008), the automotive recycling factory seeks to keep enough hulks to maintain the minimum processing rate. Therefore, constraints (3) ensure the safety stock level of hulks. Constraints (4) represent processing capacity of available sorting entities, and constraints (5) maintain their material flow balances. Constraints (6) describe the mixing operation. Mixer has been defined in the model in order to combine the various residual fractions to ASR mix fraction, which can be transported to the selected ATT plant. Constraints (7)-(9) represent specific eco-efficiency requirements imposed by ELV Directive. More detailed, percentage of recycling cannot be less than the prescribed recycling quota (constraints (7)), percentage of recovery cannot be less than the prescribed recovery quota (constraints (8)) and percentage of energy recovery cannot be larger than the prescribed energy quota (constraints (9)). In addition, efficiency of the automotive recycling factory, i.e. attained recycling, recovery and energy recovery quotas should be calculated according to ISO 22628 standards, which was especially emphasized by Santini et al. (2011). In the above mentioned standard, recyclability and recoverability rate are simply defined as the ratio between the sum of the mass of materials reused/recycled/recovered during dismantling, metal separation and non metallic residue treatment and the "complete vehicle kerb mass" (ISO 22628:2002). Finally, constraints (10)-(11) define value domain (i.e. non-negativity) of decision variables.

4. CONCLUSION

World economy has already overcome the economic crisis and the expected recovery of the metals market began. Vehicle recycling factory benefits greatly from it, as high prices for secondary metals make its business exceptionally profitable, even in strictly controlled and legally rigorous production conditions. Testing the proposed model proved that in such conditions automobile recycling factory will continuously procure the maximum quantity of hulks that it is able to process according to the planning period, as well as that it aims at achieving the highest quantity and the best quality of sorted metal flows.

The country is expected to create optimal business conditions for its legal entities and it represents an important actor in the automotive supply chain. That is why this paper gives answer about financial conditions that are required in an EU member state in order for ELV Directive to have the most positive eco-effect on the vehicle recycling factory business. In case of valid quotas, the best ecological result will be attained at a high price for ASR landfill disposal, and a low price for processing in ATT plant. On the other hand, after the 1st of January 2015, EU member states will have to raise their prices for landfill disposals and do what's in their power to lower ATT and MSWI costs if they want their vehicle recycling factories "painted in green".

ELV Directive regulates the quotas that the recycling system must comply with, while at the same time no consideration was given to the fact that dismantlers, on one side, and vehicle recycling factories, on the other, are completely independent in their business. Comprehensive testing of the proposed model showed that the control of the recycling system efficiency should be done at the level of the entire system, since that will in no way jeopardize the ELV Directive objectives.

The most important conclusion reached during the research of individual influence of available financial instruments is that the increase in price for landfill disposal will not always reduce the quantity of disposed ASR. Moreover, until the 1st of January 2015, the mentioned increase in price will have no effect at high ATT and MSWI prices, and after this date it will be justified only if the ATT price is low.

The proposed model of production planning can be of assistance not only to European vehicle recycling factories with the aim of improving their eco-efficiency and profitability, but also, for example, to Japanese and Chinese factories if the model also implements environmental efficiency requirements imposed by the Japanese ELV Recycling Law and Chinese Automobile Industry Development Policy respectively.

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