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Benefits of RFID technology for reducing inventory shrinkage

Ti-Jun Fan [a,b,*], Xiang-Yun Chang [a,b], Chun-Hua Gu [b], Jian-Jun Yi [b], Sheng Deng [a,b]

[a] School of Business, East China University of Science and Technology, Shanghai 200237, China
[b] Research center for Virtual Business, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

Inventory shrinkage is prevalent in many industries. Radio Frequency Identification (RFID) technology has been regarded as a promising solution for inventory inaccuracy. Many retailers endeavor to push their suppliers to adopt this technology. This paper considers the situation of a retailer subject to inventory inaccuracies stemming from shrinkage problems. We apply a newsvendor model to analyze how to reduce inventory shrinkage problems by deploying RFID. We study two scenarios for managing an inventory system with shrinkage problems. In the first scenario, the retailer optimizes its operations only by taking into account the inventory shrinkage problems. In the second scenario, the retailer further improves its operations by deploying RFID. We analyze inventory shrinkage problems by optimizing order quantities and expected profits in consideration with the effect of the available rate of ordering quantity, RFID read rate improvement, and the tag price, respectively. The results show that whether the retailer deploys RFID depends on the relative value of the available rate of ordering quantity and RFID read rate improvement. We also present a formulation of the threshold value of tag cost which makes the deployment of RFID cost-effective.

1. Introduction

Inventory inaccuracy is a major operation problem in many supply chains. According to DeHoratius and Raman (2008), inventory inaccuracy occurs when the inventory record does not match the physical inventory that is actually available. An empirical study by DeHoratius et al. (2001) reports that out of close to 370,000 SKUs investigated, more than 65% of the inventory records did not match the physical inventory at the store-SKU level. Moreover, 20% of the inventory records differed from the physical stock by six or more items. Most of the investigations dealing with this issue provide the factors generating errors in inventory systems, and conclude that shrinkage is the main factor generating inventory inaccuracy (Rekik, 2010).

Shrinkage includes inventory theft, spoilage, and damage. Customers can spoil or damage products by tearing a package to try on the contained cloth item, wearing down a shoe by trying it on and walking, erasing software on computers during demonstration, spilling food on clothes, or scratching a car during a test drive (Bensoussan et al., 2007). As a consequence, some products are unavailable for sale. An ECR (Efficient Consumer Response) (2003) Europe project's research shows that the scale of shrinkage in the fast-moving consumer goods sector is 2.41% of the whole turnover value of the sector. Process errors account for 27% of the shrinkage value, 7% is due to deceptions, 28% is due to internal thefts, and 38% is due to external thefts.[1]

Radio frequency identification (RFID) technology has been publicized as a promising solution for inventory shrinkage. Lee and Özer (2007) indicated that RFID can help reduce inventory shrinkage in three ways. First, the ability to accurately monitor inventory can reduce theft and avoid fraud, leading to a direct reduction of inventory shrinkage. Second, depending upon the achieved read accuracy, RFID enhances the accuracy of the information currently obtained through barcode scanning, which is more vulnerable to human error. Third, by providing visibility so that inventory records more closely correspond to actual inventory, replenishment can be more accurate, leading to fewer stockouts. From an inventory management point of view, Rekik et al. (2009) argued that RFID has two principal values. First, the visibility provided by RFID technology highlights shrinkage problems, ensuring accurate knowledge of actual inventory levels by eliminating the discrepancy between physical and information flows. Second, RFID technology “corrects” shrinkage problems by eliminating them. A study by de Kok et al. (2008) of the effects of RFID technology derived a similar result. Despite the application of RFID mainly at the case level and the pallet level, many researchers have realized its possibility for wider use at the item level as the tag cost descends, and given attention to product application, such as Gaukler et al. (2007), Zhou (2009), and Szmerekovsky and

* Corresponding author at: School of Business, East China University of Science and Technology, Shanghai 200237, China. Tel.: +86 21 6425 1022.
E-mail address: tjfan@ecust.edu.cn (T.-J. Fan).

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Zhang (2008). Therefore, we will investigate the effectiveness of RFID technology at the retail level.

1.1. Related literature

Studies related to RFID in inventory management are relatively new. There is some recent work on analysis of inventory inaccuracy. Heese (2007) considered inventory record inaccuracy in a supply chain model, where the Stackelberg manufacturer sets the wholesale price and a retailer determines how much to stock for sale to customers. By contrasting optimal decisions in a decentralized supply chain with those in an integrated supply chain, the results show that inventory record inaccuracy exacerbates the inefficiencies resulting from double marginalization in decentralized supply chains. In two other papers, Sahin (2004) and Sahin and Dallery (2009) analyze the case of a wholesaler that is not aware of inventory errors (or chooses to ignore them) in order to evaluate the efficiency loss due to errors compared with an error-free situation. They assess the effect of various actions for tackling the inventory inaccuracy issue, with a particular focus on actions such as the deployment of a new data capture technology, and finally quantify the economic impact of uncertainty on the inventory level. Contrary to these papers, rather than focusing on inventory inaccuracy in both integrated and decentralized supply chains, we explicitly model profits of the retailer with inventory shrinkage and remove operational inefficiencies by deploying RFID technology.

Among the few studies that analytically deal with the value of RFID in inventory control, Dutta et al. (2007) examine three dimensions of the value proposition of RFID and attempt to identify areas for further investigation. Lee and Özer (2007) argue that there is a huge credibility gap of the value of RFID, and that a void exists in showing how to arrive at the proclaimed values and how those values can be realized. Lee and Lee (2010) present the supply chain RFID investment evaluation model and provide a basis for enhancing our understanding of RFID value creation, measurement, and ways to maximize the value of RFID technology. Rather than analyzing the value of RFID at the pallet level in a supply chain, we study item-level RFID for coping with inventory shrinkage in a retail store. Our work is also distinguished from their model in that we consider RFID cost issues in inventory decisions. Additionally, rather than searching for retailer or manufacturer benefits from the technology in addition to those where the incentives are aligned, we are particularly interested in analytically identifying the threshold.

Camdereli and Swaminathan (2010) consider a supply chain under the misplacement of inventory and study both centralized and decentralized cases, identifying the conditions to coordinate the supply chain under the implementation of RFID. The results show that the incentives of the parties to invest in the technology are not perfectly aligned in the existence of the fixed cost of investment. Based on the relative payments of the parties for the fixed cost of investment, the incentives to adopt RFID can be characterized into regions, where they observe only one or two parties benefiting from the technology when the tag price falls into a specified region. In this paper, we research the effects of RFID adoption on the retail store rather than the whole supply chain. Instead of analyzing both the RFID tag costs and the fixed costs of technology investment, we consider only the RFID tag cost investment, since the fixed costs of technology investment account for only a relatively small part of the total cost of item-level RFID investment.

Rekik et al. (2009) is a closely related paper to our work. The focus of the authors is to analyze the problem of theft in a store by optimizing the holding cost under a service level constraint. They also analyze the value of RFID technology in the inventory system, and propose an analytical critical tag cost which makes the deployment of RFID technology cost-effective. Rather than considering perfect RFID technology which could eliminate theft errors completely, we suppose that only a part of shrinkage errors can be eliminated because RFID is imperfect, which is closer to the actual situation in retail stores. In their work, they do not consider the cost for stock-out and the incentive issues as a result of implementation of RFID. In our work, we incorporate the penalty cost for stock-out using RFID in the model and focus on the incentive of retail stores to deploy such a technology. Additionally, we further analyze the effect of available rate of ordering, RFID read rate improvement, and the tag price, respectively.

1.2. Our paper and contributions

This paper studies how to reduce the effects of inventory shrinkage problems by deploying RFID. We consider two different scenarios. In the first scenario, the retailer optimizes its operations only by taking into account the inventory shrinkage problems. In the second scenario, the retailer further improves the inventory system by deploying RFID. We analyze the effect of available rate of ordering, RFID read rate improvement, and the tag price, respectively; the results show that the decision to deploy RFID depends on the available rates of ordering and RFID read rate improvement. When the available rates of ordering fall below the critical value, the retailer gains a higher profit by deploying RFID. We also propose an analytical critical tag cost which makes the deployment of RFID cost-effective.

The remainder of the paper is organized as follows. In Section 2, we describe the issue of shrinkage and discuss the two different scenarios that can be used to model the issue. We also analyze the lemmas of our model in two scenarios. Finally, assuming that demand is subject to the uniform distribution, we derive the optimal order quantity and expected profits. In Section 3, we develop the parameters of the sensitivity analysis through a numerical example. We analyze the effect of available rates of ordering, RFID read rate improvement, and the tag price, respectively, and we also provide an analytical expression of the cost of the RFID tag, which makes the deployment cost-effective. In Section 4, we conclude our paper and point out the direction for further research.

2. A general inventory framework for inventory shrinkage

We consider that a retailer's products are provided by the supplier at a unit cost c, and the retailer sells a single seasonal product to end customers at a unit price p. The inventory decision of the retailer is made within a one-period newsvendor framework, the aim of which is to find the optimal order quantity and expected profit under uncertain demand. One of the underlying assumptions in the formulation of the newsvendor problem is that there is no misalignment between the physical and information flows, meaning that the retailer operates without execution errors (Rekik et al., 2008). Considering the shrinkage problem, the newsvendor model should be revisited.

In order to model the impact of the shrinkage problem, we define α as the random variable which reflects the effect of shrinkage on the real quantity which is available to end customers during the selling season: α is the ratio between the real quantity which is available to end customers and the total physical quantity available in the store. Under our modeling assumptions, the two situations are equivalent since knowledge of the available rate of ordering quantity and point-of-sale data will directly provide information on the realization of demand for shrinkage.

As described in the research of Rekik et al. (2009), we could reduce shrinkage through deploying RFID technology, which could provide visibility to detect shrinkage and therefore to have an accurate knowledge of the actual inventory level by eliminating the discrepancy between inventory system records and physical inventory. For the sake of simplicity, they assume throughout the paper that the effect of RFID is perfect and shrinkage errors can be eliminated completely through the deployment of RFID. According to the research of Clarke et al. (2006), only 74–79% of the variables loads had all of their tags read, and even empty boxes did not have a 100% read rate. So, it is worthwhile to analyze the imperfect scenario. In our research, only a part of shrinkage errors can be eliminated because RFID is imperfect, which is closer to the actual situation in retail stores. As illustrated in Fig. 1, when the retailer does not consider deploying RFID in inventory management, the retailer orders Q from the supplier, and only the fraction αQ is available to end customers during the selling season; the other part $(1-\alpha)Q$ is lost due to shrinkage errors. In a general setting where RFID is deployed, there is a fraction $(1-b)(1-\alpha)Q$ of the demand for shrinkage that may remain a demand for shrinkage, and the other fraction $b(1-\alpha)Q$ of the demand can be purchased by consumers with the deployment of imperfect RFID.

We consider that in the presence of shrinkage, there are two scenarios that can be analyzed depending on whether RFID is deployed by the retailer. Our analysis throughout the paper is mainly based on the comparison of these two scenarios, which can be described as follows:

Scenario 1: RFID is not deployed; the retailer is aware of an internal shrinkage problem and can estimate the distribution of the available rate of ordering quantity α. The decision about the ordering quantity is made by taking into account the shrinkage problem.
Scenario 2: The retailer decides to reduce the shrinkage problem by deploying RFID technology. Under this scenario, the portions of the inventory that avoid shrinkage through deployment of RFID can also be purchased by consumers.

The notations used in this paper are:

$\pi(Q_0)$: the expected profit of the newsvendor problem;
$\pi(Q_i)$: the expected profit of scenario $i (i=1, 2)$;
$F(x)$: the cumulative distribution function of x;
Q_0: the ordering quantity of the newsvendor problem;
Q_i: the ordering quantity of scenario $i (i=1, 2)$;
x: the random variable representing demand;
α: the available rate of ordering quantity;
b: the improvement rate of RFID;
c: the unit product purchase cost;
p: the unit product selling price;
g: the shortage cost;

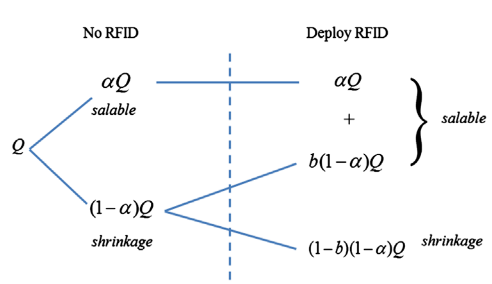

Fig. 1. Deployment of RFID by the supply chain versus the non-RFID case.

s: the unit product salvage price; and
t: the unit RFID tag price.

Considering the inventory shrinkage problems, we first make the following assumptions.

Assumption 1. $s<c<p$, in order to ensure retailers will sell products up front rather than directly salvaging them at the end of a period, $s<c$. Similarly, c should be less than p, so that the retailer could make positive profits.

Assumption 2. Compared to the RFID tag cost, the fixed costs are a small proportion of the total cost of deploying RFID. In order to limit the number of parameters considered in the analysis, the cost of the deployment of RFID only consists of the tag cost. The fixed costs of deploying RFID (reader systems, infrastructure, basic application and integration, maintenance and support, and overhead) are not integrated into our model. Estimates of these fixed costs are assumed not to vary with the model parameters and are provided by various studies (Sahin, 2004; Rekik et al., 2008).

2.1. Modeling a retail store subject to shrinkage

A newsvendor is in charge of a retail store that sells an identical product. Consider the decentralized newsvendor model with price-independent demand, wherein a manufacturer sells a single product to an independent retailer who is facing stochastic demand from the end-customer market. First, the retailer acts as if there were no inventory shrinkage, where inventory policies meet the newsvendor model. The retailer's profit will be given by

$$\pi(Q_0)=\int_0^{Q_0}(px+s(Q_0-x))dF(x)+\int_{Q_0}^{\infty}(pQ_0-g(x-Q_0))dF(x)-cQ_0 \tag{1}$$

In this model, we notice that the profits function of the retail store is composed of three parts. The first part expresses the sales revenue and the salvage value when out-of-stock happens. The reason is that the demand is less than the order quantity. The second part includes the profits of the retail store when the demand is more than the order quantity. The third part is the ordering cost from the supplier.

The retailer's profit can also be written as follows:

$$\pi(Q_0)=p(\mu+\int_{Q_0}^{\infty}(Q_0-x)dF(x))+s\int_0^{Q_0}(Q_0-x)dF(x)-g\int_{Q_0}^{\infty}(x-Q_0)dF(x)-cQ_0 \tag{2}$$

where

$$\mu=\int_0^{\infty}xdF(x) \tag{3}$$

As shown above, we define μ as the mean of demand. As presented by Camdereli and Swaminathan (2010), the expected profit function is concave in Q_0. The first derivative of $\pi(Q_0)$ is taken with regard to Q_0, and we derive the optimal order quantity.

$$Q_0^*=F^{-1}\left(1-\frac{c-s}{p+g-s}\right) \tag{4}$$

The optimal expected profit under no inventory shrinkage can be shown as follows:

$$\pi(Q_0^*)=(p+g-s)\int_0^{Q_0^*}xdF(x)-g\mu \tag{5}$$

2.1.1. *Analysis of the effect of inventory shrinkage*

In the first scenario, the retailer is aware of inventory shrinkage and optimizes its operations only by taking into account this issue —it does not deploy RFID. The retailer's profit will be given by

$$\pi(Q_1) = p(\mu + \int_{\alpha Q_1}^{\infty}(\alpha Q_1 - x)dF(x)) \\ + s\int_0^{\alpha Q_1}(\alpha Q_1 - x)dF(x) - g\int_{\alpha Q_1}^{\infty}(x - \alpha Q_1)dF(x) - cQ_1 \tag{6}$$

We notice that the expression $\pi(Q_1)$ consists of four parts. The first part expresses the profit that the retailer would get if he orders Q_1 and only αQ_1 is available to the customers. The second part expresses the salvage value at the end of the period. The third part is the penalty cost for stock-out. The last part expresses the purchase cost. The optimal order quantity and the optimal expected profit in the first scenario are expressed as follows:

$$Q_1^* = \frac{1}{\alpha}F^{-1}\left(1 - \frac{c - \alpha s}{\alpha(p + g - s)}\right) \tag{7}$$

and $Q_1^* > 0$ if and only if $\alpha > (c/(p+g))$, which is the critical condition for ordering from the supplier.

The optimal expected profit under inventory shrinkage can be derived as follows:

$$\pi(Q_1^*) = (p + g - s)\int_0^{\alpha Q_1^*} x dF(x) - g\mu \tag{8}$$

2.1.2. *Analysis of the benefits of RFID technology*

In the second scenario, the retailer further improves the inventory system by deploying RFID. The retailer's profit will be given by

$$\pi(Q_2) = p(\mu + \int_{(\alpha + b(1-\alpha))Q_2}^{\infty}((\alpha + b(1-\alpha))Q_2 - x)dF(x)) \\ + s\int_0^{(\alpha + b(1-\alpha))Q_2}((\alpha + b(1-\alpha))Q_2 - x)dF(x) \\ - g\int_{(\alpha + b(1-\alpha))Q_2}^{\infty}(x - (\alpha + b(1-\alpha))Q_2)dF(x) - (c + t)Q_2 \tag{9}$$

The optimal order quantity and the optimal expected profit in the second scenario are expressed as follows:

$$Q_2^* = \frac{1}{\alpha + b(1-\alpha)}F^{-1}\left(1 - \frac{c + t - (\alpha + b(1-\alpha))s}{(p + g - s)(\alpha + b(1-\alpha))}\right) \tag{10}$$

and $Q_2^* > 0$ if and only if $t < (p+g)(\alpha + b(1-\alpha)) - c$, which means that the retailer will order products only if the RFID tag price is lower than the threshold value.

The optimal expected profit under deployment of RFID technology can be derived as follows:

$$\pi(Q_2^*) = (p + g - s)\int_0^{(\alpha + b(1-\alpha))Q_2^*} x dF(x) - g\mu \tag{11}$$

2.2. *Determination of the optimal policy for uniform distribution*

In this section, we assume that demand and inventory shrinkage errors are uniformly distributed, which may seem somewhat restrictive but enables us to get closed form solutions for the optimal policy. The choice of using uniform distributions is also supported by other investigations that have similar motivations (Noori and Keller, 1984; Inderfurth, 2004). To gain analytical insights through closed form solutions, we assume demand is uniformly distributed in $[0,\beta]$.

The optimal order quantity under inventory shrinkage is given by

$$Q_1^* = \frac{\beta}{\alpha}\left(1 - \frac{c - \alpha s}{\alpha(p + g - s)}\right) \tag{12}$$

As the above result, the optimal order quantity under deployment of RFID technology is given by

$$Q_2^* = \frac{\beta}{\alpha + b(1-\alpha)}\left(1 - \frac{c + t - (\alpha + b(1-\alpha))s}{(p + g - s)(\alpha + b(1-\alpha))}\right) \tag{13}$$

Lemma 1.

1. *Given $Q_1^*, Q_2^* > 0$, there exists a critical value $\underline{\alpha} = min1, \alpha_0/(1-\alpha_0)$ where $\alpha_0 = c/(p+g)$, such that $Q_1^* < Q_2^*$ if and only if $\alpha < \underline{\alpha}$.*
2. *Given $Q_1^*, Q_2^* > 0$, there must exist a threshold value of the RFID tag price, $\underline{t} = (p+g)(\alpha + b(1-\alpha)) - c - \frac{1}{\alpha^2}(\alpha(p+g) - c)(\alpha + b(1-\alpha))^2$, such that $Q_1^* < Q_2^*$ if and only if $t < \underline{t}$.*

Proof.

1. Camdereli and Swaminathan (2005) show that when $\alpha_0 < 0.5$, $Q_0^* = Q_1^*$ for $\alpha = 1$ and $\alpha = \alpha_0/(1-\alpha_0)$; otherwise, $Q_1^* < Q_0^*$ for $\alpha < \alpha_0/(1-\alpha_0)$ and $Q_1^* > Q_0^*$. Furthermore, when $\alpha_0 \geq 0.5$, $Q_0^* = Q_1^*$ for $\alpha = 1$ and $Q_1^* < Q_0^*$ for $\alpha < 1$. Given this, $Q_1^* > Q_2^*$ follows.
2. The difference of $Q_2^* - Q_1^*$ is linearly decreasing in t and $Q_1^* = Q_2^*$ for $\underline{t}$; we can derive $Q_1^* < Q_2^*$ if and only if $t < \underline{t}$.

Lemma 1 (1) states that, as the inventory availability varies, the values of Q_1^*, Q_2^* become equivalent at only one value of $\underline{\alpha} = min\{1, \alpha_0/(1-\alpha_0)\}$. Further analysis will be shown in the following section. Through deployment of RFID technology, we may expect to order less products due to improved inventory availability. In lemma 1(2), we provide a threshold value for the tag price, below which it is always optimal to order more under RFID than under inventory shrinkage for appropriate ranges of inventory availability.

The optimal expected profit under inventory shrinkage is given by

$$\pi(Q_1^*) = \frac{\beta}{2}(p + g - s)\left(1 - \frac{c - \alpha s}{\alpha(p + g - s)}\right)^2 - \frac{\beta}{2}g \tag{14}$$

and the optimal expected profit under deployment of RFID technology is given by

$$\pi(Q_2^*) = \frac{\beta}{2}(p + g - s)\left(1 - \frac{c + t - (\alpha + b(1-\alpha))s}{(p + g - s)(\alpha + b(1-\alpha))}\right)^2 - \frac{\beta}{2}g \tag{15}$$

Lemma 2. *There exists a threshold value of the RFID tag price, $\underline{t} = s(\alpha + b(1-\alpha)) - c + \frac{1}{\alpha}(c - \alpha s)(\alpha + b(1-\alpha))$, such that $\pi(Q_1^*) < \pi(Q_2^*)$ if and only if $t < \underline{t}$.*

Proof. The difference of $\pi(Q_2^*) - \pi(Q_1^*)$ is linearly decreasing in t and $\pi(Q_1^*) = \pi(Q_2^*)$ for $\underline{t} = \frac{c}{\alpha}b(1-\alpha)$; we can derive $\pi(Q_1^*) < \pi(Q_2^*)$ if and only if $t < \underline{t}$.

In lemma 2, we also provide a threshold value for the tag price, below which the retailer can earn more profits under RFID. An investment in this technology always brings in more profits if and only if the tag price is less than threshold value $\underline{t}$.

3. Numerical study and results

This section examines the performance under the two scenarios and conducts analyses of the effect of available rate of ordering, the improvement rate of RFID, and the tag price, respectively. Note that in our numerical examples, we set $c=1.5$, $p=2.5$, $g=0.5$, $s=1$, $t=0.1$, and $\beta=200$.

Using Eqs. (12) and (13), the optimal ordering quantities under the two scenarios are given by

$Q_1^* = (200/\alpha)(1.5-0.75/\alpha)$, and $Q_1^*>0$ if and only if $0.5<\alpha<1$.

$$Q_2^* = \frac{200}{\alpha+b(1-\alpha)}\left(1.5-\frac{0.8}{\alpha+b(1-\alpha)}\right) \text{ and } Q_2^*>0 \quad \text{if and only if } \frac{0.54-b}{1-b}<\alpha<1.$$

Using Eqs. (14) and (15), the optimal expected profits under the two scenarios are given by

$\pi(Q_1^*) = 200(1.5-(0.75/\alpha))^2-50$, $\pi(Q_1^*)<0$ if $0.5<\alpha<0.75$, and $\pi(Q_1^*)\geq 0$ if and only if $\alpha\geq 0.75$.

$$\pi(Q_2^*) = 200\left(1.5-\frac{0.8}{\alpha+b(1-\alpha)}\right)^2-50 \text{ and } \pi(Q_2^*)<0 \quad \text{if } \frac{0.54-b}{1-b}<\alpha<\frac{0.8-b}{1-b}.$$

3.1. Analysis of available rate of ordering

The performance of the optimal ordering quantities as a function of the available rate of ordering is shown in Fig. 2. It appears that the optimal ordering quantities in scenario one become larger as the available rate of ordering increases, and the growth trend becomes slower and slower. The reason is probably as follows. Because the first derivative function and the second derivative function of the optimal ordering quantities in regard to the available rates of ordering are non-negative, the optimal ordering quantities are increasing with the available rates of ordering concavely. We also notice that the optimal ordering quantities of scenario two are an increasing function in RFID read rate improvement, and are also increasing with the available rates of ordering. The reason is similar to the above proof process. By comparing Q_1^* with Q_2^* in Fig. 2, we notice that there exists a threshold value of the available rates of ordering α^*($\alpha^*$is given in Result 1), so that $Q_2^*>Q_1^*$ if and only if $\alpha<\alpha^*$, which means that the retailer would order higher quantities in scenario two when the available rate of ordering is lower than the threshold value. Therefore, the benefit of deploying RFID to handle shrinkage errors is more significant when the available rate of ordering is lower.

Fig. 3 shows that as the available rate of ordering increases, the value of the optimal expected profits becomes larger and larger. Meanwhile, the optimal expected profit is positive if and only if the available rate of ordering is larger than the critical value. More importantly, as the RFID read rate improvement increases, the retailer can make a profit at a lower available rate of ordering. The optimal expected profits in scenario two also increase with the

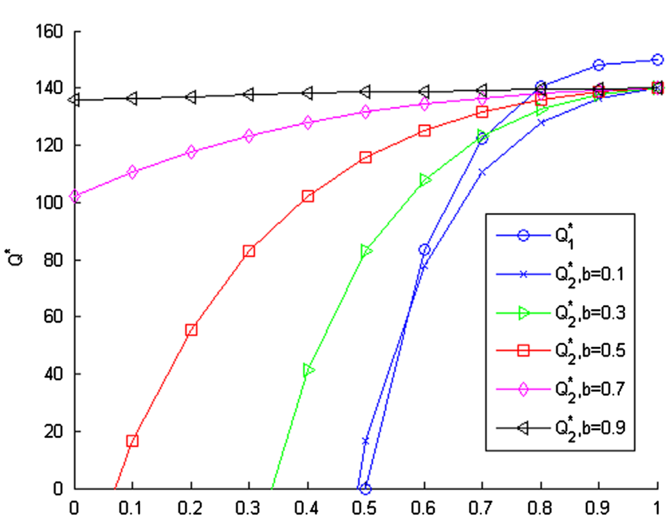

Fig. 2. Comparing Q_1^* with Q_2^* in α.

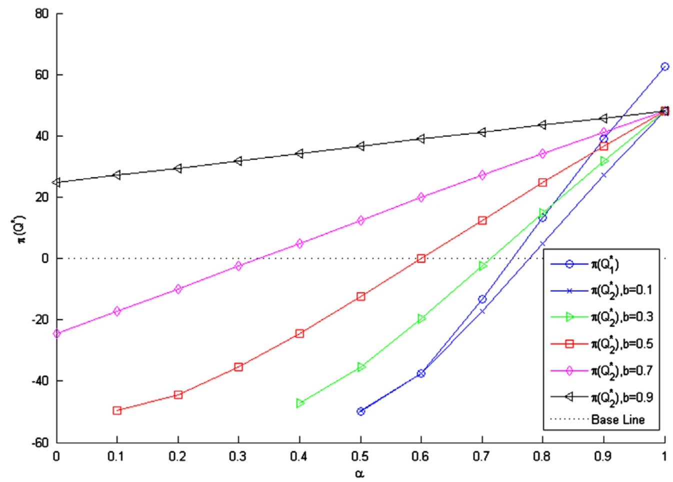

Fig. 3. Comparing $\pi(Q_1^*)$ with $\pi(Q_2^*)$ in α.

RFID read rate improvement, but the gap is continuously narrowed, which means that the effect of RFID is much better when the available rate of ordering is relatively small. The retailer can make more profits under scenario two, as the available rate of ordering is less than the threshold value. According to Fig. 3, we derive the following result.

Result 1. Given $Q_1^*, Q_2^*>0$, the retailer can make profits under scenario two if the available rate of ordering quantity is less than a threshold value. The threshold value is derived through Eqs. (14) and (15), such that $\pi(Q_1^*)<\pi(Q_2^*)$ if $\alpha<\alpha^*$.

Proof. As defined in section 3, when demand and inventory shrinkage errors are uniformly distributed, we can derive the optimal expected profits of the two scenarios. The threshold value of the available rate of ordering can be given by $\pi(Q_1^*)=\pi(Q_2^*)$.

The threshold value of the available rates of ordering $\alpha^*=bc/t+bc$ can be derived by the following equation.

$$s(\alpha^*+b(1-\alpha^*))+\frac{1}{\alpha^*}(c-\alpha^*s)(\alpha^*+b(1-\alpha^*))=c+t \tag{16}$$

It can be seen from Result 1 that it is not beneficial for the retailer to adopt RFID when α exceeds a threshold value. This is probably because the cost savings of identifying the inventory shrinkage that may induce stock-out could not compensate for the cost of investing in RFID technology. Therefore, the RFID decision depends on the proportion of available inventory after replenishment.

3.2. Analysis of RFID read rate improvement

Using Eq. (15), we derive the variation of optimal ordering quantities and the optimal expected profits with RFID read rate improvement under deployment of RFID. In Fig. 4, we notice that the optimal ordering quantities are an increasing function in RFID read rate improvement; the larger the available rate of ordering is, the greater the optimal ordering quantities increase is. The retailer decides to deploy RFID partly depending on the RFID read rate improvement. According to Fig. 5, the optimal ordering quantities are increasing both in the available rates of ordering and RFID read rate improvement, which shows that the greatest incentives to adopt the technology occur for higher values of RFID read rate improvement. The gap of the optimal ordering quantities with different available rates of ordering narrows as RFID read rate improvement increases, which indicates the substitution effect between available rate of ordering and RFID read rate improvement. We derive the following result.

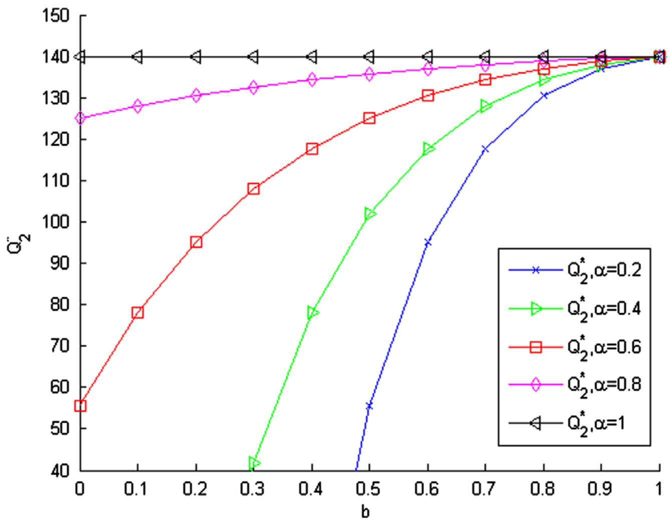

Fig. 4. Q_2^* with changes in b for different α.

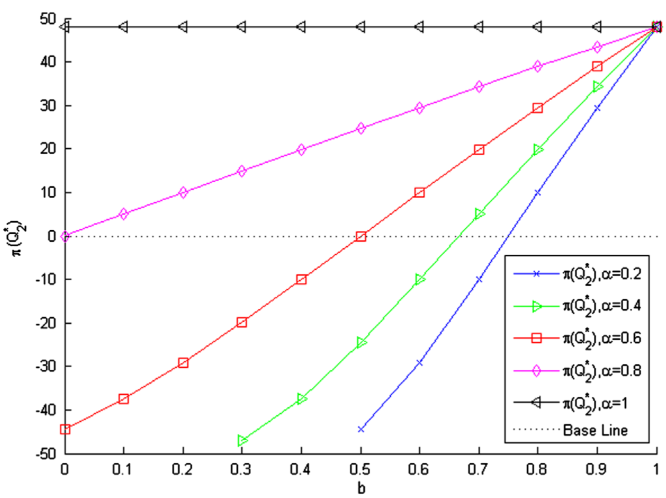

Fig. 5. $\pi(Q_2^*)$ with changes in b for different α.

Result 2.

1. The larger the available rate of ordering is, the greater the optimal ordering quantities increase is, because the higher the available rate of ordering is, the higher the profits of the RFID read rate improvement are.
2. The gap of $\pi(Q_2^*)$ with different available rates of ordering quantity narrows as RFID read rate improvement increases, which indicates the substitution effect between available rate of ordering and RFID read rate improvement.

3.3. *Analysis of RFID tag price*

We also propose an analytical critical tag cost which makes the deployment of RFID cost-effective, and we can derive a threshold value of the RFID tag cost. In Fig. 6, we illustrate the evolutions of the threshold value of RFID tag cost with available rate of ordering quantity. Note that the evolution pertaining to Fig. 6 is more intuitive if the RFID is subject to more shrinkage errors. The results show that the threshold value is decreasing with the available rate of ordering quantity and is increasing with the RFID read rate improvement. Such a result is intuitively expected, since if the shrinkage errors are not important, the RFID tag cost should be small to be adopted by the retail store.

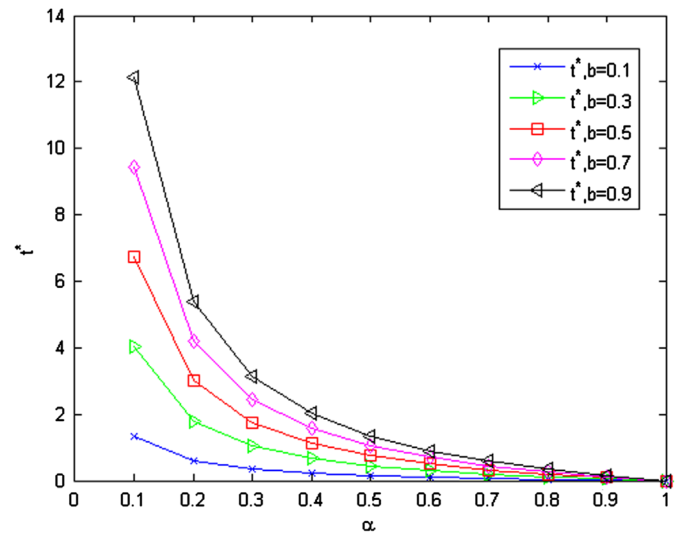

Fig. 6. t^* with changes in α for different b

Therefore, for a retailer who suffers from serious inventory inaccuracies caused by shrinkage, it is still worthy to apply RFID technology even if the tag price is at a comparatively high level. Additionally, if RFID technology performs quite well (i.e., b value is large), the benefits from RFID technology will exceed the cost induced by the high tag price, which is definitely beneficial to the retailer.

4. Conclusion

In this paper, we study incentives of retail stores in supply chains to invest in RFID to reduce inefficiencies of inventory shrinkage. We consider an improved newsvendor model to analyze the optimal order quantities and the expected profits of the supply chain with inventory shrinkage problems. Our analysis consists of two scenarios. In the first scenario, the retailer optimizes its operations only by taking into account the inventory shrinkage problems. In the second scenario, the retailer further improves the inventory system by deploying RFID. Furthermore, in this paper, we consider that only a portion of inventory shrinkage errors can be eliminated because RFID technology is imperfect, which is closer to the actual situation in retail stores. Finally, we analyze the effect of the available rate of ordering, the improvement rate of RFID, and the tag price, respectively.

We find that the incentives of the retailer to deploy RFID depend on the relative values of available rate of ordering and the improvement rate of RFID. When the value of the available rate of ordering is lower than the critical value, the retailer gains higher expected profits under the scenario of deploying RFID. The results also show that the greatest incentives to adopt the technology occur for higher values of RFID read rate improvement. The gap in expected profits with different available rates of ordering narrows as RFID read rate improvement increases, which indicates that there exists a substitution effect between available rate of ordering and RFID read rate improvement. We also propose an analytical critical tag cost which makes the deployment of RFID cost-effective, and the RFID tag cost should be small enough to be adopted by the retail store. One common result in all of our settings supports the current reactions of supply chains to RFID technology and shows that unless the tag price is cheap enough, no retail store would benefit from an investment in this technology.

Concerning the discrepancy between the quantities ordered from the supplier and the available-for-sale quantity, we have only considered the inventory shrinkage problem. Our model can be extended to include other types of problems, such as misplacement. It would be interesting to study the problem of RFID adoption in multiple sales periods.

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