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Modelling of automobile shredder residue recycling in the Japanese legislative context

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ABSTRACT

End-of-life vehicles (ELVs) represent one of the most important waste flows in Japan and 3.58 million was processed only in fiscal year 2008. In an attempt to reduce waste originating from ELVs, the Japanese Government introduced the ELV Recycling Law in 2002. Automobile shredder residue (ASR) recycling is essential to achieving the goals of the ELV Recycling Law and represents a major concern for the Japanese vehicle recycling industry. This paper proposes the tactical ASR recycling planning model, which can be used to assist Japanese vehicle recyclers to improve their profitability and ASR recycling efficiency. A numerical study is conducted in order to illustrate the potentials and applicability of the proposed modelling approach, and to gain insights into the performances of the Japanese vehicle recycling system and into the influence of the ELV Recycling Law. Sensitivity analyses demonstrate and validate the approach and its potentials. ELV Recycling Law influence is found to be crucial for the decision making on ASR recycling, as the 20% increase in valid recycling quota will cause approximately 50% decrease in the quantity of disposed ASR. We show that the stringent ASR recycling quota is easily attainable and present many interesting insights.

1. Introduction

End-of-life vehicles (ELVs) are returns generated at the products' end-of-life stage (Olugu & Wong, 2012). Nowadays, ELVs are considered a burning environmental issue, since this kind of waste contains many precious metals.

Car ownership in Japan totals around 58.3 million vehicles (JAMA, 2011b), while an average useful life of cars in only 11 years (JAMA, 2011a; Kumar & Yamaoka, 2007). Owing to the well known shortage in industrial landfill capacity in Japan, confirmed by the figure of only 176.39 million m^3 of the remaining space (MOE, 2011), the reduction of waste from vehicles has become an issue of major concern. Therefore, it is obvious that ELVs represent one of the most important waste flows in Japan and 3.58 million was processed only in fiscal year 2008 (MOE, 2010).

In an attempt to reduce waste originating from ELVs, the Japanese Government introduced the ELV Recycling Law in July 2002 (MOE, 2002). It was enforced in January 2005 and automobile manufacturers and importers (hereafter collectively called automakers) were required to collect and recover air bags, chlorofluorocarbons/hydrofluorocarbons (CFCs/HFCs) and automobile shredder residue (ASR) generated during the process of recycling ELVs. The purpose of the ELV Recycling Law is to create a new recycling system for the proper processing and disposal of ELVs and their efficient use as resources (Zhao & Chen, 2011). ASR recycling is essential to achieving the goals of the ELV Recycling Law and represents a major concern for Japanese vehicle recycling industry. According to MOE (2002), the target recycling quota for ASR is 50% by fiscal year 2010 and 70% by fiscal year 2015. ASR is usually defined as the 15–25% of ELV's mass remaining after de-pollution, dismantling, shredding of the hulk, and removal of ferrous metals from the shredded fraction (Vermeulen, Van Caneghem, Block, Baeyens, & Vandecasteele, 2011). It is the finely pulverised waste (Giannouli, de Haan, Keller, & Samaras, 2007), which is considered an energy source as it contains more than 7% combustible matter (Smink, 2007). ASR contains plastics (19–31%), rubber (20%), textiles and fibre materials (10–42%) and wood (2–5%) (Srogi, 2008; Vidovic, Dimitrijevic, Ratkovic, & Simic, 2011). It can be classified into light ASR (LASR) fraction generated during shredding of the hulk and air classification of generated material, and heavy ASR (HASR) fraction, which remains after ferrous metal separation from the heavy materials fraction (Vermeulen et al., 2011).

The two main purposes of this research are to assist Japanese vehicle recyclers to improve their profitability and ASR recycling efficiency, and to analyse how the ELV Recycling Law influences business results of the vehicle recycling system.

The remaining part of the paper is organised as follows: Section 2 provides a comprehensive literature review. Section 3 presents the ASR recycling planning model. Section 4 presents a case

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study results and discussions, and Section 5 presents the paper's main conclusions.

2. Literature review

Mathematical programming provides a powerful framework for designing sustainability systems (Srivastava & Nema, 2012). In addition, the implementation of mathematical programming models for recycling planning can significantly improve economic and ecological performances of the entire system; like in cases of paper recycling (Kara & Onut, 2010), and waste electrical and electronic products (Dat, Linh, Chou, & Yu, 2012). Therefore, mathematical programming provides an irreplaceable tool for solving important environmental problems to optimality, and this research actually represents an example of interaction between environmental engineering and operational research.

Due to the complexity of vehicle recycling subject, very a small number of research papers have been published. A detailed analysis of these papers is necessary to identify the key directions for the further development of this very important and dynamic research area.

Bellmann and Khare (2000) conducted a comprehensive study on ELV recycling systems. Numerous economic issues involved in developing markets for recycled parts were thoroughly analysed, and the concept of "critical mass" of returns for profitable recycling was suggested. Boon, Isaacs, and Gupta (2001) used Goal Programming method to model the vehicle recycling infrastructure and investigated materials streams and process profitability for several aluminium-intensive (AI) vehicle processing scenarios. Johnson and Wang (2002) created two types of optimisation models for vehicle recycling: US model, which is focused on profit only, and EU model in which optimisation depends on the predefined vehicle recycling and recovery rates. Bandivadekar, Kumar, Gunter, and Sutherland (2004) created a simulation model for material flows and economic exchanges (MFEE) to examine the effects of changes in vehicle material composition on the US automotive recycling infrastructure. They noticed that the Japanese ASR recycling quota of 70% and EU recycling/recovery quotas by 2015 are unachievable without fundamental changes. Forslind (2005) examined how the existing Sweden's vehicle recyclers, aimed at creating economic incentives and financing end-of-life management, are affected by extended producer responsibility (EPR). Choi, Stuart, and Ramani (2005) proposed a mixed integer programming model for tactical process planning in the case of traditional US automotive shredding factories. Ferrao and Amaral (2006) developed simple technical-cost models of vehicle dismantlers and shredding factories in order to assess the influence of the EU ELV Directive on their profitability. Giannouli et al. (2007) developed a methodology and model for the evaluation of waste produced from road vehicles, both at their end-of-life and during vehicle operation. Williams et al. (2007) expanded mathematical formulation from Choi et al. (2005) in order to make short-term tactical decisions regarding to what extent to process and reprocess materials through multiple passes in eddy current sorter. Qu and Williams (2008) formulated the automotive reverse production planning and pricing problem and compared two pricing strategies. Manomaivibool (2008) explored the impacts of network management on the environmental effectiveness of the programmes for the management of ELV in the United Kingdom and in Sweden from an EPR perspective. Kumar and Sutherland (2008) identified the following limitations of existing models: inadequate description of the complex material flows and economic transactions within the infrastructure, minimal consideration of market factors, lack of consideration for government policies and limited variety of examined future scenarios. Miemczyk (2008) suggested that research within production and operations management is particularly needed to consider the effects of institutional environment policies on the choice of production strategy and product recovery. Coates and Rahimifard (2009) developed 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. Kumar and Sutherland (2009) used simulation MFEE model from Bandivadekar et al. (2004). They found that with change in vehicle design the profit of shredding factories will increase over time, due to the additional revenue from the aluminium in AI hulks. Chen, Huang, and Lian (2010) thoroughly described principles and characteristics of the vehicle recycling system in Taiwan. They concluded that improving and optimising the process of operational and tactical planning is necessary. 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 Europe. However, they pointed out that the implementation of the method requires a lot of field effort. Go, Wahab, Rahman, Ramli, and Azhari (2011) presented a review on ELVs, recycling, disassemblability methods and the related fields. Simic and Dimitrijevic (2012b) presented a tactical production planning problem for vehicle recycling factories in the EU legislative and global business environments. They analysed influence of the EU ELV Directive (2000/53/EC) (EU, 2000) on the vehicle recycling factories 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. Simic and Dimitrijevic (2012a) expanded linear programming modelling framework proposed in Simic and Dimitrijevic (2012b) in order to incorporate vehicle hulk selection problem and to answer to the following questions: Can modernly 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 modernly equipped vehicle recycling facility and tested it extensively using real data. They came to the conclusion that vehicle recycling facility transformation, from traditional to modernly equipped, is not only necessary but completely justified and that the final success of the EU ELV Directive is realistic. Passarini, Ciacci, Santini, Vassura, and Morselli (2012) applied LCA to estimate potential implications of waste composition evolution in ELV recycling. They identified that innovative recycling plants, modelling mechanical and chemical recycling options, achieve the lowest impacts today due to the combination of material and energy recovery, with a consequent decrease in the residual amount of waste disposed of in landfill sites. Simic (2013) presented a holistic view of the environmental engineering issues of the ELV recycling by covering a wide range of peer-reviewed journal papers and gave an extensive content analysis overview of the literature published in the period 2003–2012. In addition, the author provided the major classification scheme and a distribution list of journal papers to identify the primary publication outlets. Blume and Walther (2013) discussed the legislative influence on the German vehicle industry and concluded that future eco-efficiency quotas are the main driving force for material flow innovations.

From the review of prior literature, it is evident that the Japanese vehicle recycling problem has been mostly neglected in previous research efforts. Since this issue presents a contemporary and highly interesting area of research, the need for its detailed analysis is evident. Owing to our research motivation emphasised in the introduction of this paper and the identified gap in the literature, we formulated and comprehensively tested the ASR recycling planning model.

3. Modelling Japanese vehicle recycling system

The main stakeholders in Japanese vehicle recycling system are automakers, who are responsible for recycling of collected air bags, CFCs/HFCs and ASR (Fig. 1). However, an integral part of the ELV Recycling Law consists of recycling fees. They are declared by automakers, and managed by a third-party fund management institution named the Japan Automobile Recycling Promotion Center (JARC). Recycling fees depend on the type of vehicle and are the sum of fees for processing fluorocarbons (FCs recycling fee), airbags (airbags recycling fee) and ASR (ASR recycling fee), and those for information handling and fund management. Vehicle users are obligated to deliver ELVs to the nearest registered collection agent and to pay the recycling fee on the purchase of new vehicles or at the time of ELV disposal. Collection agent is automobile dealer or auto repair shop that owns prefectural registration. They are required to collect ELVs and transport them to a registered CFCs/HFCs recovery company. CFCs/HFCs recovery companies recover all FCs and deliver them to a corresponding destruction facility, while ELVs are handed over to a licenced dismantling company. They dismantle ELVs according to treatment standards and forward retrieved airbags to airbag recycling facilities. Dismantlers sort and dispose of petrol, waste oil, fluids and other noxious substances that are prohibited in landfills (Zhao & Chen, 2011). In parallel, they collect valuable parts such as engines, while the remaining hulks are shipped to a licenced shredding factory for further recycling. In Japan, shredding factories are fully integrated into vehicle recycling system and according to the ELV Recycling Law they cannot choose which hulks to process. Any potential rejection of a shipment needs to be thoroughly clarified and documented. Storage time is extremely limited, as the shredding factory is required to process received hulks in the shortest possible period or to forward them to some other shredding factory.

From dismantling companies there are three hulk processing routes (Fig. 1):

(1) Shredding and separation of ferrous metals in traditional shredding factory.
When the shipment arrives from dismantling company, hulks are unloaded from transportation vehicle and stored. Hulks planned for processing are successively fed into the shredder, which shreds them into fist-size chunks. A heavy duty cyclone is usually installed on top of the shredder to vacuum LASR fraction. Heavy materials fraction passes through magnetic sorter, which diverts ferrous metals from HASR fraction. Market requirements dictate that ferrous metals fraction is first manually treated for possible impurities, and only then sold to steel industry. Export of insulated Cu wires fraction for manual recycling in China, India, etc. can provide certain financial gain for the shredding factory. Finally, LASR and HASR fractions are mixed into unique fraction and delivered to corresponding automaker, who decides about ASR recovery in a selected advanced thermal treatment (ATT) plant or disposal at the closest industrial landfill site.

(2) Shredding, separation of the various metallic fractions and partial recycling of generated ASR in contemporary shredding factory.
Contemporary shredding factory can mechanically recycle generated ASR using eddy current sorters, magnetic sorters, heavy media sorters and other (advanced) sorting equipment. Therefore, certain materials like aluminium, copper, plastics, etc. can be isolated from LASR and HASR fractions. For instance, LASR fraction can be further sorted or mixed. If the first option is chosen, then magnetic sorter separates it to ferrous metals and non-ferrous (NF) mix fractions. NF mix fraction can also be further purified to isolate NF metals or mixed. On the other hand, heavy materials fraction passes through magnetic sorter, which diverts ferrous metals from HASR fraction. The second ASR fraction is then forwarded to eddy current sorter to split NF metals and non-metals or be mixed. Both flows of NF metals are routed to heavy media sorter to separate Al-rich and Cu-rich fractions. Al-rich fraction can be sold as is or routed to eddy current sorter for further refinement from rubber, plastics and other materials.

(3) Total recycling route.
An important precondition for not mandating the shredding process is the complete dismantling of certain parts and components from vehicle hulks. For instance, wire harness and motors must be completely removed due to their significant copper content. The remaining clean vehicle shell is loaded into a triaxial press and compacted into a cube shape. Then, so called "whole recycling" facilities, which are often steel plants producing steel from scrap iron, may receive and recycle such metal cubes.

The focus of this paper is the ASR recycling at the Japanese vehicle recycling system. In accordance with the above, the system boundary in this paper begins with hulks arriving at the shredding factories (presented by the dashed line in Fig. 1). Owing to previous, the system boundary on this paper, as presented by the dashed line in Fig. 1, begins with hulks arriving at the shredding factories. Additionally, in this research only the first two routes have been considered, because in the last one no ASR is generated.

3.1. The ASR recycling planning model

The proposed model tackles a tactical ASR recycling planning problem in Japanese legislative context. Its objective is to maximise the profit of the Japanese vehicle recycling system over the planning horizon. Based on notations given in Appendix, the problem can be formulated as a linear program

$$\text{Objective Function : maximise } \mathit{Profit} \tag{1}$$

$$\mathit{Profit} = \text{Total Revenue}(TR) - \text{Total Cost}(TC) \tag{1.a}$$

$$\begin{aligned} TR = {} & \text{JARC payment to automaker for the collection of ASR}(RF) \\ & + \text{Income from the isolated metals sale}(RM) \end{aligned} \tag{1.b}$$

$$RF = F\sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i'=I'_r}^{I'_r+1}\sum_{i\in\Omega_{ri'}} X_{rii't} \tag{1.b.1}$$

$$RM = \sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i'=I'_r+2}^{I_r-1}\sum_{i\in\Omega_{ri'}} R_{rii't}X_{rii't} \tag{1.b.2}$$

$$\begin{aligned} TC = {} & \text{Hulk cost}(CP) + \text{Storage cost}(CI) \\ & + \text{Material processing cost}(CS) \\ & + \text{Transportation cost of isolated materials}(CT) \\ & + \text{ATT cost}(CA) + \text{Landfill disposal cost}(CL) \end{aligned} \tag{1.c}$$

$$CP = \sum_{t=1}^{T} C_t^P \sum_{r=1}^{R} P_{rt} \tag{1.c.1}$$

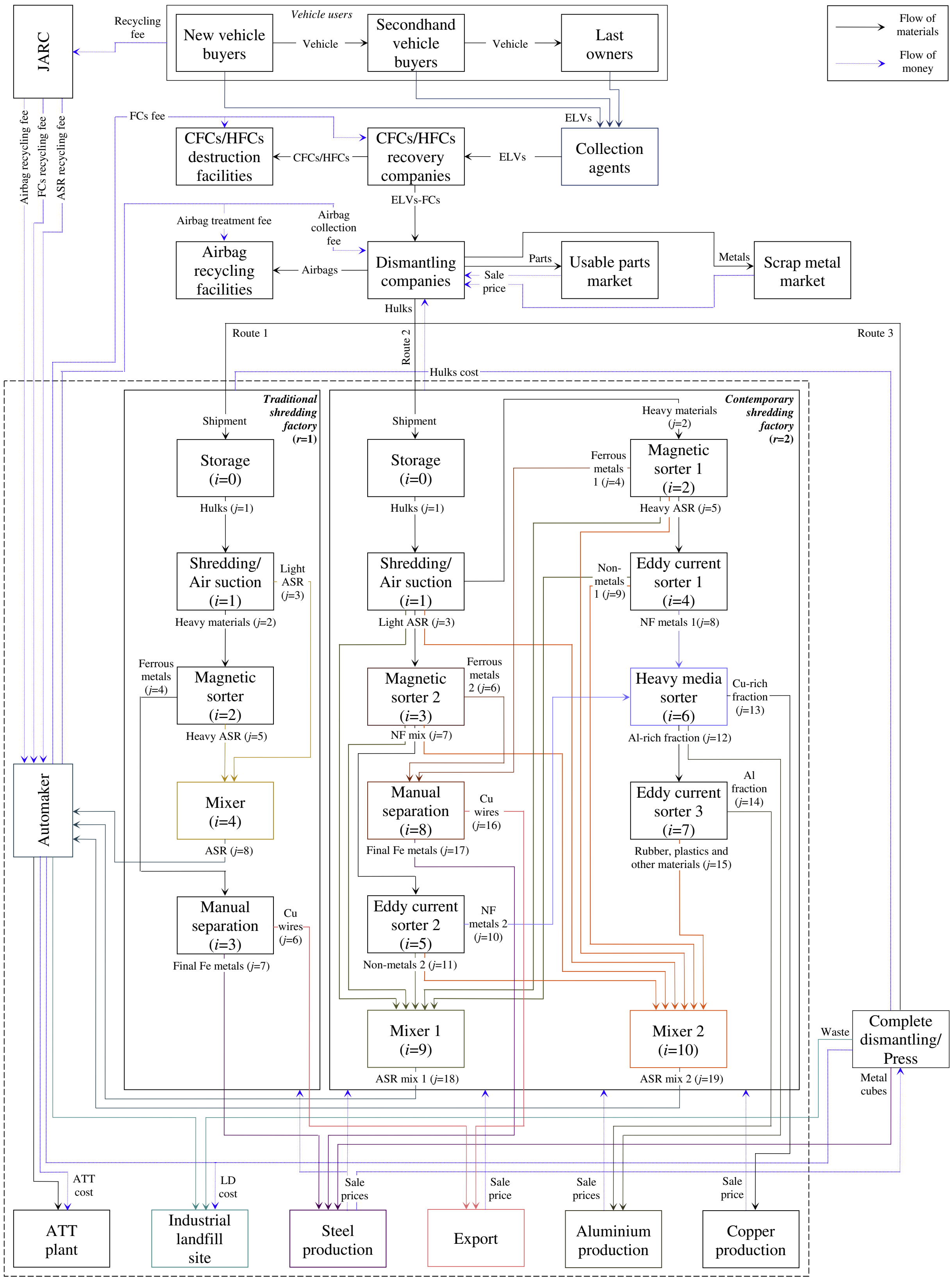

Fig. 1. Flow sheet of Japanese vehicle recycling system.

$$CI = \sum_{t=1}^{T} C_t^P \sum_{r=1}^{R} Z_{rt} S_{rt} \qquad (1.c.2)$$

$$CS = \sum_{r=1}^{R} \sum_{i=1}^{I'_r - I_r^M - 1} C_{ri}^S \sum_{t=1}^{T} \sum_{i' \in \Omega_{ri}} X_{ri'it} \qquad (1.c.3)$$

$$CT = \sum_{r=1}^{R}\sum_{i'=I'_r}^{I_r-1}\sum_{i\in\Omega_{ri'}} C^T_{rii'}\sum_{t=1}^{T} X_{rii't} \tag{1.c.4}$$

$$CA = C^A\sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i\in\Omega_{rI'_r}} X_{riI'_r t} \tag{1.c.5}$$

$$CL = C^L\sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i\in\Omega_{rI'_r+1}} X_{riI'_r+1t} \tag{1.c.6}$$

subject to:

$$S_{rt} = \begin{cases} P_{rt} + S_{r0} - X_{r01t}, & \text{if } t = 1 \\ P_{rt} + S_{rt-1} - X_{r01t}, & \text{otherwise} \end{cases} \quad \forall r \tag{2}$$

$$S_{rt} \geqslant S^S_r \quad \forall r, t \tag{3}$$

$$\sum_{i'\in\Omega_{ri}} X_{ri'it} \leqslant C_{ri} \quad \forall r, t; i = 1, \ldots, I'_r I^M_r - 1 \tag{4}$$

$$\sum_{i''\in\Psi_{rj}} X_{rii''t} = E_{rij}\sum_{i'\in\Omega_{ri}} X_{ri'it} \quad \forall r, t; i = 1, \ldots, I'_r I^M_r - 1; j \in A_{ri} \tag{5}$$

$$\sum_{i''\in\Phi_{ri}} X_{rii''t} = \sum_{i'\in\Omega_{ri}} X_{ri'it} \quad \forall r, t; i = I'_r - I^M_r \ldots, I'_r \tag{6}$$

$$\sum_{r=1}^{R}\Big(E^R\sum_{i\in\Omega_{rI'_r}} X_{riI'_r t} - Q^A\sum_{i=1}^{|\Theta_r|}\sum_{j\in A_{ri}\cap\Theta_r}\sum_{i'\in\Omega_{ri}} E_{rij}X_{ri'it}\Big) + \sum_{i'=I'_R+2}^{I_R-1}\sum_{i\in\Omega_{Ri'}} X_{Rii't} - X_{R28t} \geqslant 0 \quad \forall t \tag{7}$$

$$P_{rt} \geqslant 0, S_{rt} \geqslant 0 \quad \forall r, t \tag{8}$$

$$X_{rii't} \geqslant 0 \quad \forall r, t; i = 0, \ldots, I'_r - 1; i' \in \Phi_{ri} \tag{9}$$

The objective function in Eq. (1) seeks to maximise the profit over planning horizon. Profit is calculated in Eq. (1.a) by subtracting total cost (*TC*) from revenue (*TR*). The components of *TR* are defined in Eq. (1.b). The amount of ASR recycling deposits repaid from JARC in Eq. (1.b.1) is computed based on the quantity of ASR collected from the shredding factories and the ASR recycling fee. Eq. (1.b.2) computes income of shredding factories from the isolated metals sale. The components of *TC* are defined in Eq. (1.c). Eq. (1.c.1) calculates cost of received shipments and Eq. (1.c.2) presents storage cost for hulks that have not been assigned for processing. Eq. (1.c.3) computes cost of hulk shredding and further separation of generated material fractions. Eq. (1.c.4) calculates cost for the transport of isolated material to its final destination. ATT cost (*CA*) in Eq. (1.c.5) computes the cost of advanced thermal treatment in proper plant. Eq. (1.c.6) computes cost of ASR disposal on the nearest industrial landfill site.

Constraint (2) enforces the inventory balances. Constraints (3) ensure the safety stock level of hulks in order to protect the shredder from starvation. Constraints (4) represent processing capacity limits of available sorting entities and Eq. (5) maintains their material flow balances. Mixers have been defined in order to combine various fractions to unique waste flow (Eq. (6)). Constraints (7) represents specific eco-efficiency requirement imposed by the ELV Recycling Law, i.e. percentage of ASR recycling cannot be less than the prescribed value. Constraints (8) and (9) define value domains of decision variables.

4. Results and discussions

In this section we conduct a numerical study whose goal is twofold. First, we want to illustrate the potentials and applicability of the proposed ASR recycling planning model. Second, we want to gain insights on the profitability and eco-efficiency of the Japanese vehicle recycling system, and examine the influence of the ELV Recycling Law on the ASR recycling decisions. Afterwards, the stability of the optimal decisions is analysed by carrying out sensitivity analyses.

The following scenarios are investigated:

- *Scenario 1*-valid ASR recycling quota. The automaker has to guarantee that ASR recycling rate does not fall under 50%.
- *Scenario 2*-future ASR recycling quota (will be valid by fiscal year 2015). The automaker has to guarantee that ASR recycling rate does not fall under 70% (Ministry of the Environment (MOE), 2002).

Aiming to analyse as comprehensively as possible the performance of Japanese vehicle recycling system, in our case study we will be looking at the special case of vehicle design change influencing ASR recycling activities, i.e. the influence of the reduction of its weight by substituting ferrous metals with aluminium. As a result, for both investigated scenarios we formed 11 test problems by varying the share of steel-intensive (SI) hulks in available shipments in the interval of 0–100% with 10% step. To test the proposed model, we collected the necessary data from a great number of peer-reviewed papers and published scientific studies. All data can be found in the Online Resource 1.

Optimal decisions for all test problems were solved using the CPLEX 12.2 solver, and they are summarised in Fig. 2. As can be seen in Fig. 2, the ELV Recycling Law influences neither quantity of ASR generated in hulk shredding operation nor quantity of ASR collected by automaker. More detailed, quantities of generated and collected ASR in Scenario 1 are equal to quantities of generated and collected ASR in Scenario 2. On the other hand, the influence that the material composition of shipment has on quantity of generated ASR is clearly identified. In more detail, quantity of generated ASR is in the

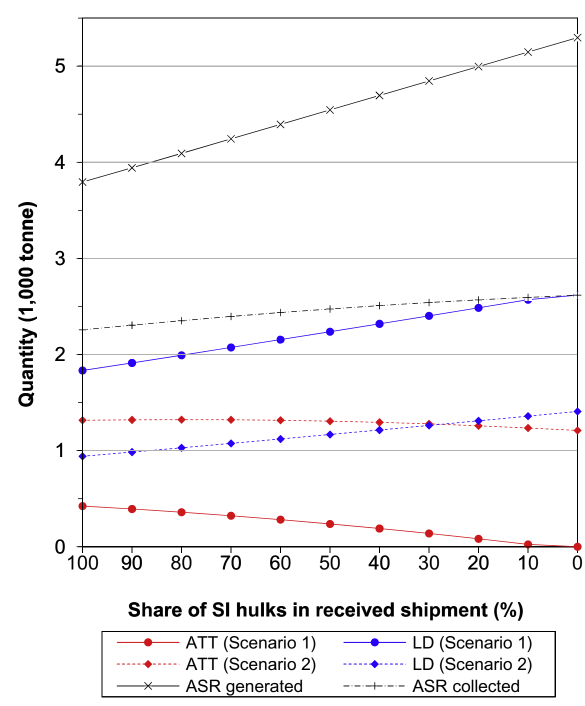

Fig. 2. Comparison of optimal decisions.

interval from 3,794.74 tonne (when only SI hulks are available) to 5,297.50 tonne (when only AI hulks are available). This can be explained in the following manner: reducing the share of SI hulks in available shipments directly increases the share of ASR in vehicle hulks, and indirectly increases the quantity of generated ASR. Therefore, the change in vehicle design (which is in this case study observed from the aspect of substituting ferrous metals with aluminium) can cause the increase in the quantity of generated ASR even up to 40%. On the other hand, quantity of ASR collected by automaker depends on the quantity of generated ASR and way of processing received hulks. For instance, traditional shredding factory always sends all the generated ASR to automaker, meaning generated and collected quantities of ASR are equivalent. In reference to the contemporary shredding factory, the generated ASR is always mechanically recycled, causing the recycling efficiency to depend on the material composition of available hulk shipments. Since AI hulks contain more NF metals, which can be considered as one of the main drivers of ASR recycling planning process, having a bigger share of this type of hulks in the received shipment indicates a more intensive mechanical recycling of ASR and smaller quantity of ASR collected by automaker.

Testing results verify that the ELV Recycling Law has crucial influence on decision making about recycling ASR. Analysing data on landfilled and thermally treated ASR presented in Fig. 2, led to conclusion that the increase of recycling quota to 70% will influence the quantity of disposed ASR to be reduced by 50%. This clearly confirms the intent of the Japanese policy makers to create sustainable vehicle recycling system.

Testing the proposed model showed that the second route is not only better, but with the adopted base values of the model parameters, also the only economically acceptable route for recycling ASR. The quantity of received hulks during every planning period is exactly the same as the shredder maximum capacity (3560 tonnes per week). Moreover, it is clearly identified that the contemporary shredding factory aims at reaching as higher level of quantity and quality of sorted metal flows as possible regardless of the shipment composition. Both ASR fractions are always mechanically recycled, primarily in order to isolate valuable NF metals. For instance, Al-rich fraction is always additionally purified, because the additional income always exceeds the costs of its sorting.

Table 1
Case study profits and ASR recycling efficiencies.

Test problem	Scenario	*s* (%)	Total profit (€)	CSF profit (€/tonne)	Automaker surplus (€/tonne)	ASR recycling efficiency (%)
1	1	100	2,364,118.21	146.94	120.35	50.00
2		90	2,421,209.24	150.35	121.54	50.00
3		80	2,482,241.53	154.04	122.76	50.00
4		70	2,547,326.43	158.01	124.03	50.00
5		60	2,615,415.57	162.22	125.34	50.00
6		50	2,688,207.85	166.76	126.73	50.00
7		40	2,763,710.80	171.50	128.14	50.00
8		30	2,842,323.60	176.47	129.61	50.00
9		20	2,925,068.41	181.76	131.16	50.00
10		10	3,010,237.51	187.21	132.75	50.00
11		0	3,091,260.47	192.56	133.40	50.59
12	2	100	2,301,973.69	146.94	92.82	70.00
13		90	2,356,640.57	150.35	93.53	70.00
14		80	2,415,225.37	154.04	94.27	70.00
15		70	2,477,824.76	158.01	95.02	70.00
16		60	2,543,448.86	162.22	95.81	70.00
17		50	2,613,776.01	166.76	96.65	70.00
18		40	2,686,817.07	171.50	97.49	70.00
19		30	2,762,954.25	176.47	98.37	70.00
20		20	2,843,245.60	181.76	99.30	70.00
21		10	2,925,946.06	187.21	100.26	70.00
22		0	3,007,049.00	192.56	101.23	70.00

s, share of SI hulks in received shipment; CSF, contemporary shredding factory.

Profits and ASR recycling efficiencies of the optimal decisions for 22 base test problems are given in Table 1. Analysis of the presented data leads to the conclusion that the business of a contemporary shredding factory will not be influenced by the introduction of stringent ASR quota. This was not unexpected, knowing that according to the ELV Recycling Law automakers were exclusively in charge of collecting and recycling ASR. In contrast, the influence that the composition of shipment material has on the profit of a contemporary shredding factory is more than evident. As AI hulks are distinguished by a higher content of NF metals (Supplementary Table S1.1 in Online Resource 1), the more available this type of hulks is, bigger the profit will be for the contemporary shredding factory. In more detail, its profit is in the interval from 146.94 €/tonne of processed hulks (when only SI hulks are available) to 192.56 €/tonne of processed hulks (when only AI hulks are available). As for business results of automakers, the 20% increase of ASR quota reduces their surplus for approximately 30 €/tonne of collected ASR. Consequently, there is no justification for the increase of ASR recycling fee even when the stringent quota is put into practise, because under those circumstances each tonne of collected ASR will bring profit from €92.82 to €101.23.

In reference to ASR recycling efficiency, even the future ASR quota is easily reached in all corresponding test problems. So, we are led to conclude that the Japanese vehicle recycling system is already prepared for the final implementation phase of the ELV Recycling Law.

4.1. Sensitivity analyses

In order to validate the applicability of developed ASR recycling planning model and previously presented results, it is inevitable to carry out sensitivity analysis. We investigate the stability of the previous results with sensitivity analyses of revenue parameters (metal prices and ASR deposit value) and cost parameters (hulk cost, transportation costs, ATT cost, landfill disposal cost and processing costs). Hence, we determine the impact of varying revenue and cost parameters on the profit of the vehicle recycling system in the case of valid and future ASR recycling quota. All revenue and cost parameters were increased and decreased by 50% with 10% step in comparison to 22 base cases. As a result, the 1540 problem instances are created and solved to optimality.

In reference to the valid ASR quota, the strongest sensitivity of the vehicle recycling system profit is evident in the metal prices

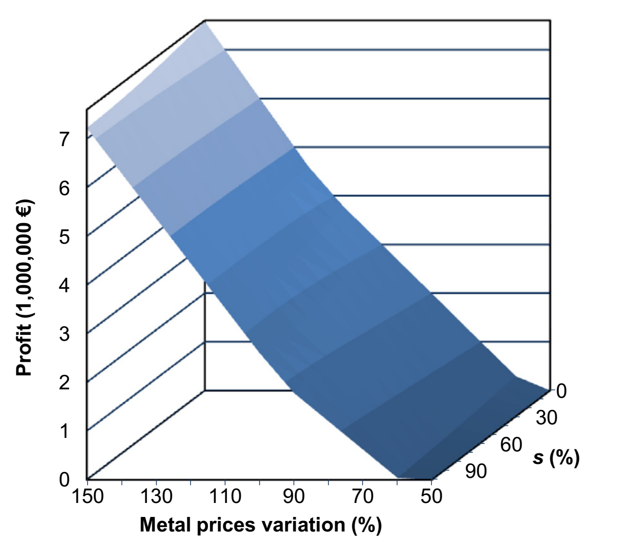

Fig. 3. Sensitivity analysis of metal prices on the profit of the vehicle recycling system in case of valid ASR quota.

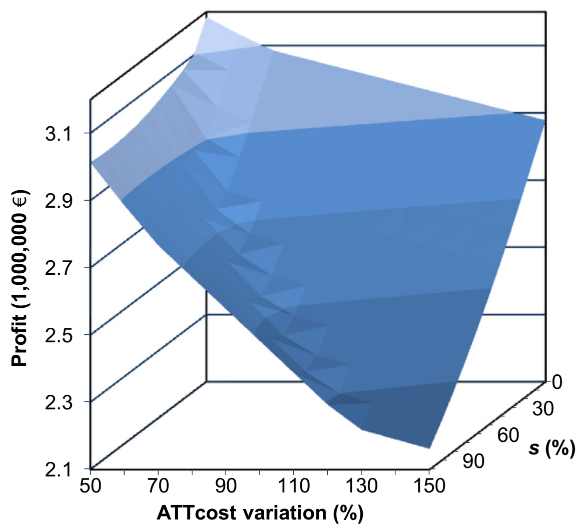

Fig. 4. Sensitivity analysis of the advanced thermal treatment cost on the vehicle recycling system profit in case of future ASR quota.

(Fig. 3). The second rank parameter is the hulk cost, the third and the fourth place are interchangeably taken by the ASR deposit value and the processing costs, the fifth rank parameter are transportation costs, while the last place was occasionally taken by the ATT cost and the landfill disposal cost (Supplementary Figs. S2.1 to S2.6 in Online Resource 2).

In reference to future ASR quota, the strongest sensitivity is again shown by the metal prices. Regarding cost parameters, the hulk cost rank first, followed by the processing costs, the transportation costs, the ATT cost and the landfill disposal cost (Supplementary Figs. S2.7 to S2.12 in Online Resource 2). Introducing stringent quota increases only the influence of the ATT cost parameter (Fig. 4), while its significance additionally grows with the change in vehicle design (i.e. the increase of ASR share in vehicle hulks). Influence on other parameters is relatively limited (significance reduction of up to 10%), except in case of the landfill disposal cost that looses significance to a great extent.

The influence of hulks shipment composition on parameters ranking is clearly identified in both scenarios. For instance, Fig. 5 displays the ASR model's sensitivity to a variation of different cost and revenue parameters in case of shipment with 70% share of SI hulks and stringent ASR quota.

5. Conclusions

In this paper we proposed the tactical ASR recycling planning model for Japanese vehicle recycling industry, which can be used to improve its profitability and recycling efficiency. We conducted a numerical study to illustrate the potentials and applicability of the proposed modelling approach, and to gain insights on the performances of the Japanese vehicle recycling system and on the influence of the ELV Recycling Law. Sensitivity analyses of recycling parameters validate the proposed modelling approach and discover that the strongest sensitivity is shown by the metal prices. Regarding cost parameters, the hulk cost rank first, followed by the processing costs, the transportation costs, the ATT cost and the landfill disposal cost. It was concluded that introducing stringent quota in fiscal year 2015 would increase only the influence of the ATT cost parameter, while the influence of the other recycling parameters would be reduced.

The change in vehicle design, which was observed from the aspect of substituting ferrous metals with aluminium, will not jeopardise Japanese vehicle recycling system. In both examined scenarios, analysis of the optimal decision identified the NF metals share as one of the main drivers of ASR recycling planning process. However, only contemporary shredding factories will be able to use high value of NF metals to their advantage, because compared to traditional shredding factories they are able to isolate them successfully. Testing of the proposed model showed that the second route is economically and ecologically better for the recycling of ASR. In addition, contemporary shredding factories aim at reaching as higher level of quality and quantity of sorted metal flows as possible regardless of the hulk material composition.

ELV Recycling Law influences neither quantity of ASR generated in hulk shredding operation nor quantity of ASR collected by automaker. However, its influence is crucial for making decisions about ASR recycling, since the 20% increase of the recycling quota will cause approximately 50% decrease in the quantity of disposed ASR. Introducing stringent ASR recycling quota will not influence profitability of contemporary shredding factories, but will reduce automakers surplus for approximately 30 €/tonne of collected ASR. However, further increase of the ASR recycling fee should not be expected, as each tonne of collected ASR can provide significant surplus for automakers. In reference to ASR recycling efficiency, even the stringent ASR quota is easily attainable. So, we can conclude that the Japanese vehicle recycling system is already prepared for the final implementation phase of the ELV Recycling Law.

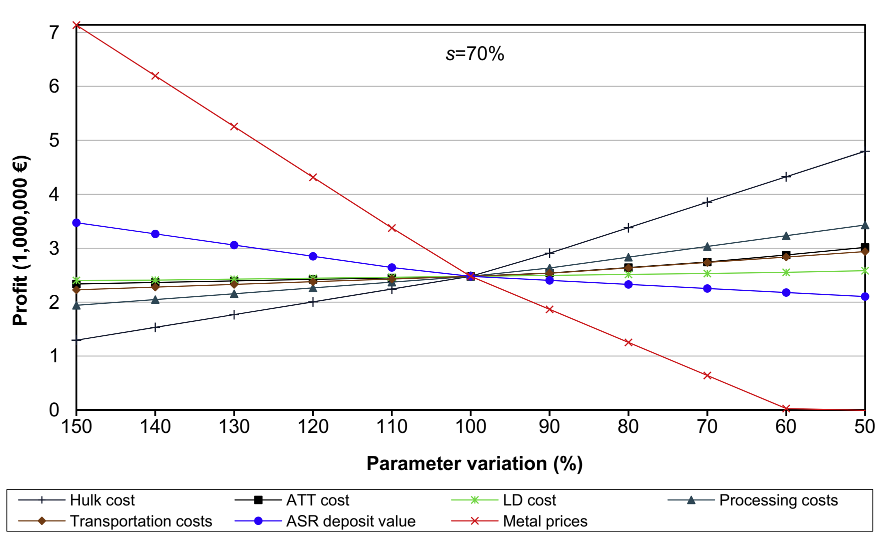

Fig. 5. Sensitivity analysis of cost and revenue parameters on the vehicle recycling system profit in case of shipment with 70% share of SI hulks and future ASR quota.

Further research in two fields would be important. The first research field consists of the modelling of vehicle recycling systems in some other countries having the contemporary ELV legislation, primarily in Korea and China. The second working area can focus on a broader analysis of the influence that the change in vehicle design might have on vehicle recycling system. Practically, this means including additional vehicle types in the analysis, such as composite-intensive vehicles, electric and hybrid electric vehicles.

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Appendix A. Notation

Indices and sets

i	index of entity (i.e. sorting equipment, storages, mixers and destinations); $i \in \{0,\ldots,I_r\}$
j	index of material flow; $j \in \{1,\ldots,J_r\}$
r	index of ASR recycling route; $r \in \{1,\ldots,R\}$
t	index of time period; $t \in \{1,\ldots,T\}$
A_{ri}	set of material flows isolated with entity i of shredding factory r; $\forall r, i \in 1,\ldots,I'_r - I^M_r - 1$
Ψ_{rj}	set of entities on which material flow j is forwarded in the case of ASR processing route r; $\forall r$, $j \in \{2,\ldots,J_r\}$
Ω_{ri}	set of entities of shredding factory r which route materials to entity i; $\forall r, i \in \{1,\ldots,I_r - 1\}$
Θ_r	set of ASR fractions generated by shredding factory r; $\forall r$
Φ_{ri}	set of entities on which material flows are routed from entity i in the case of ASR processing route r; $\forall r$, $i \in \{0,\ldots,I'_r - 1\}$

Parameters:

I_r	total number of entities in the case of ASR processing route r
I'_r	number of entities in shredding factory r
I^M_r	number of mixers in shredding factory r
J_r	number of material flows in the case of ASR processing route r
R	number of analysed ASR recycling routes
T	number of analysed time periods
S_{r0}	initial inventory weight of hulks of shredding factory r
S^S_r	safety inventory level of shredding factory r
C_{ri}	processing capacity in the case of shredding factory r and entity i per time period
E_{rij}	efficiency of sorting entity i in the case of flow j and shredding factory r in percentages
E^R	recovery (i.e. recycling and energy recovery) efficiency of ATT plant in percentages
Q^A	ASR quota
$R_{rii't}$	revenue from each unit weight of metal fraction sorted on entity i of shredding factory r and sold to destination i' in time period
C^A	advanced thermal treatment cost per weight unit
C^L	ASR landfill disposal cost per weight unit
C^P_t	hulk cost per weight unit in period t
Z_{rt}	percentage of capital cost for inventory in shredding factory r and period t
C^S_{ri}	processing cost on entity i of shredding factory r per weight unit
$C^T_{rii'}$	transportation cost per weight unit from entity i to i' in the case of ASR processing route r
F	ASR recycling deposit per weight unit

Variables:

S_{rt}	weight of hulks in storage of shredding factory r at the end of time period t
P_{rt}	weight of hulk shipments routed to shredding factory r in period t
$X_{rii'_t}$	weight of material flow forwarded from entity i to i' in the case of ASR processing route r and time period t

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eswa.2013.06.075.

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