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Two-echelon reverse supply chain in collecting waste electrical and electronic equipment: A game theory model

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ABSTRACT

This study contributes to the literature by proposing coordination strategies between recyclers and processors in the collection of waste electrical and electronic equipment. Due to the increase in e-waste and its serious environmental consequences, much attention has been paid to recycling and remanufacturing. This study proposes a two-echelon reverse supply chain and deals with the differential game model by introducing recycling publicity. Illustrative examples are used to examine the differences and changes in recovery price, quantity, and publicity effort among three case studies. The results indicate that, when a processor undertakes publicity costs, the recovery quantity can be increased by improving recovery publicity efforts, rather than raising the recovery price, but when publicity expenses are paid by the recycler, the recovery quantity may be enhanced by bringing up the unit direct recovery price while the degree of recovery publicity efforts is minimal. A centralized decision is made, and recovery price, recovery quantity, and publicity efforts are maximized. These results can help achieve an optimal approach to the recycling of waste electrical and electronic equipment in a reverse supply chain.

1. Introduction

Together, the rapid development of the electronic industry and the heavy consumption of electronic products worldwide generate 40 million tons of waste electrical and electronic equipment (WEEE) every year (Veit & Bernardes, 2015). Meanwhile, the toxic chemical and hazardous substances contained in the waste can endanger human health and the eco-environment if electronic waste is not properly treated (Tanskanen, 2013). Hence, WEEE's recycling and remanufacturing have become a crucial strategy and attracted much attention for reducing pollution and conserving natural resources. Legislation regarding the collection of waste and the increase in consumer environmental awareness have emerged as significant practices. Specifically, the European Union (EU) has formally released the "Waste Electrical and Electronic Equipment Directive" and "The Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment" (Chi, Streicher-Porte, Wang, & Reuter, 2011). In China, *"Management Measures on the Recycling and Disposal of Waste Electrical and Electronic Products (China WEEE)"* were implemented (Chung & Zhang, 2011). In practice, successful collection basically depends on the consumer's willingness and decision to act. However, due to the low environmental awareness of consumers, there are large quantities of e-waste stored or discarded. This leads to remanufacturers facing the dilemma of resource shortages. Hence, a study is urgently required to explore how to achieve effective and quick WEEE collection from consumers.

Prior studies have indicated that publicity has a positive effect on the participation of consumers in recycling waste (Ylä-Mella, Keiski, & Pongrácz, 2015; Ylä-Mella, Poikela, Lehtinen, Keiski, & Pongrácz, 2014; Yu, 2012; Zheng, Yang, Yang, & Zhang, 2017). Yu (2012) found that public propaganda in the field of recycling WEEE contributes to the conversion of the consumer from recycling intention to the final behavior. Ylä-Mella et al. (2015) discovered that increased publicity and up-to-date information provided by producer associations and retailers could help enhance public participation in recycling. Zheng et al. (2017) demonstrated that collection efforts, such as green propaganda, could play a key role in collecting toxic products that have reached the end of their life (EOL). In contrast, Burmester, Becker, Heerde, and Clement (2015) noted that pre-launch advertising and publicity may have a negative effect on consumer behavior. Moreover, Tseng (2011) stated that greening a supply chain to reduce a firm's pollution and other environmental impacts risks uncertainty, due to the presence of incomplete information and linguistic preferences.

However, most of these studies focus on the effect of publicity on consumers' behavior, lacking discussion of publicity cost allocation

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between the recycler and processor. A central part of supply chain management relies mainly on the dynamics among firms in the supply chain network, and empirical studies could benefit from using multi-echelon data, rather than studying firms in isolation (Isaksson & Seifert, 2016). "Two-echelon data" can contain information on both upstream and downstream supply chain partners. Still, though several leading academic journals contain numerous studies of publicity/advertising in the marketing of a forward supply chain (Ahmadi-Javid & Hoseinpour, 2012; Colliander & Marder, 2018; Coviello & Mariniello, 2014; Zhang, Gou, Liang, & Huang, 2013), favorable activities in a reverse supply chain are rarely discussed. A feasible method for solving the dilemma is to launch publicity activities.

This study aims to discuss the recycling performance in a two-echelon reverse supply chain by introducing a publicity perspective. As for collecting WEEE, similar to the study by Feng, Govindan, and Li (2017), two approaches, namely recyclable dealer collection and recycler collection, are used. This study considers the recycling publicity activities as being undertaken by both the recycler and processor. Three collection scenarios are explored when (i) only the processor pays the expenses; (ii) only the recycler undertakes publicity costs and (iii) the recycler and processor make joint decisions. This study assumes that both consumer environmental awareness and the recovery price of used products are influenced by the propaganda efforts. This study contributes to a publicity perspective of collection and reprocessing problems through a focus on WEEE in a reverse supply chain. There has been little research on recycling and remanufacturing WEEE while considering publicity activities in a reverse supply chain.

The research questions that this study aims to answer are:

(1) What are the equilibrium decisions and profits of each model?
(2) Which of the three models is the best for the members of a supply chain?
(3) How does publicity affect the recovery price and quantity of WEEE?

This study is organized as follows. Section 2 reviews the literature. Section 3 presents the problem description, basic assumptions, and notations. Three different waste collection models are proposed in Section 4. Section 5 conducts numerical studies of the three models and discusses the impacts of publicity on recovery price and quantity of WEEE. Finally, Section 6 presents the concluding remarks, limitations of the study, and directions for future research.

2. Literature review

This study analyzes a two-echelon reverse supply chain consisting of a recycler and a processor, then performs a game-theoretic analysis for determining and optimizing the choice of recovery channels for WEEE under the effect of publicity. The related literature can be grouped into two parts: one part reviews the selection and management of recycling channels while the other part discusses the coordination of a reverse supply chain.

Channel selection and management is an important topic in the study of reverse supply chains, and some research has been conducted to analyze the strategy of choosing recycling channels made by the collector/manufacturer in a reverse supply chain (Atasu, Toktay, & Wassenhove, 2013; Han, Wu, Yang, & Shang, 2016; Huang & Wang, 2017; Savaskan, Bhattacharya, Shantanu, Wassenhove, & Luk, 2004). For example, Savaskan et al. (2004) were the first to conduct a comparative analysis of three recycling channels, which are manufacturer-managed, retailer-managed and third-party-managed. Savaskan and Wassenhove (2006) modeled a direct product collection system to analyze the interaction between a manufacturer's reverse channel choice and the strategic product pricing decisions in the forward channel when retailing is competitive. The results show that competition among retailers would have a certain impact on the choice of recycling channels. Atasu et al. (2013) extended the work of Savaskan et al. (2004) to discuss the impact of collection cost structure on the channel choice of manufacturers and found that the optimal reverse channel choice is driven by how the cost structure moderates the manufacturer's ability to shape the retailer's sales and collection quantity decisions. Chuang, Wang, and Zhao (2014) studied the manufacturer's choice of three alternative reverse channel structures for collecting used high-tech products from consumers for remanufacturing and explored the impacts of collection cost structures and implementations of product take-back laws on the manufacturer's choice of reverse channel structures.

Recently, the impacts of some important factors affecting the performance of collecting used products from consumers and the processor/manufacturer's reverse channel choice have been examined. For example, Han et al. (2016) investigated the manufacturer's reverse channel selection from the perspectives of profitability and robustness, then found that on profitability, the direct channel outperforms the indirect channel in a favorable operational environment, while the indirect channel has higher robustness under remanufacturing risks. Huang and Wang (2017) discussed equilibrium decisions when considering the fluctuation of remanufacturing ability and saving unit cost, then proposed equilibrium schemes under technology licensing for each supply chain member. Jafari, Hejazi, and Rasti-Barzoki (2017) studied the role of channel leadership in waste recycling and revealed that, when the collector and recycler have similar decision powers, the manufacturer earns a higher profit. Hence, prior studies have explored only the roles of pricing decisions, collection costs, profitability, remanufacturing ability, and channel leadership in the reverse supply chain, but there is little discussion on the effects of advertising/publicity, even though this is a significant factor in promoting the selection and management of recycling channels. As shown in the study of Zheng et al. (2017), green propaganda is more effective than the improvement of the acquisition price in recycling toxic products (e.g., electric battery, etc.). Meanwhile, Ylä-Mella et al. (2015) revealed that, from the long-term perspective of improving WEEE recovery efficiency, raising consumer awareness by publicity is an environmentally sound method compared to adding collection points. Hence, this study aims to explore the optimal price and recycling channel choice by considering publicity.

Coordinated decision-making in a reverse supply chain plays a vital role in achieving the desired effects (Liu, Chen, & Fang, 2016) and has become a popular field for further exploration (Feng et al., 2017). From a survey of the coordination of recycling channels, Fuminori, Tamer, and Vedat (2011) modeled competitive decision-making in monopolistic and competitive take-back schemes as two-stage sequential games between competing manufacturers and recyclers. The authors found that competitive take-back schemes often achieve a win-win situation, i.e., lower product prices with higher profits for recyclers and manufacturers. Weraikat, Zanjani, and Lehoux (2016) examined the effect of having a proper coordination method between a producer of medications and third-party logistics companies responsible for collecting unwanted medications from customer zones. The experimental results indicated that introducing incentives to customers could decrease the number of uncollected medications and proper coordination with third-party logistics could guarantee a full recovery.

Regarding the role of the government, Heydari, Govindan, and Jafari (2017) analyzed the government role in improving coordinated supply chains through donating different incentives to supply chain members. The results showed that total channel profit in the coordinated case is improved and government-sponsored incentives for the manufacturer are more productive than for the retailer. In addition, by proposing some feasible contracts, the objectives of the members will be in accordance with the objective of the supply chain and achieve optimal supply chain performance. So, generally, contracts are often applied to coordinate the forward and reverse supply chains (Govindan & Popiuc, 2014; Liu, Zhao, Liu, & Chen, 2017; Zeng, 2013). Zeng (2013) explored a revenue-sharing coordination mechanism to coordinate