Waste Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Fuzzy risk explicit interval linear programming model for end-of-life vehicle recycling planning in the EU

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ARTICLE INFO

Article history:
Received 4 July 2014
Accepted 13 September 2014
Available online xxxx

Keywords:
End-of-life vehicle
Fuzzy risk explicit interval linear programming
α-Cut level
Decision maker preference type
EU ELV Directive
Uncertainty

ABSTRACT

End-of-life vehicles (ELVs) are vehicles that have reached the end of their useful lives and are no longer registered or licensed for use. The ELV recycling problem has become very serious in the last decade and more and more efforts are made in order to reduce the impact of ELVs on the environment. This paper proposes the fuzzy risk explicit interval linear programming model for ELV recycling planning in the EU. It has advantages in reflecting uncertainties presented in terms of intervals in the ELV recycling systems and fuzziness in decision makers' preferences. The formulated model has been applied to a numerical study in which different decision maker types and several ELV types under two EU ELV Directive legislative cases were examined. This study is conducted in order to examine the influences of the decision maker type, the α-cut level, the EU ELV Directive and the ELV type on decisions about vehicle hulks procuring, storing unprocessed hulks, sorting generated material fractions, allocating sorted waste flows and allocating sorted metals. Decision maker type can influence quantity of vehicle hulks kept in storages. The EU ELV Directive and decision maker type have no influence on which vehicle hulk type is kept in the storage. Vehicle hulk type, the EU ELV Directive and decision maker type do not influence the creation of metal allocation plans, since each isolated metal has its regular destination. The valid EU ELV Directive eco-efficiency quotas can be reached even when advanced thermal treatment plants are excluded from the ELV recycling process. The introduction of the stringent eco-efficiency quotas will significantly reduce the quantities of land-filled waste fractions regardless of the type of decision makers who will manage vehicle recycling system. In order to reach these stringent quotas, significant quantities of sorted waste need to be processed in advanced thermal treatment plants. Proposed model can serve as the support for the European vehicle recycling managers in creating more successful ELV recycling plans.

1. Introduction

As various resources are rapidly being depleted, recycling and recovery of end-of-life vehicles (ELVs) are considered as one of the most important methods to promote sustainable development. ELVs are vehicles that have reached the end of their useful lives and are no longer registered or licensed for use (Jekel and Tam, 2007). They are composed of many different materials that have a large impact on the environment such as mercury, cadmium, hexavalent chromium, anti-freeze, brake fluid and oils (Simic, 2013b). The growing number of ELVs worldwide offers an extensive waste flow of valuable but toxic materials to be analyzed (Gaidajis et al., 2011). In fact, ELVs are estimated to reach a volume of 14 million tonnes by 2015 just in the EU alone as their number is growing rapidly (Cherrington et al., 2012).

The transportation sector is one of the most complex and important direction of world economy development which is strongly correlated with new trends in science and innovation in technologies. However, it has proven to be particularly difficult territory for the advancement of sustainable development oriented policies (Janicka et al., 2011). Nevertheless, in an attempt to reduce waste originating from ELVs, in 2000, the EU adopted the ELV Directive (2000/53/EC) (EU, 2000). This directive fundamentally changed the business philosophy of the European vehicle recycling system that had been used for decades and had been exclusively profit-oriented, because it promulgated rising recycling and recovery targets: from January 1, 2006, a minimum of 85% recovery with a minimum of 80% recycling and a maximum of 5% energy recovery; no later than January 1, 2015, a minimum of 95% recovery with a minimum of 85% recycling and a maximum of 10% energy recovery.

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http://dx.doi.org/10.1016/j.wasman.2014.09.013
0956-053X/

The ELV recycling problem has become very serious in the last decade (Olugu and Wong, 2012) and more and more efforts are made in order to reduce the impact of ELVs on the environment (Simic, 2013a). Today, the ELV recycling planning is a well positioned and emergent research area. The relevant literature for our contribution originates from different streams of research, but from a domain-oriented point of view only the work on vehicle recycling planning is significant. Johnson and Wang (2002) created two types of deterministic optimization models for vehicle recycling: US model, which is focused on profit only, and EU model in which optimization depends on the imposed recycling/recovery quotas. Boon et al. (2003) used the Goal Programming method and provided mathematical formulation for the recycling infrastructure to assess materials streams and process profitability for several clean vehicle cases. Bandivadekar et al. (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 recycling infrastructure. Dantec (2005) created a simple technical cost model of the dismantler and shredder operations to study the recycling cost sensitivity to regional practices. Choi et al. (2005) proposed a mixed integer programming model for tactical process planning in the case of traditional US vehicle recycling factories. Amaral et al. (2006) developed a system dynamics model of the Portuguese ELV recycling infrastructure. Ferrao and Amaral (2006) developed technical cost models of vehicle dismantlers and recycling factories in order to assess the influence of the EU ELV Directive on their profitability. Ferrao et al. (2006) used data obtained from a full scale shredding experiment to develop a technical model and access the eco-efficiency performances of several vehicle recycling strategies. Williams et al. (2007) expanded a mixed integer linear programming 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. Coates and Rahimifard (2008) integrated several techniques, such as Activity based costing, regression analysis and time studies, and proposed the ELV costing framework. Qu and Williams (2008) formulated the vehicle reverse production planning and pricing problem in a nonlinear programming model, and compared market with an optimized pricing strategy in three trends for ferrous metal and hulk costs: constant, increasing and decreasing. 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. Kumar and Sutherland (2009) used simulation MFEE model from Bandivadekar et al. (2004) and revealed that with change in vehicle design the profit of vehicle recycling factories will increase over time. Li et al. (2011) presented a coupled upgrading and production mathematical programming model to identify economically efficient sorting strategies and their impact on scrap usage in the case of an individual recycling firm. Iranpour et al. (2012) discussed about the shortage of the Chinese vehicle recycling industry and illustrated three China-tailored value analyzing models: model of ELV to raw materials, model of intermediate scrap to product, and model of remanufacturing. Fiore et al. (2012) concluded that installation of post-shredding technical solutions in traditional vehicle recycling factories may lead to multi purposed opportunities for automobile shredder residue (ASR) reuse/recovery. Simic and Dimitrijevic (2012b) presented a tactical production planning problem for vehicle recycling factories in the EU legislative and global business environments. Simic and Dimitrijevic (2012a) expanded linear programming modelling framework proposed by Simic and Dimitrijevic (2012b) in order to incorporate vehicle hulk selection problem. Farel et al. (2013) proposed a framework for performance evaluation of a future ELV glazing recycling network in France and modelled, using system dynamics simulation approach, its net economic balance under different future scenarios. 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. Tasala Gradin et al. (2013) applied LCA method to compare two waste management scenarios: manual disassembly and shredding. Simic and Dimitrijevic (2013) proposed a short-term ASR recycling planning model for Japanese vehicle recycling industry, formulated as a linear program, which can be used to improve its profitability and recycling efficiency. Ruffino et al. (2014) performed an economical assessment of a hypothetical industrial recovery process of light ASR, obtained by transferring the results gathered at lab-scale to full-scale.

From the review of initial literature, it is possible to identify that there is a lack of research of uncertainties that exist in vehicle recycling systems. No previous research was reported on fuzzy based programming in the ELV recycling planning research field. In addition, none of the previous studies analyzed the linkage between decision making risk and vehicle recycling system performances when fuzziness in decision makers' preferences exists. Finally, because the fuzzy risk explicit interval linear programming approach represents novel methodology, no research papers have been carried out yet. In view of the limitations in previous works, this study aims to develop a fuzzy risk explicit interval linear programming model for ELV recycling planning in the EU. The developed model will provide optimal plans for procuring vehicle hulks, storing unprocessed hulks, sorting generated material fractions, allocating sorted waste flows and allocating sorted metals for specific decision maker preference type and desired α-cut level. Moreover, it has advantages in reflecting uncertainties presented in terms of intervals in the ELV recycling systems and fuzziness in decision makers' preferences, in the same time facilitating dynamic analysis for recycling managers in terms of ELV production planning and process control.

The remaining part of the paper is organized as follows: Section 2 presents the used materials and methods, and developed model. Section 3 presents a case study results and discussions, and Section 4 presents the paper's main conclusions.

2. Materials and methods

2.1. Interval linear programming approach

In a vehicle recycling system, it is difficult to express or obtain the overall modelling data in deterministic form. In fact, uncertainty is the key factor influencing vehicle recycling planning. For instance, in a vehicle recycling system, sorting and transportation costs are uncertain in reality, because they can vary temporally and spatially. In addition, the costs of land-filling, municipal solid waste incinerator (MSWI) and advanced thermal treatment (ATT), i.e. gate fees, which vary among EU member states and their amounts are subject to continuous change. Furthermore, processing rates of vehicle recyclers' sorting equipment and efficiency of ATT plants and MSWIs cannot be considered as deterministic values, because they depend on material flow composition. Finally, in long-term planning of vehicle recycling, observing scrap metal prices as deterministic values can be considered unacceptable. On the other hand, the overall modelling data can be obtained as interval values and the approach to tackling such a problem is called interval linear programming (ILP).

Interval linear programming is one of the tools to tackle uncertainty in mathematical programming models (Bin Mohd and Suprajitno, 2010). The ILP approach (Moore, 1979) represents an extension of the classical LP approach to an inexact environment