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Feng Tao
East China University of Science and Technology

Ti-Jun Fan
East China University of Science and Technology

Kin Keung Lai
City University of Hong Kong

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Impact of RFID technology on inventory control policy

Feng Tao[1*], Tijun Fan[1], Kin Keung Lai[2] and Lin Li[1]

[1]Department of Management Science and Engineering, East China University of Science and Technology, 130 Meilong Road, Xuhui District, Shanghai 200237, China; and [2]Department of Management Sciences, City University of Hong Kong, Kowloon Tong, Hong Kong, China

RFID application can improve operation performance in a supply chain by reducing or eliminating inventory misplacement and shrinkage. In this paper, we present a periodic review inventory model to investigate and characterize the multiperiod inventory control policies in both non-RFID and RFID cases when the firm encounters misplacement and shrinkage. The optimal inventory control policy is proved to be a two-control limit policy. The control limits in both the non-RFID case and the RFID case are analyzed and examined, while considering the impact of shrinkage and misplacement on inventory policies. A critical inventory level is determined to identify the relationship of higher inventory level control limits between the RFID case and the non-RFID case. An intensive numerical study with sensitivity analysis of selling price, misplacement rate, shrinkage rate, inventory recovery rate, and tag price is conducted. We find that when RFID technology is adopted, the inventory control policy in the RFID case is much more stable than that of the non-RFID case, as the misplaced inventory can be recovered perfectly and instantly for sale and the inventory shrinkage can be reduced by RFID technology. In addition, one of our intriguing findings is that when the shrinkage rate is below a threshold value which is independent of parameters, RFID application has no effect on inventory control policy if the misplaced inventory can be recovered in a timely manner by physical audit, which has not been revealed in previous studies.

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1. Introduction

Inventory misplacement refers to placement of the product on the wrong shelf by a customer or a salesperson, causing a temporary loss which may be recovered by physical audit; while inventory shrinkage is caused by damage or theft in the store (such as customer shoplifting) so that the product cannot be sold any more, which leads to permanent loss. These two types of factors will definitely reduce the available inventory for sale, although the records are kept unchanged accordingly in the system (Atali *et al*, 2004, 2006; Kok and Shang, 2014). As such, there exists discrepancy between inventory record and the amount of product available for sale.

This phenomenon is prevalent in many industries, i.e., it is reported by IBM that retailers suffer an inventory difference rate of 1.75% of $58 billion in revenue, and manufacturers suffer a rate of 0.22–0.73% (Alexander *et al*, 2002). Dehoratius and Raman (2008) examined nearly 370,000 inventory records from 37 stores of a large public retailer with annual sales of approximately $10 billion; they found that 65% of the records were not in accordance with the actual inventory level. Kok and Shang (2007) examined a large distribution company with an average inventory of $3 billion; the disparity is up to 1.6% of the total inventory value at the end of 2004.

Apparently, inventory misplacement and shrinkage bring uncertainty in determining inventory control policy, and weaken the performance of the supply chain. Concerning the effects of these two factors, the retailer needs to increase its inventory level in order to alleviate lost sales due to stock-out. In turn, the excessive inventory will raise the inventory cost. It has been estimated that, due to inventory misplacement and shrinkage, lost sales and inventory costs will cut profit by more than 10% (Alexander *et al*, 2002; Raman *et al*, 2001; Heese, 2007).

Radio frequency identification (RFID) technology has been publicized as an effective and promising solution to inventory misplacement and shrinkage (Dai and Tseng, 2012; Camdereli and Swaminathan, 2010; Fan *et al*, 2014). With RFID technology, the items can be tracked through the use of an RFID tag. Therefore, two principal values of this technology are observed: (1) providing product visibility that the manager can identify the item and access information such as the position status; and (2) helping the manager eliminate

Correspondence: Feng Tao, Department of Management Science and Engineering, East China University of Science and Technology, 130 Meilong Road, Xuhui District, Shanghai 200237, China.
E-mail: ftao@ecust.edu.cn

misplacement and shrinkage (Kok, 2008; Rekik *et al*, 2008). Thus, when misplacement and shrinkage are reduced or eliminated by RFID application, what inventory control policies will result? What is the impact of this technology on inventory control policies? It is necessary to answer these questions to uncover the benefits of RFID technology.

In empirical studies, shrinkage is found to be the dominant factor, and misplacement is inevitable and occurs widely. In this paper, we focus on the impact of these two factors on inventory control policy and analyze the effectiveness of applying RFID technology when the retailer encounters misplacement and shrinkage. A large majority of recent papers have considered the newsvendor solution to investigate the effect of RFID on supply chain/partner decisions (Camdereli and Swaminathan, 2010; Fan *et al*, 2014, 2015). In these models, inventory is ordered only once at the beginning of the planning horizon, and the unsold inventory is salvaged at the end of the planning horizon. However, some retailers need to periodically replenish inventory, and the unsold inventory in the current decision period is kept for sale in the next decision period. Based on these differences, we formulate a dynamic programming model to further investigate inventory control policies with RFID adoption. In general, the research questions of this study are

(1) As a newsvendor solution has been widely studied, how should we consider inventory misplacement and shrinkage in multiperiod inventory control? What is the impact of the related parameters on inventory control policies?
(2) Although RFID is a promising solution to misplacement and shrinkage, is it always optimal to invest in this new technology whenever these two factors exist?

Motivated by the issue of RFID technology adoption and previous research, we formulate a dynamic programming model for a finite planning horizon to investigate the characteristics and differences of inventory control policies by comparing a non-RFID case and an RFID case, respectively. The corresponding inventory control policies in a single-period decision epoch are characterized analytically; while in a multiperiod decision epoch, an intensive numerical study is conducted to examine the impact on inventory policy with respect to selling price, misplacement rate, shrinkage rate, and recovery rate of shrinkage. It is intriguing to find that inventory control policy is more sensitive to these parameters in the non-RFID case than in the RFID case. More importantly, there is a threshold value of inventory shrinkage below which it is unnecessary to invest in RFID technology.

The remainder of this paper is organized as follows. Section 2 provides a brief literature review of related research. In Section 3, we present the dynamic programming model for both non-RFID and RFID technology when there are inventory misplacement and shrinkage. In Section 4, we characterize the inventory control policies with single-period and multiperiod analysis. The numerical study is presented in Section 5 followed by the conclusion of this paper in Section 6.

2. Literature review

Our research pertains to inventory inaccuracy in a retail supply chain, which is widely discussed in the literature (Raman *et al*, 2001; Fleisch and Tellkamp, 2005; Thiel *et al*, 2010). Typically, the classic inventory models are based on the assumption of accurate inventory information; however, a series of the research consider the problem of inventory uncertainty (Heese, 2007; Rekik *et al*, 2008). Kok (2008) proposed a near-optimal joint inventory inspection approach to deal with the inventory inaccuracy caused by random errors. Further, Kok and Shang (2007) extended the work by providing a simple recursion to evaluate the N-stage serial supply chain cost when it suffered from inventory inaccuracy. Rekik *et al* (2008) studied the impact of different types of misplacement inventory for a supply chain under a newsvendor framework. Kang and Gershwin (Kang and Gershwin, 2004) investigated the problems resulting from information inaccuracy in an inventory system by applying (Q, R) policy. Recently, Mersereau formulated this kind of inventory replenishment problem as a Markov decisions process using a Bayesian Inventory Record (Mersereau, 2013). In that paper, the inaccurate inventory record (or unobserved perturbation of the true inventory in the paper) is referred as invisible demand, which is randomly distributed and happens after satisfying the demand. The difference is that, in our paper, the inventory misplacement and shrinkage are assumed to be constant and exogenous parameters before observing the demand, and they can be recovered or eliminated (to some extent) at the end of each decision period.

The research on RFID in the literature is also relevant to our topic. This research focuses on the value of the visibility (availability) provided by RFID in improving operational performance (Lee and Ozer, 2007; Sarac *et al*, 2010). Lee and Ozer (2007) argued that there is a huge credibility gap in both claims of RFID value and its actual value when utilized. Dutta *et al* (2007) reviewed the value proposition of RFID in three dimensions and attempted to recognize the problems for further investigation. Bottani *et al* (2010) investigated the impact of RFID on mitigating the bullwhip effect in the Italian FMCG supply chain. Lee (2010) presented a Supply Chain RFID Investment Evaluation Model, and provided a basis to understand RFID value creation, measurement, and ways to maximize the value of RFID technology. Hossain and Prybutok (2008) investigated the factors that affect consumer acceptance of RFID technology.

The third stream related to our work is the application of RFID in inventory management. Some studies investigated supply chain coordination when applying RFID technology (Heese 2007; Rekik *et al*, 2008; Gaukler *et al*, 2007; Rekik, 2011; Lim *et al*, 2013). Dai and Tseng (2012) presented a systematic approach to quantify the extent of saving from timely information and reduction in information distortion when applying RFID to eliminate inventory inaccuracy. Sahin *et al* (2004, 2008, 2009) assumed that the wholesaler is not aware of inventory errors or chooses to ignore them, and they estimated the efficiency loss due to these errors. However, studies related to RFID in inventory management are relatively new. Rekik and Sahin (2009) analyzed the shoplifting issue by optimizing the holding cost under a service level constraint. They evaluated the use of RFID technology in an inventory system, and analyzed the critical tag cost which results in cost effectiveness of RFID technology. Metzger *et al* (2013) developed an inventory control policy for RFID-enabled retail shelf inventory management when considering false-negative reads due to imperfect detection by the technology. Compared with these studies, in our paper it is assumed that, in the non-RFID case, the recovered inventory will be kept for sale in the next decision period instead of being salvaged at the end of the current decision period. Our work also differs from these models in that we consider inventory decisions in a multi-period horizon and present the inventory policy as a two-control-limit strategy. In addition, in the numerical study, we find that the impact of tag price on inventory control policy is limited.

The works most related to our research are Camdereli and Swaminathan (Camdereli and Swaminathan, 2010) and Fan *et al* (2014, 2015). The study by Camdereli and Swaminathan (2010) solely considered inventory misplacement, in which the misplaced products have positive salvage value at the end of the planning horizon. In the study by Fan *et al*, (2014), the newsvendor model is formulated to cope only with inventory shrinkage, in which the lost products cannot be found at the end of the sales season. They analyzed the effectiveness of deploying RFID technology in terms of ordering fill rate, RFID reading rate improvement, and tag price. Further, they extended the model to consider both misplacement and shrinkage simultaneously (Fan *et al*, 2015). The differences between our work and these papers are threefold: (1) a multiperiod dynamic programming model is formulated to consider the finite planning horizon inventory control strategies in daily operations; (2) the misplaced inventory can be recovered for sale in the next decision period in the non-RFID case, but can be recovered instantly for sale in the current decision period in the RFID case; and (3) we focus on both non-RFID and RFID cases to uncover the impact on inventory control policy, and find the critical value of shrinkage ratio to adopt RFID technology in the numerical study.

3. Model

Before presenting the model, we define the notations as follows:

c is the unit purchasing cost;
g is the unit tag price with RFID technology;
h is the daily holding cost of unsold product, where $h \ll r$;
p is the unit penalty cost when stock-out exists;
r is the unit sales revenue;
s is the unit salvage value;
t is the decision horizon, where $t = 1, 2, \ldots, T$;
x is the initial inventory level before replenishment;
y is the inventory level after replenishment;
α is the shrinkage ratio;
β is the misplacement percentage, where $\alpha + \beta < 1$;
δ is the shrinkage recovery rate, where $0 < \delta \leq 1$. If $\delta = 1$ the shrinkage rate can be eliminated completely. On one hand, stolen or shoplifted inventory can be detected by RFID technology so that it can be recovered for sale. On the other hand, with the help of RFID, the retailer can discover the product that is about to expire, which also can increase the availability of on-hand inventory. Unfortunately, however, RFID technology cannot identify whether a product on the shelf or in the store is damaged, so it cannot recover the damaged inventory. Therefore, to be practical, we define the shrinkage recovery rate to indicate that there are still a number of products in the inventory that cannot be recovered and sold. In this paper, we assume that the shrinkage recovery rate is zero when we do not apply RFID.
γ is the discount factor;
D is the stochastic demand with density function $f(x)$ and cumulative distribution function $F(x)$, where $E(X) < \infty$;
K is the setup cost with RFID technology.

The decision sequence in a typical period is as follows:

(a) At the beginning of the period, take the left inventory from previous period as the initial inventory level of current period;
(b) Make a decision on whether salvaging the excessive inventory or placing an order based on the inventory control policy;
(c) When demand arrives, satisfy it or get punished for stock-out;
(d) At the end of the period, left inventory, if any, is stored for sale in the next period.

Assumption 1 (A.1) *Inventory misplacement and shrinkage occur as soon as the inventory level is determined. At the end of each decision period, the inventory record is corrected to be equal to the true inventory level.*

For ease of exposition, we assume that inventory misplacement and shrinkage take place when the objective inventory level is determined at the beginning of each decision period (after salvaging and purchasing, but before demand arriving). At the end of each decision period, inventory record is corrected according to the true inventory level on hand. The second part of this assumption ensures that the inventory control policy is made on the true inventory data instead of incorrectness inventory record. For example, assume the inventory loss rate is 20%, at the end of current decision period, if the record inventory level is 10, then the true inventory level is 8 (=10 * 80%). At the beginning of next decision period, if we decide to order up to 20 and take 10 as the initial inventory level, according to A.1, the available inventory level is 16 (=20 * 80%) when the replenishment is determined. However, the true inventory level is 14.4 (=18 * 80%), which is less than expected.

Assumption 2 (A.2) *When there is no RFID, misplaced inventory can be recovered at the end of each decision period, but shrinkage inventory cannot be recovered and is lost permanently.*

If RFID is not adopted, misplaced inventory can be found and recovered by physical audit. However, it is infeasible or costly to recover the inventory as soon as it is misplaced. Thus,, it is reasonable to assume that the misplaced inventory is recovered at the end of each decision period, so that it can be salvaged (at the end of the planning horizon) or sold in the next period. Concerning shrinkage, it consists of two types: (1) theft or shoplifting—the stolen products are missing, but they are in the record; and (2) damaged or expired products—this type of product can no longer be sold. Therefore, these two types of shrinkage reduce the available quantity of inventory. It is noted that misplaced inventory and shrinkage inventory may be found and monitored *in a timely manner* by salespeople so that the inventories are recovered for sale in the current decision period—we do not take these circumstances into account in this paper.

Accordingly, in each decision period, because of inventory misplacement and shrinkage, the actual inventory that can be sold after replenishment is $(1 - \alpha - \beta)y$. The unmet demand is lost. Consequently, without RFID, the retailer's profit-to-go function could be

$$\Pi(x) = \max\left\{ \begin{array}{l} rE\min(y_w,D)+s(x-y)^+-c(y-x)^+-pE(D-y_w)^+ \\ -hE(y-\min(y_w,D))+\gamma E\Pi\left((y_w-D)^+ +\beta y\right) \end{array} \right\}, \quad (1)$$

where $y_w = (1 - \alpha - \beta)y$ is the actual inventory level after replenishment. The first term in the maximum operator is the expected revenue; the second term is the salvage value; the next three expressions are the purchasing cost, the penalty cost due to shortage, and the holding cost, respectively; and the last term is the expected discount future profit.

Considering the salvage value, at the beginning of each decision period, if the initial inventory level is higher than the objective (optimal) level, the excess inventory will be salvaged. In our model, the initial inventory levels of the current and the next decision periods are x and $(y_w - D)^+ + \beta y$, respectively. Therefore, the initial inventory in any decision period (except the first one) consists of the unsold inventory and the misplaced inventory recovered at the end of the previous decision period. This is consistent with assumption A.2. The salvaging activity as well as the purchasing, if any, is triggered at the beginning of each decision period before demand arrives such that we use the difference between the initial inventory level x and the objective inventory level y to calculate the salvage value and procurement cost. At this point, the inventory level in record is equal to the actual inventory level (according to A.1 and A.2). However, just from this moment on (i.e., the excessive inventory has been salvaged $s(x - y)^+$ or the order has been placed $c(y - x)^+$ and the updated inventory level in current decision period is realized), misplacement and shrinkage occur. In addition, it is easy to understand that the misplaced inventory incurs daily holding cost as it is recovered for sale in the next decision period. Regarding damaged or expired inventory, we consider the disposal cost as the daily holding cost for ease of formulation. It is noted that we do not consider the disposal revenue of this kind of inventory; that is, we assume the salvage value of damaged or expired inventory is zero. Finally, regarding stolen or shoplifted inventory, we take the cost of identifying and auditing the inventory as the holding cost. To this end, the holding cost is $hE(y - \min(y_w, D))$. As the misplaced inventory βy can be recovered for sale in the next decision period, we regard it as expected future profit.

Assumption 3 (A.3) *Misplaced inventory can be recovered instantly and completely by means of RFID technology, but shrinkage cannot be completely eliminated because of inventory damage.*

Analogous to the existing literature (Fan *et al*, 2015), RFID technology is assumed to perform so well that misplaced inventory can be positioned and recovered entirely for sale during the current decision period. However, when we consider shrinkage, theft, or shoplifting can easily be detected and recovered instantly, but RFID technology cannot recover damaged products, which can no longer be sold. Therefore, there is still a percentage of shrinkage (say $1 - \delta$ in our paper) that is lost permanently.

Before presenting the next assumption, let $\lambda_1 = 1 - \alpha - \beta$ and $\lambda_2 = 1 - (1 - \delta)\alpha$ so that $0 \leq \lambda_1 \leq \lambda_2 \leq 1$, and define the function $H(\lambda, a) = \frac{\lambda(r+p)(1-F(0))+a}{1-\lambda(1-F(0))}$; then we can verify that $H(\lambda_2, -c-g) \leq H(\lambda_2, s)$ and $H(\lambda_1, -c) \leq H(\lambda_1, s) \leq H(\lambda_2, s)$.

Assumption 4 (A.4) *The parameters satisfy the following condition*:

$$s < h < \min\{H(\lambda_1, -c), H(\lambda_2, -c-g)\}.$$

It is noted that the condition is unnecessary when formulating the dynamic programming model, but it is sufficient in proving the inventory control policies.

Based on the above assumptions, when RFID is adopted, inventory can be tracked in real time so that the available inventory increases as the misplacement is recovered and the shrinkage is decreased. Thus, the retailer's objective profit-to-go function could be

$$\Pi^R(x) = \max\left\{\begin{array}{l} rE\min(y_r,D)+s(x-y)^+-(c+g)(y-x)^+-pE(D-y_r)^+ \\ -hE(y-\min(y_r,D))+\gamma E\Pi^R\left((y_r-D)^+\right) \end{array}\right\} \quad (2)$$

where $y_r = (1-(1-\delta)\alpha)y$ is the inventory level under RFID technology after replenishment. Here, the misplaced inventory is recovered instantly and completely for sale, so the expression does not contain β. The main difference between the non-RFID case and the RFID case is that the misplaced inventory is recovered for sale in the next decision period (i.e., the term $\gamma E\Pi((y_w-D)^+ + \beta y)$ in Eq. (1)), but it is recovered for sale in the current decision period in the RFID case (i.e., the term $rE\min(y_r, D)$ in Eq. (2)). Clearly and intuitively, the available inventory for sale in Eq. (2) is larger than that in Eq. (1). However, considering the cost of applying RFID technology, the inventory control policy may not be easy to characterize in a multiperiod planning horizon.

When considering the fixed setup cost with RFID investment, we have

$$W(x) = -K + \Pi^R(x).$$

4. Analysis

In this section, we first analyze the one-period problem and characterize the optimal inventory control policy. Next, we consider the multiperiod model and discuss the intractability of characterizing the optimal control policy analytically, leading to a computational study in the next section.

4.1. Single-period analysis

For one period, when the retailer does not introduce RFID technology, the single-period formulation could be

$$\pi(x) = \max\left\{\begin{array}{l} s(x-y)^+-c(y-x)^++rE\min(y_w,D) \\ -pE(D-y_w)^+-hE(y-\min(y_w,D)) \end{array}\right\} \quad (3)$$

As $(D-y_w)^+ = (D-y_w) + (y_w-D)^+$, the above function can be rewritten as

$$\pi(x) = \max\left\{\begin{array}{l} s(x-y)^+-c(y-x)^++rE\min(y_w,D)-pE(D-y_w) \\ -pE(y_w-D)^+-hE(y-\min(y_w,D)) \end{array}\right\}$$

Let $\lambda_1 = 1-\alpha-\beta$; to obtain the optimal inventory control limit, define two functions

$$u(y) = \lambda_1(r+p+h)[1-F(\lambda_1 y)] - h - c \quad (4)$$

and

$$v(y) = \lambda_1(r+h+p)[1-F(\lambda_1 y)] - h + s \quad (5)$$

It is easy to get

$$\frac{\partial u(y)}{\partial y} = \frac{\partial v(y)}{\partial y} = -\lambda_1^2(r+p+h)f(\lambda_1 y) < 0$$

The inequality holds as $\lambda_1^2 > 0$, $r, p, h > 0$, $f(\lambda_1 y) > 0$, and $f(y) > 0$. Therefore, for Eq. (3), we have the following conclusion.

Theorem 1 *The optimal inventory policy for Eq. (3) is a two-control limit strategy as*

$$y^* = \begin{cases} y^L, & \text{if } x \le y^L; \\ x, & \text{if } y^L < x \le y^H; \\ y^H, & \text{if } x > y^H. \end{cases}$$

where $y^L = \arg\{u(y) = 0\}$ *and* $y^H = \arg\{v(y) = 0\}$.

Proof We resort to the proof in Eberly and Mieghem (1997) by two steps: 1) to prove the continuity and concavity of the right-hand side of Eq. (3) for any given x in the first place; and 2) to obtain the expressions of the control limit.

(1) It is readily seen that $s(x-y)^+ - c(y-x)^+$ is continuous and concave in y for any given x as $s \le c$. In addition, $rE\min(y_w, D)$ is continuous and concave with respect to y; $pE(D-y_w)^+$ and $hE(y-\min(y_w, D))$ are both continuous and convex with respect to y. Therefore, the right-hand side of Eq. (3) is continuous and concave with respect to y for any given x.

(2) In terms of the control limit, we can see that when $x = 0$, the first derivative of Eq. (3) with respect to y yields Eq. (4). With the first-order condition, we get $y^L = \arg\{u(y) = 0\}$. When x is sufficiently large, the first derivative of Eq. (3) with respect to y yields Eq. (5). With the first-order condition, we get $y^H = \arg\{v(y) = 0\}$. To prove the uniqueness of the two-control limits, we resort to A.4. Moreover, with some algebra, it is easy to get $u(0) = \lambda_1(r+p+h)(1-F(0)) - h - c > 0$, $v(0) = \lambda_1(r+p+h)(1-F(0)) - h + s > 0$ and $\lim_{y\to\infty} u(y) = -h - c < 0$, $\lim_{y\to\infty} v(y) = -h + s < 0$, which imply that there exist only one y^L and y^H such that $u(y^L) = 0$ and $v(y^H) = 0$. It can be readily verified that $y^L \le y^H < \infty$. The concavity of the objective function yields that it is optimal to do nothing on the inventory control policy whenever the initial inventory level satisfies $y^L \le x \le y^H$.

Therefore, the optimal inventory control policy for Eq. (3) is as follows: (i) to order up to y^L when the initial inventory level is below y^L; (ii) to reduce the inventory down to y^H when the initial inventory level is above y^H; and (iii) to keep the inventory level unchanged if the initial inventory level is between y^L and y^H. This completes the proof. □

Likewise, the single-period formulation with RFID technology is

$$\pi^R(x) = \max\left\{\begin{array}{l} s(x-y)^+ - (c+g)(y-x)^+ + rE\min(y_r, D) \\ -pE(D-y_r)^+ - hE(y-\min(y_r, D)) \end{array}\right\} \tag{6}$$

Let $\lambda_2 = 1-(1-\delta)\alpha$, and define

$$u_r(y) = \lambda_2(r+p+h)(1-F(\lambda_2 y)) - (h+c+g) \tag{7}$$

and

$$v_r(y) = \lambda_2(r+p+h)(1-F(\lambda_2 y)) - h + s \tag{8}$$

Theorem 2 *The optimal inventory ordering policy for Eq. (6) is a two-control limit as*

$$y_r^* = \begin{cases} y_r^L, & \text{if } x \le y_r^L; \\ x, & \text{if } y_r^L < x \le y_r^H; \\ y_r^H, & \text{if } x > y_r^H. \end{cases}$$

where ${y_r}^L = \arg\{u_r(y) = 0\}$ *and* ${y_r}^H = \arg\{v_r(y) = 0\}$.

The proof of Theorem 2 is analogous to that of Theorem 1; therefore, it is omitted here.

Intuitively, if the retailer does not apply RFID when it suffers from inventory misplacement and shrinkage, a higher inventory level must be maintained in order to satisfy demand, which leads to higher ordering levels in each decision period; however, when the retailer implements RFID technology, inventory levels can be reduced without decreasing the service level (which can be defined as the availability of product). Nonetheless, unfortunately, the relationships between corresponding inventory levels are not that clear even though we consider a single-period decision model, which is shown in Lemma 1.

Lemma 1 *Considering the inventory control policies with RFID and non-RFID technology,*

(1) *Given parameters, there exist y^* such that $v(y^*) = v_r(y^*)$. If $v(y^*) = v_r(y^*) > 0$, then $y^H > y_r^H$; if $v(y^*) = v_r(y^*) \le 0$, then $y^H \le y_r^H$, the equality only holds when $v(y^*) = v_r(y^*) = 0$.*
(2) *Given parameters, if $g = 0$, there exist y^* such that $u(y^*) = u_r(y^*)$. If $u(y^*) = u_r(y^*) > 0$, then $y^L > y_r^L$; if $u(y^*) = u_r(y^*) \le 0$, then $y^L \le y_r^L$, the equality only holds when $u(y^*) = u_r(y^*) = 0$; otherwise, the relationship between y^L and y_r^L depends on the tag price.*

Proof By definition, it is easy to verify that $0 < \lambda_1 \le \lambda_2 < 1$; the equality only holds when $\beta = 0$ and $\alpha = 0$, or $\beta = 0$ and $\delta = 0$.

(1) From Eqs. (5) and (8), we have

$$\frac{dv(y)}{dy} = -\lambda_1^2(r+p+h)f(\lambda_1 y) < 0 \text{ and } \frac{dv_r(y)}{dy} = -\lambda_2^2(r+p+h)f(\lambda_2 y) < 0$$

Therefore, both $v(y)$ and $v_r(y)$ are strictly decreasing functions with respect to y. We have

$$v(y) - v_r(y) = (r+p+h)[(\lambda_1 - \lambda_2) - (\lambda_1 F(\lambda_1 y) - \lambda_2 F(\lambda_2 y))]$$

Thus, verifying $v(y^*) = v_r(y^*)$ converts to prove $\lambda_1 - \lambda_2 = \lambda_1 F(\lambda_1 y) - \lambda_2 F(\lambda_2 y)$. With some algebra, we need to prove that there exists y^* such that

$$\frac{1-F(\lambda_2 y^*)}{1-F(\lambda_1 y^*)} = \frac{\lambda_1}{\lambda_2}. \tag{9}$$

The right-hand side of Eq. (9) satisfies $0 < \frac{\lambda_1}{\lambda_2} \le 1$, where the equality only holds when $\lambda_1 = \lambda_2$, while the left-hand side of Eq. (9) holds for any y. Next, we prove that when $0 < \frac{\lambda_1}{\lambda_2} < 1$, Eq. (9) is valid. As α, β, and δ are predetermined parameters, λ_1, λ_2, and $\lambda_1/\lambda_1\lambda_2.\lambda_2$ can be taken as constant values. Here, $F(\bullet)$ is an increasing function which implies that $F(\lambda_2 y) > F(\lambda_1 y)$ for any given y. In addition, $\lim_{y \to -\infty} \frac{1-F(\lambda_2 y)}{1-F(\lambda_1 y)} = 1$ and $\frac{1-F(\lambda_2 y)}{1-F(\lambda_1 y)} > 0$, and it is easy to verify that $G(y) = \frac{1-F(\lambda_2 y)}{1-F(\lambda_1 y)}$ is a continuous function with respect to y. Therefore, given α, β, and δ, there exists y^* such that $\frac{1-F(\lambda_2 y^*)}{1-F(\lambda_1 y^*)} = \frac{\lambda_1}{\lambda_2}$ which ensures $v(y^*) = v_r(y^*)$. In addition, as $y^H = \arg\{v(y) = 0\}$ and $y_r^H = \arg\{v_r(y) = 0\}$, and $v(y)$, $v_r(y)$ are both decreasing functions with respect to y, when $v(y^*) = v_r(y^*) > 0$, we have $y^H > y_r^H > y^*$; when $v(y^*) = v_r(y^*) < 0$, we have $y^H < y_r^H < y^*$; and when $v(y^*) = v_r(y^*) = 0$, we have $y^H = y_r^H = y^*$. This completes the proof of the first part.

(2) Similarly, we have

$$u(y) - u_r(y) = (r+p+h)[(\lambda_1 - \lambda_2) - (\lambda_1 F(\lambda_1 y) - \lambda_2 F(\lambda_2 y))] + g$$

Therefore, if $g = 0$, from the proof of part (1), we can get the conclusion. Otherwise, given other parameters, when $g > 0$, the difference of $u(y) - u_r(y)$ depends on the value of g, the tag price of RFID technology. That is, there exists a value $g^* > 0$. If $g > g^*$, then $u(y) > u_r(y)$, which implies $y^L < y_r^L$ regardless of y; if $0 \le g \le g^*$, then

$u(y) \leq u_r(y)$, which implies $y^L \geq y_r^L$ regardless of y. Intuitively, when the RFID tag price is large, compared with the non-RFID case, the retailer becomes more conservative in ordering because of cost constraint, which increases the lower inventory control limit. Equivalently, when the variable tag price increases, the marginal unit cost is larger in the RFID case than the shortage cost because of inventory misplacement and shrinkage in the non-RFID case. This completes the proof. □

It is noted that, defining λ as the available rate of inventories, then $1 - F(\lambda y)$ is the probability of lost sales. When the proportion of available inventory in the non-RFID case to that in the RFID case (namely, λ_1/λ_2) equals the proportion of probability of lost sales in the RFID case to that in the non-RFID case (namely, $\frac{1-F(\lambda_2 y)}{1-F(\lambda_1 y)}$), it determines a critical value y^* ($v(y^*)$) which the relationship between upper level inventory control limits in RFID and non-RFID cases can rely on, which is illustrated in Figure 1.

Lemma 1 states that it is not easy to determine the relationship between corresponding inventory control levels with non-RFID and RFID cases. We believe that three reasons may account for this: 1) unmet demand is lost; 2) the misplaced inventory is recovered for sale in the next period in the non-RFID case, but is recovered instantly for sale in the RFID case; and 3) the procurement cost contains the variable tag price of the new technology. The retailer needs to balance the cost, or fiscal burden, resulting from RFID with the benefit of more accurate inventory information. With the complexity of the control limits, it is difficult to identify the relationship of inventory control policies as Fan *et al* (2014, 2015) did. However, in the next section we conduct a detailed numerical study to analyze the inventory strategies, revealing some implications.

4.2. Multiperiod analysis

In this subsection, we extend the analysis to a multiperiod case. In general, we count the time backward, and truncate $\Pi(\bullet)$ into $\Pi_t(\bullet)$, which refers to the period t profit-to-go formulation.

When there is no RFID technology, the profit-to-go formulation could be

$$\Pi_t(x) = \max\left\{\begin{array}{l} s_t(x-y)^+ - c_t(y-x)^+ + r_t E\min(y_w, D_t) - p_t E(D_t - y_w)^+ \\ -h_t E(y-D_t)^+ + \gamma E\Pi_{t-1}\left((y_w - D_t)^+ + \beta y\right) \end{array}\right\} \tag{10}$$

When RFID technology is applied, the profit-to-go model could be

$$\Pi_t^R(x) = \max\left\{\begin{array}{l} s_t(x-y)^+ - (c+g)(y-x)^+ + r_t E\min(y_r, D_t) - p_t E(D_t - y_r)^+ \\ -h_t E(y-D_t)^+ + \gamma E\Pi_{t-1}^R\left((y_r - D_t)^+\right) \end{array}\right\} \tag{11}$$

Similarly, if consider the fixed investment cost of RFID technology, we have

$$W(x) = -K + \Pi_t^R(x)$$

It is noted that, in multiperiod formulations, it is intractable to verify the concavity of the objective functions

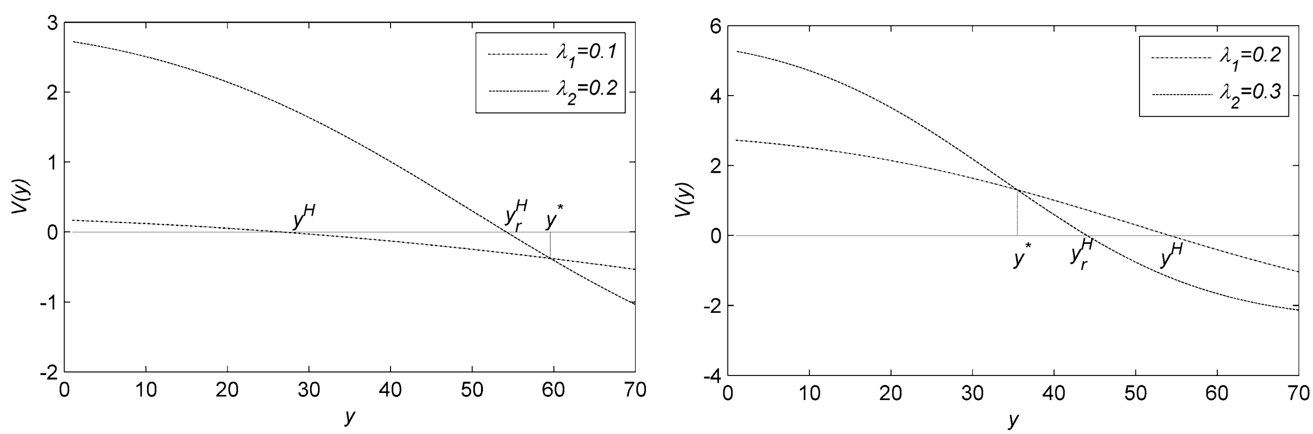

Figure 1 Shape of $V(y)$.

because of the terms $(y_w - D)^+ + \beta y$ and $(y_r - D)^+$ in the expected future profit, so that it is infeasible to obtain the analytical solution. However, the Value Iteration (VI) algorithm can find a stationary ρ-optimal policy and an approximation value to this dynamic programming, where ρ is constant and $\rho > 0$ (Puterman, 1994). In the numerical study, we apply Policy Iteration (PI) algorithm to find the optimal two-control limit policy as a representative example (Bertsekas, 1995) and the VI algorithm to find the ρ-optimal values. Nonetheless, the policy may not be unique, as shown in Figure 2. Again, this is mostly because of the maximum expression in the expected future profit (Li *et al*, 2012). When we consider a multiperiod planning horizon, it is probable that the objective function $\Pi_t(\bullet)$ is piecewisely concave (Xu and Li, 2007), which is illustrated in Figure 3 and intensively examined in the numerical study.

5. Numerical study

In this section, we conduct a computational test to investigate the optimal inventory control policies with inventory misplacement and shrinkage. All codes are written by MATLAB software and available upon request; the presented numerical results are only a small subset of the data.

We apply PI algorithm to find the optimal two-control limit inventory management policy as an illustrated example for

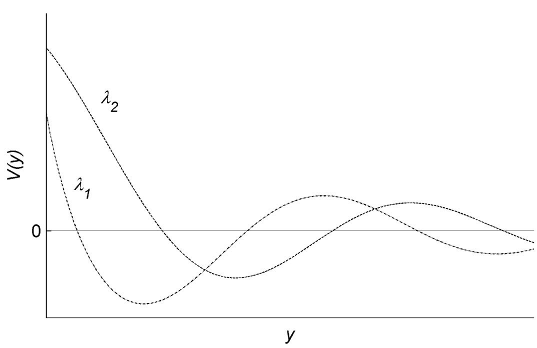

Figure 2 Shape of the control policy.

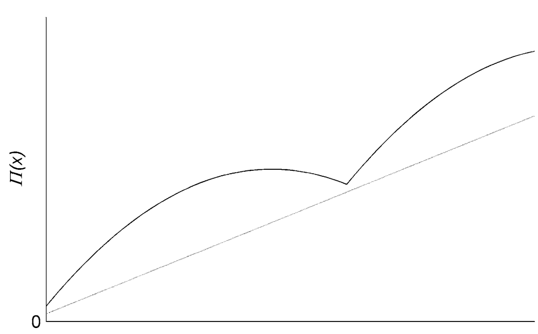

Figure 3 Shape of the optimal value.

finite planning horizon model and Gauss–Seidel Value Iteration algorithm (Eberly and Meighem, 1997), which increases the convergence to find the ρ-optimal approximation value, where $\rho = 0.00001$ in our test. For ease of computation, all parameters are set to be independent of the decision period. Without loss of generality, the demand is set to be binomial distributed with $n = 40$ and $p = 0.2$, denoted by $B(n, p)$. The remaining parameters are $s = 1$, $c = 6$, $p = 4$, $h = 2$, $g = 0.5$. It should be noted that all the tests are conducted with a number of parameter values to make sure that the conclusion is independent of a specific value. As the fixed investment cost K can only impact on the total profit, we omit it in the numerical study.

5.1. Inventory control policy for finite planning horizon

In this subsection, we apply PI algorithm to illustrate the optimal two-control limit policy as an example. Specifically, we choose misplacement rate $\beta = 0.2$ in non-RFID case, and select inventory recovery rate $\delta = 0.85$ in RFID case to find the policy when change the value of shrinkage rate α from 0.1 to 0.5 discretely.

The worst case in PI algorithm is to enumerate all the possible actions in action space to find the optimal policy. Theoretically, if the maximum demand is n, to satisfy the demand, the system state can be any value between 0 and n (both inclusive) as we consider lost sales model (in backlogged model, the state can be negative in each decision period). On the other hand, there are $n + 1$ actions need to calculate in each state. For example, if the maximum demand is 5, the state space is $\{0, 1, 2, 3, 4, 5\}$. Given a state, say 3, the action can be reducing to 0, 1, 2, or increasing to 4, 5, or keeping unchanged (=3). Therefore, the action space is $\{-3, -2, -1, 0, 1, 2\}$. Namely, it is necessary to test 6 actions in each state. In this case, the finite number of iterations in PI algorithm may reach as much as $(n + 1)^{n+1}$. To simplify the calculation, we focus on the updated inventory levels after the action is taken when consider the pattern of two-control limit policy. We know that the updated lower (y^L) and upper (y^H) bound inventory levels can be any value in $\{0, 1, 2, \ldots, n\}$ satisfying $y^L \leq y^H$. Given a pair of values of lower bound and upper bound, the action in each state is determined accordingly, which generates a new subset action space. It is surely that the optimal control policy is included in this new defined subset action space. However, in this setting, the maximum number of iterations is reduced to $\frac{(n+2)(n+1)}{2}$, which is much less than the original case. The outcome is summarized in the following Table 1.

From Table 1, we can see that the two-control limit policy may not be unique when we extend our analysis to finite period model, which is also an evidence of piecewise concavity of the objective function as mentioned in Section 4.2.

In terms of the piecewise exhibition of two-control limit policy, there are two further explanations. 1) The control

Table 1 A representative example of two-control limit policy with increment of α

α	*Non-RFID* ($\beta = 0.2$)	*RFID* ($\delta = 0.85$)
0.1	$[15]^{[16],[17]}[18]$	[11, 20]
0.2	$[16],^{[17]}[18]^{[19,\ 20]}$, $[21]^{[22]}$, [23]	[11, 16]
0.3	$[18]^{[19]}$, $[20]^{[21]}$, [22, 24]	$[11]^{[12,\ 13]}$, [14, 19]
0.4	$[19]^{[20,\ 21]},\ ^{[22,\ 23]}[24]$	[12, 22]
0.5	$[15],\ ^{[16,\ 18]}[19],\ ^{[20,\ 21]}[22],\ ^{[23,\ 24]}[25]$	[12, 20]

$^{[.]}[A, B]^{[..]}$ means if the inventory level lies in [.], raise it to A; if the inventory level lies in [..], slash it down to B; if the inventory level lies in [A, B] (inclusive), keep it unchanged.

policy may degenerate after several decision periods. For example, taking a look at the control policy in RFID case when $\alpha = 0.3$, if the inventory level exceeds 19 after satisfying the demand, it is optimal to slash the inventory level down to 19 by salvaging some product. After that, demand in the next decision period arrives, if the left inventory level is less than 11 after satisfying the demand, then it is optimal to order up to 11. From this period on, it is optimal to keep the inventory level with 11 at the beginning of each decision period after conducting inventory control policy. Therefore, the initial inventory level determines the specific policy among the optimal policies. 2) Sometimes, the two-control limit may converge to only one point such that it is better to keep the inventory level steadily during the planning horizon, i.e., if the inventory level is in [0,21] after satisfying the demand in non-RFID case with $\alpha = 0.4$, it is always optimal to keep the inventory level at 19 when conducting the inventory control policy. However, it is noted that this convergent two-control limit policy is essentially different from the base-stock inventory control policy as the latter is an order-up-to policy, while the former does not only include order-up-to decision but also contains salvaging the excessive inventory.

5.2. Sensitivity analysis

In this subsection, we conduct a sensitivity analysis on the parameters to investigate the impact of different parameters on the inventory control policies.

On selling price test. In this test, we aim to find the relationship between the selling price and the inventory control policies. The results are shown in Figure 4, where $\alpha = 0.1$, $\beta = 0.1$, $\delta = 0.9$.

It is noted that, as the planning horizon is extended to a finite period and the objective function is piecewisely concave, the inventory control policy may not follow a unique interval as analyzed in one period. It may be a consecutive multi-interval policy, which is shown in Table 1. Therefore, for ease of comparison, in this test we calculate the average inventory levels instead of the control limits. The numerous original data will be provided upon request.

In Figure 4, the horizontal axis is the selling price r, while the vertical axis is the average inventory level (hereafter AIL in short). The solid line represents the average inventory level when the inventory record is accurate; the dash line refers to the average inventory level if RFID technology is applied when inventory misplacement and shrinkage emerge; and the dash-dot line stands for the average inventory level with corresponding non-RFID case.

From Figure 4, we see that the selling price has very little impact on the inventory control policy, although intuitively, it can influence the profit directly. Because of misplacement and shrinkage, the retailer needs to keep a high level of inventory to satisfy the demand, which is the increment part shown in the figure with the dash-dot-two-arrow line. By means of RFID technology, the retailer can reduce the average inventory level, which is the decrement part shown in the figure with the dot-two-arrow line. The discrepancy between the increment and decrement is the gap, which is shown in the figure with the dash-two-arrow line, that is, Increment = Decrement + Gap. Three main reasons can account for the gap:

(1) Inventory recovery rate—the existence of unrecoverable products leads to a rise in inventory levels, which will enlarge the gap.
(2) Misplaced inventory—note that in the non-RFID case the misplaced inventory can be recovered at the end of each decision period. Therefore, it will increase the amount of available inventory at the beginning of the next decision period and incur holding cost. However, in the RFID case, it can be found instantly and be for sale in the current decision period, which reduces the gap.
(3) The tag price of RFID—because of the tag price, the unit procurement cost increases, which increases the cost of identifying the missing inventory and the average inventory level as well. This will be examined further in the following.

We know that when the selling price increases, the cost of stock-out increases accordingly. Thus, the average inventory

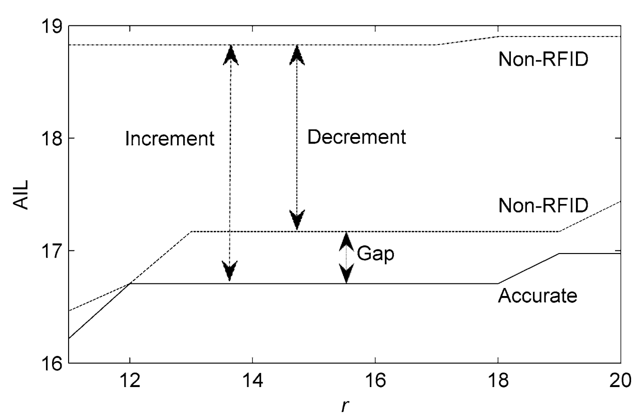

Figure 4 Inventory on selling price r.

levels in all cases increase, which is clearly demonstrated in the figure. However, in general, the significance of this impact is limited.

On misplacement rate. The test of misplacement ratio β without RFID technology is conducted. The results are shown in Figures. 5 and 6.

From our assumption, the misplaced inventory rate β does not have an impact on the RFID case. Here, we examine the impact of misplaced rate β on the inventory control policy in the non-RFID case. According to the discussion, the misplaced inventory can only be recovered for sale in the next decision period by physical audit. In other words, the misplaced inventory can be taken as storage to the next decision period. Hence, when the misplacement rate is large, it is natural to increase the reorder point because more inventories are stored for the future selling period. In addition, in the multiperiod planning horizon of the non-RFID case, the misplaced inventory not only incurs shortage cost, but also results in increased holding cost. Therefore, we conduct a numerical study on the holding cost (Figure 5) and penalty cost (Figure 6), respectively, to exactly reveal the impact of misplacement rate on the inventory control level.

From the figures, we see that as the misplacement rate increases, the inventory levels increase accordingly (mostly), which is evident. Given a misplacement rate, when holding cost decreases, say from $h = 4$ to $h = 2$, the average inventory levels increase as it is less costly to hold more inventories. However, in regard to penalty cost, the inventory levels do not present a significant decrement with the decreasing of penalty cost, say from $p = 7$ to $p = 2$. Thus, the holding cost plays a more important role when determining the inventory policy with misplacement rate. A retailer who suffers from a high rate of misplaced inventory needs to recover the inventory in a timely manner, or reduce the holding cost if the inventory cannot be recovered for sale in the current selling period. It is worthy of reminding that the average inventory level increases (decreases) as the lower threshold of inventory control policy increases (decreases), which leads to ordering of more (less) inventories in the decision horizon.

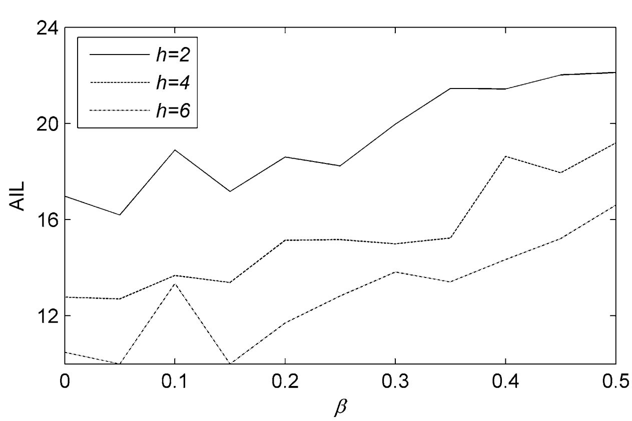

Figure 5 Inventory levels on β and h.

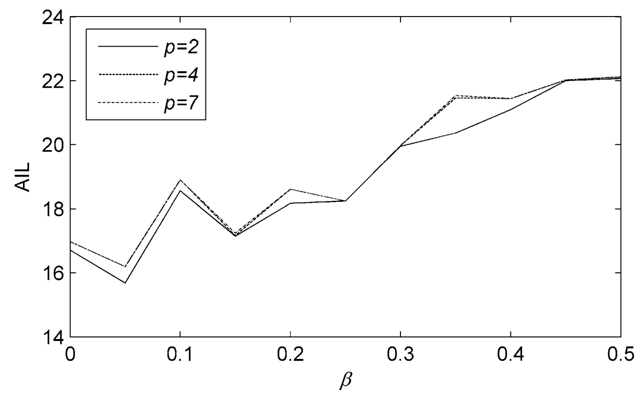

Figure 6 Inventory levels on β and p.

On shrinkage rate and recovery rate test. We conduct the test with different α and δ when RFID technology is applied. The impact of shrinkage rate α on the optimal solution is examined here, where α increases from 0.05 to 0.5 uniformly with 10 values. The results are shown in Figures. 7 and 8.

From Figure 7, we see that when there is no RFID technology, the inventory control policy becomes more sophisticated as α increases. As mentioned, in a multiperiod planning horizon, the inventory control policy consists of several consecutive two-control-limit intervals, i.e., Example 1. In general, we can view the inventory control policy as an enlarged two-control-limit policy where the lowest level of the control limits is regarded as the new lower level (12 in Example 1) and the highest level of the control limits is defined as the new upper level (25 in Example 1). This new defined two-control-limit policy provides the lower bound and upper bound of the inventory control policy. We examine these two thresholds in this test.

It is readily seen that, excluding the exceptional two points ($\alpha = 0.05$, 0.40), the lower threshold is nonincreasing with increasing of the shrinkage rate. This is mainly because the missing inventories caused by shrinkage cannot be recovered and are permanently lost; therefore, in order to satisfy the demand, it is better to raise the lower inventory level to cover the lost inventory. However, the upper threshold value is much more sensitive to shrinkage rate than the lower threshold. This can also be observed in the tests with other parameters, which are not presented here. Remember that in the formulation, we assume that the salvage value is incurred when the inventory level exceeds the threshold in each decision period, which is different from the assumption that the leftover inventories are salvaged as in the newsvendor model. When RFID technology is implemented, the inventory control policy is much more stable than that of the non-RFID case, as the misplaced inventory can be recovered perfectly and instantly for sale and the shrinkage inventory can be reduced by RFID technology. As the recovery rate is predetermined, when the shrinkage becomes larger, the lost inventory in the current decision epoch plays a role in the inventory policy; but the impact is

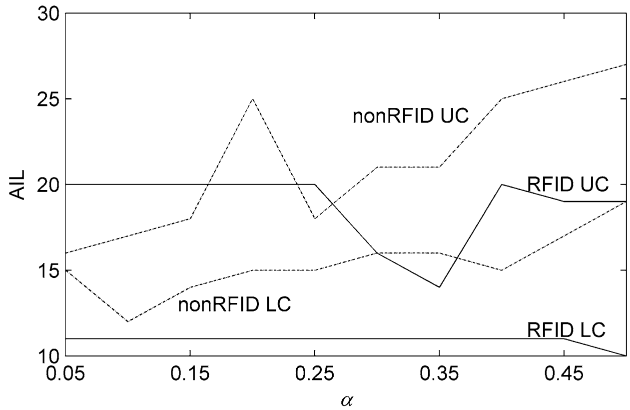

Figure 7 Control limits on α.

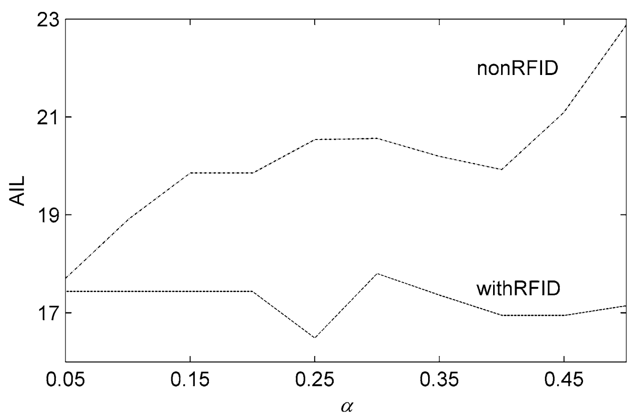

Figure 8 Inventory on α.

limited, as the two thresholds do not change too much except when $\alpha = 0.35$.

From Figure 8, the average inventory level in the non-RFID case is generally increasing with respect to α. However, in the RFID case, the average inventory level is much more stable; the retailer can keep the inventory control policy unchanged regardless of the shrinkage rate. Note that when α increases from 0.05 to 0.20, the average inventory level does not change. This finding results in further investigation of the relationship between α and δ.

Intuitively, when the shrinkage rate is large, it is better to apply the RFID technology with high performance. After conducting an intensive numerical study, we find that, given α, there exists a critical value $\delta^*(\alpha)$; when $\delta \geq \delta^*(\alpha)$, the inventory control policies do not change anymore, which means there is no need to implement RFID technology (from the inventory point of view). Figure 9 illustrates this finding. The non-RFID and RFID cases are divided by $\delta^*(\alpha)$ so that if the values of (α, δ) are in the left-hand part of Figure 9, it is unnecessary to apply RFID; while, if the values are in the right-hand part of Figure 9, it is better to introduce this new technology.

The curve $\delta^*(\alpha)$ represents that, given the shrinkage rate, when RFID is adopted, it is better to recover $\delta^*(\alpha) \times 100\%$ proportion of the shrinkage product so that the optimal revenue is achieved. The factors that affect inventory recovery rate can be categorized into three types:

(1) Nature of the product. A perishable product, such as seafood, vegetables, and some fruits, has a short life cycle, and it may deteriorate easily and lose its value. Fragile products, such as glass, china, and pottery, may easily be broken in transportation. If these kinds of products decay or are damaged and can no longer be sold, the recovery rate decreases. From the inventory side, retailers selling these types of products may not be eager to apply RFID technology.
(2) Theft. Shoplifting results in permanent inventory loss if it cannot be detected in real time, which decreases the recovery rate.
(3) Performance of RFID technology. Most of the existing papers contain the implicit assumption that RFID performs so well that it can eliminate misplacement and shrinkage perfectly, except for physical damage. However, technological demerits and incorrect operation will lead to malfunction, which results in decreasing of the recovery rate.

Laying aside the performance of RFID, damage of perishable or fragile products and shoplifting are two main factors that reduce the available items in store. Therefore, if the misplaced and shoplifted products can be recovered and monitored quite well by salespeople and the proportion of damaged products is small, considering the inventory control policy, the RFID technology seems less intriguing.

On tag price test. We reset some parameters as $\alpha = 0.2$, $\delta = 0.8$, and the tag price is increasing from 0 to 2 uniformly with 21 values.

From Figure 10, it is surprising to find that the average inventory level is (almost) increasing with respect to tag price. Apparently, when tag price increases, the procurement cost increases, which therefore leads to a reduction in the order quantity. As in the multiperiod decision model, the inventory control policy is a two-control-limit policy; the lower inventory level decreases and/or the upper inventory level increases

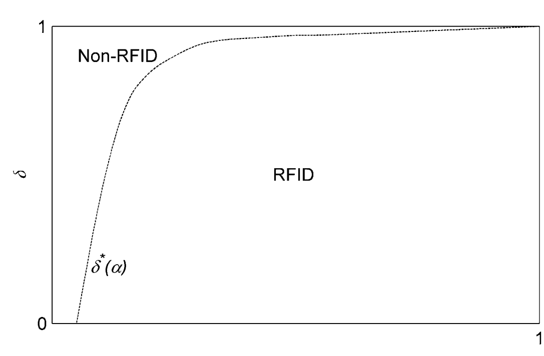

Figure 9 Relation of α and δ.

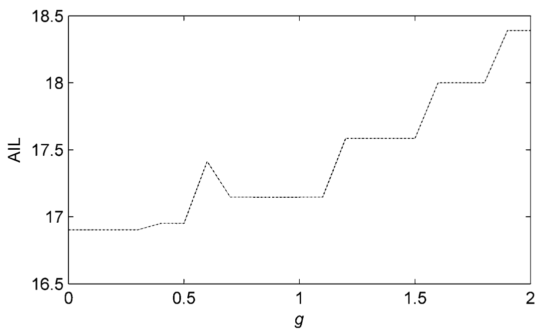

Figure 10 Sensitivity test on tag price.

will result in a decrease of the average ordering quantity. According to dynamic programming theory, when the system reaches a steady state so that a static two-control-limit policy can be applied in daily operations, if the interval of keeping the inventory unchanged is enlarged because the lower level decreases and/or the upper level increases, much more stable states emerge so that the average inventory level increases. Further, in our test, we find that the upper inventory level is much more sensitive to tag price than the lower inventory level, which implies that when the tag price decreases, the retailer needs to reduce the upper inventory level first in order to modify the inventory control policy and reduce the inventory cost. On the other hand, Fan *et al* (2014, 2015) in their study investigate a threshold value of tag price to determine the order quantity with RFID adoption by a newsvendor solution. However, when we extend the model to a finite planning horizon and concentrate on the inventory control policy, the firm can keep the policy unchanged if the tag price varies in a small interval.

5.3. Remarks

In this paper, we assume that RFID technology performs perfectly so that misplaced inventory can be recovered instantly for sale and the shrinkage resulting from theft or shoplifting can be detected in a timely manner. In practice, RFID may make a mistake, i.e., misreading or missing the signal, dropping of the tag, or malfunction of the technology. However, we can modify the parameters to fit these situations. Defining η as the performance of RFID technology, the recovered misplaced inventory now is $\eta\beta y$ instead of βy, and the detected shrinkage inventory now is $\eta\delta(1-\alpha)y$ instead of $\delta(1-\alpha)y$. This modification does not change the concavity or convexity (as mentioned before, it is intractable to identify the concavity or convexity) of the profit function in the multi-period analysis. Therefore, our conclusions can be extended, with slight modifications, to this situation, except that we need to conduct additional sensitivity analysis on RFID performance. For example, using the parameters in previous subsections and assume $\eta = 0.9$ in the first place to investigate the impact of shrinkage rate on inventory control policy, and then select $\alpha = 0.2$ to illustrate the impact of RFID performance on inventory control policy. The results are concluded in Table 2.

Table 2 informs us that, compared with the well-performing case of RFID technology (right-side column of Table 1), the inventory interval between lower bound and upper bound when RFID does not perform perfectly narrows down in general (except the case when $\alpha = 0.2$). On the other hand, we can see from Table 2 that the lower bound of inventory control policy is nonincreasing with respect to the performance of RFID technology, which will directly reduce the order frequency due to much more inventories that are recovered for sale instantly by this new technology during each decision period.

In addition, in the test of shrinkage and shrinkage recovery rate, we find that there exist threshold values (α, δ) that determine RFID adoption. Further, we find that there is a threshold value α^* (equals 0.025 in this paper) at which it is unnecessary to implement RFID technology when the shrinkage is no larger than the threshold value. Based on numerous computational tests, α^* is independent of selling price, procurement cost, salvage value, holding cost, even tag price of RFID and demand pattern. This may explain why some small retailers and perishable product retailers do not have the incentives to apply RFID technology as their shrinkage is much smaller and their misplacement can be recovered by salespeople.

It is noted that we only consider the inventory control policy when we present our conclusions. We do not intend to ignore or depreciate the benefits of this new technology, such as providing product life condition in quality management,

Table 2 A test of two-control limit policy on RFID performance η

α	*Inventory policy*[a]	η	*Inventory policy*[b]
0.1	[11, 14]	0.8	[12, 17]
0.2	[12, 22]	0.85	[12, 21]
0.3	[12, 18]	0.9	[12, 22]
0.4	[12, 14][15, 18], [19, 22]	0.95	[11][12, 13], [14, 19]
0.5	[13, 19]	1.0	[11, 16]

[a] With shrinkage α when $\eta = 0.9$.

[b] With performance η when $\alpha = 0.2$.

identifying position messages in transportation design, labor reduction, and improving supply chain efficiency.

6. Conclusion

In this paper, we consider a multiperiod model with implementation of RFID technology when considering inventory misplacement and shrinkage. A dynamic programming model is formulated to investigate the inventory control policies under both non-RFID and RFID cases. Rather than analyzing the impact on profit when implementing RFID technology, we focus on analyzing and investigating the impact on the inventory control limits with selling price, misplacement rate, shrinkage rate, shrinkage recovery rate, and tag price. The optimal inventory control policy is proven to be a two-control-limit policy. A critical inventory level is determined to identify the relationship of upper inventory level control limits between an RFID case and a non-RFID case. The numerical results show that, given the parameters, the inventory control policy of the non-RFID case is more sensitive to these parameters than that of the RFID case. When RFID is applied, the retailer can keep the inventory control policy unchanged or only slightly changed, regardless of the inventory misplacement and shrinkage.

Specifically, in the non-RFID case, the retailer needs to pay more attention to holding cost rather than penalty cost when deciding the inventory control policy. Compared with the misplacement rate, the shrinkage rate plays a more important role in determining the inventory control policy. In the RFID case, the lower control limit is nonincreasing with increasing of the shrinkage rate. The upper control limit and the average inventory level are more sensitive to the shrinkage rate than the lower control limit. Given a shrinkage rate, if the inventory recovery rate exceeds a critical value, implementation of RFID technology will have no impact on inventory control policy. In addition, the numerical study reveals that when the shrinkage ratio is below an independent threshold value (equal to 0.025 in our test), it is unnecessary to apply RFID technology, which is not observed in current studies. Thus, from an inventory control standpoint, the retailer does not have the incentive to apply RFID technology if the shrinkage is small and the misplacement can be recovered by physical audit. The test on tag price reveals that when the tag price increases, it is better to adjust the upper inventory control limit first, although the retailer can keep the ordering quantity unchanged when tag price varies by a small interval.

Finally, as with other studies of this topic, our research is not without limitations. First, we only consider the benefit for retailer by applying RFID technology, the benefit for supply chain is beyond the scope of the current paper. Second, in our paper, retailer is responsible for the tag price. It is surely that sharing the RFID tag price as others did will definitely increase the availability and applicability of this new technology, which will in turn increase the benefit of this technology. Third, in a competing market, accurate information provided by RFID technology will improve the operational performance and the competitive power, which is also beyond the scope of the present study. Finally, we do not distinguish the misplacement and shrinkage between shelf and warehouse. However, these limitations should be regarded as opportunities for future research in this area.

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