Managing Slow Moving Perishables in the Grocery Industry

Michael E. Ketzenberg*
College of Business
Colorado State University
218 Rockwell Hall
Fort Collins, CO 80523
Tel: (970) 491–7154
Fax: (970) 491–3522
Email:Michael.Ketzenberg@colostate.edu

Mark Ferguson
The College of Management
Georgia Institute of Technology
800 West Peachtree Street, NW
Atlanta, GA 30332-0520
Tel: (404) 894-4330
Fax: (404) 894-6030
Email:Mark.Ferguson@mgt.gatech.edu

February 13, 2007

* Corresponding Author

Managing Slow Moving Perishables in the Grocery Industry

Abstract

We address the value of information (VOI) and value of centralized control (VCC) in the context of a two–echelon, serial supply chain with one retailer and one supplier that provides a single perishable product to consumers. Our analysis is relevant for managing slow moving perishable products with fixed lot sizes and expiration dates of a week or less. We evaluate two supply chain structures. In the first structure, referred to as Decentralized Information Sharing, the retailer shares its demand, inventory, and ordering policy with the supplier, yet both facilities make their own profit-maximizing replenishment decisions. In the second structure, referred to as Centralized Control, incentives are aligned and the replenishment decisions are coordinated. The latter supply chain structure corresponds to the industry practices of company owned stores or vendor–managed inventory.

We measure the VOI and VCC as the marginal improvement in expected profits that a supply chain achieves relative to the case when no information is shared and decision making is decentralized. Key assumptions of our model include stochastic demand, lost sales, and fixed order quantities. We establish the importance of information sharing and centralized control in the supply chain and identify conditions under which benefits are realized. As opposed to previous work on the VOI, the major benefit in our setting is driven by the supplier's ability to provide the retailer with fresher product. By isolating the benefit by firm, we show that sharing information is not always Pareto improving for both supply chain partners in the decentralized setting.

Keywords: value of information, vendor managed inventory, supply chain management, perishable inventory

1. Introduction

We place our research in the context of the grocery industry and, more specifically, in the area of managing perishables. The quality, variety and availability of perishables have become an order winning criteria of consumers, representing the primary reason many consumers choose one supermarket over another (Hennessy 1998, Tortola 2005, Axtman 2006). In turn, retailers have responded by dramatically increasing the number of SKUs they offer for sale (Tortola 2005, Boyer 2006). In some categories, such as produce, the average number of items stocked has doubled in the past five years and the trend is expected to continue (Axtman 2006).

From an operational perspective, the growth in perishables creates additional challenges for retailers. Increasing product variety creates a larger assortment over which demand is spread, contributes to an increasing number of slow moving perishables, and increases product spoilage (Boyer 2006). Spoilage is a significant component of total store shrink, with current estimates indicating that shrink costs an average supermarket approximately $450,000 per year. While perishable departments account for only 30% of total store sales, they contribute 56% to total store shrink (National Supermarket Research Group 2003). Moreover, the amount of shrink in perishables departments has consistently increased over the past six years (Tortola 2005). From this perspective, the link between variety and spoilage is readily apparent. There are generally a minority of products in an assortment that are high volume and account for the vast majority of sales which leaves a preponderance of low volume products accounting for a small percentage of sales. Some retailers report that as much as 75% of their SKUs are slow moving (Småros et al. 2004). Our own analysis of item movement at a division of Albertson's, consisting of seventy stores, indicates that 75% of packaged produce items are slow movers – selling less than a case per day with more than half (52%) of the items' case sizes composed of ten units or less.

Clearly, efficient management of both fast and slow moving perishables are important elements to store profitability, but the management focus is different for each. For fast moving items, spoilage principally arises when the product is unwrapped, displayed in bulk, and subject to consumer handling (Tortola 2005). For slow moving packaged items, the challenge is managing inventory levels so that the product sells before its expiration date (Falck 2005). In this paper, we restrict our analysis to the management of slow moving packaged perishables. Growth in these products is expected to continue as variety increases (Chanil and Major 2005), yet maintaining a proper balance between inventory and service level is particularly acute (Falck 2005). The case size (number of units packaged, ordered, and shipped together) imposes certain restrictions, as the size of a single case often represents several days of supply. Even with small case sizes, low demand rates coupled with high demand variability challenge grocers in their ability to minimize spoilage, resulting in spoilage rates that can exceed 40% (Pfankuch 2006).

We evaluate two common prescriptions cited in the literature to improve the management of perishable products: sharing information on demand or current inventory levels and coordinating replenishment activities (Falck 2005, Småros et al. 2004, Lee et al. 1997a,b). Although there is anecdotal evidence from practitioner activity that such initiatives have significant value, due to privacy and competitive issues, success stories are rarely communicated and many industry participants are quick to point out other opportunities like reducing case sizes (Småros et al. 2004). Hence, there remains a lack of understanding among both academics and practitioners regarding the value of these initiatives.

We address the value of information (VOI) and the value of centralized control (VCC) in the context of a two–echelon, serial supply chain with one retailer and one supplier that provides a single perishable product to consumers. Replenishment decisions are limited to zero units or a single case and the lead-time is effectively zero since an order placed after observing demand one day arrives before demand occurs the next day. When the supplier is unable to meet a demand request from the retailer with stock on hand, an emergency shipment is incurred at a significant penalty cost. The product's lifetime is fixed and deterministic once produced. Any unsold inventory remaining after the lifetime elapses must be discarded (outdated) at zero salvage value. These assumptions capture characteristics of slow-moving packaged perishables with expiration dates of less than a week, where daily demand rates are typically less than a case, and overnight replenishments are available.

We evaluate two scenarios. In the first scenario, named Decentralized Information Sharing (DIS), both supply chain members share their inventory levels and replenishment policies with the other, but each facility makes its own profit maximizing replenishment decisions. In the second scenario, named Centralized Control (CC), decision making is coordinated and corresponds to the practice of vendor–managed inventory (VMI). We formulate the respective scenarios as Markov Decision Processes (MDPs) and measure the VOI and VCC as the marginal improvement in expected profit a supply chain achieves relative to the case of traditional replenishment. Key characteristics of our model include stochastic demand, lost sales, and fixed order quantities.

We establish the importance of information sharing and centralized control, identifying the conditions where substantial benefits are realized. Through a numerical study, we find, on average, that by sharing information, product freshness increases 18%, outdating decreases by nearly 40%, and total supply chain expected profit increases 4.2%. With centralized control, average expected profit increases 5.6%, but product freshness may decrease and, consequently, outdating my increase. Moreover, the benefit of sharing information in the absence of coordination is not always Pareto improving for both firms. We also provide some insights into the problem when the case size may be changed. The literature promotes the choice of case sizes as another significant opportunity to reduce spoilage (Falck 2005, Småros 2004, Larson and DeMarais 1999) and our results support this claim as the VOI and VCC are significantly reduced when an optimal case size is chosen. We also find the VOI and VCC are significantly reduced when the supplier's revenue is freshness dependent.

The rest of the paper is organized as follows: §2 reviews the literature, §3 defines the model, §4 presents our numerical study with discussion, and §5 concludes the paper. An online appendix (Ketzenberg and Ferguson, 2006) provides additional details of our models and results.

2. Literature Review

Our research draws on two separate research streams: perishable inventory theory and the VOI. Progress on the combined problem of multi–echelon inventory and perishable inventory systems has been limited. We are aware of only a few contributions in this area, the majority are motivated by the management of blood banks and focus almost exclusively on the allocation problem. Yen (1965), Cohen et al. (1981), Prastacos (1981), and Goh et al. (1993) are representative examples. Fujiwara et al. (1997) provide the most recent contribution to the literature and the only one we are aware of that directly addresses perishable food products. They consider a two–stage inventory system at a single facility where the first stage consists of the whole product (e.g. meat carcasses) made up of multiple sub–products (e.g. cuts of meat) while the second stage consists solely of the sub–products. .They derive optimal ordering and issuing policies for this scenario, but do not address the VOI or the VCC.

There are a few papers that explore the VOI in serial supply chains for non-perishable products. Bourland et al. (1996), Chen (1998), Gavirneni et al. (1999), Lee et al. (2000), and

Raghunathan (2001) are representative examples. Unlike the majority of these examples where the VOI and VCC are often small in the context of non-perishable serial supply chains, we show significantly larger benefits due to the ability of the supplier to provide fresher product.

Beyond our study, Ferguson and Ketzenberg (2006) (here after referred to as FK) is the only study we are aware of that addresses the VOI in the context of perishable inventory. In their study, the supplier shares its age–dependent inventory state with the retailer. In contrast, we examine the reverse flow of information where the retailer shares its age-dependent inventory state and demand information with the supplier. We also compare information sharing to centralized control. Finally, we note that FK model a retailer in a large distribution network where the supplier's ordering policy is not dependent on a single retailer's actions whereas we model a serial supply chain where the retailer's actions are material to the supplier's decisions.

Despite the differences in the supply chain structures modeled, some of our results reinforce those of FK. Our average improvement in total supply chain expected profit of 4.2% is similar to their average improvement of 4.4% (assuming a FIFO issuing policy). In both cases, the profit improvement is primarily driven by a reduction in outdating and an increase in the final customer service level. While we find that when the supplier's demand is freshness dependent (the retailer orders less from a supplier who historically provides older items), the VOI is minimal, FK studied freshness dependent demand at the retail customer level and found the VOI increases in the sensitivity of demand to product freshness. The difference in these findings indicates the importance of measuring where in the supply chain demand is affected by product freshness. Finally, we show the majority of the additional benefits obtained from centralized control of the supply chain (an average of 4.2% for VOI versus 5.6% for CC) can be obtained from sharing inventory age related information. This issue is not addressed in FK.

3. Model

The setting is a serial supply chain consisting of a retailer and a supplier who provide a single perishable product to consumers. The product has a deterministic lifetime of $M + 1$ periods. Throughout its life, the utility of the product remains constant. When the product expires it is outdated without any salvage value. This assumption corresponds to the wide–spread use of product expiration dates on packaged goods such as fresh meat and seafood, deli, ready-made meals, and fresh cut fruit and vegetables.

We assume a periodic review inventory model for each facility. For the retailer, the order of events each day follows the sequence: 1) receive delivery, 2) outdate inventory, 3) place order, and 4) observe and satisfy demand. Orders placed in the current period arrive before demand in the next period. Retail demand is discrete, stochastic, and stationary over time. Let D denote total demand in the current period, with probability mass function $\phi(\cdot)$, mean μ, variance σ^2, and C the corresponding coefficient of variation. Unsatisfied demand is lost. We normalize the retailer's revenue per unit of satisfied demand to one dollar and predicate the unit purchase cost on the product margin m_0, expressed as a percentage of unit revenue. A holding cost h_0 (h_1) is assessed on ending inventory at the retailer (supplier) respectively.

The retailer's replenishment decision q is restricted to either zero or Q units, where the batch size Q represents the bundle of units that are packaged, shipped, and sold together. The fixed batch size captures certain economies of scale in transportation and handling and is common, both in practice (Falck 2005, Småros et al. 2004) and in the literature on the VOI (Moinzadeh 2002, Cachon and Fisher 2000, Chen 1998). Because of increasing levels of product variety there are many slow moving perishable products where a single batch of replenishment is sufficient to satisfy expected demand during the order cycle. In §5, we show how our model can also be used to find an optimal value of Q.

The replenishment lead-time is one period. Since the product is perishable, inventory may be composed of units with different ages. Let i_x denote inventory, after outdating and before demand, that expires in x periods, where $x = 1, \ldots, M$ and M is the maximum product shelf life at the retail echelon. Let $\vec{i} = (i_1, i_2, \ldots, i_M)$ represent the vector of inventory held at each age class and define $I = \sum_{x=1}^{M} i_x$. Demand is satisfied using a FIFO inventory issuing policy and inventory is not capacitated.

For the supplier, the order of events each period follows the sequence: 1) receive delivery, 2) observe and satisfy demand, and 3) place order. An order placed by the retailer corresponds to a demand at the supplier in the same period. Since the supplier only observes orders of Q units and faces no ordering cost, the supplier replenishes in orders of Q units. We assume the supplier orders from a perfectly reliably exogenous source (i.e. the outside source has ample capacity) and the lead-time is one period (i.e. whenever Q units are ordered they become available at the start of the next period). Thus, the supplier faces uncertainty only in the timing of the order arrivals. If the supplier receives an order and does not have units in stock to fulfill it, the supplier pays an expediting charge that allows it to meet the order in the same period. Thus, the retailer always receives its order request at the beginning of the following day.

The supplier's replenishment policy corresponds to a time phased order point policy incorporating safety lead-time. Denoted by α, safety lead time represents the number of periods the supplier waits after receiving a retailer order before it places its own replenishment order: $\alpha \in (0, 1, \ldots, M)$. The safety lead-time is based on the supplier's critical fractile, determined from its cost of being early or late with a replenishment order. This policy is optimal for a firm facing intermittent demand with deterministic quantities, uncertain timing, and non–perishable inventory (Silver et al. 1998). Employing such a policy ensures no supplier outdating. This is because the longest possible time between retail orders is M periods and, at that time, the age of product at the supplier has a minimum life of two periods remaining. This statement requires a further condition: the retailer never intentionally goes through a period with zero inventory, thus assuring the interval between retail orders never exceeds M periods. These assumptions are supported by practice where 1) outdating at supplier echelons is trivial compared to the retail echelon and 2) there exists a strong emphasis on high, retail, in-store availability.

3.1 No Information Sharing (NIS) Case

We begin by establishing a base case where the retailer does not periodically share information pertaining to its replenishment process or inventory position. Hence, this case corresponds to traditional replenishment practices in which the supplier only observes the timing between the retailer's orders.

3.1.1 NIS Case: Retailer's Policy

We formulate the retailer's replenishment problem as a MDP where the objective is to find an optimal reorder policy that maximizes expected profit. The linkage between periods is captured through the one period transfer function of the retailer's age dependent inventory. This transfer is dependent on the current inventory level, any order placed in the current period, the realization of demand D in the current period, and the remaining lifetime of any replenishment inventory (represented by the position x within the vector $\vec{i}$ that is updated with the replenishment quantity). The remaining lifetime of replenished inventory, denoted as A, is a function of the number of periods since the last retailer order L, where $A, L \in \{1, 2, ..., M\}$, and the supplier's safety lead–time α.

For ease of exposition, let $(z)^+ \equiv \max(z, 0)$ and z' denote a variable defined for the next period, whereas a plain variable z is defined for the current period. Let $\vec{i}'$ denote the retailer's inventory level in the next period and $\tau(\vec{i}, D, q, A)$ denote the one period transfer function.

Then $\vec{i}' = \tau(\vec{i}, D, q, A)$ where

$$i'_x = \begin{cases} \left(i_{x+1} - \left(D - \sum_{z=1}^{x} i_z \right)^+ \right)^+ & if\ 0 < x < A \\ q & if\ x = A \end{cases}.$$

Now, let $G(I)$ denote the retailer's one period profit function where

$$G(I) = \sum_{D=0}^{\infty} \left[\min(D, I) - h_0 (I - D)^+ \right] \phi(D).$$

We now introduce the retailer's MDP. The value $\bar{c}$ is the equivalent average return per period when an optimal policy is used. The extremal equation is

$$f(\vec{i}, L) + \bar{c} = \max_{q \in \{0, Q\}} \left\{ G(I) - q(1 - m_0) + \sum_{D=0}^{\infty} f\left(\tau(\vec{i}, D, q, A), L' \right) \phi(D) \right\} \tag{1}$$

where

$$A = \begin{cases} M & if\ L \le \alpha \\ M - L + \alpha + 1 & if\ L > \alpha \end{cases} \tag{2}$$

$$L' = \begin{cases} 1 & if\ q = Q \\ L + 1 & if\ q = 0 \end{cases} \tag{3}$$

Since the state and decision spaces are discrete and finite and profit is bounded, there exists an optimal stationary policy that does not randomize (Putterman, 1994 pg 102 - 111). The left hand side of (1) defines an extremal equation by the vector of inventory $\vec{i}$ and the number of periods L since the last order was placed. The right hand side of (1) computes the total expected profit composed of the one period profit function, the purchase cost associated with any new order, and future expected profit. Equation (2) determines the remaining lifetime of any receipts. Note if $L \le \alpha$, then $A = M$ since replenishment occurs through expediting. Also, (2) assumes the retailer knows both the supplier's safety lead–time α and the age of replenishment A. The retailer can readily deduce these values given the replenishment history with the supplier. Finally, (3) updates the number of periods since the last order was placed

3.1.2 NIS Case: Supplier's Policy

The supplier's objective is to make ordering decisions that minimize its inventory related cost. A sample path of the supplier's inventory level follows a renewal process with the renewal occurring each time the retailer places an order. Since the supplier is only concerned with the timing of its replenishment, the problem reduces to a myopic cost minimization problem the supplier faces each period he ends with zero units in inventory. If the supplier does not have inventory when the retailer places an order, the supplier pays an expediting charge of *b*. If the supplier does have inventory and the retailer does not order, the supplier pays a holding cost of h_1 for each of the Q units it holds.

Let $\psi_{\tilde{D}}(\beta)$ denote the probability of the retailer placing a replenishment order β days after the last order, $\beta \in (1, 2, ..., M)$. The supplier's decision is to choose a value for α so that expected cost is minimized, as expressed by:

$$\min_{\alpha}\left(\sum_{\beta=1}^{M}\begin{cases}-b\psi_{\tilde{D}}(\beta) & \alpha \ge \beta \\ -Qh_1(\beta-\alpha-1)\psi_{\tilde{D}}(\beta) & \alpha < \beta\end{cases}\right).$$

The expectation of the suppliers profit is taken over all probabilities for the retailer ordering within the next M days and takes into consideration two conditions: 1) $\alpha \geq \beta$, the case when the retailer orders prior to the supplier receiving replenishment so that the retailer's replenishment is satisfied through expediting, and 2) $\alpha < \beta$, the case where the supplier holds inventory at the time it receives a retailer replenishment order. In this case, the supplier incurs holding cost for $\beta - \alpha - 1$ days. Let α^* denote the value that minimizes the above expression.

In Appendix A, we characterize the distribution $\psi_{\tilde{D}}(\beta)$. Note we assume the supplier acts honorably and does not attempt to increase its profit by ordering earlier than the safety lead-time so the product's useful life at the retailer will be shorter, forcing the retailer to order more frequently. While there may be a short-term incentive for the supplier to act in this manner, the long-term negative consequences do not typically make it worthwhile, as the retailer would eventually figure out the supplier's deceitfulness.

To express the supplier's expected profit per period, some additional notation is required. Let $\pi_{\vec{i},L}$ denote the steady state probability that the retailer is in state $\left(\vec{i}, L\right)$ and let $q^*_{\vec{i},L}$ denote the retailer's corresponding optimal replenishment decision for this state. Further, let m_1 denote the supplier's margin per unit expressed as a percentage of its unit revenue. The supplier's expected profit per period is

$$\sum_{\vec{i}} \sum_{L} \begin{cases} \left[m_1 (1 - m_0) q^*_{\vec{i},L} - b\right] \pi_{\vec{i},L} & \textit{if } L - \alpha \leq 0 \textit{ and } q^*_{\vec{i},L} > 0 \\ \left[m_1 (1 - m_0) q^*_{\vec{i},L} - h_1 \left(Q - q^*_{\vec{i},L}\right)\right] \pi_{\vec{i},L} & \textit{if } L - \alpha > 0 \\ 0 & \textit{otherwise} \end{cases} .$$

3.2 Decentralized Information Sharing (DIS) Case

The DIS Case builds on the NIS Case so that now the retailer shares its inventory state and replenishment policy with the supplier. Decision-making, however, remains independent. As before, we start by formulating the retailer's MDP and then proceed to the supplier's policy.

3.2.1 DIS Case: Retailer's Policy

The retailer's optimization is similar to the NIS Case except it is now necessary to track the supplier's inventory state since the supplier's replenishment decision is now state–dependent on the retailer's inventory position. Here, we track the supplier's age dependent inventory by using A – the remaining *retail* shelf life, since the age at the supplier is simply $A+1$ if the supplier holds inventory. This involves a slight change in interpretation, since now A takes values in $\{0,1,...,M\}$ and $A=0$ corresponds to the state when the supplier has zero inventory and, implicitly, the age of replenished items will be M due to expediting. Since we now track the supplier's inventory with A, we drop L from the state space. The extremal equation is

$$f\left(\vec{i},A\right)+\bar{c}=\max_{q\in\{0,Q\}}\left\{G\left(I\right)-q\left(1-m_0\right)+\sum_{D=0}^{\infty}f\left(\tau\left(\vec{i},D,q,A\right),A'\right)\phi\left(D\right)\right\} \tag{4}$$

where

$$A'=\begin{cases}A-1 & if\ \alpha^*\geq\beta \text{ and } q=0\\ M & if\ \alpha^*<\beta\\ 0 & otherwise\end{cases}. \tag{5}$$

Note that (5) determines the supplier's inventory state in the next period, predicated on both the retailer's order and the supplier's replenishment decision. In the next section, we describe the supplier's policy that incorporates the information shared by the retailer.

3.2.2 DIS Case: Supplier's Policy

Under the DIS Case, the supplier's decision is to choose a value for α so that expected cost is minimized, as expressed by:

$$\min_{\alpha}\left(\sum_{\beta=1}^{M}\begin{cases}-b\psi_{\tilde{D}}\left(\beta\middle|\,\vec{i}\right) & \alpha\geq\beta\\ -Qh_1\left(\beta-\alpha-1\right)\psi_{\tilde{D}}\left(\beta\middle|\,\vec{i}\right) & \alpha<\beta\end{cases}\right).$$

The conditional distribution $\psi_{\tilde{D}}\left(\beta\middle|\,\vec{i}\right)$ is a function of the retailer's one-period inventory state transition probabilities and the optimal ordering decisions resulting from (4). Since the retailer and supplier replenishment decisions are inter-related and decision–making is decentralized, some discussion is warranted regarding the order in which the values for q^* and α^* are determined. We employ the following solution procedure: 1) Given a system state $\left(\vec{i},A\right)$, condition on the decision $q=0$ and compute the optimal supplier policy $\alpha^*\,|q=0$. 2) Compute the corresponding expected average profit for the retailer given these decisions. 3) Provide the same treatment to the condition for the decision $q=Q$ and find both the optimal supplier policy $\alpha^*\,|q=Q$ and the associated expected average profit for the retailer. 4) Choose the value q^* that maximizes the retailer's expected profit. Details are provided in Appendix B.

As in the NIS Case, the supplier's expected average profit per period is determined from the limiting behavior of the retailer in steady state. Letting $\pi_{\vec{i},A}$ denote the steady state probability that the system is in state $\left(\vec{i},A\right)$ and $q^*_{\vec{i},A}$ denote the corresponding optimal retailer replenishment decision, the supplier's expected profit per period is

$$\sum_{\vec{i}}\sum_{A}\begin{cases}\left[m_1(1-m_0)q^*_{\vec{i},A}-b\right]\pi_{\vec{i},A} & if\ A=0\ and\ q^*_{\vec{i},A}>0\\ \left[m_1(1-m_0)q^*_{\vec{i},A}-h_1\left(Q-q^*_{\vec{i},A}\right)\right]\pi_{\vec{i},A} & if\ A>0\\ 0 & otherwise\end{cases}.$$

3.3 Centralized Control (CC) Case

In the CC Case, a central decision maker seeking to maximize total supply chain profits makes replenishment decisions for both the retailer and the supplier. This corresponds to the practice of vendor–managed inventories (VMI). The retailer no longer places orders with the supplier. Instead, we interpret the decision variable q as a planned shipment from the supplier to the retailer. In addition, the supplier's replenishment order λ is now added to the decision space of the MDP. It is never optimal for the supplier to place an order in a period where it already has Q units in inventory. To see why, we offer an informal proof by contradiction. Assume the supplier places a replenishment order when there are already Q units in stock at the supplier level. This will bring the supplier's inventory level up to $2Q$ units but the retailer is restricted to ordering either 0 or Q units each period. Thus if the supplier postpones its ordering decision to the period when the retailer places its order, then total system cost is reduced without affecting the service level. Therefore, the supplier will never replenish with a positive quantity on-hand.

For convenience, let $c_1 = Q(1-m_0)(1-m_1)$ denote the supplier's purchase cost. Assuming $h_1 < h_0$ **(**otherwise it is never optimal to hold inventory at the supplier) the extremal equation is

$$f(\vec{i},A)+\bar{c} = \max_{q\in(0,Q),\ \lambda\in(0,1)}\left(\begin{array}{l} G(I)-c_1\lambda+\sum_{D=0}^{\infty}\left[f\left(\tau\left(\vec{i},D,q,A\right),A'\right)\right]\phi(D)\\ -\begin{cases}0 & if\ A=0\ and\ q=0\\ b-c_1 & if\ A=0\ and\ q>0\\ h_1(Q-q) & otherwise\end{cases}\end{array}\right). \qquad (6)$$

Since the objective is to maximize system–wide profit, the optimization expressed in (6) omits the transfer price between the supplier and the retailer. Instead, expected profit maximized in the MDP is the sum of the one period profit function, the purchase cost to the supplier for regular replenishment, the purchase cost plus penalty cost for any supplier expediting, holding costs applied to ending inventory for both facilities, and future expected profit. The age of the inventory at the retailer carries over from (5) in the DIS Case and is not repeated here.

The resulting policy determines the optimal timing for the retailer and the supplier to replenish based on the quantity and age of the inventory on hand at the retailer. The solution procedure differs from the previous policies since now both the retailer's decision and supplier's decision are considered simultaneously to solve for the optimal supply chain expected profit. Hence, the decision space has been expanded to cover an exhaustive search for the optimal decisions in each inventory state.

Further consideration of the policy structure leads to the following observations. First, with the elimination of double marginalization and the fact that market mediation risk is now shared collectively by the supply chain, we expect that customer service levels will increase relative to the first two scenarios. Second, the corresponding increase in supply may well decrease product freshness at the point of sale and increase the level of outdating. Third, so long as the difference in the marginal cost of holding inventory between the retailer and supplier is less than the marginal cost of a lost sale, the supplier's role will shift to become a cross docking facility, passing along inventory to the retailer as soon as it arrives. These observations are supported by the results of an extensive numerical study to which we now proceed.

4. Numerical Study

We evaluate the VOI in the DIS Case and the VCC in the CC Case where VOI and VCC are the % improvement in expected total supply chain profit, relative to the NIS Case. Specifically,

$$VOI = \frac{\left(E\left[\text{Profit}_{DIS}\right] - E\left[\text{Profit}_{NIS}\right]\right)}{E\left[\text{Profit}_{NIS}\right]} \text{ and } VCC = \frac{\left(E\left[\text{Profit}_{CC}\right] - E\left[\text{Profit}_{NIS}\right]\right)}{E\left[\text{Profit}_{NIS}\right]}.$$

Consumer demand $\phi(\cdot)$ corresponds to a truncated negative binomial distribution with a maximum value of 50 (any probabilities for demand exceeding 50 are redistributed proportionately within the truncated limit of the distribution). See Nahmias and Smith (1994) regarding the advantages of assuming negative binomial distributions for retail demand. Across our numerical experiments, the mean of the distribution is held constant at four and the Coefficient of Variation (*C*) is treated as a parameter to the model using the values reported below. Each period represents a day and the holding cost at each echelon is 40% of the purchase cost, measured on an annual basis. In total, we consider 972 experiments that comprise a factorial design for all combinations of the following parameters:

$$C \in (0.5, 0.6, 0.7) \quad M \in (4, 5, 6) \quad Q \in (8, 9, 10) \quad m_0 \in (0.4, 0.5, 0.6)$$

$$m_1 \in (0.4, 0.5, 0.6) \quad b \in (0.05c_1, 0.10c_1, 0.15c_1, 0.20c_1)$$

Our selection of parameter values is motivated by values observed in practice for several common and slow moving packaged perishables in product categories like fresh meat and seafood, deli, ready-made meals, and fresh cut fruit and vegetables. Products in these categories are highly perishable although daily item movement is often less than the case size, which itself is generally small as confirmed by a study we conducted at a 70 store division of a regional grocer. At the same time, our selection is constrained by the computational feasibility of the resulting MDP, since the size of the state space expands exponentially with the vector of age–

dependent inventory. Notwithstanding, the range of parameter values considered covers an extensive selection of products (Office of Technology Assessment Report, 1979).

We use value iteration to compute the results for the respective MDPs and then solve the accompanying state transition matrices using the method of Gaussian elimination to evaluate steady state behavior as described in Kulkarni (p. 124). In §4.1, we discuss our general observations and in §4.2 we report the results of our sensitivity analysis.

4.1 Results and General Observations

In general, we find both information sharing and centralized control lead to considerably fresher product for sale at the retailer. In Table 4.1, we report the VOI for the entire supply chain and for each member under a decentralized structure (DIS Case) and the corresponding VCC for the total supply chain under a centralized structure (CC Case), at given percentiles of the 972 experiments. For example, the 0.50 percentile denotes the median values. From this table, three observations emerge: 1) the VOI is lower than the VCC, although it can still be substantial, 2) the VOI is not necessarily shared equally between the retailer and the supplier, and 3) both the VOI and VCC are sensitive to model parameterization and depend largely on system behavior as we discuss for each case below.

	DIS Case			CC Case
Percentile	Total	Retailer	Supplier	Total
0.00	0.0%	0.0%	-10.1%	0.0%
0.25	0.8%	1.2%	-1.6%	1.2%
0.50	3.3%	4.1%	0.3%	4.6%
0.75	7.0%	10.1%	4.8%	8.7%
1.00	13.3%	26.9%	19.0%	16.0%
Mean	4.2%	6.2%	1.6%	5.6%

Table 4.1: VOI (DIS Case) and VCC (CC Case) across experiments

4.1.1 DIS Case Observations

In the DIS Case, information sharing enables the supplier to better time the arrival of its replenishment with the timing of retail orders. In turn, the freshness of product (measured in terms of the expected average lifetime remaining) replenished at the retailer increases from an average of 3.77 periods to 4.46 (18.3% increase). Thus, product outdating at the retailer decreases by an average of 39.0%. This increased product freshness also enables the retailer to boost its service level by 3.1% on average.

The change in retailer performance has two direct effects on the supplier. The change reflects both a decrease in outdating at the retailer and an increase in retailer service. When the increase in retailer service (and hence units of satisfied demand) exceed the reduction of outdating, the supplier realizes a net increase in retailer orders and is better off. When the opposite occurs the supplier is worse off. Across experiments, we find that half of the time, the combination results in a net decrease in retailer orders which can be as large as a 10.5% reduction. In the other half of the experiments, there is a net increase in retailer orders which can be as large as an 18.5% increase. Even though the supplier is able to reduce its expected inventory related costs in all experiments; these savings are generally trivial compared to the increase or decrease in revenue that arises through the change in retailer behavior. In §4.2 we evaluate the conditions that affect the retailer's order stream in a sensitivity analysis.

Total supply chain profit always improves with information sharing, even when the supplier's profit decreases. An important avenue for future research is to explore how certain contracts and incentives can be implemented so that the maximum benefits from information sharing can be realized and be Pareto improving for both firms. In the absence of such contracts, it is doubtful the supplier will be a willing participant.

4.1.2 CC Case Observations

With centralized control, the improvement in total supply chain profit is greater than the improvement observed with information sharing. On average, the VCC is 27% greater than the VOI. There are two effects at work here. First, there is minimal value in holding inventory at the supplier. Thus, the supplier serves a cross–docking function wherein any replenishment it receives is immediately sent onward to the retailer. We observe an average decrease of 44% in the supplier's expected inventory holding costs and a related average improvement of 24% in the freshness of the product delivered to the retailer. This represents over a 5% improvement in product freshness relative to the DIS Case.

The second effect comes from the elimination of double marginalization (the stocking decision at the retailer is predicated on the entire supply chain's profit, not just the retailer's as in the NIS and DIS Cases). Consequently, the retailer's service level increases an average of 7.0%. This represents a considerable improvement when compared to the DIS Case. To provide higher service, more inventory is positioned at the retailer and, therefore, the system may experience an increase in outdating relative to both the NIS and DIS Cases.

4.2 Sensitivity Analysis

Generally, we find that the VOI and the VCC are sensitive to product perishability, the retailer's ability to match supply and demand, and the size of the penalty for mismatches in supply and demand. We illustrate sensitivity to each parameter in Figure 4.1. The height of each bar corresponds to the average VOI and VCC across experiments for the parameter value specified on the x-axis. We discuss these relationships and provide a more complete set of performance measures in an online appendix (Ketzenberg and Ferguson; 2006).

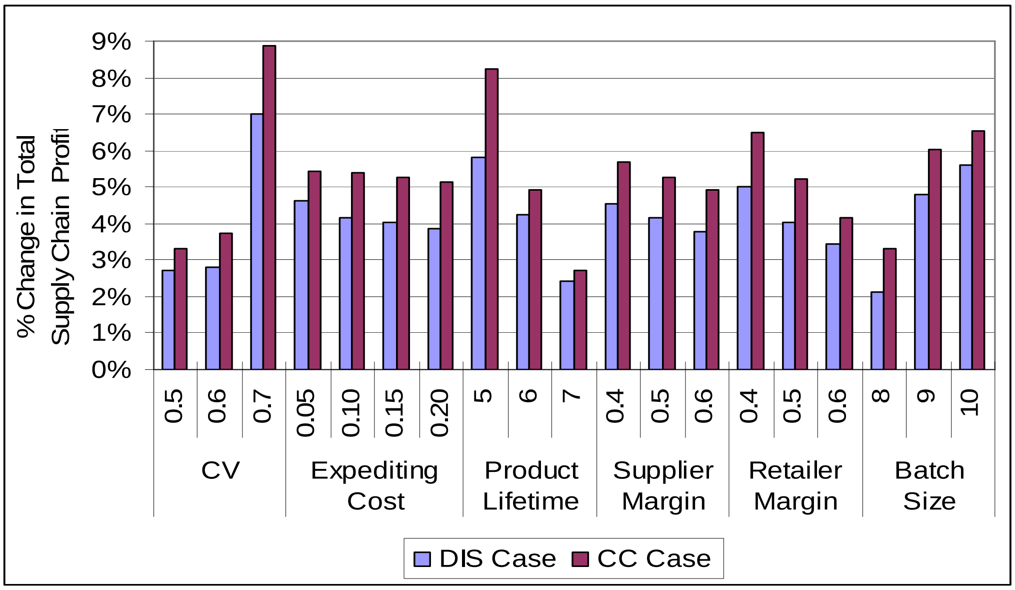

Figure 4.1: Sensitivity of the average VOI/VCC for each fixed parameter value

5. Discussion

Our results show that the VOI for perishable items can be significant. As opposed to studies that address the VOI for non-perishable items, the VOI for perishables is derived by the supplier's ability to provide a fresher product. Indeed, for non perishables our results show the VOI is trivial and quickly drops off for lifetimes greater than five days. The benefits of information sharing, however, are not shared equally between the retailer and the supplier. In a decentralized control supply chain, the retailer receives the larger average benefit and, in many cases, the supplier can be harmed.

On average, we find the total supply chain profits increase an average of 4.2% with information sharing and 5.6% with centralized control. Compared to previous studies on non-perishable suppy chains, these values may seem small. There are several reasons the VOI and VCC are small in our study. Starting with the VOI; our serial supply chain setting isolates the effect of a lower spoilage cost on the VOI. Previous studies on non-perishable products used a distribution network structure to show positive values for the VOI. By knowing the inventory levels at each retailer, the warehouse can better anticipate future orders and save on fixed costs. In a serial chain such as our structure, the VOI is negligible if the product is non-perishable because the warehouse does not achieve these savings with only one retailer. Thus, the VOI values in our study are purely based on the reduction in spoilage cost.

For the VCC; there are two reasons the values are small in our study. First, for most products in the grocery industry, inventory carrying costs are small compared to the opportunity of a lost sale. With such small holding cost, there is little incentive to minimize inventories other than for reasons of shelf space and hence service levels are generally quite high. The prospect of outdating for perishables does increase the overage cost and pushes downward pressure on service levels. Yet, they remain high in practice as well as in our study where we generally observe service levels in the range of 88%-95%. Hence, with little opportunity to improve on already high service levels, the VCC remains low compared to cases with significant lost sales. Second, we restrict the supplier to offering a 100% service level to the retailer by ensuring that all replenishment requests are met either from stock-on-hand or through an emergency order. This type of replenishment guarantee is also common in practice but it reduces the double marginalization effect that might be observed if the supplier was allowed to choose a service level based purely on her underage and overage costs.

On average, the VOI obtains approximately 70% of the VCC, thus information sharing alone garners the majority of the benefit of centralized control. In an industry with high levels of competition, significant legacy relationships, and a great deal of mistrust between supply chain partners, this may be significant for retailers who remain reluctant to give up decision-making control of their inventory. We find supply chains benefit the most from information sharing or centralized control when product lifetimes are short, batch sizes are large, demand uncertainty is high, and when the penalty for mismatches in supply and demand are large.

Clearly the batch size is an important model parameter that we have assumed is exogenously determined. Even so, we can also use the model to find the optimal Q by searching for the largest total supply chain profit over the range of Q for which it is viable to stock and sell the product. In a supplemental study that is available as an online appendix (Ketzenberg and Ferguson; 2006), we show that 1) case size optimization can achieve the same level of benefits as information sharing and centralized control and 2) the VOI and the VCC are trivial when the optimal case size is chosen. Given the relative costs of these initiatives with the costs of changing case sizes, supply chains may find it more beneficial to optimize case size and avoid the privacy issues of sharing information and control issues with centralized decision-making (Småros et al. 2004). Regardless, our results make clear that with current industry case sizes, local optimization (packaging and handling) can significantly undermine total system efficiency. We note, however, that these results are particular to the single case ordering restriction.

There are two other limiting model restrictions to our study worth further consideration. First, we assume that supplier receives the same revenue per unit, regardless of its product freshness and, second, the retailer accepts delivery of product without regard to its remaining lifetime. From a practical perspective, however, it is reasonable to expect that 1) a supplier with fresher product may obtain a higher price than a supplier with older product and 2) the retailer may refuse shipment if the remaining product lifetime is too short. In the online supplement

(Ketzenberg and Ferguson; 2006), we test how these two relaxations affect the VOI and the VCC. In this study, we assume a simple linear model of freshness dependent pricing. We also assume that the retailer will only accept a replenishment when the product lifetime is long enough so that expected profit is strictly positive. Under these conditions, we find that as price sensitivity to product freshness increases, the supplier obtains a larger portion of the total value through information sharing and centralized control. At the same time, however, the total value obtained for the supply chain through either initiative (VOI or VCC) rapidly diminishes.

There are a number of important issues still to be addressed. While we look at the VOI and VCC, we do not propose contracts that provide firms with the incentive to share/use the information or to act in a centralized manner. As another pursuit, we find few studies that provide a direct comparison between the relative efficacy of information sharing and centralized control, an important issue for industries where legacy relationships and high levels of competition provide barriers to implementation. Other areas for future research include the modeling of distribution supply chains, longer lead-times, different issuing policies, and capacity restrictions on the supplier.

References

Axtman, B. (2006), "Ripe Opportunities," *Progressive Grocer*, 85(4), 76-80.

Bai, L., C. Alexopoulos, M. Ferguson and K. Tsui (2005), "A Simple and Robust Batch-Ordering Inventory Policy For Unobserveable Demand," Georgia Tech School of Industrial and Systems Engineering Working Paper.

Bourland, K. E., S. G. Powell, and D. F. Pyke (1996), "Exploiting Timely Demand Information to Reduce Inventories," *European Journal of Operational Research*, 92, 239-253.

Boyer, M. (2006) "Lost in SKUs," *Progressive Grocer*, 85(7), 118-121.

Chanil, D. and M. Major (2005), "Higher Yields," *Progressive Grocer*, Section 2005 Annual Product Operations Review, 84(16), 48-57.

Cachon, G. and M. Fisher (2000), "Supply Chain Inventory management and the Value of Shared Information," *Management Science*, 46(8), 1032-1048.

Chen, F. (1998), "Echelon Reorder Points, Installation Reorder Points, and the Value of Centralized Demand Information," *Management Science*, 44(12), S221–234.

Cohen, Morris A., William P. Pierskalla, and Hsiang-chun Yen (1981), "An Analysis of Ordering and Allocation Policies for Multi-Echelon, Age-Differentiated Inventory Systems," *TIMS Studies in the Management Sciences*, 16, 353-378.

Falck, Carl Michael (2005), "Efficient Store Ordering," Helsinki University of Technology, Department of Industrial Engineering and Management, Masters Thesis, 73 pages.

Feller, W. (1949), "Fluctuation theory of recurrent events," *Transactions of the American Mathematical Society*, 67, 98-119.

Ferguson, M. and M. Ketzenberg (2006), "Sharing Information to Improve Retail Product Freshness of Perishables," *Production and Operations Management*, 15(1), 57-73.

Fitzgerald, S. (2003), "Perishing Profits," *Canadian Grocer*, Toronto, 117(4), 38.

Fujiwara, Okitsugu, Hanijanto Soewandi, and Dayani Sederage (1997), "An optimal ordering and issuing policy for a two-stage inventory system for perishable products," *European Journal of Operational Research*, 412-424.

Gavirneni, S., R. Kapuscinski and S. Tayur (1999), "Value of Information in Capacitated Supply Chains," *Management Science*, 45(1), 16-24.

Goh, C., B. Greenberg, and H. Matsuo (1993), "Two-stage Perishable Inventory Models," *Management Science*, 39(5), 633-649.

Ketzenberg, M. and M. Ferguson (2006), "Appendix to Managing Slow Moving Perishables in the Grocery Industry," http://smartech.gatech.edu/handle/1853/3199/browse-date

Kulkarni, V. (1995), Modeling and Analysis of Stochastic Systems, Chapman & Hall.

Larson, P. D, and R.A. DeMarais (1999), "Psychic Stock: An Independent Variable Category of Inventory," *International Journal of Physical Distribution & Logistics Management,* 29(7/8), 495-501.

Lee, H.L., P. Padmanabhan, and S. Whang (1997), "Information Distortion in a Supply Chain: the Bullwhip Effect," *Management Science*, 43(4), 546-558.

Lee, H., K. So, and C. Tang (2000), "Information Sharing in Supply Chain," *Management Science*, 46(5), 626-643.

Lehmann, E. (1990), Elements of Large Sample Theory. Springer-Verlag, New York.

Moinzadeh, K. (2002), "A Multi–Echelon Inventory System with Information Exchange," *Management Science*, 48(3), 414–426.

Nahmias, S. (1982), “Perishable Inventory Theory: A Review,” *Operations Research*, 30(4), 680-707.

Nahmias, S. and S. Smith (1994), “Optimizing Inventory Levels in a Two Echelon Retailer System with Partial Lost Sales,” *Management Science,* 40(5), 582–596.

Office of Technology Assessment Report (1979), “Open Shelf-Life Dating of Food,” NTIS order #PB80-101629, August.

Pfankuch, B. (2006), Store Manager of Albertson’s, Fort Collins, CO, Personal Interview, May, 23 2006.

Prastacos, G. P. (1981), “Allocation of a Perishable Product Inventory,” *Operations Research*, 29(1), 95-107.

Putterman, M. (1994), Markov Decision Processes: Discrete Stochastic Dynamic Programming, John Wiley & Sons, Inc.

Raafat, F. (1991), “Survey of Literature on Continuously Deteriorating Inventories*,” Journal of the Operational Research Society*, 42(1), 27-37.

Raghunathan, S., (2001), “Information Sharing in a Supply Chain,” *Management Science,* 47(4), 605-610.

Ross, S., (1996), Stochastic Processes. John Wiley & Sons, New York.

Silver, E., Pyke, D., and R. Peterson, (1998), Inventory Management and Production Planning and Scheduling, Wiley.

Småros, J., Angerer, A., Fernie, J., Toktay, L. B., and Zotteri, G. (2004), "Logistics Processes of European Grocery Retailers," Helsinki University of Technology Working Paper.

The National Supermarket Research Group (2003), “2003 National Supermarket Shrink Survey,” www.retailcontrol.com.

Tortola, J. (2005), “Loss Leader”, *Progressive Grocer*, 84(7), 14-15.

Yen, H. (1965), “Inventory Management for a Perishable Product Multi-echelon System,” Unpublished Ph.D. Dissertation, Department of IE/MS, Northwestern University, Evanston, IL.

Appendix A
Retailer Order Probabilities in the NIS Case

Here, we characterize the distribution $\psi_{\tilde{D}}(\beta)$ introduced in §3.1.2. Without information sharing, the supplier only knows the batch size Q and the history of the number of periods since the retailer's last order β. We follow the procedure outlined in Bai et al. (2005) to show how this information is used to determine the retailer's order distribution.

Let X_i be a random variable representing the usage of the product (sales and outdating) at the retailer on day i for i = 1, …, M. The X_i s are independent with the same mean and variance, but they may come from different distributions. Assuming the retailer uses a reorder point inventory control policy (a reasonable assumption in this industry), once the retailer's approximate inventory position I_i is below the reorder point r, then an order quantity of size Q will be ordered at time t_i. Thus, during the time interval $[t_{i-1}, t_i)$ with length $\tilde{D}_i = t_i - t_{i-1}$, the relationship between accumulated usage and the retailer's inventory position can be expressed as $I_i = I_{i-1} + Q - \sum_{j=1}^{\tilde{D}_i} X_j$. Then the accumulated usage during time interval $\tilde{D}_i$ is

$\sum_{j=1}^{\tilde{D}_i} X_j = I_{i-1} + Q - I_i$. Therefore, an interval length $\tilde{D}$ can be defined by the minimal value of n for which the nth accumulated usage is greater than Q, that is,

$$\tilde{D} = N(Q) + 1 \equiv \min\{n : S_n = X_1 + X_2 + \cdots + X_n > Q\}, \qquad \text{(A.1)}$$

where $N(Q) \equiv \max\{n : S_n = X_1 + X_2 + \cdots + X_n \le Q\}$.

The following lemma from Feller (1949) provides the reasoning basis of the first two moments of the demand distribution for deriving the estimates.

LEMMA. *If the random variables* $X_1, X_2, \ldots$ *have finite mean* $\mathrm{E}[X_i] = \mu$ *and variance*

$\mathrm{Var}[X_i] = \sigma^2$*, and* $\tilde{D}$ *is defined by* (A.1)*, then* $\mathrm{E}[X_i]$ *and* $\mathrm{VAR}[X_i]$ *are given by:*

$$\mathrm{E}[\tilde{D}] = \frac{Q}{\mu} + o(1) \quad \textit{and} \quad \mathrm{Var}[\tilde{D}] = \frac{Q\sigma^2}{\mu^3} + o(1) \quad \text{as } Q \to \infty \quad \textit{respectively.}$$

The next theorem provides the asymptotic distribution of $\tilde{D}$. Its proof is a trivial extension to Theorem 3.3.5 in Ross (1996).

THEOREM. *Under the assumptions of the Lemma,* $\tilde{D}$ *has the asymptotic normal distribution with mean* Q/μ *and variance* $Q\sigma^2/\mu^3$:

$$\tilde{D} \to \mathrm{N}(Q/\mu, \sqrt{Q\sigma^2/\mu^3}) \text{ as } Q \to \infty.$$

According to Theorem 2.7.1 of Lehmann (1990), the theorem still holds even when the daily usages are not identically distributed, but are independent with finite third moments. While an asymptotic distribution may cause concern for small values of Q, our simulation studies show it provides good estimates for the distribution parameters over the values of Q used in this paper. Thus, we let $\psi_{\tilde{D}}(\beta)$ represent the cdf of $\tilde{D}$ with a mean of Q/μ and a variance of $Q\sigma^2/\mu^3$.

Appendix B
Solution Procedure for the DIS Case

```
PROCEDURE f(i⃗, A)
  FOR q = 0 TO Q STEP Q                          ;Evaluate q = 0 (1st)and q = Q  (2nd).
      Profit:= G(I) − q(1 − m0)                  ;Initialize profit to one period profit.
      IF (q>0) or (A=0)  THEN                    ;If supplier has no inventory going
          Determine λ                            ;  into next period, determine λ.
      ELSE                                       ;if supplier has inventory going into
          λ:= 0                                  ;next period, then no supplier order.
      FOR D = 0 TO MAX DEMAND                    ;Evaluate all realizations of demand.
          Profit = Profit + f(τ(i⃗, D, q, A), A′)φ(D)   ;add in future expected profit.
      ENDFOR (D)
      IF q<Q THEN                                ;if 1st time through, then save results
         BEGIN                                   ;for later comparison to q = Q.
            SaveProfit:=Profit
            SaveLambda:= λ
          END
      ELSE                                       ;2nd time through, compare profit
          IF Profit< SaveProfit THEN             ;of q=0 (Saveprofit) to q = Q (Profit).
             BEGIN                               ;Case q = 0 > q = Q.
                q*:=0                            ;Set optimal decisions and
                f(i⃗, A):= SaveProfit             ;expected profit.
                λ*:= SaveLambda
              END
           ELSE                                  ;Case q = Q > q = 0.
              BEGIN
                q*:=0                            ;Set optimal decisions and
                f(i⃗, A):=Profit                  ;expected profit.
                λ*:= λ
              END
   ENDFOR (q)
ENDPROCEDURE
```