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Coordination in a two-stage capacitated supply chain with multiple suppliers

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ABSTRACT

The aim of this paper is to coordinate the inventory policies in a decentralized supply chain with stochastic demand by means of contracts. The system considered is a decentralized two-stage supply chain consisting of multiple independent suppliers and a manufacturer with limited production capacities. The suppliers operate on a make-to-stock basis and apply base stock policy to manage their inventories. On the other hand, the manufacturer employs a make-to-order strategy. Under the necessary assumptions, each supplier is modeled as an $M/M/1$ make-to-stock queue; and the manufacturer is modeled as a $GI/M/1$ queue after deriving an approximate distribution for the interarrival times of the manufacturer. Once the supply chain is modeled as a queuing system, centralized and decentralized models are developed. Comparison of the optimal solutions to these models reveals that the supply chain needs coordination. Three different transfer payment contracts are examined in this paper. These are the backorder and holding cost subsidy contracts, the transfer payment contract based on Pareto improvement, and the cost sharing contract. Each contract is evaluated according to its coordination ability and whether it is Pareto improving or not. The results indicate that all three contracts can coordinate the supply chain. However, when the Pareto improvement is taken into account, the cost sharing contract seems to be the one that will be preferred by all parties.

1. Introduction

Intensifying competition in today's business environment has highlighted the need to optimize the design and management of supply chains. Starting with effective product design, the selection of suppliers, facility location decisions, inventory management, distribution strategies, information technology, and finally the coordination and integration activities are critical factors for an effective supply chain.

Supply chains generally consist of multiple agents, such as suppliers, manufacturers, warehouses, and distribution centers. In a supply chain, if there is a single decision maker who tries to optimize the overall system, the structure is referred to as centralized (Simchi-Levi et al., 2000). However, generally the various agents have conflicting objectives even when they belong to the same entity. For instance, manufacturers would prefer to produce in large lot sizes in order to reduce setup costs. This would increase inventory amounts, and hence holding costs, which contradicts the objectives of the warehouses. On the other hand, a supply chain in which each agent tries to optimize its own system is referred to as decentralized.

A centralized system leads to global optimization, whereas a decentralized system results in local optimization of the agents. Therefore, to achieve the global optimal solution in a decentralized supply chain, the conflicting objectives of the agents should be aligned through coordination issues.

Supply chain coordination can be accomplished via contracting on a set of transfer payments between the supply chain members. A contract is said to coordinate the supply chain if each member acts rationally according to the supply chain optimal solution, i.e. the decentralized solution is equal to the centralized solution. There are also other initiatives for coordinating a supply chain, such as quick response, efficient consumer response, and vendor managed inventory.

The scope of this paper is the coordination of inventory policies in a decentralized supply chain with stochastic demand by means of contracts. The system considered is a decentralized two-stage supply chain consisting of multiple independent suppliers and a manufacturer. The system operates in a manufacture-to-order environment, i.e. the suppliers and the manufacturer employ make-to-stock and make-to-order strategies, respectively. The manufacturer orders each component from a particular supplier and production cannot start until all components arrive. The transfer times between the suppliers and the manufacturer are negligible. The inventory of each component at each supplier is controlled by a $(S-1,S)$ base stock policy. The suppliers and the manufacturer have a limited production capacity. Backorders are allowed in the system and the capacity of the backlog queue at each supplier is infinite. End-customer demand arrives in single units and

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it is stochastic. To the best of our knowledge, the coordination of the inventory policies in a capacitated supply chain with *multiple* suppliers has not yet been explored.

The paper is organized as follows. Section 2 presents a review of the related literature. In Section 3, first an approximate interarrival time distribution is developed for the manufacturer for the case of two or more suppliers. Then, the supply chain is modeled as a queuing system and performance measures are obtained: the average outstanding backorders and the average inventory level of the suppliers, the average number of jobs in the manufacturer's system, and the average outstanding backorders at the manufacturer. In Section 4, the centralized and decentralized models are presented, and the optimal solutions to these models are derived. Comparison of the optimal solutions shows that the supply chain needs coordination. Thus, contracts are prepared between the suppliers and the manufacturer. In Section 5, three different transfer payment contracts to coordinate the supply chain are examined. These are the backorder and holding cost subsidy contracts, the transfer payment contract based on Pareto improvement, and the cost sharing contract. Then, each contract is evaluated according to its coordination ability and whether it is Pareto improving or not. Section 6 presents a numerical study to compare the contracts based on some examples. Finally, concluding remarks are given in Section 7.

2. Literature review

This study is composed of two main parts: modeling the supply chain as a queuing system and coordination of the supply chain via transfer payment contracts. Therefore, we will also analyze the literature in two parts. In the first part, the literature on series system models and make-to-stock queues is reviewed; and this is followed by a review of the contracting literature concerned with the coordination of decentralized supply chains with stochastic demand.

2.1. The literature on series system models and make-to-stock queues

The first model of a series system with stochastic demand is presented in a study by Clark and Scarf (1960). They consider a multi-echelon inventory problem and define the optimal policy for finite planning horizons. The extension of their study to infinite horizons is performed by Federgruen and Zipkin (1984), and other refinements are made by Rosling (1989), and Chen and Zheng (1994). See Zipkin (2000) for a more detailed review of the related literature.

Apart from the studies mentioned above, Lee and Zipkin (1992), Buzacott et al. (1992) and Gupta and Selvaraju (2006) study the modeling of series systems with limited capacity. All of these studies consider a system in which each stage holds inventory managed by base stock policy. In addition, Buzacott et al. (1992) also consider an MRP system to initiate the work release to each stage. Since our paper aims at modeling a capacitated two-stage system, the modeling approaches of these studies are described in more detail below.

Under the assumptions of a Poisson demand process and exponential service times, Lee and Zipkin (1992) approximate the point process describing the release of units from a stage by a Poisson process. Then, each stage behaves like an $M/M/1$ queue. They also define some performance measures such as the average customer backorders outstanding, the average work-in-process inventory, and the average finished-goods inventory. Buzacott et al. (1992) develop bounds and approximations for shipment delays based on a sample path analysis. Assuming that demands occur according to a Poisson process and unit production times are exponentially distributed, the authors approximate the congestion at the second stage of a two-stage base stock system using an $M/M/1$ queue. They also derive the distribution of the time between releases to the second stage and develop an alternative approximation using a $GI/M/1$ queuing model. Finally, Gupta and Selvaraju (2006) propose a modification to the approximations of Lee and Zipkin (1992) and Buzacott et al. (1992). They derive performance measures such as the average number of units that need to be processed at the second stage, the average inventory at each stage, and the average number of backorders outstanding for a two-stage system. They also investigate systems with more than two stages.

Before closing this section, it is worth mentioning the studies on single-stage make-to-stock queues, which date back to Morse (1958). Buzacott and Shanthikumar (1993) study various make-to-stock queuing models and obtain their performance measures. Another study is by Bai et al. (2004), who derive the interdeparture time distributions for make-to-stock queues controlled via base stock policy. The main findings of their study are the interdeparture time probability distributions and squared coefficient of variations for the base stock inventory queues with birth and death processes, such as $M/M/1$, $M/M/c$, and $M/M/\infty$ inventory queues. Finally, Sanajian and Balcıoğlu (2009) study the steady-state distribution of the number of customers in a $GI/G/1$ make-to-stock queue. The reader is further referred to Lee and Zipkin (1992) and Buzacott and Shanthikumar (1993) for a more detailed review of the literature on make-to-stock queuing models.

The distinguishing feature of our study is that there are multiple members at the first stage of the supply chain. Therefore, none of the results in the literature can be used to model the manufacturer as a queuing system in our study. Note that the suppliers in our system cannot be modeled as an $M/M/n$ make-to-stock queue. Instead, they should be modeled as n different $M/M/1$ make-to-stock queues since the end-customer demand triggers each supplier at the same time as explained in Section 3. Therefore, the interdeparture time distribution of an $M/M/c$ make-to-stock queue obtained by Bai et al. (2004) is also inapplicable to our study.

2.2. The literature on supply chain contracts

The contracting literature on supply chains with stochastic demand can be mainly divided into two categories. Most of the research is on the coordination of supply chains in a single-period setting, i.e. the newsvendor model and its extensions. There are also relatively fewer studies on the coordination of supply chains in an infinite horizon setting.

The scope of this paper is the stochastic models in an infinite horizon setting that investigates the coordination of the inventory policies in a decentralized supply chain. The literature in this area can be mainly analyzed in two groups. Some of the studies consider an uncapacitated supply system (Lee and Whang, 1999; Chen, 1999; Cachon and Zipkin, 1999; Cachon, 2001) and some of them deal with capacitated supply chains (Cachon, 1999; Caldentey and Wein, 2003; Jemaı and Karaesmen, 2004; Gupta and Weerawat, 2006; Hennet and Arda, 2008). It is worthful to note that the key distinction in the studies considering uncapacitated and capacitated supply chains is that inventory theory is used in the former, whereas queuing theory is used in the latter. Since our study deals with a capacitated supply chain, the studies falling into this area are described in more detail below. See Cachon (2003) for a more thorough review of the related literature.

All the studies investigating a capacitated supply chain consider a two-stage system with a single member at each stage. The other similarities between these studies are as follows: the base stock policy is used as the inventory control policy; a game theoretical framework is used in the models; and the capacitated member or members are modeled using queuing theory. Among these studies, different contracts are investigated to coordinate the supply chain.