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The closed-loop supply chain network with competition, distribution channel investment, and uncertainties

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ABSTRACT

In this paper, a closed-loop supply chain network is investigated with decentralized decision-makers consisting of raw material suppliers, retail outlets, and the manufacturers that collect the recycled product directly from the demand market. We derive the optimality conditions of the various decision-makers, and establish that the governing equilibrium conditions can be formulated as a finite-dimensional variational inequality problem. We establish convergence of the proposed algorithm that can allow for the discussion of the effects of competition, distribution channel investment, yield and conversion rates, combined with uncertainties in demand, on equilibrium quantity transactions and prices. Numerical examples are provided for illustration.

1. Introduction

The path toward sustainability to demonstrate environmental and social responsibility has led to an increasing attention to the lifecycle of a product with a focus on value-added recovery activities [1,2]. For example, in 2007 alone, Kodak collected 120 million single-use cameras [3], and in 2000, Fuji Xerox was the first to achieve zero landfill of used products in Japan [4,5]. The study of closed-loop supply chain (CLSC) networks is used to maximize the value created from product take-back, recovery, and re-distribution which reuses the entire product, and/or some of its modules [6–8]. Product take-back activities have received attention, in part, by legislation such as the Paper Recycling Directive, the End-of-Life Vehicle Directive, and the Waste Electrical and Electronic Equipment Directive (WEEE) within the European Union, intended to give manufacturers incentives to reduce the environmental burden of their end-of-life (EOL) products, while also removing the growing waste management cost from municipal governments [9].

Even before the emergence of product take-back laws, some firms were already participating in voluntary product recovery, as reported by Kodak, FujiFilm, Hewlett–Packard, IBM Europe, and Xerox to name a few. An environmentally friendly firm can use a sustainable product program as a strategic tool for not only environmental improvement, but also to enhance the environmental image of their brand, generate revenue, serve their customers, and reduce production costs [10]. For example, on a life cycle basis, remanufacturing photocopiers consumes 20–70% less materials, labor, and energy and generates 35–50% less waste than conventional manufacturing using virgin materials [11]. Additionally, production costs are further reduced since the cost for a remanufactured part is generally 30–50% less than a new part would be [9].

There is an abundant amount of research available on the topic of CLSC management. For a comprehensive review of published literatures we refer the reader to the work of [12–15]. Based on the concept of equilibrium, first explored in a general forward supply chain setting by Nagurney et al. [16] and Nagurney and Toyasaki [17] provide a variational inequality CLSC formulation model which involve manufacturers, retailers, and demand markets, with the inclusion of recycling. Subsequently, Yang et al. [18] expanded on the work of Nagurney and Toyasaki [17], and incorporated the work of Hammond and Beullens [19] and Sheu et al. [20], to strategically model the oligopolistic closed-loop supply chain, which include manufacturers who are involved in the production of a homogeneous commodity from raw materials and reusable materials, and recovery centers that can get subsidies from government organizations.

However, there is limited contribution in the literature that addresses the complexity that arises from the large number of

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actors in a decentralized CLSC system [6], which increases the intensity of competition, combined with significant product EOL issues [21]. This paper provides an innovative framework to study the effects of competition, combined with distribution channel investment, yield and conversion rates, uncertainties in demand, and the resulting implications on equilibrium quantity transactions and prices in the CLSC network. In the subsequent paragraphs, we discuss the motivation for the study of these issues since environmental recovery is an option that is underutilized as firms are unsure how to mitigate the ambiguity surrounding economic performance.

Interestingly, even though the remanufacturing sector is larger than the U.S. domestic steel industry with annual sales over $53 billion [22], currently, very little, if any, value is recovered by the manufacturer [6] due to various yield factors. For example, Hewlett–Packard estimates that returns cost them as much as 2% of total outbound sales and less than 50% of the value of those product returns are being recovered [23]. The yield rate affects the viability of any recycling option by external factors such as the product's condition as a result of its utilization profile (affected by light vs heavy use and individual care for the products) [24], the ambiguity related to the product material content [25], and the product's structural design and level of modularity, which may make the disassembly process more or less difficult [26].

The economic viability of a recovery program is affected by not only the uncertainty in yield, which takes into account the conversion rates of recycled components to "like-new" products, but also the ambiguity surrounding customer demand [27]. Demand uncertainty is a known problem faced by firms to determine suitable levels of output before demand is known, which is classically known as the "newsboy" problem in operational research literature [28–30]. Inderfurth [31] studied the impact of uncertainties on recovery behavior but was restricted by stationary demands and return patterns. They determined, however, that in a non-stationary situation the impact of uncertainties could be even stronger, since excessive returns might happen more often. Shi et al. [32] studied the production planning problem for a multi-product closed loop system, in which the demands and their returns are uncertain and price-sensitive [33], but developed the model to include only the manufacturer's decision-making problem. In particular, we note that Dong et al. [34] studied the demand uncertainties in the decentralized supply chain network; but their model only considers the forward supply chain network.

Finally, we assume the manufacturers' recovery system investment is related to the collection efforts of the EOL products directly from the demand market. A direct collection system is evident in practice in response to increasing customers' demands for the removal of products as a service associated with the sale of new products. EOL products are collected either with monetary compensation or as a free-of-charge disposal where almost no costs are incurred to the end-users. Sprint PCS and Gateway customers may be paid for used, working technology products through trade-in programs; Apple offers free computer take-back and recycling with the purchase of a new Macintosh system; and Hewlett–Packard and Xerox Corporation provide free shipping and cartridge boxes for customer returns [35]. Given this information, it would make sense to include in our CLSC network model the assumption that the return rate and volume of the used product flow depends on the level of manufacturers' investment in the direct collection system [12,36].

In summary, the major innovations and contributions that differentiate this paper from the above mentioned works is: (1) we consider that the manufacturers can invest in the reverse supply channel to increase the recycled product volume; (2) the CLSC model captures the uncertainty in demand, which is associated with penalties, namely, inventory and shortage costs; (3) uncertain yield rate is modeled. We use the expected value since the probability distribution function of the yield rate is known. This information can be estimated based on historical data [37] and references therein. (4) We simultaneously consider multiple decision-making entities such as the raw material suppliers, the manufacturers, and the retailers, and study the equilibrium prices and transactions.

The paper is organized as follows: in Section 2, we develop the CLSC network model with decentralized decision-makers consisting of raw material suppliers, retail outlets, and the manufacturers that collect the recycled product directly from the demand market. We derive the optimality conditions of the various decision-makers, and establish that the governing equilibrium conditions can be formulated as a finite-dimensional variational inequality problem.

In Section 3, we study qualitative properties of the equilibrium pattern, and under reasonable conditions, establish existence and uniqueness results. We discuss the characteristics of the functions in the variational inequality that enable us to establish convergence. This can allow for the discussion of the effects of competition, reverse distribution channel investment, yield rates, combined with uncertainties demand on equilibrium quantity transactions and prices. We illustrate the model by applying the modified projection algorithm to CLSC numerical examples in Section 4. The paper concludes with Section 5, in which we provide a summary of the paper and future research directions.

2. The closed-loop supply chain with competition and distribution channel investment with uncertainties in yield and demand

In this section, we develop the CLSC network model. In particular, we consider W material suppliers involved in the supply of raw material to N manufacturers, who make a homogeneous product. Moreover, there are M retailers who deal with the local demand markets and face uncertain demands. Each retailer is assumed to be responsible for dealing with its own demand market. Such an assumption has been used in the CLSC literature (see [34] for example). Consumers in these demand markets can return their used products to manufacturers at a price. We assume that the consumer is indifferent in their demand for brand-new products or remanufactured returns into as-new products, which is a common assumption used in the CLSC literature (cf. [38]). Furthermore, manufacturers choose the level of investment in such "reverse distribution channels" for the channel establishment and maintenance. It is reasonable to assume that the higher the investment in these reverse channels, the higher volume of recycled product the manufacturer can collect (we refer the reader to the discussion in Introduction [24,25]). The structure of the CLSC network is depicted in Fig. 1.

We denote a typical raw material supplier by m, a typical manufacturer by i, and a typical retailer/demand market by j. To make the presentation clear, we also list the relevant variables/notations below:

- q^w_{mi} is the amount of raw material supplier m sells to manufacture i (w stands for *raw*). Group these variables into a WN-dimensional column vector Q^w.
- q^f_{ij} is the amount of product manufacture i sells to retailer j. Group these variables into an NM-dimensional column vector Q^f.
- q^b_{ji} is the amount of used product sold by the consumers on demand market j to manufacture i (b stands for *backward*) which depends on the manufacturer i's distribution channel investment I_{ji}.