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Interval-parameter chance-constraint programming model for end-of-life vehicles management under rigorous environmental regulations

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ABSTRACT

As the number of end-of-life vehicles (ELVs) is estimated to increase to 79.3 million units per year by 2020 (e.g., 40 million units were generated in 2010), there is strong motivation to effectively manage this fast-growing waste flow. Intensive work on management of ELVs is necessary in order to more successfully tackle this important environmental challenge. This paper proposes an interval-parameter chance-constraint programming model for end-of-life vehicles management under rigorous environmental regulations. The proposed model can incorporate various uncertainty information in the modeling process. The complex relationships between different ELV management sub-systems are successfully addressed. Particularly, the formulated model can help identify optimal patterns of procurement from multiple sources of ELV supply, production and inventory planning in multiple vehicle recycling factories, and allocation of sorted material flows to multiple final destinations under rigorous environmental regulations. A case study is conducted in order to demonstrate the potentials and applicability of the proposed model. Various constraint-violation probability levels are examined in detail. Influences of parameter uncertainty on model solutions are thoroughly investigated. Useful solutions for the management of ELVs are obtained under different probabilities of violating system constraints. The formulated model is able to tackle a hard, uncertainty existing ELV management problem. The presented model has advantages in providing bases for determining long-term ELV management plans with desired compromises between economic efficiency of vehicle recycling system and system-reliability considerations. The results are helpful for supporting generation and improvement of ELV management plans.

1. Introduction

End-of-life vehicles (ELVs) are returns generated at the product's end-of-life stage (Cruz-Rivera and Ertel, 2009). They have become a major waste stream regionally and globally (Arbitman and Gerel, 2003; Fiore et al., 2012; Cossu et al., 2014; Widmer et al., 2015). Worldwide, the amount of ELVs reached over 40 million units per year in 2010 (Sakai et al., 2014; Cossu and Lai, 2015). Moreover, ELVs are estimated to reach a volume of 79.3 million units per year by 2020 (WRME, 2014).

The management of ELVs is currently one of the most important ecological topics worldwide (Singh and Lee, 2015). However, intensive work on ELV management is necessary in order to more successfully tackle this fast-growing environmental challenge. In addition, in vehicle recycling systems, there are various uncertainties that should be considered. In fact, uncertainty seems to be the key factor influencing the management of ELVs. For instance, the capacities of sorting entities fluctuate in time depending on the variations of ELV composition and equipment conditions. The costs of transportation are influenced by various factors including gas prices, labour charges, etc. The processing costs are mainly influenced by electricity prices, and management and maintenance expenses. All those uncertainties cause serious difficulties in decision making processes. Moreover, vehicle recycling systems worldwide have been forced for over a decade to operate under rigorous environmental regulations: the EU promulgated the ELV Directive (2000/53/EC) (EU, 2000), Japan introduced the Law on recycling of ELVs (MOE, 2002), China issued the Technical policy for the recovery and utilization of automobile products (NDRC, 2006), Korea introduced the Act on the resource circulation of electrical and electronic equipment and vehicles (EMK, 2007), etc. Therefore, a development of effective system analysis method for supporting

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ELV management constrained by rigorous environmental regulations under uncertainty is strongly desired.

Previously, a number of research works were undertaken for solving various issues of ELV management problem. Different modeling techniques were used for solving allocation problems (Simic, 2015a), location-allocation problems (Harraz and Galal, 2011b; Mahmoudzadeh et al., 2011, 2013), production planning problems (Simic, 2015b; Simic and Dimitrijevic, 2012a,b, 2013a, b, 2015) and network design problems (Harraz and Galal, 2011a; Merkisz-Guranowska, 2011, 2013; Pavlovic et al., 2011; Vidovic et al., 2011; Farel et al., 2013; Mora et al., 2014; Ene and Öztürk, 2015; Demirel et al., 2016). Simic (2015a) integrated the interval programming and two-stage stochastic programming in order to solve the problem of ELV allocation from provincial collection networks to vehicle recycling factories under resource scarcity. The linear programming method has been usually applied for solving production planning problems (Simic and Dimitrijevic, 2012a,b, 2013a). However, because of the uncertainties in production planning processes, interval linear programming (Simic and Dimitrijevic, 2015), risk explicit interval linear programming (Simic and Dimitrijevic, 2013b) and fuzzy risk explicit interval linear programming (Simic, 2015b) approaches were used to deal with them. A number of mixed integer linear programming studies were conducted for supporting location-allocation (Mahmoudzadeh et al., 2011, 2013) and network design (Vidovic et al., 2011; Merkisz-Guranowska, 2011, 2013; Mora et al., 2014; Ene and Öztürk, 2015; Demirel et al., 2016). Some research works based on the simulation approach (Gołębiewski et al., 2013; Farel et al., 2013) and lexicographic mixed integer goal programming (Harraz and Galal, 2011a) have previously been applied to network design problems.

From the review of previous literature, it is evident that a number of systems analysis methods are proposed for solving various ELV management problems. However, the above methods can hardly deal with uncertainties in the right-hand sides (where the right-hand side expression represents everything placed on the right side of a mathematical expression) presented as random variables with known probability distributions. Chance-constrained programming, one of the main methods of stochastic mathematical programming, is an effective way to deal with uncertainty on the right-hand side of the optimization models. Moreover, no previous study in the ELV management research area has reported on the development of chance-constraint programming associated with inexact optimization. In fact, no previous study has reported on chance-constraint programming for some end-of-life management system.

In view of the limitations of previous works, this study aims to develop an interval-parameter chance-constraint programming model for end-of-life vehicles management under rigorous environmental regulations. A case study will be provided to demonstrate the potentials and applicability of the developed model.

In detail, this research will: (1) introduce the interval-parameter chance-constrained programming approach to the field of ELV management; (2) introduce chance constraints into the modeled ELV management problem thus supporting extensive analysis of the trade-off between system profit and failure risk; (3) efficiently handle uncertainties expressed as intervals and probability distributions; (4) thoroughly examine the risk of violating ELV management system constraints under uncertainty; (5) study the influence of rigorous environmental regulations to ELV management systems; (6) successfully address the complex relationships between different ELV management sub-systems (authorized treatment facilities, vehicle recycling factories, metal producers (e.g., steel mills, aluminium production plants, cooper production plants) and waste entities (e.g., landfill sites, municipal solid waste incinerators, advanced thermal treatment plants)); (7) search for optimal patterns of ELV procurement from multiple regions, production and inventory planning in multiple vehicle recycling factories, and allocation of sorted material flows to multiple final destinations under rigorous environmental regulations and maximized profit; and (8) apply the formulated model to multi-period planning of the provincial ELV management system, generating procurement, production, inventory and allocation plans for profit-maximized recycling of ELVs.

The remaining part of the paper is organized as follows: Section 2 describes the considered problem and presents the interval-parameter chance-constraint programming model for end-of-life vehicles management under rigorous environmental regulations. Section 3 presents case study results and discussions. Section 4 presents conclusions of the work.

2. Methodology

2.1. Statement of the problem

Consider a provincial ELV management system shown in Fig. 1. Vehicle users from R provincial regions are required to deliver ELVs to authorized treatment facilities located (usually within a certain radius) in their region. Authorized treatment facilities are required to extract/remove and store separately: fuel, motor oil, oil from transmission system, hydraulic oil (including absorber oil), cooling liquid, liquid from the brake system, and other liquids and hazardous substances if any (Berzi et al., 2013; Cossu and Lai, 2013). Subsequently, they sell decontaminated and flattened (usually with mobile auto presses) ELVs to H vehicle recycling factories located in their province for further recycling.

Vehicle recycling factories are responsible for vehicle hulks shredding, sorting generated material fractions, and transporting sorted waste flows and isolated metals to waste entities (landfill sites, municipal solid waste incinerators (MSWIs), advanced thermal treatment (ATT) plants (which combine material recycling with energy recovery)) and metal producers (steel mills, aluminium production plants, copper production plants) located in their province respectively (Fig. 1). When ELV shipments arrive from authorized treatment facilities, ELVs are unloaded from large (semi-)trailers and stored. ELVs 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 light automobile shredder residue (ASR) fraction (Figs. 4–6). Afterwards, magnetic sorter separates light ASR into non-ferrous mix and ferrous metals (Jordão et al., 2016). The non-ferrous mix is further purified on eddy current sorter to separate non-ferrous metals and non-metals. On the other hand, heavy materials fraction passes through magnetic sorter, which diverts ferrous metals from heavy ASR fraction (Cossu et al., 2014). Isolated ferrous metals fractions are firstly mixed and afterwards sold to one of n_1 available steel mills. The heavy ASR fraction is forwarded to eddy current sorter (Cossu et al., 2014), which separates it into non-ferrous metals and non-metals fractions. The isolated non-metals fractions are sent to provincial MSWIs, landfill sites or ATT plants. The non-ferrous metals fractions are routed to a heavy media sorter, which is filled with heavy liquids, to separate Al-rich fraction and Cu-rich fraction. Isolated Cu-rich fraction is sold to one of n_3 copper production plants located in the considered province. The Al-rich fraction can be sold as is to one of n_2 aluminium production plants or routed to eddy current sorter for further refinement from the rubber, plastics and rest (RPR) fraction. The isolated RPR fraction can be either incinerated in one of m_1 available MSWIs or disposed of in one of m_2 provincial landfills.

This is a complex waste management system with many of its components being uncertain. Normally, the quantities of collected,