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Managing inventories in a two-echelon dual-channel supply chain

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Abstract

We present a two-echelon dual-channel inventory model in which stocks are kept in both a manufacturer warehouse (upper echelon) and a retail store (lower echelon), and the product is available in two supply channels: a traditional retail store and an Internet-enabled direct channel. The system receives stochastic demand from two customer segments: those who prefer the traditional retail store and those who prefer the Internet-based direct channel. The demand of retail customers is met with the on-hand inventory from the bottom echelon while the demand in the Internet-enabled channel is fulfilled through direct delivery with the on-hand inventory from the upper echelon. When a stockout occurs in either channel, customers will search and shift to the other channel with a known probability. A one-for-one inventory control policy is applied. In order to develop operational measures of supply chain flexibility, we define a cost structure which captures two different operational cost factors: inventory holding costs and lost sales costs. We discuss several insights that are evident from the parametric analysis of the model. We also examine the performance of two other possible channel distribution strategies: retail-only and direct-only strategies. Computational outcomes indicate that the dual-channel strategy outperforms the other two channel strategies in most cases, and the cost reductions realized by the flexibility of the dual-channel system may be significant under some circumstances.

Keywords: Inventory; Supply chain management; Channels of distribution; E-commerce; Direct marketing

1. Introduction

Consider a two-echelon inventory system that consists of a manufacturer with a warehouse at the top echelon and a retail store at the bottom echelon. The manufacturer uses both a traditional retail store and an Internet-enabled channel to distribute its products. Demand from customers at the retail store is met with the on-hand inventory from the bottom echelon while orders placed through the Internet-enabled channel are satisfied directly with the on-hand inventory from the top echelon. Such a system is called a two-echelon dual-channel distribution system, or, more

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generally, a multi-echelon multi-channel distribution system.

The advent of the Internet has made it easier for companies who traditionally distribute their products through retail stores to engage in online direct sales. It has facilitated the adoption of multi-channel distributions. Moriarty and Moran (1990) pointed out that dual or multiple channels would become the dominant design for computer industry in the 1990s. In fact, the movement to multiple channels of distribution has also occurred in other industries. According to a recent survey, about 42% of top suppliers in a variety of industries, such as electronics, appliances, sporting goods, and apparel, have begun to sell directly to consumers over the Internet (Tedeschi, 2000). Evidently, as indicated by Keskinocak and Tayur (2001), companies are increasingly using new Internet-enabled sales channels along side the traditional retail channels to achieve supply chain flexibility.

Although the Internet-enabled channel is the motivation of this paper, the adoption of dual-channel distribution is not a novel phenomenon in the e-business era. Dual-channel distribution may take many forms, one of which is when a manufacturer both sells through intermediaries and directly to consumers (Preston and Schramm, 1965). The literature on distribution channels has pointed out important economical reasons for serving different customer segments with different channels (e.g., Moriarty and Moran, 1990; Rangan et al., 1992; Anderson et al., 1997). Because customers are heterogeneous in terms of their channel preference (Kacen et al., 2002), multiple channels may reach potential buyer segments that could not be reached by a single channel and may thus help to increase the market coverage. Also, dual channels may help companies to increase customers' awareness and loyalty of their products.

Despite its advantages, the adoption of dual-channel distribution introduces new management concerns. From a logistics perspective, combining the existing retail distribution channel with a new Internet-based direct distribution channel may cause havoc on the product demand structures, and thus may require companies to redesign the optimal inventory allocations in the two-echelon distribution environment. The fundamental task in connection with the two-echelon inventory problem is to find the balance between the stock levels at the top and the bottom echelons. How do companies set stock levels to achieve better channel performance when a new Internet-based direct distribution is introduced alongside the existing retail channel? In this paper, we incorporate the Internet-enabled direct channel into a traditional two-echelon inventory system and construct a model to determine the optimal inventory control levels for each echelon.

The analysis of multi-echelon inventory systems that pervades the business world has a long history. Clark and Scarf (1960) introduced the concept of echelon stock. Inventory control in multi-echelon systems is known to be a challenging research area. Because of the complexity and intractability of the multi-echelon problem, Hadley and Whitin (1963) recommend the adoption of single location, single echelon models for the inventory systems. Sherbrooke (1968) constructed the METRIC model, which identifies the stock levels that minimize the expected number of backorders at the lower echelon subject to a budget constraint. This model is the first multi-echelon inventory model for managing the inventory of service parts. Thereafter, a large set of models that generally seek to identify optimal lot sizes and safety stocks in a multi-echelon framework were produced by many researchers (e.g., Deuermeyer and Schwarz, 1981; Moinzadeh and Lee, 1986; Svoronos and Zipkin, 1988; Axsäter, 1990, 1993; Nahmias and Smith, 1994; Aggarwal and Moinzadeh, 1994; Grahovac and Chakravarty, 2001). In addition to analytical models, simulation models have also been developed to capture the complex interactions of the multi-echelon inventory problems (e.g., Clark et al., 1983; Pyke, 1990; Dada, 1992; Alfredsson and Verrijdt, 1999).

The study of multi-channel supply chains in the direct versus retail environment has emerged only recently. The focus of this stream of literature is on channel competition and coordination issues in the setting where the upstream echelon is at once a supplier to and a competitor of the downstream echelon (e.g., Rhee and Park, 1999; Tsay and Agrawal, 2003; Chiang et al., 2003). These papers analyze the dual-channel design problem by modeling the price and/or service interactions between upstream and downstream echelons. They do not deal with inventory issues.

While multi-echelon inventory control policies have been extensively studied, the theoretical basis for multi-echelon multi-channel inventory problem has not yet been well developed. One common arrangement of the extant multi-echelon inventory models assumes that the supply chain system consists of several locations whose supply–demand relationships form a hierarchy: each location places orders with one direct predecessor in the supply chain (see Svoronos and Zipkin, 1991 for more details). In this setting, one location may receive orders from several direct successors, but the successors have to be at the same echelon. Although a handful of papers have considered the model that allows some locations to bypass its direct predecessor and place orders with locations at a higher echelon or at the same echelon (e.g. Grahovac and Chakravarty, 2001), those orders are considered as emergency orders and only happen in the event of a stockout at their direct predecessor. With the trend of adopting a multi-channel distribution strategy in the recent business environment and with the development of third-party logistics, including the emergence of highly competent suppliers such as Federal Express (Narus and Anderson, 1996), the inventory distribution system wherein one location can concurrently receive orders from more than one echelon is not uncommon. Nevertheless, the inventory modeling literature thus far offers little guidance in approaching this subject.

Against this backdrop, a primary objective of this paper is to make a contribution to this important line of inquiry. Specifically, in our model the manufacturer at the upper echelon at once receives orders from its retailer and from the end customers through a direct channel. We assume that demand at the retail store is met with the retailer's on-hand inventory, while orders placed through the direct channel are shipped directly to customers with the manufacturer's on-hand inventory. We construct an analytical model and define a cost structure that captures inventory related operational costs to evaluate the performance of a two-echelon dual-channel supply system. Parametric analysis based on the model is conducted by varying the key parameters in the cost structure to obtain generalizable results. We explicitly compare the performance of three types of channel distribution strategies: retail-only distribution, dual-channel distribution, and direct-only distribution (see Fig. 1).

The recent frequently observed trends of increasing variety, customization and complexity of products have created a challenge to effective inventory management. For many products including furniture, appliances, electronics, spare parts, and fashion-oriented products, the demand for each particular product item in the product line is usually low, and it is relatively costly to hold high stock levels at the store to fill the demand. As the lost sales costs of these types of products are

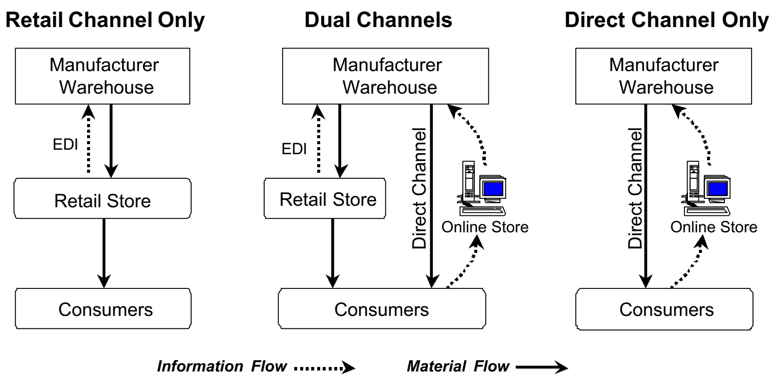


Fig. 1. Three types of channel distribution system.

substantial, the pressure of maintaining a high demand fill rate is put on the entire supply chain. One-for-one control policies, also known as order-for-order replenishment policies, are widely recognized in the literature for the management of products that exhibit low demand rates. Adopting these inventory policies in the multi-echelon dual-channel inventory system, we argue that adding the Internet-enabled direct channel along side the existing retail store can increase supply chain flexibility and can thus significantly reduce overall inventory holding costs and lost sales costs.

2. Two-echelon dual-channel inventory model

The topology and product flows of the two-echelon dual-channel supply system considered in the paper are illustrated in Fig. 2.

2.1. Model assumptions

The product is available for customers at both the retail store and the Internet-based direct channel (which will henceforth call the direct channel for brevity). The system receives stochastic demand from two customer segments: those who prefer the traditional retail store and those who prefer the direct channel. Suppose each segment has an independent demand arrival rate. Specifically, we assume that customers arrive at the retail store according to a Poisson process with constant intensity λ_r, and orders placed through the direct channel are in accordance with a Poisson process with rate λ_d. Demand of the retail customers is satisfied with the on-hand inventory at the retail store, while any order placed online is fulfilled through direct delivery with the on-hand inventory at the manufacturer warehouse. Let $\lambda = \lambda_r + \lambda_d$ be the total demand rate of the product, and let α be the proportion of consumers who prefer buying the product directly online. Then we have $\lambda_r = (1-\alpha)\lambda$ and $\lambda_d = \alpha\lambda$. We call α the *direct channel preference rate*.

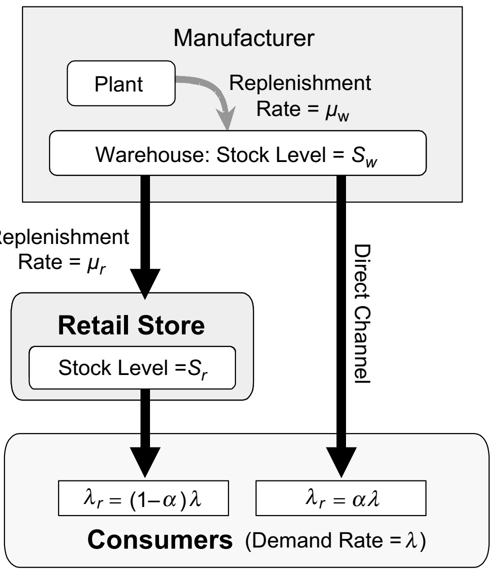


Fig. 2. Two-echelon dual-channel inventory system.

Suppose that no backorder is allowed for customers. In other words, a lost-sales model is assumed. When a stockout occurs in the retail store, some proportion, say β_r, of retail customers are willing to search and buy the product in the direct channel. We call β_r the *retail-customer search rate*. Likewise, we assume that some proportion β_d of customers who incur a stockout when ordering directly from the warehouse are willing to search and buy the product at the retail store. We call β_d the *direct-customer search rate*. Not that $\beta_d = 1$ models the situation wherein on-hand inventory in the retail store is allowed to fill online orders when the manufacturer warehouse is out of stock. When a stockout occurs in either channel, customers who are unwilling to shift to the other channel result in lost sales. In addition, customers are lost when both the retail store and the manufacturer warehouse are out of stock simultaneously.

We assume that replenishment lead times for both the warehouse and the retail store are independent exponential random variables with means $1/\mu_w$ and $1/\mu_r$, respectively. A one-for-one replenishment inventory policy is applied, and replenishment backorders from the retail store are allowed at the manufacturer warehouse. A customer served from stock on hand will trigger a replenishment order immediately by EDI (electronic data interchange). Therefore, the information lead time is assumed to be zero. Under this replenishment inventory policy, the inventory position is kept constant at a base-stock level. The base-stock levels at the warehouse and the retail store are denoted by S_w and S_r, respectively.

2.2. The Markov model

For convenience, the notation for the model is summarized in Table 1. Based on the assumptions in the previous section, the corresponding Markov model can be constructed with the state space (x, y), where

$$x = \text{stock on hand at manufacturer warehouse}, \quad -S_r \leqslant x \leqslant S_w \tag{1}$$

and

$$y = \text{stock on hand at retail store}, \quad 0 \leqslant y \leqslant S_r. \tag{2}$$

Note that the stock on hand at the manufacturer warehouse can be negative because we assume that replenishment backorders from the retail store are allowed at the manufacturer warehouse. There are four events which lead to a change of state: (1) a customer arrives at the retail store, (2) an order is placed through the direct channel, (3) a replenishment order arrives at the manufacturer warehouse, and (4) a replenishment order arrives at the retail store. Let π_{xy} be the steady-state probability that x items are on hand at the manufacturer warehouse and y items are on hand at the retail store. Then the flow balance equations that require that for all states the input and output rates to each state be equal are given by

$$\begin{aligned}
&[(S_w - x)\mu_w + (S_r - y - [x]^-)\mu_r \\
&\quad + \delta_{xy}(\psi_y^r \lambda_r + \psi_x^d \lambda_d)]\pi_{xy} \\
&\qquad = [S_w - (x-1)]\mu_w \pi_{(x-1)y} \\
&\qquad\quad + [S_r - (y-1) - [x]^-]^+ \mu_r \pi_{x(y-1)} \\
&\qquad\quad + (\lambda_r + \beta_d \rho_{xy}^d \lambda_d)\pi_{(x+1)(y+1)} \\
&\qquad\quad + (\lambda_d + \beta_r \rho_{xy}^r \lambda_r)\phi_x \pi_{(x+1)y} \quad \text{for} \\
&\quad x = -S_r, -S_r + 1, \ldots, S_w \quad \text{and } y = 0, \ldots, S_r,
\end{aligned} \tag{3}$$

where $[x]^- = \max\{0, -x\}$, $[x]^+ = \max\{0, x\}$, and

$$\delta_{xy} = \begin{cases} 0 & \text{if } x \leqslant 0 \text{ and } y = 0, \\ 1 & \text{otherwise}, \end{cases} \tag{4}$$

$$\psi_y^r = \begin{cases} \beta_r & \text{if } y = 0, \\ 1 & \text{otherwise}, \end{cases} \tag{5}$$

$$\psi_x^d = \begin{cases} \beta_d & \text{if } x \leqslant 0, \\ 1 & \text{otherwise}, \end{cases} \tag{6}$$

$$\phi_x = \begin{cases} 1 & \text{if } x \geqslant 0, \\ 0 & \text{otherwise}, \end{cases} \tag{7}$$

$$\rho_{xy}^r = \begin{cases} 1 & \text{if } x \geqslant 0 \text{ and } y = 0, \\ 0 & \text{otherwise}, \end{cases} \tag{8}$$

$$\rho_{xy}^d = \begin{cases} 1 & \text{if } x < 0, \\ 0 & \text{otherwise}. \end{cases} \tag{9}$$

The left-hand side of (3) reflects the average transitions from state (x, y). The first two terms in the bracket are the rates at which in-transit replenishment orders arrive at the manufacturer warehouse and the retail store, respectively. The last term in the bracket specifies the transitions due to receiving demand. Specifically, δ_{xy} states whether the manufacturer warehouse and the retail store are simultaneously out of stock or not (Eq. (4)). ψ_y^r captures the assumption that a proportion of customers, β_r, will switch to the direct channel

Table 1
List of notation

List of notation	
λ	Total demand rate
α	Direct channel preference rate, $0 \leqslant \alpha \leqslant 1$
λ_r	Customer arrival rate at the retail store, $\lambda_r = (1-\alpha)\lambda$
λ_d	Customer arrival rate at the direct channel, $\lambda_d = \alpha\lambda$
β_r	Retail-customer search rate, $0 \leqslant \beta_r \leqslant 1$
β_d	Direct-customer search rate, $0 \leqslant \beta_d \leqslant 1$
μ_w	Manufacturer warehouse replenishment rate
μ_r	Retail store replenishment rate
S_w	Base-stock level at the manufacturer warehouse
S_r	Base-stock level at the retail store
x	On-hand inventory at the manufacturer warehouse
y	On-hand inventory at the retail store
π_{xy}	Steady-state probability

when the retail store is out of stock (Eq. (5)), and ψ_x^{d} captures the assumption that a proportion of customers, β_{d}, will switch to the retail store when the warehouse is out of stock (Eq. (6)).

Conversely, the right-hand side of (3) represents the average transitions into state (x, y). The first two terms indicate the transitions due to receiving in-transit replenishment orders from the manufacturer and the retail store, respectively. The last two terms denote the transitions due to satisfying demand by inventory on hand at the retail store and the manufacturer warehouse, correspondingly.

We can find the steady-state probabilities by solving the corresponding system of linear equations which contains the balance equations given in (3) and the normalizing constraint:

$$\sum_{x=-S_{\mathrm{r}}}^{S_{\mathrm{w}}} \sum_{y=0}^{S_{\mathrm{r}}} \pi_{xy} = 1. \tag{10}$$

The steady-state probabilities are uniquely determined and will be used to compute measures of the performance of the two-echelon dual-channel system.

To verify the balance equations and better understand the system, in Fig. 3(a) we specify the possible state space and the corresponding transition rates using the case when $S_{\mathrm{w}} = 2$ and $S_{\mathrm{r}} = 2$. The resulting steady-state probabilities for a set of parametric values are given in Fig. 3(b) for illustrative purposes.

3. Economic analysis of channel performance

In this section, we conduct an economic analysis of the model to evaluate the performance of the two-echelon dual-channel system. We define a cost structure that takes into account two different operational cost factors, the long-run average inventory holding cost and the long-run average lost sales cost. [2] In the sections that follow, these cost factors are specified in terms of the steady-state probabilities.

3.1. Long-run average inventory holding cost

Suppose that the system operates over an infinite horizon. Given the steady-state probabilities, the long-run average inventories for the manufacturer warehouse and the retail store, respectively, can be modeled as

$$I_{\mathrm{w}} = \sum_{x=1}^{S_{\mathrm{w}}} \sum_{y=0}^{S_{\mathrm{r}}} x\pi_{xy} \tag{11}$$

and

$$I_{\mathrm{r}} = \sum_{x=-S_{\mathrm{w}}}^{S_{\mathrm{w}}} \sum_{y=1}^{S_{\mathrm{r}}} y\pi_{xy}. \tag{12}$$

Let h_{w} and h_{r} be the inventory holding costs incurred by the firm per item per time unit at the manufacturer warehouse and the retail store, respectively. Then, the long-run average inventory holding cost, C_{H}, is determined by

$$C_{\mathrm{H}} = h_{\mathrm{w}} I_{\mathrm{w}} + h_{\mathrm{r}} I_{\mathrm{r}}. \tag{13}$$

The first portion of C_{H} specifies the inventory holding cost from the manufacturer warehouse, while the second part specifies the inventory holding cost generated by the retail store.

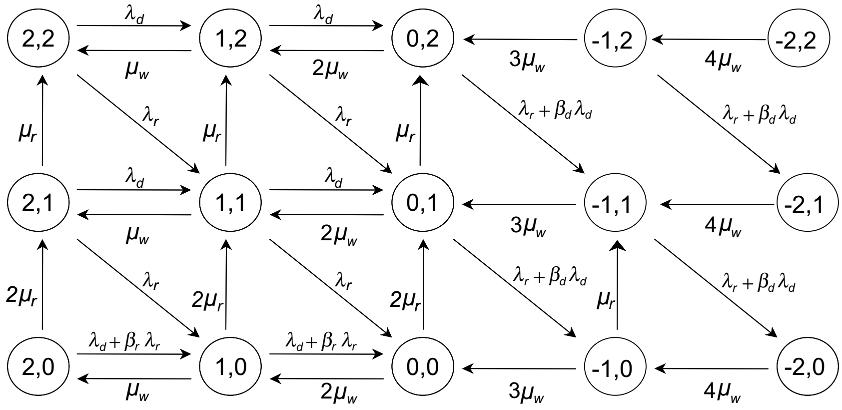
3.2. Long-run average lost sales cost

Recall that when a stockout occurs in either channel, customers who are unwilling to shift to the other channel result in lost sales. Moreover, customers are lost when both the retail store and the manufacturer warehouse are out of stock simultaneously. The probabilities that a stockout occurs only at the manufacturer warehouse and only at the retail store, respectively, depends upon the steady-state probabilities in the following way:

$$L_{\mathrm{w}} = \sum_{x=-S_{\mathrm{r}}}^{0} \sum_{y=1}^{S_{\mathrm{r}}} \pi_{xy} \tag{14}$$

[2] Henceforth, for brevity, the inventory holding cost will refer to the long-run average inventory holding and the lost sales cost will refer to the long-run average lost sales cost.

(a) Transition Diagram *($S_w = S_r = 2$)*



(b) Steady-State Probabilities π_{xy}

y \ x	2	1	0	-1	-2
2	0.2118	0.2513	0.1308	-	-
1	0.0332	0.1039	0.1101	0.0535	-
0	0.0031	0.0159	0.0344	0.0368	0.0151

Note. Parametric Values: $\lambda_r = \lambda_d = 7.5$, $\mu_w = 10$, $\mu_r = 20$, $\beta_r = \beta_d = 0.5$

Fig. 3. Transition diagram and steady-state probabilities for the case when $S_w = S_r = 2$: (a) transition diagram ($S_w = S_r = 2$); (b) corresponding steady-state probabilities π_{xy}.

and

$$L_r = \sum_{x=1}^{S_w} \pi_{x0}, \tag{15}$$

while the probability that both channels are simultaneously out of stock is given by

$$L_b = \sum_{x=-S_r}^{0} \pi_{x0}. \tag{16}$$

Assume that the opportunity cost of losing a customer is l per customer. Then we can specify the total long-run average lost sales cost as

$$C_L = l(1-\beta_r)L_w\lambda_r + l(1-\beta_d)L_r\lambda_d + lL_b(\lambda_r+\lambda_d). \tag{17}$$

The first portion of C_L reflects the lost sales cost from the retail store caused by those customers who are unwilling to shift the channel when the retail store is out of stock. The second portion describes the lost sales cost from the direct channel caused by those customers who are unwilling to shift to the other channel when the manufacturer warehouse is out of stock, and the last portion captures the lost sales cost due to the simultaneous stockout in both channels. Note that the lost sales rate can be represented as $C_L/l\lambda$, where $l\lambda$ is the lost sales cost if all the customers are lost. The system fill rate, therefore, is $1 - C_L/l\lambda$. Since l and λ are constant, C_L can be regarded as an implicit indicator of the system fill rate.

3.3. Total cost and optimal base-stock levels

We will use the sum of the inventory holding cost and the lost sales cost to evaluate the performance of the two-echelon dual-channel inventory system. Therefore, the total cost in our analysis is defined as $C_H + C_L$. The only decision variables are the base-stock levels, S_w and S_r. Therefore, we can view total long-run cost as a function of S_w and S_r, that is,

$$\begin{aligned}\mathrm{TC}(S_{\mathrm{w}}, S_{\mathrm{r}}) &= h_{\mathrm{w}} \sum_{x=1}^{S_{\mathrm{w}}} \sum_{y=0}^{S_{\mathrm{r}}} x\pi_{xy} + h_{\mathrm{r}} \sum_{x=-S_{\mathrm{w}}}^{S_{\mathrm{w}}} \sum_{y=1}^{S_{\mathrm{r}}} y\pi_{xy} \\ &\quad + l(1-\beta_{\mathrm{r}})\lambda_{\mathrm{r}} \sum_{x=1}^{S_{\mathrm{w}}} \pi_{x0} + l(1-\beta_{\mathrm{d}})\lambda_{\mathrm{d}} \sum_{x=-S_{\mathrm{r}}}^{0} \sum_{y=1}^{S_{\mathrm{r}}} x\pi_{xy} \\ &\quad + l(\lambda_{\mathrm{r}} + \lambda_{\mathrm{d}}) \sum_{x=-S_{\mathrm{r}}}^{0} \pi_{x0}. \end{aligned} \tag{18}$$

The objective is to find the base-stock levels that minimize this specification of total cost.

Lemma 1. *Suppose $h_{\mathrm{w}} > 0$ and $h_{\mathrm{r}} > 0$. There exist stock levels, $\widehat{S}_{\mathrm{w}}$ and $\widehat{S}_{\mathrm{r}}$, such that $\mathrm{TC}(S_{\mathrm{w}}, S_{\mathrm{r}}) > l\lambda \geqslant \mathrm{TC}(S_{\mathrm{w}}^*, S_{\mathrm{r}}^*)$, $\forall S_{\mathrm{w}} \geqslant \widehat{S}_{\mathrm{w}}$ and $\forall S_{\mathrm{r}} \geqslant \widehat{S}_{\mathrm{r}}$.*

Proof. See Appendix A. □

Lemma 1, which is intuitionally appealing, implies that by applying complete enumeration, the base-stock levels S_{w}^* and S_{r}^* that minimize $\mathrm{TC}(S_{\mathrm{w}}, S_{\mathrm{r}})$, and the associated minimal total cost $\mathrm{TC}(S_{\mathrm{w}}^*, S_{\mathrm{r}}^*)$, can be found. We can stop the enumeration when we find some stock levels, $\widehat{S}_{\mathrm{w}}$ and $\widehat{S}_{\mathrm{r}}$ whose associated total cost $\mathrm{TC}(\widehat{S}_{\mathrm{w}}, \widehat{S}_{\mathrm{r}})$ is greater than its theoretical upper bound $l\lambda$.

4. Parametric analysis

To generate insights and obtain generalizable results from the two-echelon dual-channel inventory model, we now conduct a numerical study using the model developed in Section 3. Note that since our model is based on a queueing-theoretic foundation, the computational results yield an exact evaluation of system performance.

4.1. Base parametric values

The main purpose of our numerical study is to gain managerial insights through a qualitative investigation of how system parameters affect model performance. After examining a variety of parametric values that are considered to be realistic, we found that certain parametric values generate similar qualitative patterns and results. Therefore, while there are numerous scenarios for the experiments, we avoid redundancy by choosing a set of parametric values, given in Table 2, as the base parametric values. A FORTRAN program was written to do the parametric analysis of the two-echelon dual-channel inventory model in the previous section. Additionally, Routines LSLRG [3] and LFSRG [4] in the IMSL MATH/LIBRARY were used to solve the system of linear algebraic equations for the steady-state probabilities.

4.2. Computational results of the base parametric values

Fig. 4 illustrates the computational results of the analysis with the base parametric values. Different values of α, the direct channel preference rate, which range from 0 to 1 with step value 0.05, are used in the analysis. For each value of α, optimal stock levels and the corresponding cost structure are computed. The plots in Fig. 4(a) indicate that, in general, the optimal base-stock level at the manufacturer warehouse increases as α increases, while on the other hand, the optimal base-stock level at the retail store decreases in α. From Fig. 4(b), we see that the plots of the corresponding inventory holding costs at the manufacturer warehouse and the retail store reflect similar patterns. The results conform to our intuition.

Fig. 4(b) shows that the lost sales cost has an irregular appearance. There is no clear trend that can be identified. Unlike the lost sales cost, the total cost in Fig. 4(b) exhibits a smoother appearance. It tends to move downward as the direct channel preference rate increases. This is

[3] Routine LSLRG solves a system of linear algebraic equations having a real general coefficient matrix. It first computes an LU factorization of the coefficient matrix based on Gauss elimination with partial pivoting. The solution of the linear system is then found using LFSRG.

[4] Routine LFSRG finds the solution to the linear system $Ax = b$ by solving the triangular systems $Ly = b$ and $Ux = y$. The forward elimination step consists of solving the system $Ly = b$ by applying the same permutations and elimination operations to b that were applied to the columns of A in the factorization routine. The backward substitution step consists of solving the triangular system $Ux = y$ for x.

Table 2
Base parameter values

Base parametric values for illustrative examples	
System-related parameters	
Warehouse replenishment rate	$\mu_w = 10$
Retail store replenishment rate	$\mu_r = 20$
Customer-related parameters	
Demand arrival rate	$\lambda = 15$
Retail-customer search rate	$\beta_r = 0.5$
Direct-customer search rate	$\beta_d = 0.5$
Cost-related parameters	
Inventory holding cost at warehouse (per item per time unit)	$h_w = 50$
Inventory holding cost at retail store (per item per time unit)	$h_r = 80$
Lost sales cost (per customer)	$l = 1000$

mainly because when α is high, the system holds a relative higher base-stock level at the manufacture warehouse and a relative lower base-stock level at the retail store. Given that the inventory holding cost is lower at the manufacturer warehouse than that at the retail store, the system could have a lower total inventory holding cost when α is high.

4.3. Effects of search rates

The model specifies that when a stockout occurs in either channel, customers shift to the other channel with a known probability. Recall that we defined the *retail-customer search rate*, β_r, as the proportion of the retail store customers who will search the product at the direct channel when a stockout occurs at the retail store, and the *direct-customer search rate*, β_d, as the proportion of the direct channel customers who will search the product at the retail store when stockout occurs at the direct store. In this section, we investigate the impact of search rates on the performance of the two-echelon dual-channel model by plotting the graphs of the corresponding optimal total costs in (β_r, β_d) space.

We consider two different values of the direct channel preference rate, $\alpha = 0.25$ and $\alpha = 0.75$. The results are shown in Fig. 5. By assumption, customers who will not search and shift to the other channel result in lost sales when a stockout occurs. As a result, we might expect that higher search rates would reduce the lost sales cost and thus yield a lower optimal total cost. When $\alpha = 0.25$, Fig. 5(a) shows that optimal total cost decreases in both β_r and β_d, a result that is consistent with our intuition. However, the result is counterintuitive when $\alpha = 0.75$. In Fig. 5(b), we see that the optimal total cost may, perversely, increase in β_d, the direct-customer search rate, when $\alpha = 0.75$. After closely examining the impact of β_d on the total cost, we learn that a higher direct-customer search rate may decrease the total inventory holding cost, while at the same time, it

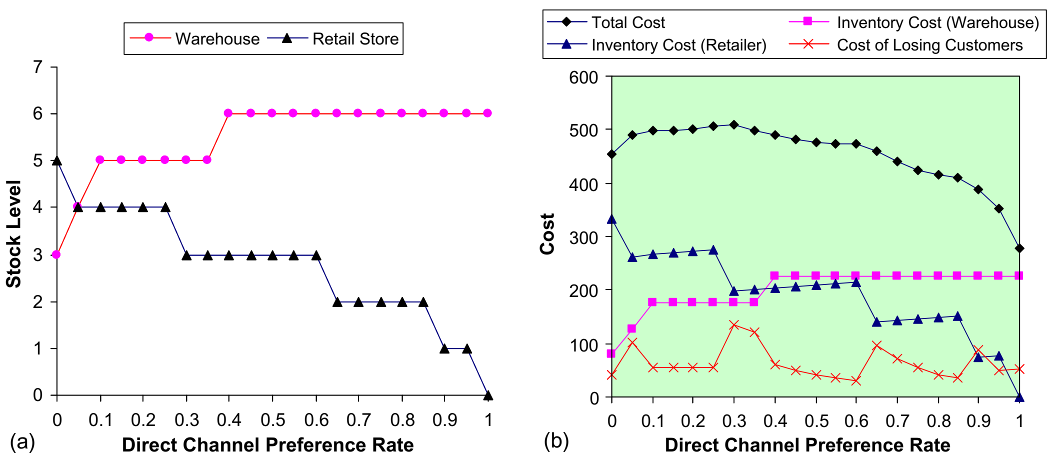


Fig. 4. Base case computational results: (a) optimal base-stock levels; (b) cost structure.

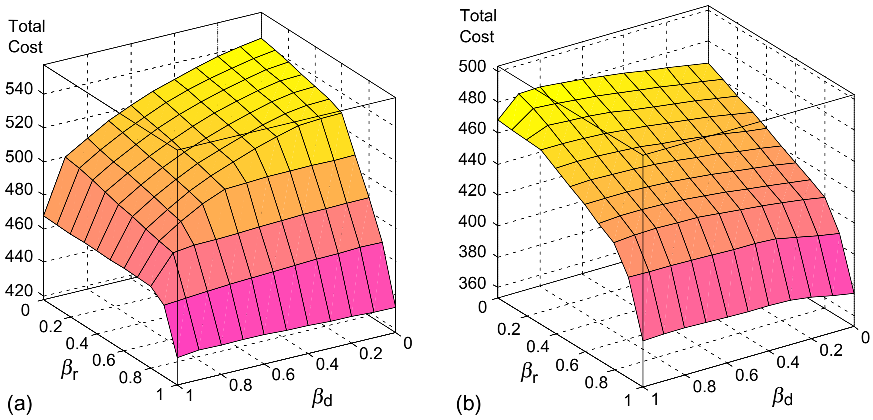


Fig. 5. Impact of search rates on total cost: (a) direct channel preference rate, $\alpha = 0.25$; (b) direct channel preference rate, $\alpha = 0.75$.

may increase the total lost sales cost. Since the benefit from the inventory holding cost reduction may not be significant enough to compensate for the detriment from the increase in the total lost sales cost, total cost may decrease in β_d.

The result of analysis can be applied to evaluate the benefit of adopting an information technology that is capable of providing up-to-date inventory information of each supply chain entity. With the information of current inventory status at each channel, the company can keep customers informed about the product availability at the other channel and guide them to locate the product in the event of a stockout. Clearly, the information technology adoption may help to increase β_r and/or β_d since it helps to reduce customers' search cost. According to the result of our analysis, it is interesting to note that increasing the customers' willingness to switch channels when a stockout occurs can possibly increase the total inventory related cost. As a result, companies need to be circumspect when adopting a new technology.

4.4. Scenario analysis

To understand more about the impact of each parameter on the optimal base-stock levels and the corresponding total cost, we now conduct more numerical analyses by changing the parametric values of holding cost, lost sales cost, demand rate, and replenishment rates with low and high variations. The outcomes from different scenarios are juxtaposed in Fig. 6 to demonstrate sensitivity implications. Note that unless otherwise noted, the same parametric values in the base scenario are used for the study.

(a) *Impact of holding cost*: Fig. 6(a) shows that the difference between the unit inventory holding costs at the warehouse and the retail store does not have a significant impact on the optimal base-stock levels. However, the impact on the optimal total cost is very significant when the direct channel preference rate α is low.

(b) *Impact of lost sales cost*: Fig. 6(b) provides evidence that a higher unit lost sales cost may result in higher optimal base-stock levels at both the warehouse and the retail store. Not surprisingly, the total cost is higher in the high lost sales cost scenario for all values of the direct channel preference rate.

(c) *Impact of demand rate*: Fig. 6(c) shows that while the system keeps higher base-stock levels at the warehouse and the retail store in the high demand rate scenario, the impact of the demand rate on the optimal base-stock level at the retail store appears to be relatively insignificant when the direct channel preference rate is high. As we anticipated, total costs in the high demand rate scenario are higher than those in the low demand rate scenario.

(d) *Impact of replenishment rates*: If it is possible to improve the replenishment rate, is it more

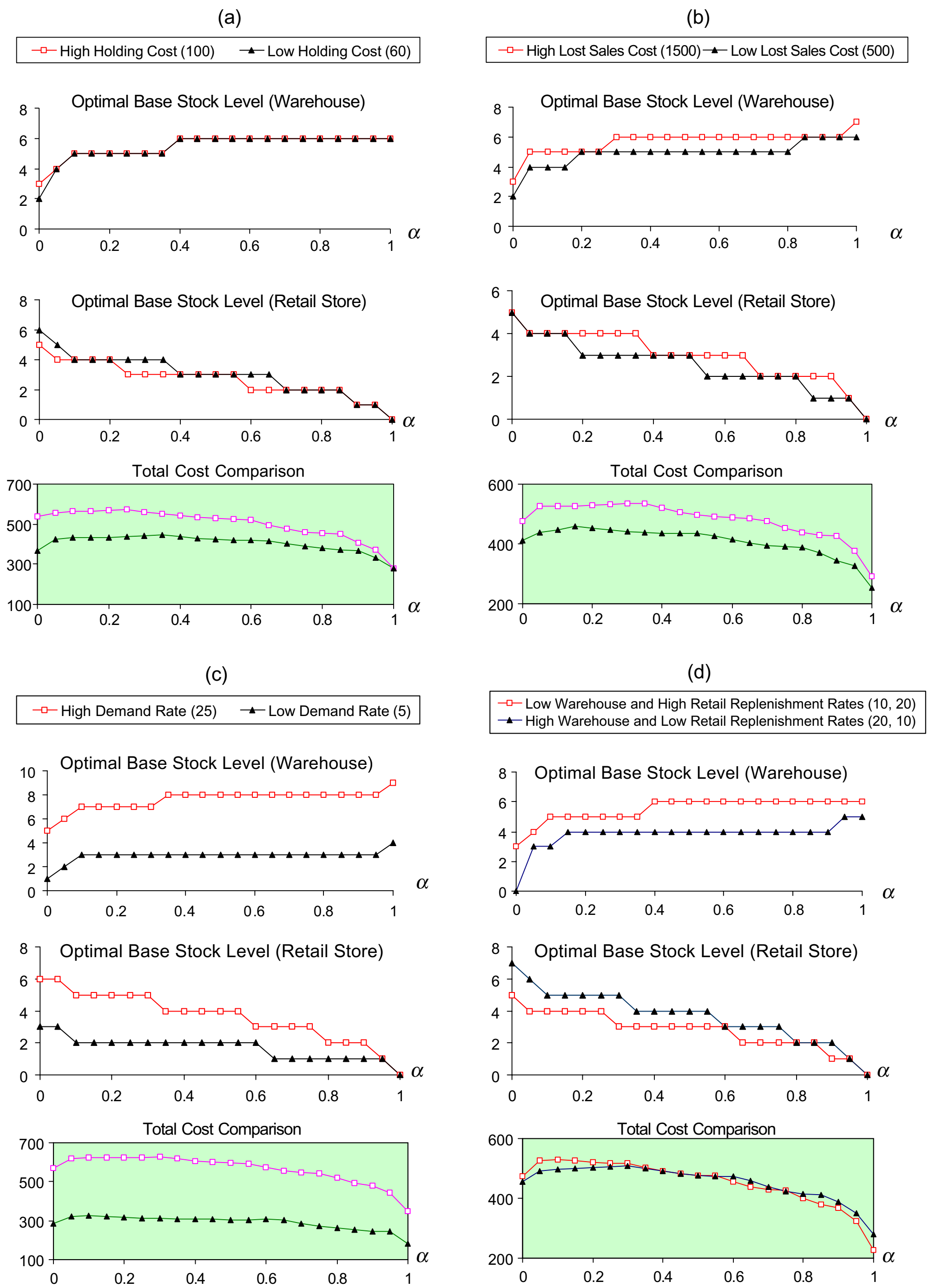


Fig. 6. Scenario analysis: (a) holding cost (h_r); (b) lost sales cost (l); (c) demand rate (λ); (d) replenishment rates (μ_w, μ_r).

favorable to have a higher warehouse replenishment rate or a higher retail replenishment rate? To answer this question, we compare the performance of two scenarios. In the first scenario, the warehouse replenishment rate is lower than the retail replenishment. Conversely, in the second scenario, the warehouse replenishment rate is higher than the retail replenishment. Fig. 6(d) shows that, in general, the base-stock level at the warehouse in the first scenario is higher than that in the second scenario, while on the contrary, the base-stock level at the retail store in the first scenario is lower than that in the second scenario. In terms of system performance, we find that a high retail replenishment rate is desirable when the customer arrival rate at the retail store is high, and a high warehouse replenishment rate is more beneficial when the customer arrival rate at the direct channel is high.

5. Evaluation of other channel strategies

Instead of using both the retail store and the direct channel, a firm can just use either one of the two channels to fulfill the demand. Now that we have evaluated the performance of the dual-channel strategy, we investigate the performance of the other two channel strategies, retail-only and direct-only channel strategies.

5.1. Retail-only strategy

By using the retail-only channel strategy, the function of the firm's website is to market and promote the product. Customers are not allowed to place orders online, and no demand is fulfilled directly from the manufacturer warehouse. For comparison, we use the same assumptions and notation of the dual-channel model. Thus, β_d, the direct-customer search rate, is interpreted as the proportion of the direct channel customers who will buy the product at the retail store due to the absence of the direct channel. Also, since there is no direct channel, all the retail store customers are lost when a stockout occurs at the retail store. In other words, the retail-customer search rate $\beta_r = 0$.

To evaluate the performance of the retail-only strategy, the balance equations of the Markov model in (3) are modified as follows:

$$\begin{aligned}
&[(S_w - x)\mu_w + (S_r - y + [x]^-)\mu_r + \delta(\lambda_r + \beta_d\lambda_d)]\pi_{xy} \\
&\quad = [S_r - (y-1) + [x]^-]^+ \mu_r \pi_{x(y-1)} \\
&\qquad + [S_w - (x-1)]\mu_w \pi_{(x-1)y} \\
&\qquad + (\lambda_r + \beta_d\lambda_d)\pi_{(x+1)(y+1)} \quad \text{for} \\
&\quad x = -S_r, -S_r + 1, \ldots, S_w \quad \text{and} \\
&\quad y = 0, \ldots, S_r,
\end{aligned} \tag{19}$$

where

$$\delta = \begin{cases} 0 & \text{if } y = 0, \\ 1 & \text{otherwise.} \end{cases} \tag{20}$$

Using the modified balance equations and the same cost structure as in the original model, the optimal base-stock levels and the corresponding total cost for the retail-only strategy can be obtained in an analogous fashion.

5.2. Direct-only strategy

In the direct-only channel strategy, the role of the retail store is to provide the showroom and to display the product. Customers can only place orders through the direct channel, and demand is fulfilled directly from the manufacturer warehouse. Following the same model assumptions, β_r, the retail-customer search rate, is interpreted as the proportion of the retail customers who will buy the product online when the retail store is not used to fulfill demand. Under the channel strategy, all direct customers are lost when stockout occurs at the warehouse since the product cannot be purchased from the retail store. Therefore, the direct-customer search rate is $\beta_d = 0$.

To evaluate the channel performance of the direct-only strategy, let π_x be the steady-state probability of x items on hand at the warehouse, $0 \leqslant x \leqslant S_w$. The balance equations for the system are

$$(S_w - x)\mu_w\pi_x = (\lambda_d + \beta_r\lambda_r)\pi_{x+1}, \quad x = 0, \tag{21}$$

$$\begin{aligned}
&[(\lambda_d + \beta_r\lambda_r) + (S_w - x)\mu_w]\pi_x \\
&\quad = (S_w - x + 1)\mu_w\pi_{x-1} + (\lambda_d + \beta_r\lambda_r)\pi_{x+1}, \\
&\quad x = 1, \ldots, S_w - 1,
\end{aligned} \tag{22}$$

$$(\lambda_d + \beta_r\lambda_r)\pi_x = \mu_w\pi_{x-1}, \quad x = S_w. \tag{23}$$

By solving this system of linear equations with the normalizing constraint, $\sum_{x=0}^{S_w} \pi_x = 1$, the steady-state probabilities are found to be

$$\pi_x = \frac{[(\lambda_d + \beta_r\lambda_r)/\mu_w]^{S_w - x}}{(S_w - x)! \times \sum_{i=0}^{S_w}[(\lambda_d + \beta_r\lambda_r)/\mu_w]^i / i!}, \quad x = 0, \ldots, S_w. \tag{24}$$

Given the closed form solution for the steady-state probabilities, we can easily apply the cost structure of the original model to find the optimal base-stock levels and the corresponding total cost.

5.3. Channel performance

In this section, we conduct the numerical experiments of the retail-only and the direct-only channel strategies. In order to compare the channel performance, the computational results from the two demand fulfillment strategies are juxtaposed with the results developed for the dual-channel strategy. Fig. 7 presents the computational outcomes with the base parametric values given in Table 2. Not surprisingly, the results show that the total cost of using the retail-only channel strategy increases in α, the direct channel preference rate, while on the other hand, the total cost of using the direct-only channel strategy decreases in α. As indicated in Fig. 7, in the base scenario, the dual-channel strategy outperforms the other two channel strategies for all values of α.

5.3.1. When are cost reductions realized by the dual-channel strategy significant?

To identify the potential benefits of using dual-channel distributions, we now compare the optimal total cost in the dual-channel system to the minimum total cost that can be achieved in a single-channel system. With the set of base parameter values as a foundation, we consider two scenarios: high search rates ($\beta_r = \beta_d = 0.75$) and low search rates ($\beta_r = \beta_d = 0.25$). Fig. 8 graphs the ratio of the optimal total cost from using dual channels to the optimal total cost from using either the retail store or the direct channel, depending on whichever results in a lower cost. We see that when the value of α is around 0.5, that is, when the number of direct customers is close to the number of retail customers, the dual-channel strategy could lead to an impressive cost reduction. We calculated the cost reductions that are obtained by using dual-channel strategy (compared to using one single channel): when $\beta_r = \beta_d = 0.75$, the average cost reduction for all values of α is 54%, and when $\beta_r = \beta_d = 0.25$, the average cost reduction for all

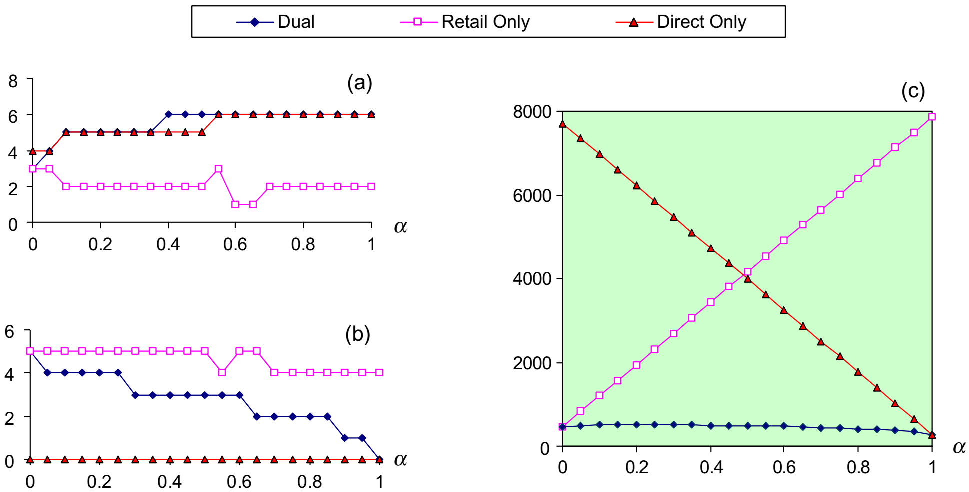


Fig. 7. Comparison of channel performance: (a) optimal base-stock level (warehouse); (b) optimal base-stock level (retail store); (c) total cost comparison.

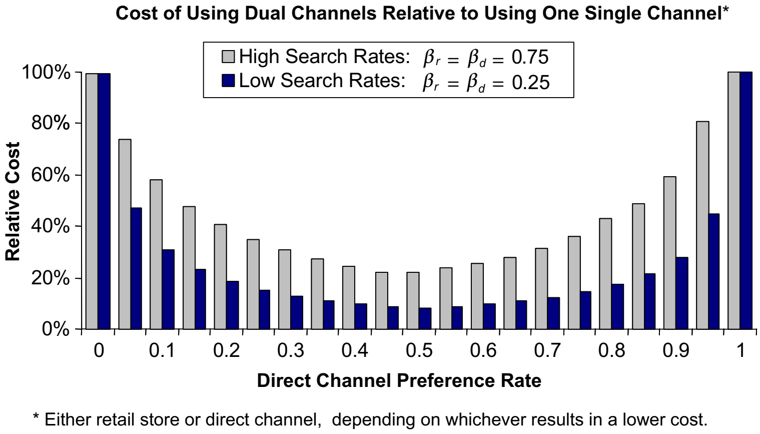


Fig. 8. Cost of using dual channels relative to using one single channel.

values of α is 73%. Clearly, when the search rates are low, cost reductions realized by the dual-channel strategy are more remarkable.

5.3.2. Does the dual-channel strategy always pay off?

The computational results presented above demonstrate that the dual-channel approach is a dominant strategy. Does it imply that the dual-channel strategy always pays off? Recall that the cost structure for the evaluation of channel performance consists of only two cost factors: inventory holding and lost sales costs. As one might anticipate with this simple cost structure, a single-channel system cannot compete with a dual-channel system. It is clear that the dual-channel system mitigates some of the risk of incurring stockouts that cannot be avoided in the single-channel system. Would the benefits of a dual-channel system continue to hold, however, if other costs are considered? For example, because we may have to hire more employees and/or acquire more facilities, maintaining an additional sales channel, no matter how crude, costs extra money. If we consider the cost incurred to operate a distribution channel as fixed cost, and take it into account when evaluating the performance of a channel strategy, then, as shown in Fig. 9, the dual -channel strategy may not always be dominant. Fig. 9 implies that with the fixed cost being considered, the retail-only channel strategy is the best distribution design when α is sufficiently low, while on the other hand, using the direct-only channel strategy is the best when α is sufficiently high. The dual-channel strategy pays off when α is moderate.

6. Model variations

Several variations of our performance evaluation procedure are possible. For example, customers who purchase online usually have to pay a shipping-and-handling (S&H) fee. Therefore, marginal costs incurred by the firm for the product sold through the retail store and the direct channel (denoted by c_r and c_d, respectively) may be different. In our model, we do not consider marginal costs because we implicitly assume $c_r = c_d$. [5] To relax this assumption, the total marginal costs can be incorporated into the total cost function given in (18) for the performance evaluation. Specifically, we can model the total marginal costs as: $c_rQ_r + c_dQ_d$, where Q_r and Q_d, respectively, are the steady-state expected direct and retail sales volumes, and

[5] We also implicitly assume that the unit sales prices in the two channels are identical. Therefore, when $c_r = c_d$, the profit margins in the two channels are the same, and we can normalize c_r and c_d to zero by decreasing the unit lost sales cost. As a result, it is trivial to consider the marginal costs when $c_r = c_d$.

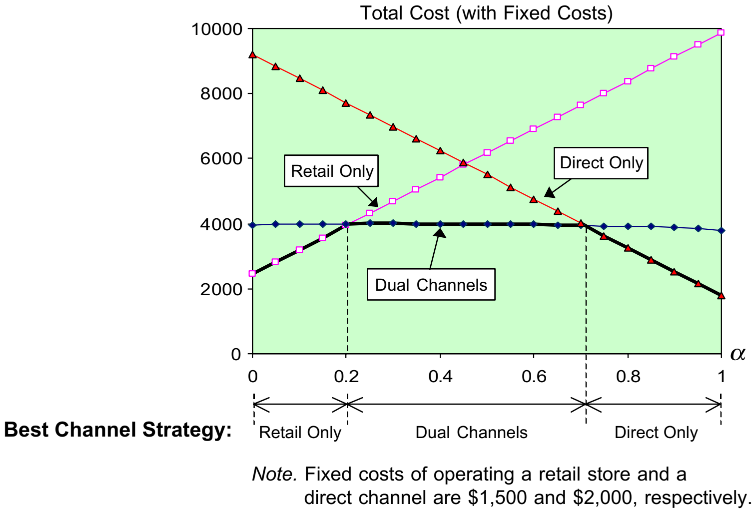


Fig. 9. Channel performance with fixed costs being considered.

$$Q_{\mathrm{d}} = \lambda_{\mathrm{d}} \sum_{x=1}^{S_{\mathrm{s}}} \sum_{y=0}^{S_{\mathrm{r}}} P_{xy} + \beta_{\mathrm{r}} \lambda_{\mathrm{r}} \sum_{x=1}^{S_{\mathrm{s}}} P_{x0}, \tag{25}$$

$$Q_{\mathrm{r}} = \lambda_{\mathrm{r}} \sum_{x=-S_{\mathrm{r}}}^{S_{\mathrm{s}}} \sum_{y=1}^{S_{\mathrm{r}}} P_{xy} + \beta_{\mathrm{d}} \lambda_{\mathrm{d}} \sum_{x=-S_{\mathrm{r}}}^{0} \sum_{y=1}^{S_{\mathrm{r}}} P_{xy}. \tag{26}$$

Note that charging a shipping-and-handling fee may affect the customers' willingness to switch channels. If this factor can be measured empirically, it will be interesting to compare the channel performance of the system with a S&H fee to that without a S&H fee. [6]

We have used inventory related costs as a criterion to evaluate channel performance. It may be, however, that achieving a high customer service level is an important objective for the system. Therefore, another possible variation of our model is to use the fill rate as the objective of the system optimization model for the evaluation of channel performance.

[6] Another offsetting factor is the avoidance of state taxes when purchasing online. In many instances the tax saving more than offsets the added S&H.

7. Concluding remarks

The two-echelon dual-channel inventory model presented in this paper is based on queuing models. Using analytical methods, we develop operational measures of supply chain flexibility by defining a cost structure which captures two different operational cost factors: inventory holding cost and lost sales cost. Our analysis leads to an exact evaluation of system performance.

To evaluate the possible benefits of using the dual-channel strategy, we also examine the performance of two other channel strategies: retail-only and direct-only strategies. Based on numerical examples, we show that the dual-channel strategy is dominant in most cases. The cost reductions that are obtained by using dual-channel strategy could be very significant, especially when the number of direct channel customers is close to the number of retail store customers, and/or when customers are less willing to deviate from their desired channel.

In this paper, we analyze the impact of customers' search rates (willingness to switch to the other channel when a stockout occurs) on the channel performance. The result of analysis offers immediate managerial implications since the search rates may be affected by several factors that are controllable by a company. For example, the company's adoption of an information technology that is capable of providing up-to-date inventory information of each supply chain entity may help to increase the search rates because it helps to reduce customers' search cost. The improvement on some channel characteristics, such as lead time for product delivery, may also increase the search rates. Our result indicates that, surprisingly, increasing the customers' search rates cannot always improve the channel performance. It can possibly increase the total inventory related cost. Therefore, companies need to be very cautious about their managerial actions.

We are not aware of any inventory model that handles the multi-echelon system with multiple channels receiving demand from different market segments. Our model is a contribution in this important line of inquiry. However, due to the complex nature of the problem, the model imposes potentially limiting assumptions. For example, the framework of analysis in this paper is the one-for-one inventory mode, where customer demands are modeled as a Poisson process. The results from our model may change if different inventory policies and different demand characteristics are applied. Therefore, a more extensive investigation may be warranted. Furthermore, albeit providing an appropriate starting point for exploring the multi-echelon inventory problem with multiple channels, our idealized supply chain, which consists of only one retail store at the bottom echelon, is not always realistic. While some theoretical justification and approximation regarding the pooling effect can be obtained by viewing the demand rate in the retail store as the aggregate demand of all retail stores, the model is not able to precisely determine the optimal base-stock level for each individual retail store. Clearly, studies seeking to tackle the problem in a multi-retailer setting would be valuable.

In our model, the manufacturer carries finished goods inventory to service demands from its retailer and direct customers. In other words, we assume a make-to-stock production system. In some practical cases, a make-to-order strategy or assemble-to-order production strategy may be implemented. The application of an expanded list of production strategies to the two-echelon dual-channel supply chain is another potential area to extend this research.

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Appendix A

Proof of Lemma 1

For some $\widetilde{S}_r > 0$, we have

$$\begin{aligned} C_H(S_w, \widetilde{S}_r) &= h_w \sum_{x=1}^{S_w} \sum_{y=0}^{\widetilde{S}_r} x\pi_{xy} + h_r \sum_{x=-S_w+1}^{S_w} \sum_{y=1}^{\widetilde{S}_r} y\pi_{xy} \\ &\geqslant h_w \sum_{x=1}^{S_w} \sum_{y=0}^{\widetilde{S}_r} x\pi_{xy} \\ &\geqslant h_w S_w^2 T_{S_w}, \ \forall S_w > 0, \end{aligned} \tag{A.1}$$

where $T_{S_w} = \sum_{y=0}^{\widetilde{S}_r} \pi_{S_w y} > 0, \quad \forall S_w > 0$. Since $\lim_{S_w \to \infty} \inf\{T_{S_w} : S_w > 0\} > 0$, there exists a non-negative integer N_1 such that $m = \inf\{T_{S_w} : S_w > N_1\} > 0$.

Let M be an arbitrary real number; $M > 0$. Since $\lim_{S_w \to \infty} h_w S_w^2 = \infty$, there exists a non-negative integer N_2 such that $\forall S_w > N_2$ implies $h_w S_w^2 > \frac{M}{m}$.

Now let $N = \max\{N_1, N_2\}$. We have $S_w > N$ implies $h_w S_w^2 T_{S_w} > m \frac{M}{m} = M$; i.e., $\lim_{S_w \to \infty} h_w S_w^2 T_{S_w} = \infty$. Therefore, from (A.1), we know $\lim_{S_w \to \infty} C_H(S_w, \widetilde{S}_r) = \infty$.

Since $\lim_{S_w \to \infty} C_H(S_w, \widetilde{S}_r) = \infty$ and $C_H(S_w, \widetilde{S}_r)$ is increasing in S_w, there exists a base-stock level $\widehat{S}_w$ such that $C_H(S_w, \widetilde{S}_r) > l\lambda$, $\forall S_w > \widehat{S}_w$. Hence,

$$\begin{aligned} \mathrm{TC}(S_w^*, S_r^*) &\leqslant \mathrm{TC}(0,0) \\ &= C_H(0,0) + C_L(0,0) = l\lambda < C_H(S_w, \widetilde{S}_r) \\ &\quad + C_L(S_w, \widetilde{S}_r) = \mathrm{TC}(\widetilde{S_w, S_r}), \ \forall S_w > \widehat{S}_w. \end{aligned}$$

Similarly, we can prove that for some $\widetilde{S_w} \geqslant 0$, there exists a base-stock level $\widehat{S}_r$ such that $\mathrm{TC}(S_w^*, S_r^*) \leqslant l\lambda < \mathrm{TC}\left(\widetilde{S_w}, S_r\right)$, $\forall S_r > \widehat{S}_r$. $\square$

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