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Multi-period closed-loop supply chain network equilibrium with carbon emission constraints

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ABSTRACT

One effective method to reduce industry's environmental footprint is the use of a closed-loop supply chain (CLSC). Based on the traditional forward supply chain, the CLSC incorporates collection and remanufacturing to reduce waste and satisfy environmental goals. In this study, we consider the CLSC network equilibrium, comprising manufacturers, retailers, demand markets and recyclers, in a multi-period planning horizon. In the scenario considered, all of the manufacturers make homogeneous products and have two types of mandatory carbon emission constraints during manufacturing/remanufacturing; one of which can be called a periodic carbon emission constraint, and the other, a global carbon emission constraint. Based on variational inequality and complement theory, the optimal behaviors and the equilibrium conditions of various players in the CLSC network are formulated, and the governing network equilibrium model is established. A modified projection and contraction algorithm is used to solve the model. The validity of the proposed model and the impact of the two types of carbon emission constraints on network equilibrium are demonstrated with numerical examples. The managerial insights obtained in this paper lead to areas of future research into CLSC networks.

1. Introduction

In recent years, supply chain management has become one of the most important research fields. Products are made from fresh raw materials, distributed via certain channels and ultimately reach consumers, in what can be called the forward supply chain. Products purchased by consumers are then used and become end-of-life (EOL) products. After this, EOL products are collected and disposed of by recyclers, and finally sent to manufacturers to remanufacture (Ferrer and Swaminathan, 2010), in what is known as the reverse supply chain. The reverse supply chain can be integrated with the traditional forward supply chain to form a closed-loop supply chain (CLSC). Some researchers have found that regulatory laws and economic benefits are important driving factors that influence the adoption of reverse supply chain and CLSC management (Diabat et al., 2013; Hong et al., 2014). In practice, many large companies, such as Kodak, FujiFilm, Hewlett-Packard, IBM Europe and Xerox, to name a few, have implemented CLSC management successfully (Qiang et al., 2013). We refer readers to work in the literature, such as Souza (2013) and Govindan et al. (2015), to gain a comprehensive understanding of CLSC management.

"Green supply chain management" (GSCM) (Srivastava, 2007; Diabat and Govindan, 2011) is a process in which supply chain operations are carried out with a focus on environmental and low carbon issues. GSCM has a substantial influence on CLSC operations, because the manufacturing and remanufacturing process is one of the main carbon emission activities (Benjaafar et al., 2013), e.g. the remanufacturing of automobiles, heavy equipment and a large variety of electrical products (John et al., 2008). As more and more policies and laws are enacted to require firms to reduce their carbon emissions – such as the Kyoto protocol (John et al., 2008; Absi et al., 2013), EU-ETS and RGGI (Hepburn, 2007) – manufacturers must figure out how to balance economic benefits in the process of production, collection and remanufacturing, and the environment costs under carbon emission regulations.

At present, as mentioned above, there exist a variety of carbon emission regulation policies worldwide, and each have differences in their objectives. The most common carbon regulation policies include carbon tax policies, carbon emission cap-and-trade policies and mandatory carbon emission capacity policies (Liu et al., 2015). Among these, a mandatory carbon emission capacity policy, also known as a command-and-control policy, is the strictest and most rigid. Furthermore, in a multi-period environment,

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Absi et al. (2013) proposed four types of carbon emission constraints, namely, a periodic carbon emission constraint, a global carbon emission constraint, a cumulative carbon emission constraint and a rolling carbon emission constraint. Of these four, the first two policies can be classified into the case of a mandatory carbon emission policy. In view of the fact that a mandatory carbon emission policy is more common in many Chinese provinces, this paper will focus only on this kind of policy.

Due to the interaction of operations, CLSC often form a CLSC network with different tiers, including the manufacturer tier, the retailer tier, the demand market tier and the recycler tier, with multiple players in each tier. Recently, seeking to describe the competing and coordinating relations, and the equilibrium conditions, has become one of the hottest topics in CLSC management. Some researchers (Hammond and Beullens, 2007; Yang et al., 2009) expanded previous work from individual CLSC strands to CLSC networks. However, those investigations were limited to the static case, which is only a preliminary step in understanding what happens in reality. In fact, a CLSC network is a complicated dynamical system resulting from interacting agent relationships, competition of firms, economic globalization, and other fluctuating factors (Sarimveis et al., 2008). With this in mind, this paper will model the multi-period dynamic CLSC network equilibrium. We discretize the decision-making time into several planning periods (one period can be a season, half a year or even longer). In one planning period the parameters in the CLSC network are stable, whereas across different periods, there may be some changes, such as fluctuations of the price of raw materials or variations in demand and market size. When one player makes decisions in a given period, this affects the CLSC network equilibrium in subsequent periods. Furthermore, as mentioned above, it is indispensible to take into account carbon emissions in CLSC operations. In this context, this paper also introduces two types of mandatory carbon emission policies (periodic carbon emission constraints and global carbon emission constraints), and investigates their impact on the optimal behavior of players and the performance of the CLSC in the long term.

This paper is organized as follows. In Section 2, we review the relevant literature. In Section 3, we state the assumptions and notations used. In Section 4, the optimal behaviors of various players under two types of mandatory carbon emission policies in the CLSC network are modeled, and, in turn, the governing equilibrium condition of the whole CLSC network is provided. In Section 5, the solution algorithm for the model is proposed, and the validity analyses and managerial insights are illustrated with numerical examples. Finally, in Section 6, the conclusions of the entire paper and suggestions for future research are given.

2. Literature review

There are two streams of research related to our work. We will briefly review the literature in each of these, and point out the differences between the existing research and our study.

The first stream of research related to our work concerns carbon emission issues surrounding supply chains, which are highly relevant topics in game theory, environmental protection, international transactions and company operation research (Baranzini et al., 2000; Diabat and Simchi-Levi, 2009; Kuik and Hofkes, 2010; Ismer and Neuho, 2007; Zhang, 2010; Eyland and Zaccour, 2012; Zhao et al., 2012). However, it is only recently that carbon emissions have gradually been incorporated into reverse supply chain and CLSC modeling, and studies carried out have been mainly on the facility location problem (Kannan et al., 2012; Gao and Ryan, 2014). In terms of production and pricing decisions, Fahimnia et al. (2013) proposed an optimization model to evaluate the impacts of carbon pricing on a CLSC and implemented it in an Australian case study. Liu et al. (2015) presented three optimization models to examine three types of carbon emission regulation (mandatory carbon emission capacity, carbon tax and cap-and-trade) on remanufacturing decisions with limited information of demand distribution. Under the cap-and-trade mechanism, Chang et al. (2015) established two-period CLSC models to explore the optimal production decisions for independent demands and substitutable demands. However, these three papers focus primarily on the decisions of a monopoly manufacturer or a CLSC strand, but not on the CLSC network.

The second stream of research related to our work concerns CLSC network equilibrium. Nagurney and Toyasaki (2005) focused on the increasing environmental concern of electronic waste, and presented an integrated framework model of the management and recycling of such waste. Hammond and Beullens (2007) constructed an oligopolistic CLSC network model including manufacturers and demand markets under WEEE legislation. Yang et al. (2009) expanded the work of Hammond and Beullens (2007), and Nagurney and Toyasaki (2005), to model a CLSC network which includes suppliers, manufacturers who are involved in the manufacturing and remanufacturing of a homogeneous product from raw materials and collected materials, retailers, and recovery centers that collect EOL products from demand markets. Based on the competition among players and the quantity of collected EOL products which is related to the reverse channel investment, Qiang et al. (2013) established a CLSC network model in an environment with uncertain demand. Although these papers lay a solid foundation for our work, they are confined to studying the case of single-period and static environments.

In reality, there is more than one opportunity for manufacturers to acquire returns and make operational decisions, so the study of dynamic production and pricing policies in two-period, multi-period and infinite planning horizon settings is of great importance in theory and practice. Indeed, this has already been addressed in depth (Ferrer and Swaminathan, 2010; Chen and Chang, 2012; Wu, 2013). In terms of network structure, Beckman and Wallace (1969) were the first to point out time-dependent phenomena and they proposed the time-dependent network equilibrium problem. Other recently published papers include Cruz and Wakolbinger (2008), Hamdouch (2011) and Cruz and Liu (2011). However, these works are limited to traditional forward supply chains. Until now, the only study on dynamic CLSC network equilibrium was by Feng et al. (2014). They developed a CLSC super network model based on evolutionary variational inequality theory and projected dynamical systems, in which demand was seasonal and manufacturers invested the reverse distribution channel for incentivizing consumers to return more EOL products.

Our study differs from Feng et al. (2014) in the following three ways. First, they established a continuous-time dynamic CLSC network equilibrium model, but ours is a discrete-time model. Second, they chose the manufacturer as the collection agent, whereas we employ a third party, e.g. a substantive recycler, to engage in collection because, in practice, they are more professional and widespread. Third, they did not take into account carbon emissions. However, it is an inevitable trend that carbon emission polices will have a growing influence on CLSC operations and, therefore, in this paper we introduce two mandatory carbon emission constraints and analyze their impact on the CLSC network equilibrium.