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Inter-temporal inventory competition and the effects of capacity constraints

Konstantin Kogan [a],*, Charles Tapiero [b]

[a] Dept. of Management, Bar-Ilan University, Ramat-Gan 52900, Israel
[b] Dept. of Finance and Risk Engineering, Polytechnic Institute of New York University, New York, NY 11201, USA

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ABSTRACT

This paper addresses an intertemporal inventory competition between a supplier (a provider, manufacturer) and a retailer engaged in a supply chain. The paper's focus is on the effect of capacity constraints on both parties when demands are seasonal. The paper provides a comparative study of two solution approaches, one is based on supply chain competition and the other is based on system wide optimization. Our results demonstrate that with dynamic inventory competition, the retailer reduces inventory costs by reducing the response period to higher demands while increasing the supply requests compared to the system-wide optimal approach. As a result, the supplier's inventory costs increase. An example illustrating these particular facets of the problem and its application is presented and discussed in light of the supplier and the retailer coordinating policies.

1. Introduction

The effect of intra-supply chain competition on supply chain performance in general and inventory policies in particular is well studied for a static framework. Extensive reviews include a historical analysis of Girlich and Chikán (2001) in the development of mathematical approaches to inventories management using classical optimization and game theory; discussions on integrated inventory models (Goyal and Gupta, 1989); game theory in supply chains (Cachon and Netessine, 2004); competition and coordination (Leg, Parlar, 2005; Banerjee et al., 2007; Lee and Byong-Duk, 2010). Numerous papers are devoted to the effect of competition on supply chains. Specifically, spatial interactions and their influence on optimal inventory policy were discussed by Bogataj (1996) and employed to show how to use MRP and input–output analysis to investigate the results of customers' behavior when the supply units compete for customers (Bogataj and Bogataj, 2001). Further, the effects of competition were studied in a two-component assembly system with stationary stochastic demands and constant component replenishment lead times (Chu et al., 2006). Based on static games their study points out to deterioration of system performance caused by decentralized inventory control. A static framework was also used by Li et al. (1996) pointing out that the total system profit is higher with cooperation. Further, the optimal order quantity of the buyer is larger with cooperation than with non-cooperating parties.

However, contemporary business conditions are often characterized by seasonal demand and a continuously changing environment, which requires real time adjustments in supply chains' policies. Such problems are notoriously difficult due to time and the complex organizational frameworks that underlie supply chains' operations (see for example, Basar and Olsder, 1982; Feichtinger and Jorgenson, 1983; Kogan and Tapiero, 2007, 2008a).

The purpose of this paper is to focus on the inventory policies of a specific supply chain that recognizes both the time varying (seasonal) character of retail demands and the inventory capacity constraints (see also Tapiero, 1972 on Capacity Constraints and Storable Output). For example, housing, automobile sales and energy demands tend to follow cycles (see, for example, Russell and Taylor, 2000). Capacity processing constraints are also common to a broad number of problems where seasonal and peak demands may recur and where the processing capacity available is limited. In some cases, firms use emergency suppliers as well as back up alternatives, which may be costly or unavailable when demands to be met materialize. Generally, Just in Time Manufacturing combined with a Flexible manufacturing Capacity has been trumpeted as a strategic approach to deal with these problems—diversifying a production capacity to handle multiple types of demands. Similarly, improved supply chain demand forecasts (which are notoriously difficult due to their dependence of the supply chains' capacities) have also been used to improve capacity utilization and reduce inventory costs. In this context, a number of such issues pertaining to inventory control have been studied (see also Sulem and Tapiero, 1993; Tapiero and Grando, 2006); albeit, their intertemporal and differential game implications neglected.

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* Corresponding author. Tel.: +972 545323761; fax: +972 5353329.
E-mail address: kogank@mail.biu.ac.il (K. Kogan).

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In some mono and strategic product systems (such as the supply of water by a water provider to a municipality, electricity supply to a city, etc.), supply chains are confronted with seasonal (and mostly predictable) demands along with both production and supply capacity constraints. Some papers have recognized these effects (Desai, 1996; He et al., 2007) and have suggested that seasonal demands may be met through process (production) smoothing rather than accounting explicitly for the capacity constraints (or seeking alternatives and back up supply sources). In particular, Desai provides a numerical analysis of the open-loop Stackelberg equilibrium under unlimited manufacturer and retailer capacities.

Further motivation for the paper may be found in water based supply chains, where the water provider (a Water Utility) supplies one or a number of clients (Municipalities) (see also Kogand and Tapiero, 2008b). In such situations, water supplies from natural sources may be insufficient and therefore, Municipalities turn to additional sources of supply (more distant sources, desalination plants, recycling plants, etc). For example, in 2001–2002, Maine experienced the worst drought in over thirty years. Water in streams, lakes and groundwater dropped to record-low levels (Lombard, 2004). The drought exposed vulnerabilities in the state's public water supply, highlighting a need for water use planning and management even in a “water-rich” state like Maine. The situation is of course much worse in many other States. Water supplies are strongly influenced by the timing of drought relative to the seasonal demand patterns of a specific system. A closer look at the affected systems reveals that they operate close to their safe yield during times of high demand, even in a non-drought year. During the summer of 2001, a combination of drought conditions and increased seasonal demand have pushed a vulnerable supply system “over the edge”, forcing them to implement water use restrictions and tap into back-up supplies (Schmitt, 2003). Simultaneously, desalination and other means (albeit costly) to recuperate water supplies have become important alternatives to reckon with. It is for such reasons that the World Bank has supported significantly a “water production” program and the management of water resources, currently used in around 130 countries. As a result, the cumulative installed desalination capacity has grown at a rate of about 7% each year. Such a strategic approach to water management is likely to be a dominant factor in an age of resources constraints with water supply chains including independent public–private partnerships, which become the rule rather than an exception (Shiva, 2002). Such supply chains involve, of course, complex dynamic problems, confronted with seasonal demands, droughts, limited supplies and constrained desalination capacities as well as intra-competition (between Municipalities, as well as Municipalities and water providers) in the water supply chain.

Unlike previous studies relating to inventory games, this paper focuses on the effects of mutual inventory policies in a supply chain characterized by capacity constraints throughout the supply chain. In such an environment each party will seek to reduce its inventory costs by passing them to the other parties. A typical case to these effects is a Vendor Managed Inventories (VMI) practice where manufacturers (of cars for example) impose on their dealerships their own car inventory holdings. Similarly, water supply chains discussed above are an additional and important case in point. These strategic “inventory outsourcing” effects are due to the intra-supply chain competition, which therefore requires a game theoretical framework for their analysis. When these effects are combined with seasonal demands, the resulting problems may be acute. By the same token, an upsurge of giant retailers (e.g., WALLMART) able to dictate production and inventory policies on their suppliers is also providing a strong motivation for this paper. In this spirit, the paper develops an asymmetric differential game with the retailer being the Stackelberg leader (Stackelberg, 1952) and derives an open-loop Stackelberg equilibrium under seasonal demands. We then compare the equilibrium with the system-wide optimal solution of the corresponding centralized supply chain derived by Kogan and Lou (2002). Consequently, we shall show analytically the effects of competition on supply chain performance as well as discuss coordination aspects for improving the performance.

2. Problem formulation

For our purposes, we consider a game in a two-echelon supply chain consisting of a single supplier (manufacturer, franchisee and water provider) delivering a product type to a single retailer (franchiser, Municipality) over a period of time, T. The planning horizon is assumed to be infinite with a seasonal (periodic) variation in demand. Further, we assume that the time between the seasons is sufficiently long in order for the supply chain to revert to the state it was in before the season began.

We consider two distinctive features of this supply chain game. First, we assume an exogenous customer demand, implying that the quantities produced and sold by the supply chain cannot affect the price level of the product, i.e., the price elasticity of demand is close to zero. Such low price elasticity is typical when the substitute products are scarce or the necessity for the product is high (as it is the case for water, gasoline, etc.). The second distinctive feature is linked to the production and supply capacities, which as discussed above, are assumed to be finite. These constraints complicate the problem we face by introducing multiple switching points due to competing inventory decisions and varying demands. For this reason, in analyzing the differential inventory game with exogenous demand, we shall focus only on the effects of the inventory dynamics on production decisions and their associated costs.

Explicitly, assume that both the supplier and the retailer have a storage capacity for holding end-products and let the retailer's inventory holding cost be h_r^+, per product and time unit; while the backlog cost is h_r^- per product and per unit time. The latter stipulation implies that all deficient products from the retailer's side will be backlogged and either delivered to the customers when the retailer catches up with supplies (the case of “lost sales” can be considered as well but is clearly a special case) or delivered from a safety stock immediately while the safety stock is replenished with the supplies. Similarly, if cumulative production by the supplier exceeds cumulative supplies requested by the retailer, an inventory holding cost is incurred by the supplier, h_s^+. Otherwise there is a backlog cost paid, h_s^-. Any shortage of products at the supplier's side is immediately replenished by delivering products to the retailer from a safety stock. Similar to the retailer's safety stock, the supplier's safety stock will be restored as the supplier catches up with production, i.e., as soon as possible. This is of special importance if the supplier utilizes natural water resources as well, and thereby withdrawal above the safe yield (the maximum amount of water that can be pulled out within a period of time) may lead to irreversible impact on the environment and water quality. We assume that the cost associated with the risk of depleting the safety stock is higher than that with holding the safety stock. Therefore, the adopted safety stock level, Q_s, is sufficiently high to cope with seasonal fluctuations in the retailer's orders.

The retailer's backlog cost is traditionally related to loss of customer goodwill if the retailer has no safety stock. On the other hand, the supplier's shortage cost is related to the risk of depleting the safety stock. Indeed, if the cost, R, of risk associated with one product lacking in the safety stock for one time unit is