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On the cooperation of recycling operations

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ABSTRACT

This paper addresses two important issues that may affect the operations efficiency in the recycling industry. First, the industry contains many small-scale and inefficient recycling firms, especially in developing countries. Second, the output from recycling a waste product often yields multiple recycled products that cannot all be sold efficiently by a single firm. To address these two issues, this paper examines how different firms can cooperate in their recycling and pricing decisions using cooperative game theory. Recycling operations under both joint and individual productions with different cost structures are considered. Decisions include the quantity of waste product to recycle and the price at which to sell each recycled product on each firm's market. These decisions can be made jointly by multiple cooperating firms to maximize total profit. We design allocation schemes for maximized total profit to encourage cooperation among all firms. Managerial insights are provided from both environmental and economic perspectives.

1. Introduction

With soaring prices for natural resources and advances in technology, recycling not only plays an important role in waste management, but also has become a lucrative business. For example, the United Nations Environment Programme reports that 23% of the weight of cellular phones is metals, a percentage far richer than any natural mine, and a mobile phone can contain over 40 different metal elements. There are billions of cellular phones sold each year and will become obsolete in a few years, providing a huge source of recyclable waste [43]. While one hurdle confronting recycling is its high cost, the rising prices of raw materials for electronics and automobile parts increase incentives to recycle (moneycontrol.com [36]). Srivastava [44] points out that sustainable development can be achieved together with higher profits. Recycling is the key component to achieving this goal through generating profit from waste. Further, legislation mandates higher requirements for recycling. Kanari et al. [29] report that in the European Union, about 75% of the content of end-of-life vehicles is recycled and the remainder is regarded as waste to be sent to landfills. However, environmental legislation requires that waste be reduced to no more than 5% by 2015.

Recycling has difficulty achieving both environmental friendliness and commercial success, especially for complex waste products such as electrical and electronic equipment (Cui and Forssberg [11]). Recycling such waste products, through disassembly, chemical and physical processing, and further processing, generates multiple recycled products, which creates complex operations management problems, because the recycled products are produced roughly along a fixed output ratio for each product, which is often inconsistent with demand for the products. A similar situation exists in the mining industry. For example, multiple types of precious metals are conglomerated together in rare-earths, and a separation process is needed to isolate them (Areddy [3]).

The above described difficulty in recycling is more serious when recycling is conducted on a small scale. The city of Guiyu, home to more than 5500 electronics waste recycling firms, many operating in a family-workshop style, has become the most polluted area in China due to the wastes generated from recycling (crunchgear.com [10]). Cooperation among multiple parties is important for efficient and profitable recycling (Roy and Whelan [42]). Recently, the Chinese government has issued policies to accelerate integration in the recycling industry, in the pursuit of an economies of scale effect (greenbiz.com [18], Hicks et al. [28]). Also, Alcoa, a leading integrated aluminum company, bought partial ownership of Electronics Recyclers International to collaboratively make aluminum electronics more sustainable (Dignan [14]). We note that in practice it is challenging for thousands of small-scale recycling firms to cooperate. Our work is not necessarily exploring the current issue in recycling industry. We view the cooperation among recycling firms as important emerging practice and opportunities

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that should be encouraged, and hence use cooperative game to help the decisions in recycling quantity, pricing, and fair allocation of total profit. Meanwhile, to pursue social welfare, the government has certain responsibility to improve the efficiency of the recycling industry as a whole. To this end, cooperative game models will provide useful insights to the government with respect to the best achievable, as well as a benchmark for other scenarios.

This paper studies how different firms can cooperate in their recycling and pricing decisions using cooperative game theory. Specifically, we consider a common waste product that can be recycled and reproduced into different recycled products with a fixed output ratio for each product. We consider two types of recycling operations. First, in *joint production*, the firms use a common facility for recycling. Second, in *individual production*, each firm uses its own facility for recycling. Both recycling types can be capacitated or not. Further, for each type of recycling operations, we consider three types of nondecreasing cost functions: linear, convex, and with economies of scale. The recycling operations considered represent different scenarios with respect to the transportation of the waste product, the sharing the recycle facility, and the limited supply of the waste product. After recycling, the firms sell the reproduced products into individual markets. Decisions include the quantity of the common waste product to recycle and the price at which to sell each recycled product on each firm's market. These decisions can be jointly made by multiple cooperating firms to maximize total profit. We formulate the recycling problem as a cooperative game which studies whether the maximum total profit can be fairly allocated to the participating firms. Depending on the type of recycling operations and cost functions, there are 12 different games. We show that none of these games is convex. For each of the games, we either provide a fair allocation of the maximized total profit of all the firms to encourage cooperation, or show the none existence of such an allocation.

For an extensive literature review on recycling and its role in a supply chain, please refer to Gungor and Gupta [25], Srivastava [44], and Akçali [1]. Since our focus is on economically driven recycling, the types of waste product that best fit our model are automobiles (Bellmann and Khare [5], Qu and Williams [41]) and electrical and electronic equipment (de Fazio et al. [13], Krikke et al. [32]). Cui and Forssberg [11] review the mechanical recycling process for waste electrical and electronic equipment. Hicks et al. [28] study legislative and market responses to the recycling and disposal of electrical and electronic waste.

Our work is in the broad area of the planning and control of recycling and remanufacturing from an operational perspective. Guide et al. [21] and Guide et al. [22] examine capacity planning, structure complexity, and scheduling in remanufacturing. A review over product, process, and organizational design in remanufacturing is set forth in Bras and McIntosh [6]. Guide [20] describes industry practice in planning and control of remanufacturing. However, recycling with the output of multiple reproduced products has received limited attention in the literature.

Recycling operations can be modeled as a disassembly process, as by Gupta and McLean [26], Lee and Xirouchakis [33], and Kim et al. [30,31]. It is also similar to certain production process with multiple types of output, e.g., Lu and Qi [34]. Our work differs from the above literature in that we consider the recycling and pricing decisions of multiple firms, with the focus on cooperation among these firms.

Cooperative game theory has been extensively applied to encourage cooperation at operational levels, such as in scheduling (Curiel et al. [12], Aydinliyim and Vairaktarakis [4]), queueing (García-Sanz et al. [16], Yu et al. [46], Anily and Haviv [2]), and ordering and inventory management (Chen [8], Chen and Zhang [9], Zhang [47], Hall and Liu [27]). A common feature of these studies is that there is an optimization problem underlying the game, which often can be formulated as mathematical programs, such as linear or nonlinear program. Duality theory plays an important role in fairly allocating total cost or profit to different parties.

Cooperative games modeling production systems can be traced back to the seminal work by Owen [39], who examines the linear production game. The underlying optimization problem is to maximize the output value of multiple products subject to linear resource constraints. All players act as an exchange economy by pooling resources together. Important extensions of the linear production game include the multicommodity flow game [35] and the inventory centralization game ([19,8,9], among others [40]. Our model can be regarded as a nonlinear production game with extendable resources, but differs from existing work in two aspects. First, we model and provide managerial insight for cooperative decisions that specifically arise from the recycling industry, and consider firms that make recycling and pricing decisions jointly, as motivated by the finding that in price-sensitive markets, such as for cellular phones, recycling firms can exercise control over the prices of recycled products [24,23]. Second, we consider different types of recycling operations with different cost structures, and develop results that significantly enrich the literature.

Game theoretic analysis has been used to evaluate recycling operations to a limited extent. Nagurney and Toyasaki [38] model the reverse supply chain management of electronic waste. They consider decision makers in four tiers: sources of electronic waste, recycling firms, processors, and consumers. The corresponding decisions in a multi-tiered recycling network are modeled using a noncooperative game. Apparently, the present work is among the first to study recycling operations using cooperative games.

In summary, this paper uses cooperative game models to address two unique features in some recycling industry: the existence of many small-scale recycling firms and the yield of multiple recycled products. Meanwhile, there are also other important issues in different scenarios of the recycling industry, such as different quality grade of the waste product, and different efficiency in the waste collection process. We aim to extend our model to incorporate these issues in the future.

The remainder of this work is organized as follows. Section 2 formally defines the cooperative games that model the cooperative recycling and pricing decisions among different firms, and summarizes our main findings. Sections 3 and 4 discuss the existence of core allocation for the games under joint and individual production, respectively, with different forms of recycling cost functions. Section 3 provides a special case in which a core allocation can be found efficiently. Concluding remarks are provided in Section 5. All proofs appear in Appendix S1.

2. The game model

2.1. Recycling operations

There are n firms engaged in a recycling business, transforming a *common waste product* into m recycled products, along a fixed output ratio for each product. Without loss of generality, we scale the unit of each recycled product such that one unit of the common waste product can be transformed into one unit of each recycled product.

Let $N = \{1,2,\ldots,n\}$ denote the recycling firms and $M = \{1,2,\ldots,m\}$ denote the recycled products. We consider two types of recycling operations. First, in joint production, the firms use a common facility for recycling, and have cost function $C(q)$, where $q \geqslant 0$ is the quantity of the waste product recycled. In case of capacitated production, we have $q \leqslant Q$, where $Q \geqslant 0$ is a constant. Joint production models a centralized recycling facility. Second, in individual production, each firm uses its own facility for recycling, and has cost function $C_i(q_i)$, where $q_i \geqslant 0$ is the quantity of the waste product recycled by firm i. In case of capacitated production,