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Modelling of WEEE recycling operation planning under uncertainty

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ABSTRACT

Recycling is very important especially for hazardous materials considering their negative impacts on the environment. Waste electrical and electronic equipment (WEEE) is generally classified under hazardous waste. Determination of process methods and quantities of WEEE to be processed is significantly important since it enables the efficient operation and management of recycling systems. The presence of uncertainty in these systems requires to develop appropriate decision-making tools to deal with uncertain parameters in recycling-operation planning problems. In this study, we propose a linear programming (LP) model for multi-period operation planning for recycling of WEEE considering fuzzy parameters: demand, quantity of WEEE to be processed, operational capacity of resources, amount of output obtained from WEEE and processing times. The model aims to maximize the total profit by determining the best recycling strategies and types, quantity and stocks of WEEE to be recycled during the planning term. The solution method is based on ranking methods of fuzzy numbers through the comparison of their expected intervals. The proposed LP model is illustrated using a case study with experimental analysis. The findings indicated that the nature of fuzzy parameters have critical effect on the total cost and the total revenue at different levels. The results also show that the uncertainty in recycling of WEEE is a crucial factor in developing consistent plans to achieve the economic sustainability of recycling facilities.

1. Introduction

Due to rapid technology changes and fashion-driven demand, like many other product types, electrical and electronic equipment (EEE) may become waste within a few months to a few years (Ikhlayel, 2018). Therefore, the quantity of waste electrical and electronic equipment (WEEE) has been progressively increasing all over the world. Predictions made in recent years show that 20–50 million tons of WEEE are generated annually worldwide, and this quantity increases by at least 3%–5% every year (Robinson, 2009; UNEP, 2006). WEEE may consist of more than 1000 different substances of various sizes and shapes. Due to the hazardous materials contained in WEEE, such as lead, mercury, and cadmium, many countries have imposed regulations on their manufacturers and consumers to recover WEEE (EU, 2003a, b, 2011, 2012). Since WEEE also contains considerable amounts of valuable materials, such as gold, palladium and copper (Widmer et al., 2005), recovery of WEEE offers a potential economic gain (Cesaro et al., 2017). Please refer to a literature review conducted by Pérez-Belis et al. (2015) to find out the main research areas in the field of WEEE.

Today, there are various recovery options for WEEE including reuse, repair, recycling, remanufacturing and disposal. Recycling is the process of retrieving the material content of used and nonfunctioning products through a series of operations, including sorting, disassembly and bulk recycling. Determining the process methods and types and quantities of WEEE to be recycled using related processes is an important operational-level decision for the planning of recycling systems (Gungor and Gupta, 1999; Ilgin and Gupta, 2010). However, operational level decisions need to be made under the complex and mostly unknown nature of WEEE whose material content may vary based on its age and type (Robinson, 2009). Due to this structural complexity, a high level of variability and uncertainty is expected in recycling operations of WEEE and resulting outcomes (Musee et al., 2008a, 2008b). For instance, recycling processing times and the amounts of retrieved materials and components from WEEE may fluctuate even in the group of same type of products. Similarly, other internal and external aspects of WEEE recycling bring additional uncertainties,

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such as the quantity and the content of WEEE to be processed, demand for the output of WEEE recycling systems and operational capacities of resources. One can handle these issues using stochastic modelling approaches if there are sufficient historical data for uncertain parameters. However, for the case of recently developing areas like WEEE recycling, it is difficult to generate actual and exact random distributions due to the lack of reliable historical data. In these cases, a powerful alternative is to use fuzzy set theory (Bellman and Zadeh, 1970), which provides a framework to handle different kinds of uncertainty issues.

Therefore, the main objective of this paper is to contribute to the enhancement of uncertainty-focused studies in the WEEE recycling literature. In order to achieve this, a mathematical model for the multi-period operation planning problem considering fuzzy parameters in the WEEE recycling environment is provided. In order to solve the model, the *ranking method of fuzzy numbers through the comparison of their expected intervals* (Jiménez, 1996; Jiménez et al., 2007; Parra et al., 2005; Pishvaee and Torabi, 2010) was utilized. This method a computationally efficient method because it aims to compare fuzzy parameters to solve linear problems by preserving its linearity. Therefore, the method can be conveniently used to solve large models such as the proposed model in this study. The solution of the model determines the process methods and types and quantities of WEEE to be recycled in order to maximize the total profit by considering all related cost and benefit terms associated with WEEE recycling operations. Additionally, in order to enhance the decision maker's flexibility, scenario analysis was carried out for different membership degrees of fuzzy parameters by applying a full factorial design.

The remainder of this paper is structured as follows. In Section 2, related literature is provided and the contribution of the study is clearly identified. Section 3 describes the problem environment and the LP model of the problem with fuzzy parameters is formulated. Section 4 presents a way to transform the fuzzy model into a crisp model. An illustrative example is presented in Section 5. Numerical results are given and alternative scenarios analyzed in Section 6. Finally, the last section contains conclusions and remarks about possible future developments.

2. Literature review

In the literature, there are several papers addressing the planning of WEEE recycling operations. Their contributions are briefly given as follows in a chronological order. Sodhi et al. (1999) and Sodhi and Reimer (2001) presented mathematical models for planning of recycling operations, including disassembly, bulk recycling and smelting. Ploog and Spengler (2002) and Spengler et al. (2003) developed a mixed-integer linear programming model for integrated planning of acquisition, disassembly and bulk recycling in WEEE recovery. Stuart and Christina (2003) and Rios and Stuart (2004) studied scheduling issues in recycling, considering staging, manual disassembly and bulk recycling operations using discrete event simulation. Qin and Stuart (2003) and Lu et al. (2006) paid special attention to short-term bulk recycling planning and proposed mixed integer programming models to determine processing and reprocessing levels. Shih and Lee (2007) presented a heuristic approach which identifies the optimum disassembly sequence and decides when to stop the disassembly and send the product to shredder. Abu Bakar and Rahimifard (2008) and Rahimifard et al. (2009) developed and improved a computer-aided recycling process planning system for WEEE recycling operations. Renteria et al. (2011) and Renteria and Alvarez (2012) presented a methodology for the selection and design of operations of a recycling system handling mainly television sets and monitors. Achillas et al. (2013) presented a methodological framework based on the cost-benefit analysis to decide the depth of disassembly and they applied the framework to a case study of an electronic product. Choi and Fthenakis (2014) constructed mathematical models considering the macro- and micro-level recycling issues of photovoltaic-panel wastes, which are classed as WEEE. Vanegas et al. (2015) proposed several modelling techniques and metrics within a procedure to design pre-treatment recycling companies and they analyzed the recycling of LCD TVs. Capraz et al. (2015) presented a mixed-integer linear programming model to determine the best operation planning strategy for a WEEE facility dealing with the bidding process. The authors also highlighted the need for studies dealing with the fuzzy and stochastic nature of WEEE recycling. Capraz et al. (2017) evaluated alternative layout configurations for WEEE disassembly systems in recycling facilities with an efficient simulation modeling approach. Tolio et al. (2017) recently reviewed the design, management and control issues of de- and remanufacturing systems.

Although it is important, there are only a few studies that consider the fuzzy nature of recycling systems. Simic and Dimitrijevic (2013) formulated a risk explicit interval linear programming model, which makes plans including procuring, sorting and allocation decisions, for long-term planning of the vehicle recycling systems. They used interval approach to model uncertain parameters. Simic (2015) considered fuzziness in his linear programming model for end-of-life vehicle recycling planning, including uncertainties in the preferences of decision makers. Kalayci et al. (2015) used triangular fuzzy membership functions for disassembly task times in their disassembly-line balancing problem found in a WEEE recycling environment. Additionally, fuzziness in WEEE recycling management is considered in a few studies by using fuzzy multi-criteria decision-making tools (Bereketli et al., 2011; Che, 2010; Colesca et al., 2014; Ulukan and Genevois, 2012; Yeh and Xu, 2013).

The summary presented above indicate that there is a need for more research efforts in the literature to understand and deal with the uncertainty nature of the WEEE recycling planning problems. So, this study contributes to the advancement of relatively less studied area of the planning of WEEE recycling systems under uncertainty. This study differentiates from previous studies in the literature as it proposes a more realistic LP model by simultaneously taking into account fuzzy parameters such as demand, quantity of WEEE to be processed, operational capacity of resources, amount of output obtained from WEEE and processing times for multi-period operation planning for recycling of WEEE. The model detailed in the next section aims to answer the following questions for a decision maker in a WEEE recycling system operating in a fuzzy environment:

- How much and what type of WEEE do we need to recycle in each period?
- Which recycling processing methods do we need to use in each period?
- What are the best inventory levels for both WEEE and the resulting output of recycling for us to carry?
- What are the required capacities of recycling process methods in each period?

3. Problem formulation

The proposed LP model is detailed in this section. Assumptions, sets of indices, parameters and decision variables of the model are