The Value of Advance Supply Information in Retail Competition: A Simulation Study

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The application of Radio Frequency Identification (RFID) technology in supply chain management has been widely reported and extensively studied in last decade. RFID improves the visibility of inventory and lead time information among supply chain partners. Although various technical benefits due to this increased visibility have been broadly discussed by practitioners, how to integrate RFID information into business practice to obtain financial benefit has not been specifically addressed in extant literature. This study considers a supply chain in which retailers use upstream advance supply information (supplier's current availability and remaining lead-time of open orders) to make inventory replenishment decisions. This study focuses on the value of supply information instead of the demand information which has been extensively studied in previous researches. A simulation study was conducted under various scenarios.

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I. INTRODUCTION

Radio Frequency Identification (RFID) is one of Automatic Identification and Data Capture technologies. RFID technology was initially developed in the 1920s and the first implementation can be traced back to the 1940s during World War II by the British Air Force. Although RFID technology has been in existence for several decades, the application of RFID in business operations is still in its early stages and has more room to improve (Shutzbery, 2004).

The major motivation for retailers to adopt RFID is the immediate operational benefits that can be gained. For instance, RFID can help retailers reduce theft and loss, locate items more readily, provide suppliers with better information on real-time demand for products, and improve the speed of product distribution. Retailers can also benefit from reduced inventory because the improved supply chain visibility facilitates better demand forecasting, lower safety stocks, and lower order cycle times (Thillairajah, Gosain, and Clarke, 2005). AT Kearney Consulting (2003) estimates that retailers will benefit from the adoption of RFID with a 5 percent inventory reduction, 7.5 percent labor and cost reduction in stores and warehouses, and a reduced stock-out cost of as high as 7 percent of revenues. Consistent with this general assessment, the initial savings and benefits to Wal-Mart in the first few years of RFID implementation are estimated as: $6.7 billion in reduced labor cost, $600 million in out-of-stock supply chain cost reduction, $575 million in theft reduction, $300 million in distribution and warehouse tracking, and $180 million in reduced inventory costs (ROI-Watch, 2003; Asif and Mandviwalla, 2005). Procter & Gamble estimates that RFID implementation could reduce its inventory of $3.5 billion by half and save $400 million annually (Roberti, 2002 and 2003; Srivastava, 2004).

Most current applications of RFID are only within a single facility (e.g., a retail store, a warehouse) and/or only for a single process (shipping or receiving). These internal implementations will undoubtedly bring immediate benefits to the adopters. In addition, RFID can also provide benefits to other supply chain partners if the real-time RFID data, regarding inventory and delivery status, can be shared throughout the entire supply chain. Supply chain partners can expect benefit from the mitigation of the bullwhip effect which indicates the distortion of demand information along supply chain. Although RFID is not a panacea for creating a perfect supply chain, it can radically change the way companies produce and distribute their products. However, companies need to deploy RFID and identify where benefits may most likely occur (Hardgrave and Miller, 2006).

The visibility of inventory and material flow through the supply chain leads to a reduction in loss caused by information inefficiency. Deloitte Consulting reported a 3.5 percent loss of total sales each year in the U.S. grocery industry, an estimated $40 billion, because of the supply chain information inefficiency (Phaneuf, 2004). Once the application of RFID emerged in supply chain management, it attracted extensive attention from both academia and business practitioners (Prater, Frazier, and Reyes, 2005; Reyes and Jaska, 2006; Reyes and Frazier, 2007).

Although the various benefits due to the increased visibility provided by RFID have been broadly discussed by practitioners, how to integrate RFID information into business practice and how much benefit can be expected from this change have not been specifically addressed in extant literature. So far, most benefits recognized by retailers and manufacturers have come from improvements in internal operation efficiency. However, only when coupled with business applications can raw RFID data be converted into profitable information. In fact, any RFID capability is part of an application's infrastructure which utilizes RFID-enabled data. Dining and Schuster (2004) found that system integration is the biggest hurdle for adopting RFID at Dell rather than the tag costs usually considered by other practitioners. Accenture Report (2004) indicated that 68 percent of the manufacturers they surveyed thought that the greatest benefit came across multiple organizations and within retail store operations. In addition, RFID can provide competitive differentiation through supply chain collaboration. For example, International Paper, Procter & Gamble, and Wal-Mart conducted a smart shelf pilot project. Store clerks alerted the suppliers when items needed to be replenished. The speed at which items were selling was also tracked to calculate when and how much product needed to be ordered to prevent stock-out (Shutzberg, 2004).

Identifying the sources of benefits and achieving them by integrating RFID data into the existing supply chain practice remain unsolved. In this study, we consider a two-echelon supply chain and conduct a simulation study under different scenarios. This research bridges the gap between the expected benefits from RFID and the necessary changes in business process to integrate RFID-enabled data into routine decision-making processes. The research questions addressed are:

(a) How much financial benefits/risks can a retailer expect from RFID adoption/non-adoption?
(b) How to integrate the real-time RFID data into an existing business practice (e.g. inventory replenishment and production scheduling)?

In order to utilize the prominent technical features of RFID, the adopter needs to consider strategic changes in business processes as well as organizational changes

(Sullivan and Happek, 2005). RFID technology provides mass data and information, but how to mine this data for business value remains a challenge and an opportunity as well (Hardgrave and Miller, 2006). For example, RFID could provide retailers more accurate upstream supply availability and lead-time information to make better inventory replenishment decisions. Using the model proposed in this study, retailers can estimate the potential benefits from RFID adoption in advance. The risks of a wait-and-see approach are evaluated by comparing a RFID-enabled retailer and a non-RFID-enabled one.

II. LITERATURE REVIEW

In this section, we briefly review extant literature on demand and supply uncertainty, information sharing, and the application of RFID in supply chain management.

2.1. Demand and Supply Uncertainty

Combined with order batching and price variation, demand uncertainty is one of the major causes of the bullwhip effect which refers to the amplification of variability in order quantity as one moves upstream in a supply chain (Forrest, 1958; Lee, Padmanabhan, and Whang, 1997). Demand information has been used in supply chain coordination to dampen upstream variability propagation, especially under a capacitated and stochastic situation (e.g., Balakrishnan, Geunes, and Pangburn, 2004; Wijngaard, 2004; Bollapragada and Rao, 2006; and Boute, Disney, Lambrecht, and Houdt, 2007). In addition to sharing current demand information (orders received from end users), retailers can also share their forecasts on future demand, which is defined as advanced demand information (ADI), with their suppliers. ADI offers suppliers additional information and opportunities for better production planning and inventory replenishment decision making. There is a line of research focused on sharing ADI with the distributors or the manufacturers in supplier chains (Thonemann, 2002; Moinzadeh, 2002; Ozer, 2003; Ozer and Wei, 2004). However, note that ADI contains a high degree of uncertainty since it depends on historical data based forecasts.

Similar to the effect of downstream demand information shared upstream, the supply uncertainty that originated from the upstream supply chain also has an impact on downstream retailers' performance. Supply uncertainty includes supply capacity uncertainty and lead time uncertainty. For instance, production (supply) capacity is one of the most broadly shared types of information in the PC supply chain according to a survey conducted by Anderson Consulting (Lee and Whang, 2000). In turn, insufficient supply capacity results in lead time uncertainty. While stochastic lead time may be caused by delivery delay, the major source of lead time uncertainty comes from production delays in the manufacturing plant, such as machine breakdowns, raw materials shortages, or insufficient labors. The lead time uncertainty also has an impact on safety stock in inventory control (Chopra, Reinhardt, and Dada, 2004; Simchi-Levi and Zhao, 2005). The value of sharing lead time information among supply chain partners is investigated in Dobson and Pinker (2006).

The study on stochastic lead time in the supply chain can be traced back to Kaplan (1970) who considered stochastic lead time with a known distribution in his dynamic inventory model. Later on, Ehrhardt (1984) proposed (s, S) policies for a dynamic inventory model with stochastic lead time in a period review and single item inventory system. Eppen and Martin (1988) presented a model for determining the safety stock under stochastic lead time and demand. Song and

Zipkin (1996) developed an inventory model that included a Markovian replenishment lead time and derived an optimal state-dependent base-stock policy for a periodic review system. Later, Chen and Yu (2005) extended Song and Zipkin's work to investigate the value of the replenishment order lead time information in a single-location inventory model. They assume that the supplier knows the exact lead time for a retailer's incoming order and is willing to share it with the retailer. Their numerical examples demonstrate a significant value by sharing upstream supply (lead time) information with the downstream retailer.

More specifically, Simchi-levi and Zhao (2005) studied the impact of stochastic lead times on safety stock positioning. They derived recursive equations for the backorder delays in a single-product multistage supply chain. Jain and Mionzadeh (2005) study a supply chain model in which there is a two-way information sharing mechanism where the manufacturer shares inventory availability and production capacity information with the retailer. A two-level state-dependent base-stock policy is proposed by Jain and Mionzadeh (2005) in a continuous-time Markov decision process. In their model, the lead time is a function of the retailer's order size. This is the first work that considers the joint effect of order size and lead time. For an extensive review of the information sharing literature including demand and supply information, see Hung, Jason, and Mak (2003).

In this study, we explore how retailers can utilize advance supply information (ASI) which includes order size and the remaining lead time regarding the supplier's open orders. In a traditional inventory replenishment decision-making process, retailers need to determine when and how much to order based on their own inventory position and the forecasted demand. With RFID, retailers can access the distributor's on-hand inventory information and ASI for making better inventory replenishment decisions. The implementation of RFID in the supply chain makes this practice possible.

2.2. Information Sharing

Information sharing has been proposed as a strategic methodology to integrate the supply chain to mitigate the bullwhip effect (Lee and Whang, 2000). The value of information sharing has also been investigated from different perspectives, (e.g., inventory management, lead time reduction, and supply chain coordination) and under different scenarios, (e.g., stochastic demand and capacitated supply) (Bourland, Powell, and Pyke, 1996; Chen, 1998; Aviv and Federgruen, 1998; Gavirneni, Kapuscinski, and Tayur, 1999; Lee, So, and Tang, 2000; Cachon and Fisher, 2000; Yu, Yan, and Cheng (2001); Simchi-Levi and Zhao, 2005; Croson and Donohue, 2005).

Yu, Yan, and Cheng (2001) investigates the benefits of information sharing based on a case study of an electronic components manufacturer and distributor in Hong Kong. They defined the value of information sharing at different integration levels. The top line (level 1) is referred to as a decentralized system in which the inventories at different sites of the supply chain are managed separately. Level 2 indicates a coordinated case in which the demand information sharing is realized between retailers and manufacturers but the inventory decisions are still made individually. Level 3 is referred to as a centralized situation under which the inventory decisions are based on supply chain optimization. New technologies such as electronic data interchange and RFID provide technical assurance for synchronized information sharing.

2.3. RFID in Supply Chain Management

RFID, as a technology, enables real time information sharing among supply chain partners, which can mitigate both demand and supply uncertainty if it can be adopted throughout the supply chain. Lapide (2004) studied how upstream partners in a supply chain can improve their forecast on demand to reduce bullwhip effects by sharing RFID-enabled demand information.

Most current applications of RFID focus on how to improve internal efficiency (e.g. lower labor requirements, more accurate inventory information) for a single business process (e.g. shipping and receiving in warehouses, shrinkage control at stores) within a company. The corresponding benefits are evaluated accordingly (Intermec Report, 2004; Asif and Mandviwalla, 2005). However, the application of RFID at the supply chain level is expected to derive larger benefits for each supply chain partner (Accenture Report, 2004; Dining and Schuster, 2004).

Li and Visich (2006) conducted a comprehensive literature review to demonstrate the challenges and opportunities of RFID implementation in supply chain management. They first summarized the impacts of RFID on each supply chain partner, (i.e., retailers, distributors, and manufacturers). Second, they discussed the impact of RFID on the supply chain as a whole. Different from its application within one company, RFID provides continuous information throughout the entire supply chain, (e.g., tracking the movement of products from manufacturer plants to retailers). This increased synchronization enables supply chain coordination such as collaborative planning, forecasting, and replenishment decisions.

Hardgrave and Miller (2006) made an effort to clarify some ambiguities (10 myths) of RFID regarding sensitive personal information security, data collection and storage, technology reliability, among other concerns. The facts disclosed by the authors in current RFID implementation projects have twofold impacts: first, do not set an unreasonable expectation on a new technology, (e.g., RFID cannot be read 100 percent); second, the clarification of some hypes eliminates the fear of RFID and facilitates its adoption. For example, personal information security is one obstacle to adopt RFID. However, RFID tag only stores limited information for a certain application and in order to interpret the meaning of the data other supportive databases are needed.

Among the few pioneering rigorous quantitative research on the implementation of RFID in supply chain, Lee, Cheng, and Leung (2004) developed a simulation model of continuous inventory replenishment for a three-echelon supply chain to analyze the effect of RFID application on inventory reduction and service level improvement. Their results demonstrate that RFID-enabled retailer can reduce back order quantity by 22 to 99 percent (under different scenarios) and cut down the retailer's average inventory by 16 percent with the improvement in inventory accuracy. In addition, the application of RFID in shelf inventory replenishment reduces the retailer's shelf lost sales from 84 to 99 percent and cuts down its shelf average inventory by 11 to 16 percent and reduces its back room inventory by 30 percent, and finally reduces the retailer's overall inventory by 23 percent. They also examined the impact of the application of RFID in supply chain on each partner's performance. For example, they detected that the distributor reduced back orders completely and cut down average inventory by 23 to 47 percent. Although the above results heavily depend on the setting of the system parameters (e.g., reorder point, demand distribution pattern), this work provides an explicit interpretation where and how the adoption of RFID can produce benefits in a supply chain. Heese (2007) studied the impact of inventory record inaccuracy on stocking decisions and profits in a decentralized supply chain. He derived the RFID cost thresholds for the retailer and the manufacturer making RFID adoption decisions in an integrated and decentralized supply chain respectively.

Lee and Ozer (2007) reviewed some ongoing quantitative research on the application of RFID. The authors deem that solid model-based analyses are needed to fill up the credibility gap of the value of RFID and how this value can be realized. More specifically, Gaukler (2005) developed a (*Q, R*) inventory replenishment model for the retailer to place an emergency order strategically by integrating RFID order progress information into the decision-making process with uncertain demand and uncertain supply lead-time. The numerical example demonstrated a 2.8 to 4.5 percent overall costs saving resulting from the complete visibility obtained by RFID for the retailer. Out of the total saving, 47 to 65 percent can be attributed to the availability of product progress information (supply information) alone. Later, Gaukler, Seifert, and Hausman (2007) developed an analytical model to explore the benefits of item-level RFID to manufacturers and retailers. They also studied how to allocate the cost of item-level RFID tags between manufacturers and retailers in order to maximize supply chain profit under different market power settings.

III. THE MODEL

Two simulation models are developed to identify the value of advance supply information (ASI). The base model is used to examine the situation without RFID as a baseline. In the RFID-enhanced model, we assume the distributor and one out of two retailers are RFID-enabled and the ASI is shared between them. The existence of another retailer without RFID furnishes us an opportunity to investigate the risk for a non-RFID retailer competing with a retailer with RFID. The rectangular box in Fig. 1 defines our study scope in the supply chain.

We assume the retailers use on-hand inventory to satisfy customers' demand and excess demand is backordered at a penalty cost. The distributor holds its own inventory to serve two retailers in a first-come-first-serve manner. In the base model, there is no RFID. The distributor and retailers use a periodic review base-stock policy to manage their inventory. In the RFID model, we name the retailer without RFID as control retailer, while the retailer with RFID as focus retailer. The focus retailer will use ASI to make inventory decisions while the control retailer will follow the same base-stock policy in the base model. The ASI sharing enables the focus retailer to predict the occurrence of a disturbance (e.g., a possible stock out at the distributor's site at a future time) and adjust the inventory replenishment policy timely. With this setting, the results (total costs for each retailer) show not only the benefits for the focus retailer but also the loss for the control retailer since two retailers compete on the supply of the distributor. For a better understanding of the benefit of utilizing RFID data, we assume two retailers facing the same demand pattern.

The total cost, including holding costs, shortage costs, and ordering costs during a rolling horizon, is used as the objective function in both the base and RFID models. Apparently, the total costs for two retailers will be the same in the base model because we assume both retailers face the same demand distribution and adopt the same inventory replenishment policy. In the RFID model, the difference of total costs between two retailers presents the benefits of the adoption of RFID. In the RFID model, the distributor shares his inventory availability information and the lead-time status of open orders with the focus retailer in a timely manner (see Fig. 2).

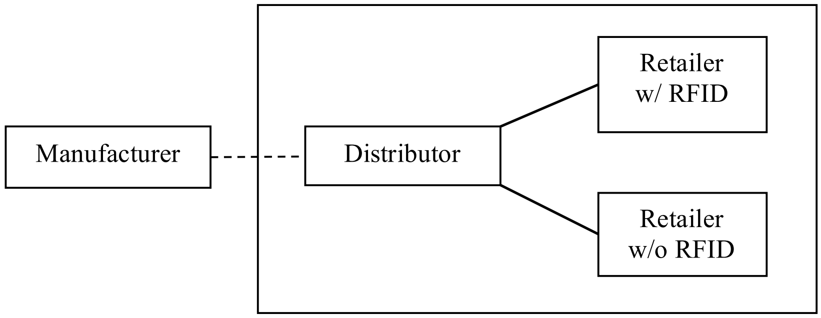


FIGURE 1. SCOPE OF THE STUDY.

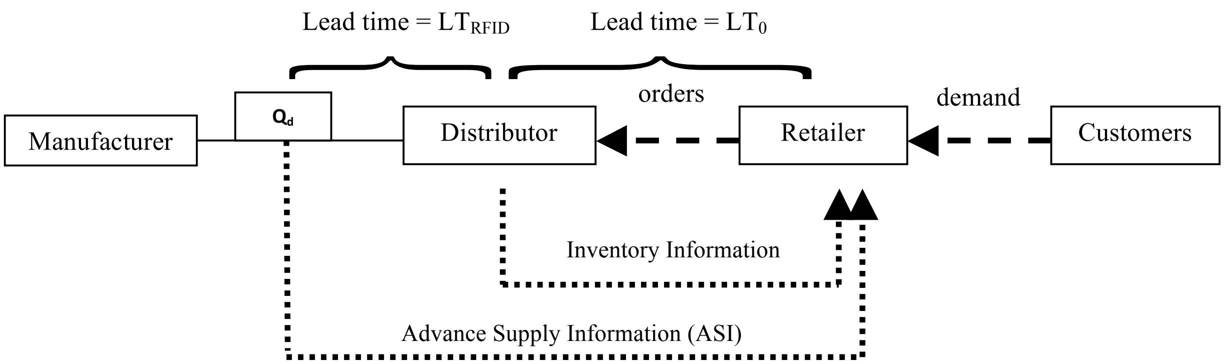


FIGURE 2. RFID-ENABLED MODEL.

LT_0 is the delivery time between the distributor and the retailer. LT_{RFID} indicates the remaining lead-time of a distributor's open order, Q_d. We consider a multi-period single-product inventory planning problem. During each period, the sequence of actions is taken as follows:

Step 1. At the beginning of each period, the distributor and the two retailers update their on-hand inventory information. All scheduled orders arrive at the beginning of each period.

Step 2. At the end of each period, after realizing the customer demand, the retailers update their on-hand inventory (or backorder) information and inventory position including all open orders.

Step 3. The control retailer determines whether or not a purchase order needs to be placed with the distributor. The distributor can deliver the order to the retailer immediately if s/he holds sufficient inventory. Otherwise, the distributor will cumulate the oncoming orders until enough products are available, and then deliver them to the control retailer. No partial shipment is allowed because we assume that the ordering cost is fixed. Finally, the distributor's on-hand inventory and inventory position records are updated accordingly.

Step 4. The focus retailer obtains the distributor's supply information (e.g., available on-hand inventory) and ASI (e.g., the quantity and the remaining lead-time of all open orders) through the RFID system.

Step 5. The focus retailer decides whether or not an order needs to be placed with the distributor and how much to order by solving a rolling horizon problem considering ASI. The distributor will deliver the focus retailer's order immediately if s/he has sufficient inventory. Otherwise, the distributor will cumulate oncoming orders until enough stock is available. No partial shipment is allowed. The distributor's on-hand inventory and inventory position information are updated accordingly.

Step 6. The distributor determines if an order should be placed to the manufacturer. If the distributor places an order, a random lead-time following a known distribution will be acknowledged by the manufacturer and will be available to the distributor and the focus retailer immediately. The information of open orders and inventory position at the distributor's site is updated accordingly.

Step 7. Repeat the above process through Steps 1 to 6 for the entire rolling horizon.

Lee and Whang (2000) stated that capacitated supply is one of the major reasons for lead-time uncertainty. We assume that after the distributor places an order, the corresponding lead-time will be acknowledged by the manufacturer immediately. There are several factors influencing the manufacturer's response to the distributor's order (e.g., production rate, inventory of raw materials, the probability of machine breakdown etc.). In this study, we attribute all these factors into the uncertainty of lead-time without individual identification. The application of RFID enables the retailer to better estimate the expected arrival time and the quantity of a coming order at the distributor's site. Therefore, when the focus retailer makes a replenishment decision, he can predict the lead time based on ASI by adjusting the order quantity. The lead time of a focus retailer's order is quantity-sensitive and can be predicted following a piecewise structure:

$$LT_t = \begin{cases} LT_0 & \text{if } Q_{FR} \le I_d^t \\ LT_0 + LT_{RFID}^1(t) & \text{if } I_d^t < Q_{FR} \le I_d^t + Q_d^1 \\ LT_0 + LT_{RFID}^2(t) & \text{if } I_d^t + Q_d^1 < Q_{FR} \le I_d^t + Q_d^1 + Q_d^2 \\ \vdots & \vdots \\ LT_0 + LT_{RFID}^N(t) & \text{if } I_d^t + \sum_{i=1}^{N-1} Q_d^i < Q_{FR} \le I_d^t + \sum_{i=1}^{N} Q_d^i \\ LT_0 + E(LT_M) & \text{if } Q_{FR} > I_d^t + \sum_{i=1}^{N} Q_d^i \end{cases} \quad (1)$$

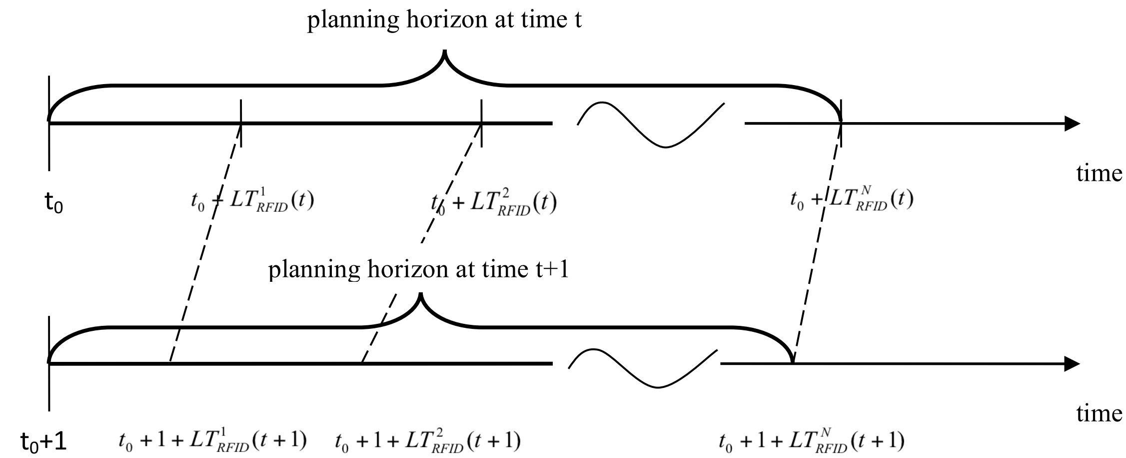
Where, $LT_{RFID}^1(t)$ is the remaining lead-time of the distributor's first oncoming order at time *t*. If $Q_{FR} > I_d^t + \sum_{i=1}^{N} Q_d^i$, the lead-time also depends on the expected manufacturer's production time, LT_M. But it is beyond the scope of this study. Table 1 summarizes the notations used in this study.

Consider a rolling horizon starting from period t_0 to $t_0 + LT_{RFID}^N(t_0)$ in which the latest distributor's open order will arrive. Where, $LT_{RFID}^N(t_0)$ is the remaining lead-time of the N^{th} distributor's open order at the end of period t_0. Therefore, we have ASI up to the period $t_0 + LT_{RFID}^N(t_0)$. Once time moves on one period, the rolling horizon is moved between $t_0 + 1$ and $t_0 + 1 + LT_{RFID}^N(t_0 + 1)$ if there is no additional ASI available (see Fig. 3a).

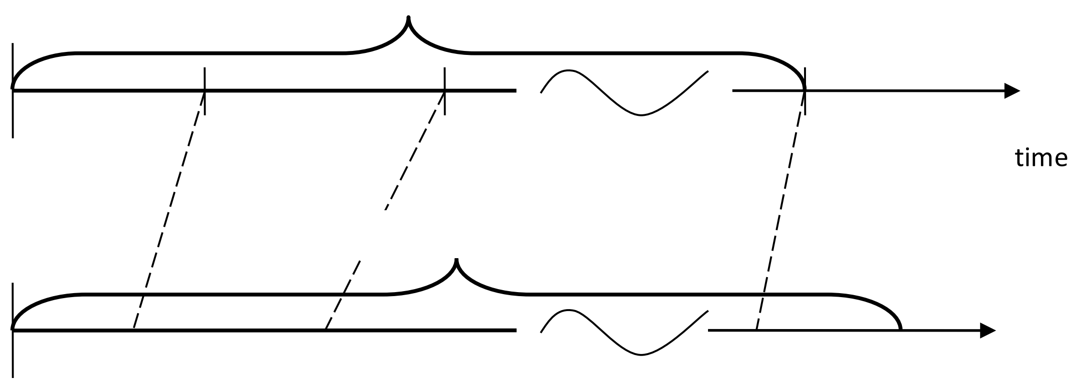
$LT_{RFID}^{N}(t_0+1)$ is the remaining lead-time of the N^{th} distributor's open order at the end of the period t_0 +1. If the focus retailer receives additional ASI (e.g., the distributor places a new order), the rolled-over time horizon will cover periods from t_0 +1 to $t_0+1+LT_{RFID}^{M}(t_0+1)$. The coverage of ASI extends to the period $(t_0+1)+LT_{RFID}^{M}(t_0+1)$ (see Fig. 3b). M is greater than N.

TABLE 1. NOTATIONS.

$FR=$	index of the focus retailer
$CR=$	index of the control retailer
$d=$	index of the distribution center
$I^t=$	inventory at the end of period *t*
$p_r^t=$	$\begin{cases} 1, \text{the retailer places an order during period t} \\ 0, \text{otherwise} \end{cases}$
$IP^t=$	inventory position at the end of period *t*
$D_t=$	Customer demand during period *t*
$f(D)=$	Probability density of customer demand *D*
$F(D)=$	Cumulative distribution function of customer demand *D*
$h=$	inventory holding cost rate ($/unit/period)
$\pi=$	backordering cost rate ($/unit/period);
$O=$	ordering cost ($/order)
$B^t=$	total back orders at the end of period *t* (units)
$Q_{ij}=$	The quantity of a retailer's order released in period *i* and scheduled receipt in period *j* (*i*<*j*)
$LT_{RFID}^{n}(t)=$	The remaining lead time of the distributor's n^{th} open order at time *t*



a) Rolling horizon without new information



b) Rolling horizon with additional information

FIGURE 3. ROLLING HORIZON DEMONSTRATION.

At the end of period t, the retailer's ending inventory and back orders are,

$$I_r^t = \left[I_t^{t_0} + \sum_{j=t_0+1, i<j}^{t} Q_{ij} - \int_{t_0+1}^{t} f(D)dD \right]^+ ,$$

$$B_r^t = -\left[I_t^{t_0} + \sum_{j=t_0+1, i<j}^{t} Q_{ij} - \int_{t_0+1}^{t} f(D)dD \right]^- \qquad (2)$$

Where, $\int_{t_0+1}^{t} f(D)dD$ is the total demand from period $t_0 + 1$ to t.

There is a holding cost associated with the retailer's ending inventory. Similarly, a shortage cost occurs with any back orders. If the retailer places an order in period t, the ordering cost is O_r regardless of the order size.

p_r^t is a binary variable to indicate whether or not the retailer places an order in period *t*. The retailer can predict the lead-time from *Eq.* (1) based on the order quantity. Therefore, the total cost incurred in period *t* for the retailer is,

$$K_t = h_r I_r^t + \pi_r B_r^t + O_r p_r^t \tag{3}$$

How to tackle the value of the inventory in the last period of a rolling horizon will impact the final results for the whole rolling horizon problem. This issue has been studied by Fisher et al. (2001). We adopted their results as follows. $V(I_r^T)$ is the salvage value of the ending inventory of I_r^T,

$$V(I_r^T) = O_r - \frac{h_r}{D_T}(Q^* - I_r^T)^2 \tag{4}$$

where, Q^* is the retailer's optimal order quantity. Given a rolling horizon from period T_0 to T_0+L, the total costs in the last period of T_0+L is,

$$K_{t_0+L} = h_r I_r^{t_0+L} + \pi_r B_r^{t_0+L} + O_r p_r^{t_0+L} - V(I_r^{t_0+L}) \tag{5}$$

The optimal rolling horizon problem for the focus customer is,

$$Minimize\ TC(t_0) = \sum_{i=t_0}^{t_0+L} K_i \tag{6}$$

Subject to:
Capacity constraints:

$$\sum_{k=t_0}^{t} Q_r^{kl} \le I_d^0 - B_d^0 + \sum_{j=t_0}^{t}\sum_{i=0}^{j} Q_d^{ij}$$

$\forall\, t \in (t_0, t_0 + L)$.
All variables are positive.

The solutions to the above problem depend on the distribution of the customer demand and the supply lead-time. A closed-form solution is not guaranteed due to the complexity of the problem. We conducted a simulation in the next section to numerically demonstrate the effects of integrating RFID-enabled ASI into the retailer's inventory replenishment policy.

IV. NUMERICAL ILLUSTRATIONS

We conduct a simulation study to demonstrate the value of real-time ASI to the focus retailer in a single-product supply chain with supply uncertainty. Three lead-time distribution patterns and three distributor's expected service levels (DESLs) are considered to explore how and how much ASI sharing can bring the benefits to a retailer. Furthermore, the impacts of ASI sharing on the distributor, the control retailer, and the entire supply chain performance are also examined respectively.

We develop a simulation model in MatLab and an optimization model in GAMS for solving the rolling-horizon problem that the focus retailer is facing. The length of rolling horizon depends on the number of periods in which the ASI is available.

4.1. Simulation Settings

For the purpose of simplicity and focusing on the effect of ASI, we assume that each retailer is facing a constant demand (300 units/period) in order to rule out the effect of demand uncertainty. For the same purpose, the lead time from the distributor to the retailer is set to 0. Table 2 lists all parameters for the retailer.

Hence, the distributor serving two retailers faces a constant demand of 600 units per period and adopts a periodic review base stock inventory replenishment policy (R_d, S_d).

The reorder point (R_d) and the order-up-to level (S_d) are based on the distributor's expected service level (DESL) listed in Table 3 in which the discrete distribution parameters for the lead-time between the manufacturer and the distributor are given. Consider the ASI sharing between the distributor and the focus retailer in the RFID model. We focus on the effect of ASI sharing obtained by RFID on mitigating supply lead-time uncertainty.

TABLE 2. THE RETAILER'S DATA.

Demand for each retailer (unit/period)	Holding cost ($/period/unit)	Shortage cost ($/period/unit)	Ordering cost ($/order)	Lead time from the distributor to the retailer (period)
D	h_r	π_r	O_r	LT
300	1	5	150	0

Note: The optimal order size (EOQ) for the retailer is $\sqrt{2O_r D/h_r} = \sqrt{2*300*150/1}$ =300 units.

TABLE 3. THE DISTRIBUTOR'S DATA.

		Discrete lead-time of distributor's order								
		Case I			Case II			Case III		
		Base model	RFID model	*t* value	Base model	RFID model	*t* value	Base model	RFID model	*t* value
Distributor's expected service level 50%	Inventory (units)	0	266.417	23.655**	0	327.750	32.372**	0	396.583	24.279**
	Back orders (units)	316.988	84.750	-28.602**	319.706	101.167	-24.340**	386.513	81.917	-9.2139**
	Inventory cost ($)	1584.94	690.17		1598.53	833.58		1932.56	806.17	
80%	Inventory (units)	0	224.583	37.306**	0	217.750	26.273**	0	316.167	20.954**
	Back orders (units)	89.981	25.833	-25.880**	95.888	18.833	-34.475**	147.675	24.417	-26.588**
	Inventory cost ($)	449.91	353.75		479.44	311.92		738.38	438.25	
100%	Inventory (units)	0	147.167	691.303**	0	146.500	613.530**	0	149.167	483.885**
	Back orders (units)	12.375	5.250	-12.547**	11.981	6.083	-10.446**	0	0.750	2.015*
	Inventory cost ($)	61.88	173.42		59.91	176.92		0	152.92	

TABLE 4. SIMULATION RESULTS OF THE FOCUS RETAILER.

Discrete lead time distribution (probability)		Distributor's expected service level		
		50%	80%	100%
		Distributor's (R_d , S_d) ordering policy parameters		
Case I	LT=6 (50%), LT=8 (30%), LT=10 (20%)	R_d = 3600 S_d = 6600	R_d = 4800 S_d = 7800	R_d = 6000 S_d = 9000
Case II	LT=8 (50%), LT=10 (30%), LT=12 (20%)	R_d = 4800 S_d = 7800	R_d = 6000 S_d = 9000	R_d = 7200 S_d = 10200
Case III	LT=10 (50%), LT=12 (30%), LT=15 (20%)	R_d = 6000 S_d = 9000	R_d = 7200 S_d=10200	R_d = 9000 S_d = 12000
Distributor's inventory holding cost rate = $1 /unit/period; Distributor's inventory shortage cost rate = $5/unit/period.				

*p < 0.025, **p < 0.005

4.2. Simulation Results and Discussion

We first tested the base model without RFID. The simulation results from the base model are used as the baseline for comparison with the parallel results from the RFID model. We assume that the lead-time associated with each distributor's purchasing order follows a known discrete distribution. The distributor's reorder points (R_d) are based on the DESL and the lead-time distribution. For example, 50 percent of the distributor's orders will arrive within 10 periods, 30 percent within 12 periods, and 20 percent within 15 periods. If the distributor expects an 80 percent service level, he needs to set a reorder point of 7,200 (=600x12) to ensure 80 percent purchase orders will arrive within 12 periods. In both base and RFID models, back orders are allowed. In the RFID model, only the focus retailer adopts RFID. The distributor can only share ASI with the focus retailer. Table 4 compares the results for all parties in the base model and the RFID model.

4.2.1. The Benefits of ASI Sharing

Table 4 shows that the inventory increases in the RFID model when the focus retailer integrates ASI into his/her replenishment decision-making process. We detect that higher increases occur with lower settings of DESL. The lower distributor's safety stock due to lower DESL increases the possibility of the retailer's stock outs. The distributor's stock outs, which are more predictable with ASI sharing lead to a higher inventory at the retailer's site. It's worth mentioning that even when the DESL is set to 100 percent, the focus retailer still holds some inventories. That is because, first, the setting of 100 percent expected service level is based on an ideal situation in which both retailers and the distributor follow EOQ-based replenishment policies. However, in the RFID model, the focus retailer's order sizes varied over time. Second, the sequence of the operations impact the retailer's inventory as well.

Table 4 also shows that the increased inventory in the RFID model is higher with lower DESL. The longer lead-time (case III) causes even more inventory increase. Obviously, the focus retailer needs to hold more inventories against the uncertainty caused by the combination of low DESL and long lead-time. With 100 percent DESL, the increased inventory of the focus retailer is mainly caused by the order sizing issues instead of the supply uncertainty. Therefore, the focus retailer's inventory levels are close under different lead-time distributions.

In the RFID model, the compensations for the higher inventories of the focus retailer are the lower back orders and higher customer service levels. Table 5 compares the simulation results in the base model and the RFID model and presents the decreases in back orders except for one. Under the setting of 50 percent DESL, the reductions of back orders (232~305 units/period) are much higher than those under 80 percent DESL setting (64~123 units/period) and those under 100 percent DESL setting (-0.75~7 units/period). Note that the reduction of back orders under 100 percent DESL is trivial and even slightly increased because high safety stock level eliminates most backorders. Overall, the retailer can reduce 49 to 83.5 percent back orders through ASI sharing. Obviously, holding more inventories will reduce the amount of stock outs. In order to determine whether or not it is financially appropriate for the focus retailer to invest on RFID system, Table 6 shows the focus retailer's total costs.

TABLE 5. THE FOCUS RETAILER'S BACKORDER REDUCTION.

Distributor's expected service level	Discrete distribution of distributor's order lead time		
	Case I	Case II	Case III
	The focus retailer's reduction on back orders		
	Units (%)	Units (%)	Units (%)
50%	232.238 (73.3)	218.539 (68.4)	304.596 (78.8)
80%	64.148 (71.3)	77.055 (80.4)	123.258 (83.5)
100%	7.125 (57.6)	5.898 (49.0)	-0.75 (-----)

TABLE 6. THE FOCUS RETAILER'S INVENTORY COST SAVING.

Distributor's expected service level	Discrete distribution of distributor's order lead time		
	Case I	Case II	Case III
	The focus retailer's inventory cost saving		
	$ (%)	$ (%)	$ (%)
50%	894.77 (56.45)	764.95 (47.85)	1126.39 (58.28)
80%	96.16 (21.37)	167.52 (34.94)	300.13 (40.65)
100%	-111.54 (------)	-117.01 (------)	-152.92 (------)

TABLE 7. SIMULATION RESULTS OF THE CONTROL RETAILER.

			Discrete distribution of distributor's order lead time								
			Case I			Case II			Case III		
			Base model	RFID model	*t* value	Base model	RFID model	*t* value	Base model	RFID model	*t* value
Distributors expected service level	50%	Inventory (units)	0	0	---	0	0	---	0	0	---
		Back orders (units)	257.100	235.667	-1.537*	259.725	317.333	4.290***	338.981	292.417	-2.444**
		Inventory cost ($)	1285.50	1178.33	---	1298.63	1586.67	---	1694.91	1462.08	---
	80%	Inventory (units)	0	0	---	0	0	---	0	0	---
		Back orders (units)	60.469	74.833	2.899***	64.163	61.750	-0.500	116.738	91.0	-2.657***
		Inventory cost ($)	302.34	374.17	---	320.81	308.75	---	583.69	455.00	---
	100%	Inventory (units)	0	0	---	0	0	---	0	0	---
		Back orders (units)	0	1	3.269***	0	1.083	4.951***	0	1.83	4.819***
		Inventory cost ($)	0	5	---	0	5.42	---	0	9.17	---

***p<0.005, **p<0.01, *p<0.1

Managers also concerned the financial benefits of RFID adoption. Table 6 presents the effects of ASI sharing on the focus retailer's inventory costs consisting of the inventory holding costs and the backordering costs. Although the RFID implementation increases the inventory holding costs, the reductions on the backordering costs lower the focus retailer's total costs. The focus retailer's total costs are reduced significantly (48~58 percent) with the 50 percent DESL, while the distributor has the highest possibility (50 percent) of stock out with the existence of the supply lead-time uncertainty. When the focus retailer predicts a potential stock out at the distributor's site through ASI sharing, s/he will start to cumulate inventory against potential supply shortage in future. For the same reason, a medium reduction (21~41 percent) occurs with 80 percent DESL. However, the focus retailer's total costs increase with 100 percent DESL because the distributor holds sufficient inventory to mitigate supply lead time uncertainty. Meanwhile, the focus retailer might overreact to the supply uncertainty and lead to slight cost increase as observed. Therefore, ASI sharing has potential benefits to the retailer only when the distributor has the possibility of stock out. Otherwise, the overreaction to the potential lack of supply may result in additional inventory and the subsequent costs to the retailer. In addition, the effect of ASI sharing is more notable when the lead time is longer.

Since the control retailer (without RFID) competes with the focus retailer (with RFID) on the limited supply, it is also valuable and interesting to examine how ASI sharing between the distributor and the focus retailer will affect the control retailer. In both base and RFID models, the control retailer follows the same base stock (R_r, S_r) inventory replenishment policy. The order-up-to level, S_r, is equal to the economic order quantity (EOQ) because we assume the demand is constant in order to focus on supply uncertainty only. Although the control retailer follows the same replenishment policy in both models, his/her performances are different because the focus retailer obtains ASI in the RFID model and can adjust his/her ordering policy accordingly.

The ASI sharing between the distributor and the focus retailer affects the control retailer's performance in two ways. First, the focus retailer will store more products due to the early awareness of the possible stock outs at the distributor's site. This activity may cause the increase of the control retailer's back orders because two retailers are competing on the limited supply. Second, the increased distributor's inventory in the RFID model provides a higher service level to the control retailer as well, especially when the lead- time is long (case III). Therefore, the final impacts on the control retailer's performance (see Table 7) is a joint effect of these two factors. Although the control retailer could indirectly benefit from the focus retailer's RFID adoption, most likely s/he has the risk of higher level of back orders as shown in Table 8 when the competition is the dominant factor. Furthermore, comparing with the significant reduction of the back orders for the focus retailer, the control retailer is certainly in an adverse position. The simulation results summarized in Table 9 confirm that there exists both positive and negative effects on the control retailer's performance. The study on the control retailer's performance helps the managers to decide whether or not RFID adoption is an appropriate strategy under a certain situation.

TABLE 8. THE CONTROL RETAILER'S BACKORDER REDUCTION.

Distributor's expected service level	Discrete distribution of distributor's order lead time		
	Case I	Case II	Case III
	The control retailer's back order reduction		
	units (%)	units (%)	units (%)
50%	-21.433 (-8.34)	57.608 (22.18)	-46.564 (-13.74)
80%	14.364 (23.75)	-2.413 (-3.76)	-25.738 (-22.05)
100%	1.000 (------)	1.083 (------)	1.83 (-------)

TABLE 9. THE CONTROL RETAILER'S INVENTORY COST CHANGE.

Distributor's expected service level	Discrete distribution of distributor's order lead time		
	Case I	Case II	Case III
	The control retailer's inventory cost change		
	$ (%)	$ (%)	$ (%)
50%	-107.17 (-8.34)	288.04 (22.18)	-232.83 (-13.74)
80%	71.83 (23.75)	-12.06 (-3.76)	-128.69 (-22.05)
100%	5.00 (------)	5.42 (------)	9.17 (-------)

V. DISCUSSION AND CONCLUSION

Fig. 4 demonstrates the mechanism of how ASI sharing benefits the focus retailer. There exists a critical point regarding to the distributor's inventory level which will trigger the focus retailer's inventory replenishment activity. The focus retailer knows that the distributor's next open order of Q_d will arrive in T periods. In order to avoid a stock out before the distributor builds up his inventory, the retailer needs to keep sufficient inventory indicated by the curve of $M(I_{FR})$ which is determined backwards from time t_0+T to current time t_0 based on the forecast of the customer demand. Note that the required inventory may not be necessarily kept at the retailer's site, but the focus retailer must monitor the distributor's inventory level to ensure the possibility of having the required inventory to avoid stock out. The curve of I_{FR} presents the focus retailer's on-hand inventory. The curve of $E(I_d)$ indicates the expected distributor's inventory level with the prediction on the control retailer's ordering pattern.

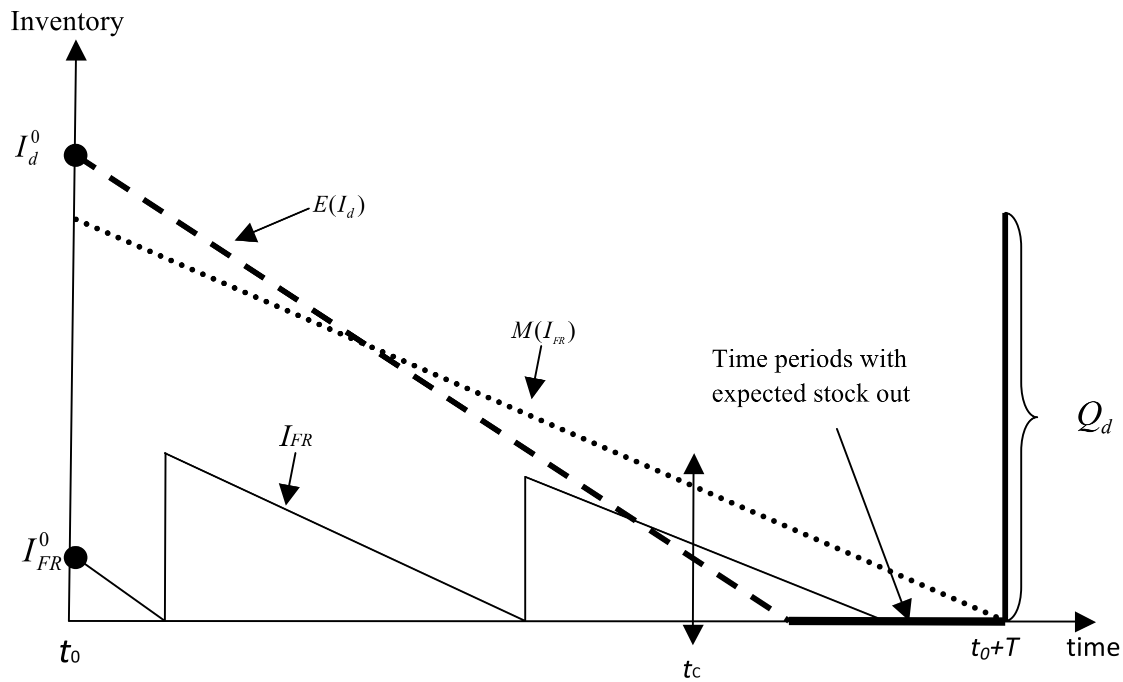


FIGURE 4. THE CRITICAL POINT FOR THE FOCUS RETAILER

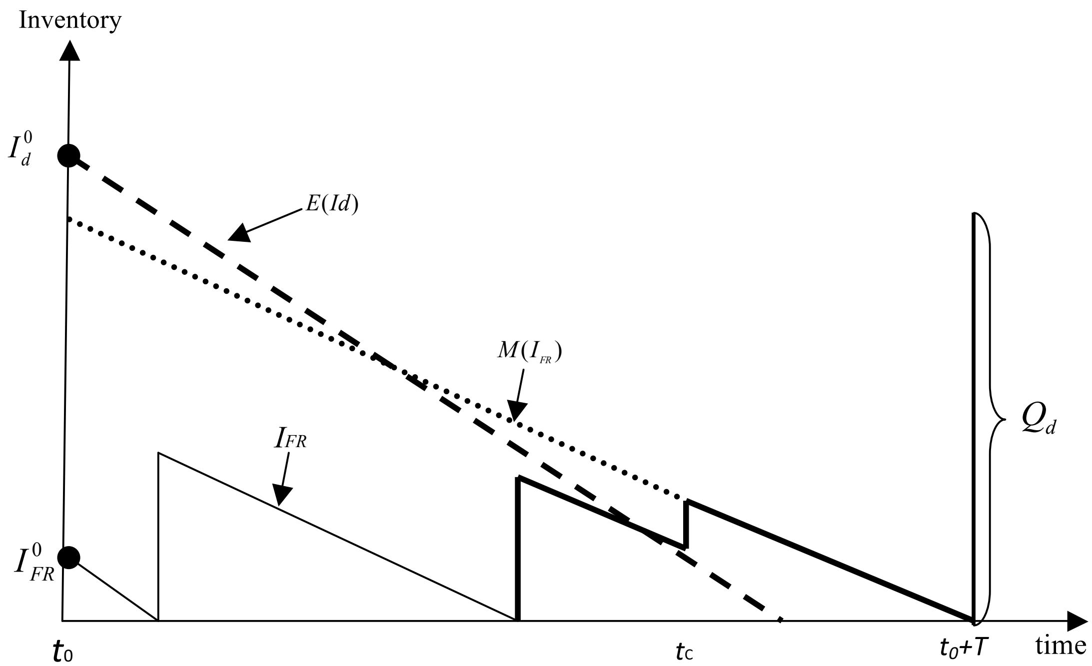


FIGURE 5. THE FOCUS RETAILER'S RESPONSE TO ASI

At time t_c, the focus retailer is in the middle of a review cycle. Therefore, the focus retailer should not place a replenishment order. However, at this moment, the sum of the focus retailer's inventory and the distributor's inventory is equal to the minimal required inventory for the focus retailer. In other words, after time t_c, the focus retailer will most likely experience a stock out in future if the focus retailer does not order all distributor's current inventory right away. One amendment could be that the focus retailer orders the distributor's entire remaining inventory at time t_c to match the minimal required inventory. An additional ordering cost occurs and the order quantity is $I_d(t_c)$.

This research contributes to the literature with a new concept and definition of advance supply information (ASI). In contrast to the advance demand information, the ASI refers to, in short, the information on future supply in term of the quantity and the timing. The emergence of RFID technology makes it possible to share ASI efficiently and effectively between the supplier (distributor) and the buyer (retailer). Our model integrates the real-time ASI facilitated by RFID system into the retailer's inventory replenishment decision-making process to explore further business benefits. The numerical simulation helps managers to evaluate the expected benefit from RFID.

In addition to the potential benefits obtained by the adoption of RFID, the simulation results for the control retailer's reveals the potential risk associated with a late adoption of RFID when s/he competes with the focus retailer on limited supply. In this study, we consider the joint effects of order quantity and lead time uncertainty. We find that the focus retailer can accurately predict the lead time by adjusting order quantity with ASI sharing.

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