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The equilibrium of closed-loop supply chain supernetwork with time-dependent parameters

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ABSTRACT

In this paper, we develop a closed-loop supply chain supernetwork model including suppliers, manufacturers, retailers and consumers at demand market, in which the demand for product is seasonal (t), and the sensitivity (w) of demand to price is another key factor which effects consumers' demand. Moreover, the manufacturers invest the reverse distribution channel for incenting consumers to return more used products. Based on the Evolutionary Variational Inequalities (EVI) theory and Projected Dynamical Systems (PDS), the equilibrium condition of closed-loop supply chain is formulated, and the model is verified reasonably by numerical example.

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1. Introduction

There has been an abundant amount of researches available on the topic of supply chain management in recent years, such as the dominance of works from Nagurney et al. (2002a,b) and Nagurney and Toyasaki (2005), Hammond and Beullens (2007), Yang et al. (2009), Qiang et al. (2013) have expanded former works in supply chain. However, there is limited contribution in the literatures those address the static case in the supply chain management which is only a first approach to understand the reality and is the ideal state should be achieved by the entire supply chain under the optimal condition. Actually, supply chains are complicated dynamical systems because of the result of changes in customers' preferences/demand, the globalization of the economy and the stringy competition among companies (Sarimveis et al., 2008).

Furthermore, the dynamic problem existing in supply chain has also gained other scholars' attention beyond the limitation of research on traffic network. Pan et al. (2009) stated the dynamic lot sizing problem in closed-loop supply chain where the capacities of production, disposal and remanufacturing are limited, and backlogging is not allowed. Jia and Hu (2011) studied the combined problem of pricing and ordering for a perishable product supply chain in a finite horizon and results in finite horizon were extended into an infinite horizon later in their paper. In reverse, consumers should choose the selling strategy to deal with dynamic pricing in supply chain as the purpose of gaining much more profit, which is stated in paper (Fasli and Kovalchuk, 2011).

Due to the increasing complexity of supply chain systems and different stages in supply chains supervised by different groups of people with different managing philosophies, it is difficult to make decisions for participants (Sarimveis et al., 2008). In paper (Hamdouch, 2011), Hamdouch used a new concept of purchasing strategy to model the strategic behavior of retailers and consumers at demand markets in a capacitated supply chain network with demand functions varying over

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time. Besides, the complexity of supply chain system is caused by uncertainty (Nagurney and Matsypura, 2005; Friesz et al., 2011) as well, so there are different orders of products in different periods of time, and Li et al. (2011) made some researches on such a problem. In reverse supply chain, Yan (2012) formulated a two-stage dynamic model including the recycling process of the retailer and the remanufacturing process of the manufacturer.

The time-dependent phenomenon has been pointed out by Beckman and Wallace (1969), and they claimed the network equilibrium problems about time-dependent formulation. After that, Daniele (Daniele et al., 1998, 1999; Daniele, 2004, 2010) has made a lot of researches, and for the first time the authors formulated a general dynamic network where an Evolutionary Variational Inequality are expressed to gain both quantity and price formulations for traffic equilibrium.

Nagurney et al. (2007) constructed a dynamic electric power supply chain network model in which the known demand varies over time by utilizing an Evolutionary Variational Inequality formulation. Nagurney and Matsypura (2005) began to pay attention to the dynamics of a global supply chain network economy in the presence of risk and uncertainty, which allows for electronic transactions between the manufacturers and the retailers as well as between the distributors and the retailers.

Generally, Pan et al. (2009) used dynamic programming algorithms to make a study on the production, disposal and remanufacturing options in period t which is the index of a given planning horizon T. Nagurney and Matsypura (2005) studied the dynamics of the prices at the retailers or at the distributors and the dynamics of the product transaction by using variational inequilibrium theory which is usually adopted by many other scholars in analysis of dynamics supply chain. The model with uncertainty and disruption in paper (Friesz et al., 2011) is formulated as a complex dynamic Nash game. The infinite dimensional duality theory and the Evolutionary Variational Inequalities in paper (Daniele, 2010) were used to formulate the behaviors of decision-makers in dynamics supply chain; however, the author made some suggestions to get over the critical phase as a result without the computational procedures. Beyond that, such a problem in Nagurney et al. (2007) can be solved according to theoretical results obtained by Cojocaru et al. (2005, 2006a,b) in the unification of Evolutionary Variational Inequality and Projected Dynamical Systems. This paper adopts these theoretical results as well.

On the basis of lots of researches above, this paper mainly studies consumers' demand for products which is seasonal (t) by itself, that is, the demand is time-varying with greater demand near the middle of a year. Ross et al. (2008) pointed that the demand for consumer electronics, toys, and other products is highly seasonal. This is of course due to some emergencies, such as seasonal natural disasters, order congestion or machine breakdowns, but it also depends on consumers' demand for products in essence.

Taking the demand for fan in summer for example, this paper established a closed-loop supply chain supernetwork model in which the demand for fan is seasonal obviously, with greater demand in summer and less that near the end (start) of a year. And a simple cosine function is applied to express such a demand. In addition, differ from general closed-loop supply chain, manufacturers is assumed to take the responsibility of the third party recycling center in reverse logistic, that is collecting used product directly from the demand market, and in forward supply chain manufacturers make homogeneous product with both raw material and used product. Furthermore, manufacturers choose the level of investment I_{ki} on reverse distribution channels for the channel establishment and maintenance, and for incenting consumers to return more (Qiang et al., 2013).

In the paper of Daniele (2010), he assumed that all variables (such as shipments and prices) are functions of time t, which is significant to describe the complexity and evolution of human relations from the macroscopic view, but we think it is inappropriate for problem calculation because of the correlation among shipments and/or prices. Therefore, we consider that one of the variables is a function of time t, and others may also change over time, then the problem can be solved easily. Besides, Daniele (2010) chose price functions increasing progressively over time, such as $\rho^1_{111}(t) = 2t$, however, we doubt the rationality of such setting because the price cannot be increasing all the time in reality. Unlike Daniele (2010), supply disruption (such as machine breakdown, storms and congestion due to orders) is an emergency accident considered in this paper for decision-makers, which is likely to happen in some parts of the year, so decision-makers must ensure the amount of the supply of products to meet consumer demand at all time in a dynamic environment seen from Figs. 2 and 4, and some measures are provided in Section 5 to protect against disruption. Furthermore, from a mathematical point of view, we formulate the equilibrium condition of closed-loop supply chain based on the Evolutionary Variational Inequalities (EVI) theory and Projected Dynamical Systems (PDS), which are convenience to solve such problem.

This paper is organized as follows: In Section 2, we develop and describe the closed-loop supply chain supermetwork model with time-dependent parameters. Section 3 optimizes behaviors of decision-makers in model. In Section 4, we establish the equilibrium condition of closed-loop supply chain and study the qualitative properties of the equilibrium pattern. Numerical example is provided for illustration in Section 5. Finally, this paper is concluded in Section 6.

2. The closed-loop supply chain supernetwork model with time-dependent parameters

The closed-loop supply chain supernetwork model with time-dependent parameters investigated is illustrated in Fig. 1, which consists of raw material supplier s ($s = 1, \ldots, l$), manufacturer i ($i = 1, \ldots, m$), retailer j($j = 1, \ldots, n$) and consumers at demand market k ($k = 1, \ldots, o$).

Either plane in Fig. 1 describes the logistics flow in the closed-loop supply chain. There usually have several decision-makers at the same level, and we use the dash lines to simplify some of them in figure. The forward logistics are expressed

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