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Optimizing reverse logistic costs for recycling end-of-life electrical and electronic products

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ABSTRACT

With accelerating technological changes and market expansions of electrical and electronic products (EEPs) during the last few decades, much focus and effort have been placed on the waste of these products. In order to reduce their negative impacts on the environment and human, at the end of their product lifecycles, their wastes need to be properly handled, processed, disposed, and if applicable, remanufactured, recycled or reused. Based on the analysis of the waste EEPs (WEEPs) reverse logistic network, this paper presents a mathematical programming model which minimizes the total processing cost of multiple types of WEEPs. The monetary factors considered in the model include the costs of collection, treatment, and transportation as well as sales income with different fractions of returned products. Based on the proposed model, the optimal facility locations and the material flows in the reverse logistic network can be determined. A sensitivity analysis of the proposed model is also presented. Finally, a numerical example is illustrated to gain a better insight into the proposed model.

1. Introduction

Accelerating technological changes and market expansions of electrical and electronic products (EEPs) make these products obsolete very quickly, leading to a significant increase in waste EEPs (WEEPs). According to the Environmental Protection Agency (EPA), there are 20–50 million metric tons of WEEPs generated worldwide every year, comprising more than 5% of all municipal solid waste. Developing countries are estimated to triple their output of WEEPs by 2010. In the US alone, some 14–20 million personal computers are thrown out every year. In Western Europe, 6 million tons of WEEPs were generated in 1998 and the amount of WEEPs is expected to increase by at least 3–5% per annum. By 2010, the European Union will be producing around 12 millions tons of electrical and electronic waste annually (Nagel, 1997). In China, it was estimated that about 1.6 million obsolete EEPs were generated in 2003 with TV accounting for nearly half of the total (Liu, Tanaka, & Matsui, 2006).

WEEPs are non-homogeneous and complex in terms of materials and components. Some of their material or components are highly toxic (Dimitrakakis, Janz, Bilitewski, & Gidarakos, 2009; Hicks, Dietmar, & Eugster, 2005), while some others may have high residual value (Achillas, Vlachokostas, Moussiopoulos, & Banias, 2010; He et al., 2006; Iakovou et al., 2009; Kang & Schoenung, 2005; Kumar & Putnam, 2008; Nnorom & Osibanjo, 2009; Truttmann & Rechberger, 2006). In view of the negative effects of WEEPs on the environment and humans, and the valuable materials that can be extracted and reused from WEEPs, legislations in many countries have focused their attention on the management of WEEPs, and new techniques have been developed for the recovery of WEEPs. In particular, the European Union (EU) adopted the 2002/96/EC and 2002/95/EC (Restriction of Hazardous Substances-RoHS directive), which causes essential changes in the field of electronic scrap recycling (Directive 2002/96/EC and Directive 2002/95/EC). Producers are requested to finance the collection, treatment, recovery, and environmentally sound disposal of WEEPs. The directive imposes a high recycling rate of all targeted WEEPs. Reuse, recycling and recovery rates ranging from 50% to 80% according to the category of the equipment considered, must be achieved by producers of EEPs (He et al., 2006).

Since the reverse logistic of WEEPs is an important step of WEEPs treatment, there is a growing number of research on material recycling models for specific products (Barros, Dekker, & Scholten, 1998; Kroon & Vrijens, 1995; Nunes, Mahler, & Valle, 2009; Realff, Ammons, & Newton, 1999; Reynaldo & Jurgen, 2009; Slack, Gronow, & Voulvoulis, 2009; Spengler, Püchert, Penkuhn, & Rentz, 1997), as well as reverse logistic networks (Demirel & Gökçen, 2008; El-Sayed, Afia, & El-Kharbotly, 2010; Fleischmann, Krikke, Dekker, & Flapper, 2000; Jayaraman, Guide, & Srivastava, 1999; Kannan, Sasikumar, & Devika, 2010; Mutha & Pokhare, 2009; Salema, Povoa, & Novais, 2006; Williams et al., 2007). However, studies specifically addressing WEEPs problems (Deepali, Philipp,

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& Markus, 2005; Geraldo & Chang, 2010; Grunow & Gobbi, 2009; Jang & Kim, 2010; Lee, Chang, Wang, & Wen, 2000; Liu et al., 2006; Rahimifard, Abu Bakar, & Williams, 2009) are rare and still limited to some specific areas of WEEPs reverse logistics. Therefore, this paper presents a mathematical model for multi-products reverse logistic network so that the total reverse logistic cost can be minimized. The monetary factors considered in the model include the cost of collection, treatment, and transportation as well as sales income from returned products. Based on the proposed model, the optimal facility locations and the material flows in the reverse logistic network can be determined.

The rest of the paper is organized as follows. The reverse logistic network model is proposed in Section 2. Section 3 contains the mathematical formulation of the model. The proposed model is illustrated through an example in Section 4. Finally, conclusions are provided in Section 5.

2. Reverse logistic model

Reverse logistics is the collection and transportation of used products and packages (Mutha & Pokhare, 2009). Various researchers classified the reverse logistic process differently. Fleischmann et al. (2000) categorized the recovery process into collection, inspection/separation, re-processing, disposal and re-distribution. Liu et al. (2002) and He et al. (2006) defined recovery process as a combination of re-use, service, re-manufacture, recycle, and disposal, while Thierry et al. (1995) divided recovery into repair, refurbish, remanufacture, cannibalize, and recycle. Bereketli, Genevois, Albayrak, and Ozyol (2011) showed that reuse, recycling, and disposal are generally three different ways of treating WEEE. Nevertheless, the main components of the recovery process involve in these alternatives can be explained as follows.

Reuse is the second-hand trading of products for use as originally designed. Reusable parts can be removed from the product, returned to a manufacturer where they can be reconditioned and assembled into new products (Liu et al., 2006). Recycling (with or without disassembly) includes the treatment, recovery, and reprocessing of materials contained in the used products or components in order to replace the virgin materials in the production of new goods (He et al., 2006). Re-manufacturing is the process of removing specific parts of the waste product for further reuse in new products. Disposal is the processes of incineration (with or without energy recovery) or landfill (He et al., 2006).

The proposed model considers the design of a multi-echelon reverse logistic network that consists of collection sites, disassembly sites, treatment sites (recycling facilities and repairing facilities), and final sites (disposal facilities, primary and secondary markets), as shown in Fig. 1.

Reverse flow starts with the collection of the returned products. These products are first received at collection sites such as retailers and permanent drop-off sites and then transported to disassembly sites. At the disassembly sites, the returned products are separated into components or parts, which are classified into four categories: disposal, recyclable, repairable, and reusable. The treatment sites (repairing facilities and recycling facilities) receive components from disassembly sites. Faulty or old components are treated at repairing facilities. In recycling facilities, different types of materials are treated separately. Plastics and ferrous metal fractions are treated by iron smelters. Most non-ferrous metals are sent to copper smelters, aluminum smelters, and lead smelters. These materials can be recycled into generated material. Hazardous materials such as americium, mercury, and lead acid batteries are sent to special landfills or processing. Final sites encompass disposal facilities, secondary markets and primary markets. The generated materials are delivered to primary markets. Hazardous or non-recyclable materials are transported to disposal facilities. Reusable

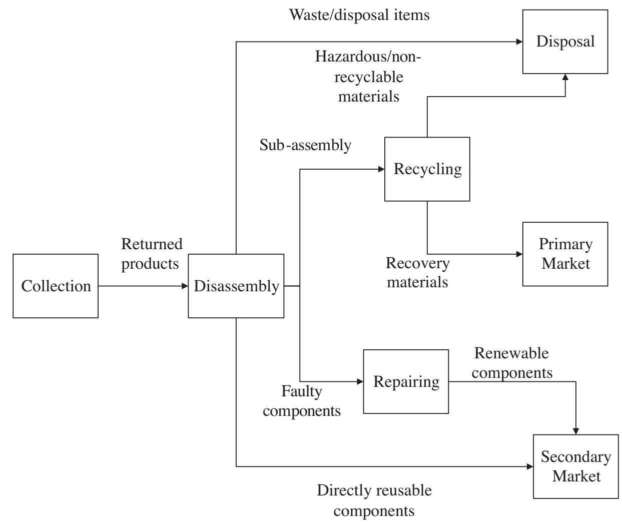

Fig. 1. Flow of returned products in the reverse logistic network.

components and renewable components are sold at the secondary markets.

Transportation of returned products is one of the main activities in reverse logistics. In a reverse logistic network, products to be recovered need to be physically moved throughout the entire recovery process. Thus, in many cases, transportation costs greatly influence economic viability of products recovery. In addition, excess transportation has significant environmental impact and is in conflict with the motivation of recycling. Therefore, carefully design and control of the transportation means are crucial in the success of reverse logistics.

The volume and the weight of a product are the two main factors influencing the ease of transportation and thus the transportation cost. Products in the reverse logistics can be classified into types. Different types of products lead to different volume changes during the recycling process. For the first type, such as books, the product volume remains the same during the recycling process. The volume of the second type of products is reduced. For example, the volume of the recycled plastics is in most of the cases reduced because they normally contain voids and can be compressed into smaller and compact existence. The third type of products will result in an increase in the volume during the recycling process typically because the disassembly of the product yields components containing more cavities or voids. For example, recycling personal computers produces cases, CPUs, power supplies, etc.

Recycled WEEPs may belong to different types at different stages. When a returned product is sent from a collection site to a disassembly site, its volume and weight are not changed. However, at disassembly sites, the returned product can be disassembled into parts such as chassis and components, which increase of the total transportation volume. On the other hand, some parts of the product may be compressed into a more compact form before further processing and transportation.

The variation of the transportation cost and the disassembly of products into different types are illustrated by the disassembly tree of product P_1 in Fig. 2. The disassembly site receives product P_1 from the collection site with the transportation cost of 20 dollars per unit. At the disassembly site, product P_1 is disassembled into five parts. For component C_1, the frame of P_1, its volume equals to the original volume of the product although its weight is less than that of the original product. The transportation cost of C_1 can be as high as that of P_1, since the transportation of component C_1 is charged by volume. In the case of sub-assembly S_1, component C_2, disposal D_1, and faulty component C_3, they are charged