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The governing dynamics of supply chains: The impact of altruistic behaviour☆

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Abstract

This paper analyses an infinite horizon two-echelon supply chain inventory problem and shows that a sequence of the optimum ordering policies does not yield globally optimal solutions for the overall supply chain. First-order autoregressive demand pattern is assumed and each participant adopts the order-up-to (OUT) policy with a minimum mean square error forecasting scheme to generate replenishment orders. To control the dynamics of the supply chain, a proportional controller is incorporated into the OUT policy, which we call a generalised OUT policy. A two-echelon supply chain with this generalised OUT policy achieves over 10% inventory related cost reduction. To enjoy this cost saving, the attitude of first echelon player to cost increases is an essential factor. This attitude also reduces the bullwhip effect. An important insight revealed herein is that a significant amount of benefit comes from the player doing what is the best for the overall supply chain, rather than what is the best for local cost minimisation.

Keywords: Multi-echelon inventory; Order-up-to policy; Collaboration; Inventory costs; Optimisation; Base-stock policy

1. Introduction

Arrow, Harris, and Marschak (1951) introduced the (s, S) ordering policy; Karlin (1960) studies the order-up-to (OUT) policy, that is, the $s = S$ case of the (s, S) policy. Karlin shows that if the purchase cost is linear and set-up costs do not exist, the optimal policy in each period can be characterised by a single critical number. Assuming an ARIMA (Box, Jenkins, & Reinsel, 1994) demand process, minimum mean square error (MMSE) forecasting, linear inventory holding and stock-out costs and zero lead-time, Johnson and Thompson (1975) show that the OUT policy is optimal. The OUT policy is widely employed in the real business world. Indeed, at least two of the four largest UK grocery retailers use this policy to replenish stores and DCs (e.g. Potter, Naim, & Disney, 2004). Focusing on the OUT policy, we examine a collaboration scheme that minimises the total supply chain costs for a two-echelon case.

For a single echelon of a supply chain, Vassian (1955) introduced an ordering policy with a work in progress (WIP) feedback loop and showed that this ordering policy minimises the variance of the net inventory levels. In addition, Vassian showed that the minimised variance of the net inventory level is identical to the variance of the error in the forecast of demand over the lead-time. In this paper, we call Vassian's ordering policy *the traditional OUT policy*. Note that several researchers adopt an alternative expression for the OUT policy that exploits a time varying OUT target (e.g. Alwan, Liu, & Yao, 2003; Lee, So, & Tang, 2000; Zhang, 2004), however, the dynamics given by these two expositions is identical (Hosoda, 2005; Hosoda & Disney, 2006).

From Vassian's seminal contribution, it is obvious that in a single echelon of a supply chain, the traditional OUT policy is an optimal policy for minimising the variance (or standard deviation) of inventory levels over time. In a multi-echelon supply chain scenario, however, it might be reasonable to

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assume that a sequence of the traditional OUT policies may not be optimal anymore as there is no guarantee that a succession of local minimisations will result in a global optimum.

The traditional OUT policy does not provide much freedom to manipulate the dynamics of the ordering process. By incorporating a proportional controller into the traditional OUT policy, however, a much richer policy is created where we have more flexibility to shape the ordering process. Using control theory techniques, several researchers have successfully manipulated the variances of the net inventory level with the addition of proportional controllers (e.g. Dejonckheere, Disney, Lambrecht, & Towill, 2003; Disney & Towill, 2003; Disney, Towill, & Van de Velde, 2004) in a policy's feedback loops. A comprehensive review on ordering policies with proportional controllers can be seen in Disney and Towill (2005). This research is motivated by a question; by incorporating a proportional controller into the traditional OUT policy and tuning the value of it properly, can the performance of the traditional OUT policy supply chain be improved upon? Our research purpose is to identify whether a particular form of collaboration (redistributing inventory costs) can achieve a better overall performance, and to quantify the benefit of this collaboration.

Assuming the market demand process follows the first-order autoregressive (AR(1)) process, Hosoda and Disney (2006) analyse a three-echelon supply chain with a traditional OUT policy and MMSE forecasting. They present a formula for the variances of net inventory levels at each echelon level and conclude that there is no benefit of the information sharing in terms of lowering these variances. This paper is a sequel to Hosoda and Disney (2006). From here, we refer it as HD and will use HD's model as a benchmark for performance comparisons.[1]

2. Literature review

Many types of collaboration between participants in the supply chain have been studied from the point of reducing uncertainties in a supply chain. However, counter intuitively, not all results strongly support the benefit of collaboration.

Graves (1999) studies a two-echelon supply chain with the OUT policy and a non-stationary demand process and finds that sharing demand information brings no benefit to the upstream player. Kim and Ryan (2003) analyse the value of demand information sharing using a model with an unknown demand process and the exponential smoothing forecasting mechanism. They conclude that sharing demand data can significantly reduce up-stream costs in the supply chain. However, the benefit is limited when a large amount of historical order data is available. Assuming a known demand process and an MMSE forecast, Raghunathan (2001) reports similar results in that the set of order history data contains all the necessary information to reduce up-stream costs. Gavirneni, Kapuscinski, and Tayur (1999) find that the benefit of information sharing increases as capacity increases since higher capacity provides the supplier with some flexibility in production planning. Assuming that the manufacturer can receive market demand information from the retailer even during time periods in which the retailer does not order, Simchi-Levi and Zhao (2003) report that there is a benefit of information sharing if the production capacity is very large and that the benefit partially depends upon the timing of information sharing. In their model, i.i.d. demand is assumed. Aviv and Federgruen (1998) conclude that the benefit from sharing demand information only is limited and that the vendor managed inventory (VMI) program (where information on inventory levels is also shared) has much more potential and can reduce costs on average by 4.7%.

Bourland, Powell, and Pyke (1996) study the impact of the frequency of market demand information sharing on the inventories in a two-echelon supply chain with normally distributed demand. They show that in a certain setting, as a result of more frequent demand information sharing, the expected inventories at the second echelon can be lowered by 26%. However, at the same time, those at the first echelon have increased by 4.2%. Using a two-echelon supply chain model, Aviv (2001) studies the benefit of collaborative forecasting and finds that the reduced level of uncertainty in the forecasting improves the cost performance of the supply chain. As the traditional OUT policy ensures that the variance of net inventory levels and the variance of forecast error over the lead-time are identical, HD indicates that to minimise the variance of net inventory levels, the MMSE forecast is an essential ingredient. They also show that each player does not necessarily need to share any information to improve its performance, since all the necessary information required to increase performance is already contained in the ordering process.

From the literature review, a useful general insight might be drawn. If market demand information sharing is already transmitted to the supply chain frequently, the benefit coming only from the reduced uncertainties by a collaboration is at best minor.

3. The objective function and model assumptions

We consider an infinite horizon two-echelon inventory problem. Assuming that the inventory related costs in the supply chain are directly proportional to standard deviation of the net inventory levels (e.g. Zipkin, 1995) at each echelon, we employ an objective function that is the sum of these standard deviations. The objective function can be expressed as

$$J = \sqrt{\mathrm{Var}(NS_1)} + \sqrt{\mathrm{Var}(NS_2)},$$

where $\mathrm{Var}(NS_n)$ is the variance of net inventory levels at echelon n. It should be noted that there is no fixed ordering cost in our model, as is commonly assumed (e.g. Aviv & Federgruen, 1998; Gavirneni et al., 1999; Johnson & Thompson, 1975; Simchi-Levi & Zhao, 2003). The aim of this paper, therefore, is to analyse a form of supply chain collaboration between players that reduces the value of J.

A periodic review system is assumed and all of the results here are consistent whichever review period is adopted (day,

[1] Due to the space limitation, we have used Hosoda (2005) as the reference to all proofs in this paper. However, appendices proving the assertions claimed in this paper are available upon request.