END-OF-LIFE VEHICLE RECYCLING IN THE REPUBLIC OF SERBIA: INTERVAL LINEAR PROGRAMMING MODEL FOR LONG-TERM PLANNING UNDER UNCERTAINTY

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Abstract: *Nowadays, end-of-life vehicles (ELVs) are considered as a burning environmental issue, since this kind of waste contains many precious metals. Recycling and reuse of ELV parts and components, and metal recovery are important to governments, manufacturers, suppliers, dismantlers and vehicle recycling factories worldwide. Current, not so bright, situation in the Republic of Serbia regarding the recycling of ELVs and a noticeable tendency towards creation of economically sustainable recycling system represent major motives for projection and modeling of vehicle recycling system that would be the most cost-effective and eco-efficient in the long run. In this paper, interval linear programming (ILP) approach is used to formulate model for optimal long-term planning in the Serbian vehicle recycling factories under uncertainty. Presented ILP model is valuable for supporting the construction and/or modernization process of vehicle recycling system in the Republic of Serbia.*

Keywords: *End-of-life vehicle, Interval linear programming, Republic of Serbia, Serbian ELV Ordinance, Uncertainty.*

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1. INTRODUCTION

The management of special wastes flows is currently one of the most important ecological topics worldwide. From the angle of quantity, end-of-life vehicles (ELVs) represent one of top priority wastes.

ELV recycling problem has in the last several years become rather important in the Republic of Serbia as well. By passing the National strategy of waste management with the attached EU advancement program, Waste management law, Waste management strategy for period 2010-2019 and the Ordinance on the management of ELVs in the Republic of Serbia (Serbian ELV Ordinance) (MERS, 2010), the Government managed to include Serbia in the group of countries that took long term solving of vehicle recycling problem responsibly and constructively.

In the Republic of Serbia, there is no vehicle recycling system. This process is carried out only in a few simple plants for recycling of metal waste that are in no way sufficiently equipped to successfully respond to this exceptionally complex task. On the other hand, vehicle recycling issue is being given more attention, especially since 2008 when the new Waste management law was passed. However, although article 55 of this Law is dedicated to the management of ELVs, from the vehicle recycling aspect this regulation cannot be considered contemporary. That is why the Waste management strategy for period 2010-2019, passed in May 2010, pays special attention to the vehicle recycling problem. This strategy clearly emphasizes the need to set up economically sustainable vehicle recycling system as soon as possible. The Serbian ELV Ordinance came into effect in December 2010 and Appendix 3, in the tradition of the Directive on end-of-life vehicles 2000/53/EC (EU ELV Directive), regulates ecological requirements for collection, reuse and recycling of ELVs. More detailed, from January 1, 2015, recycling rate and recovery rate must not be smaller than 80% and 85% respectively, while energy recovery rate cannot be more than 5%. Additionally, on January 1, 2019, of stringent quotas are planned to be introduced: minimal rates of recycling and recovery of 85% and 95% respectively, and maximal energy recovery rate of 10%.

The main objective of this paper is to develop an interval linear programming (ILP) model for long-term planning of vehicle recycling in the Republic of Serbia. This model could have significant practical value, as it may serve as the basis for the development of modern recycling system in the Republic of Serbia.

The remaining part of the paper is organised as follows: Section 2 presents review of state-of-the-art papers published in the past five years. Section 3 presents the used methodology, and developed ILP model. Section 4 presents preliminary results analysis and short discussion. Section 5 presents the paper's main conclusions.

2. LITERATURE REVIEW

In this section, an overview of the recent literature related to the environmental engineering issues in the area of ELV recycling is performed in order to identify the key direction(s) for the further development of this very dynamic research area.

Kumar and Sutherland (2009) created a simulation model for material flows and economic exchanges to examine the effects of changes in vehicle material composition on the US recycling infrastructure. They found that with change in vehicle design the profit of vehicle recycling factories will increase over time, due to the additional revenue from the aluminium in aluminium intensive vehicle hulks.

Mathieux and Brissaud (2010) proposed method to build an end-of-life product specific material flow analysis and applied it to aluminium coming from end-of-life commercial vehicles in EU. However, they pointed out that the implementation of the method requires a lot of field effort.

Vermeulen et al. (2012) proposed a set of seven sustainability indicators suitable for assessing and comparing industrial waste treatment processes. The proposed overall sustainability assessment method is applied to ASR case study. It is outlined that recycling combined with energy recovery was the most sustainable processing strategy as it enabled to reach the EU ELV Directive quotas set by 2015. Simić and Dimitrijević (2012b) presented a tactical production planning problem for vehicle recycling factories in the EU legislative and global business environments. They analyzed influence of the EU ELV Directive on the vehicle recycling facilities business and concluded that future eco-efficiency quotas will not endanger their profitability. In addition, they recommended that the control of the recycling system efficiency should be done at the system level because it will in no way jeopardise the EU ELV Directive objectives. Simić and Dimitrijević (2012a) expanded linear programming modelling framework proposed by Simić and Dimitrijević (2012b) in order to incorporate vehicle hulk selection problem and to answer to the following questions: Can contemporary equipped vehicle recycling facility conduct profitable business? Are EU ELV Directive's eco-efficiency quotas actually attainable? How will the commenced change in vehicle design influence vehicle recycling facilities? To do so, they provided a production planning model of a contemporary equipped vehicle recycling facility and tested it extensively using real data. They came to the conclusion that vehicle recycling facility transformation, from traditional to contemporary equipped, is not only necessary but completely justified and that the final success of the EU ELV Directive is realistic.

Simić and Dimitrijević (2013a) proposed a short-term ASR recycling planning model for Japanese vehicle recycling industry, which can be used to improve its profitability and recycling efficiency. The change in vehicle design, observed from the aspect of substituting ferrous metals with aluminium, will not jeopardize Japanese vehicle recycling system. Influence of the Japanese law on recycling of ELVs is found to be crucial for the decision making on ASR recycling, as the 20% increase in valid ASR recycling quota will cause approximately 50% decrease in the quantity of disposed ASR. Simić and Dimitrijević (2013b) developed a risk explicit interval linear programming model for optimal long-term planning in the EU vehicle recycling factories to analyze the linkage and trade-offs between decision risk and system performances. They found that introduction of the stringent eco-efficiency quotas will radically reduce the quantity of land-filled wastes in EU; waste quantities routed to the landfills will be reduced from 3.5 to 11.0 times, the waste shipped to the ATT plants will be larger in quantity than the waste shipped to the landfills, while the waste combustion in MSWIs will increase to up to 4.4 times.

From the review of previous literature, it is evident that there is a lack of research of uncertainties that exist in vehicle recycling planning and none of the previous studies analysed vehicle recycling problem in the Republic of Serbia. Moreover, not so bright situation in the Republic of Serbia regarding the recycling of ELVs and a noticeable tendency towards creation of economically sustainable recycling system represent additional motives for projection and modelling of vehicle recycling system that would be the most cost-effective and eco-efficient in the long run. On the other hand, in a vehicle recycling system, it is difficult to express or obtain the overall modelling data in deterministic form. However, they all can be obtained as interval values and the approach to tackling such a problem is called interval linear programming. It can deal with the uncertain modelling parameters expressed as intervals without any distributional information. Therefore, ILP approach is used in this paper to describe and treat imprecise and uncertain parameters.

3. METHODOLOGY

3.1 Overview of the projected Serbian vehicle recycling system

Fig. 1 presents flow diagram of the projected vehicle recycling system in the Republic of Serbia. It was created on the basis of the following documents: 1. Serbian ELV Ordinance; 2. Waste management strategy for period 2010-2019; 3. Waste management law; 4. National strategy of waste management with the attached EU advancement program.

It is evident in Fig. 1 that there are four actor groups involved in vehicle recycling procedure in the Republic of Serbia. The first group includes vehicle users that are at the same time also network sources. This group consists of new vehicle buyers, second-hand vehicle buyers and/or last owners. Every vehicle user is required to deliver ELV to the person that does collection and/or its primary treatment, i.e. dismantling (MERS, 2010).

The second group is represented by collection agents and dismantling companies. Collection agents entity consists of scrap yards, vehicle dealers and repair shops. Serbian ELV Ordinance enacted that they must have proper license to conduct this business and storage space.

Vehicle recycling factory represents dominant participant of the projected system. Besides, currently there is no vehicle recycling factory in the Republic of Serbia, but the integrated process of dismantling and primary recycling is done only in several plants for metal waste treatment. More detailed, Serbian Government allowed recycling of end-of-life vehicles to only nine companies. They are by no means sufficiently equipped to successfully fulfil the very complex task of vehicle recycling. That is why it is necessary to build a vehicle recycling factory as soon as possible, as it would have significance not only for the Republic of Serbia, but for the whole region as well.

Lastly, the fourth actor's group consists of seven final destinations. In integrated recycling system, vehicle recycling factory can allocate sorted waste flows to several waste entities, i.e. landfill, MSWI or ATT plant. It should be mentioned that in the region there isn't a single plant for advanced thermal treatment and that is why this entity is presented with dashed line in Fig. 1. In addition, municipal solid waste incinerator does not exist in the region. On the other hand, sorted metals can be allocated to steel mill, copper production plant and aluminium production plant. Collected insulated cooper wires are sold to secondary material buyers for further recycling.

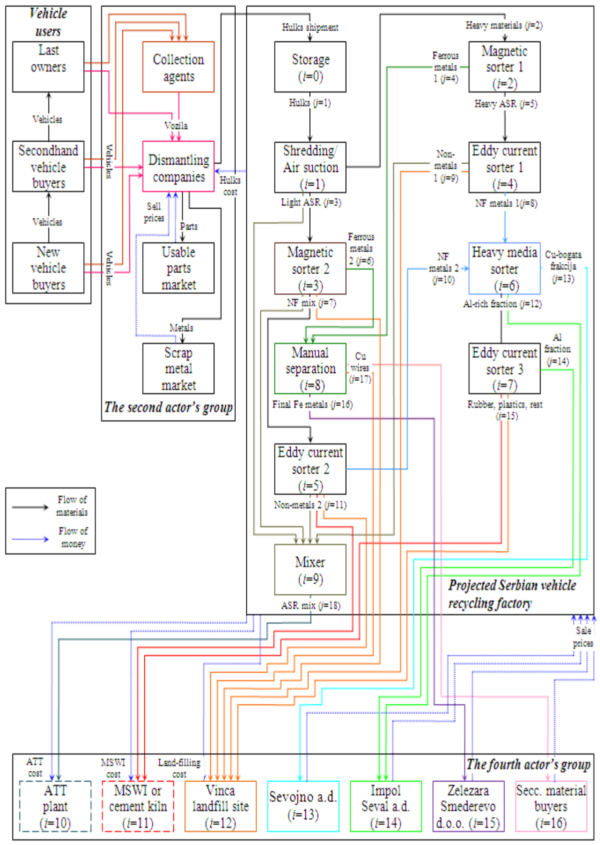

Figure 1. Flow sheet of the projected Serbian vehicle recycling system

3.2 ILP model for long-term planning of vehicle recycling in the Republic of Serbia under uncertainty

Many methods have been developed to deal with uncertainties. One of them is the ILP method (Tong, 1994).

The proposed model tackles a long-term end-of-life vehicles recycling planning problem in the Republic of Serbia. Its objective is to maximize profit of the projected contemporary equipped vehicle recycling factory over the planning horizon. The formulated model provides optimal interval solutions for procurement, storage, hulk shredding, processing liberated material fractions, recycling, advanced thermal treatment (if plant of this type is available), incineration in MSWI (if incinerator is available or incineration is arranged with the local cement kiln) and land-filling. It is formulated as follows:

$$\text{Max } f^{\pm} = \sum_{t=1}^{T} \sum_{i'=I-|M|}^{I-1} \sum_{i \in \Omega_{i'}} R_{ii't}^{\pm} X_{ii't} - \sum_{t=1}^{T} CP_t^{\pm} P_t$$
$$- \sum_{t=1}^{T} \sum_{i'=1}^{I-I'-2} \sum_{i \in \Omega_{i'}} CS_{i't}^{\pm} X_{ii't} - \sum_{t=1}^{T} Z_t^{\pm} CP_t^{\pm} S_t$$
$$- \sum_{t=1}^{T} (CA_t^{\pm} + CB_t^{\pm}) Y_t - \sum_{t=1}^{T} \sum_{i'=I-I'+1}^{I-1} \sum_{i \in \Omega_{i'}} CT_{ii't}^{\pm} X_{ii't} \quad (1)$$
$$- \sum_{t=1}^{T} CM_t^{\pm} \sum_{i' \in \Omega_{I-I'+1}} X_{i' I-I'+1 t}$$
$$- \sum_{t=1}^{T} CL_t^{\pm} \sum_{i \in \Omega_{I-I'+2}} X_{i I-I'+2 t}$$

subject to:

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

$$S_t \ge S_{min}^{\pm}, \quad t = 1,\dots,T \quad (3)$$

$$\sum_{i' \in \Omega_i} V_i^{\pm} X_{i'it} \le \Lambda, \; i = 1,\dots,I-I'-2; \; t = 1,\dots,T \quad (4)$$

$$\sum_{i'' \in \Psi_j} X_{ii''t} = E_{ij}^{\pm} \sum_{i' \in \Omega_i} X_{i'it}, \quad i = 1,\dots,I-I'-2; \; j \in A_i; \; t = 1,\dots,T \quad (5)$$

$$\sum_{j \in A_i} \sum_{i'' \in \Psi_j} X_{ii''t} = \sum_{i' \in \Omega_i} X_{i'it}, \quad i = 1,\dots,I-I'-2; \; t = 1,\dots,T \quad (6)$$

$$Y_t = \sum_{i \in \Omega_{i'}} X_{ii't}, \; i' = I - I' - 1; \; t = 1,\dots,T \quad (7)$$

$$\sum_{i' \in M} \sum_{i \in \Omega_{i'}} X_{ii't} + ER_{I-I'}^{\pm} Y_t \ge Q_R X_{01t}, \; t = 1,\dots,T \quad (8)$$

$$\sum_{i' \in M} \sum_{i \in \Omega_{i'}} X_{ii't} + \left(ER_{I-I'}^{\pm} + EE_{I-I'}^{\pm}\right) Y_t + EE_{I-I'+1}^{\pm} \sum_{i \in \Omega_{I-I'+1}} X_{i I-I'+1 t} \ge Q_{R'} X_{01t}, \quad t = 1,\dots,T \quad (9)$$

$$EE_{I-I'}^{\pm} Y_t + EE_{I-I'+1}^{\pm} \sum_{i \in \Omega_{I-I'+1}} X_{i I-I'+1 t} \le Q_E X_{01t}, \; t = 1,\dots,T \quad (10)$$

$$P_t \ge 0, \; S_t \ge 0, \; Y_t \ge 0, \quad t = 1,\dots,T \quad (11)$$

$$X_{ii't} \ge 0, \; i = 0,\dots,I-I'-2; \; i' \in \Phi_i; \; t = 1,\dots,T \quad (12)$$

In previous modelling formulation *indices and sets* are: i is index of entity; $i \in \{0,\dots,I\text{-}1\}$; j is index of material flow; $j \in \{1,\dots,J\}$; t is index of time period; $t \in \{1,\dots,T\}$; A_i is set of material flows isolated with sorting entity i; $i \in \{1,\dots,I\text{-}I'\text{-}2\}$; Ψ_j is set of entities on which material flow j is forwarded; $j \in \{2,\dots,J\}$; Ω_i is set of entities that route materials to entity i; $i \in \{1,\dots,I\text{-}1\}$; Φ_i is set of entities on which materials are routed from entity i; $i \in \{0,\dots,I\text{-}I'\text{-}1\}$; and M is set of various metal producers in the Republic of Serbia. *Parameters* of developed model are: I is number of entities; J is number of material flows; T is number of analysed time periods; I' is number of destinations; S_0 is initial inventory weight of vehicle hulks; $S_{min}^{\pm}$ is interval value of safety inventory level; $V_i^{\pm}$ is interval value of processing time per unit weight on entity i; Λ is duration of planning period in time units; $ER_i^{\pm}$ is interval value of recycling efficiency of destination i in percentages; $EE_i^{\pm}$ is interval value of energy efficiency of destination i in percentages; $E_{ij}^{\pm}$ is interval value of efficiency of sorting entity i in the case of material flow j in percentages; Q_R is Serbian ELV Ordinance recycling quota; $Q_{R'}$ is Serbian ELV Ordinance recovery quota; Q_E is Serbian ELV Ordinance energy quota; $R_{ii't}^{\pm}$ is interval value of revenue from each unit weight of metal fraction sorted on entity i and sold to destination i' in period t; $CA_t^{\pm}$ is interval value of advanced thermal treatment cost in period t per weight unit; $CM_t^{\pm}$ is interval value of incineration cost in MSWI or cement kiln in period t per weight unit; $CB_t^{\pm}$ is interval value of transportation cost per weight unit of ASR mix fraction in period t; $CL_t^{\pm}$ is interval value of land-filling cost per weight unit in period t; $CP_t^{\pm}$ is interval value of vehicle hulks procurement cost per weight unit in period t; $Z_t^{\pm}$ is percentage of capital cost for inventory in period t; $CS_{it}^{\pm}$ is sorting cost per weight unit in the case of entity i and period t; and $CT_{ii't}^{\pm}$ is transportation cost from entity i to destination i' per weight unit in period t. Finally, *variables* of developed model are: S_t is weight of vehicle hulks in storage at the end of period t; P_t is weight of incoming vehicle hulks procurement in period t; $X_{ii't}$ is weight of material flow routed from entity i to i' in period t; and Y_t is weight of ASR mix fraction in period t.

The objective function (1) seeks to maximise the vehicle recycling factory's profit over the planning horizon. In the objective function, the first term represents income from sale of the isolated metals. The second term of the objective function represents procurement costs of vehicle hulks from dismantling companies, the third term calculates material fragmentation and sorting costs, and the fourth term relates to the storage cost for hulks that have not been assigned for recycling. The fifth term of the objective function calculates cost for advanced thermal treatment of isolated ASR. The sixth term of the objective function relates to transportation costs of sorted metals to the final destinations and isolated waste materials to the waste entities. The sixth term of the objective function defines costs of incineration in MSWI or in cement kiln. The last term of the objective function calculates the costs of land-filling.

Constraints (2) enforce the inventory balances. Constraints (3) ensure the safety stock level of vehicle hulks in order to protect the shredder from starvation. Constraints (4) represent the processing capacity of shredder and sorting entities, while constraints (5)–(6) maintain their material flow balance. Constraints (7) describe operations of mixing light ASR fraction, non-ferrous mix fraction, the first and the second non-metals fractions into the ASR mix fraction. The presence of constraints (7) in the model for long-term planning of vehicle recycling in the Republic of Serbia under uncertainty makes sense only when ATT plant is available. Constraints (8)-(10) represent specific eco-efficiency requirements imposed by the Serbian ELV Ordinance. Finally, constraints (11)-(12) define the value domains of decision variables used in the proposed model.

4. RESULT ANALYSIS AND DISCUSSION

In this section formulated model is applied to a numerical case study which analyzes period 2013-2014 (characterized with the absence of law regulation on the vehicle recycling system in the Republic of Serbia), three scrap metal price trends are investigated, as well as the availability of final destinations for sorted waste flows (Table 1)[2]. More detailed, investigated scrap metal price trends were: slight volatility trend (the market prices for sorted metals and vehicle hulks slightly change at [-2.50; 2.50] %/year value interval), moderate growth trend (the price values increase at [2.51; 5.0] %/year value interval) and strong growth trend (the price values increase at [5.01; 15.0] %/year value interval). Additionally, to account for the dynamics of various modelling parameters, long-term planning horizon is divided into two periods, each having a time interval of one year.

Optimal decisions for all created test problems were solved using the LINGO 13.0 solver on a Toshiba Qosmio with an Intel Core i5-430 M mobile technology processor. The CPU times for all test problems varied from less than one second to several seconds.

Table 1. Overview of created test problems

Test problem	Scenario	Availability of thermal treatment entities	
		ATT plant	Incinerator
1	Slight volatility trend	Unavailable	Unavailable
2		Unavailable	Available
3	Moderate growth trend	Unavailable	Unavailable
4		Unavailable	Available
5	Strong growth trend	Unavailable	Unavailable
6		Unavailable	Available

Profits per ton of processed vehicle hulks and recycling, recovery, and energy recovery efficiencies of the optimal decisions for the 6 test problems are summarised in Table 2.

Table 2. Case study profits and eco-efficiencies

Test problem	Algorithm solution	Profit	Recovery rate (%)	Recycling rate (%)	Energy recovery rate (%)
1	The best	306.86	82.96	82.96	0.0
	The worst	106.13	82.96	82.96	0.0
2	The best	312.45	92.94	82.96	9.98
	The worst	106.13	82.96	82.96	0.0
3	The best	315.22	82.96	82.96	0.0
	The worst	129.39	82.96	82.96	0.0
4	The best	320.81	92.94	82.96	9.98
	The worst	129.39	82.96	82.96	0.0
5	The best	388.57	82.96	82.96	0.0
	The worst	115.49	82.96	82.96	0.0
6	The best	394.30	92.94	82.96	9.98
	The worst	115.49	82.96	82.96	0.0

Analysis of the financial results of the projected vehicle recycling factory shows that the lowest profit of [106.13; 306.86] €/tonne of processed vehicle hulks was made in the first test problem (when scrap metal prices showed slight volatility trend and there was no possibility for waste incineration), and the highest profit of [115.49; 394.30] €/tonne of processed vehicle hulks was made in the sixth test problem (when scrap metal prices showed strong growth trend and waste incineration was a viable option). Such a result is a direct consequence of the sixth test problem predicting a far more suitable trend in scrap metal prices change. In addition, it should be mentioned that a higher value of the right profit bound was made in test problems which allowed incineration of isolated waste (i.e. the best solutions of test problems 2, 4 and 6), because in that situation incineration presents a financially more favorable destination for isolated waste materials. Availability of incinerator (MSWI and/or cement kiln incinerator) did not influence calculations of the worst solution of test problems 2,

[2] Due to page limitation data used in this numerical study is not presented. All data is available upon request.

4 and 6, because then land-filling is more cost-effective than incineration.

Regarding the eco-efficiency, recovery and recycling rates were 82.96%, except in the situations when it was possible to incinerate isolated waste and decision making was optimistically oriented. More detailed, when the best solution of test problems 2, 4 and 6 were explored, it was found that recovery rate and recycling rate were increased to 92.94% and 9.98% respectively (Table 2).

As for the inventory management, their level was during entire testing equal to the safety inventory level. In addition, it has been identified that vehicle recycling factory favours the approach of ordering the exact quantities of hulks that can be processed, which clearly indicates their intention to avoid unnecessary costs for storing excess hulks.

Regarding the sorting decisions, it has been clearly identified that the vehicle recycling factory aims at reaching the highest possible level of quantity and quality of sorted metal flows, regardless of the value of eco-efficiency quotas. Both ASR fractions are always mechanically recycled, primarily in order to isolate valuable non-ferrous metals. The Al-rich fraction is always additionally purified, because the additional income always exceeds the costs of its sorting.

5. CONCLUSION

The formulated model can reduce the risk of uncertain situations in the projected Serbian vehicle recycling system (Fig. 1). It provides optimal solutions to fully interval ELV recycling planning problem which helps the recycling managers to analyze economic activities and to arrive at the best decisions. More detailed, it useful for creating optimal long-term plans for procuring vehicle hulks, sorting generated material fractions, allocating sorted waste flows and allocating sorted metals.

Presented model can be of assistance not only to domestic ELV recyclers, but also to our policy makers in order to analyse the Serbian ELV Ordinance influence on vehicle recycling industry behaviour.

Future research will focus on more extensive testing of the proposed model and creating strategic production guidelines for Serbian vehicle recycling system, and making capacity strategies for all waste entities.

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