Journal of Cleaner Production 142 (2017) 2028–2044

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Investigation of RFID investment in a single retailer two-supplier supply chain with random demand to decrease inventory inaccuracy

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ARTICLE INFO

Article history:
Received 6 March 2016
Received in revised form
14 November 2016
Accepted 14 November 2016
Available online 16 November 2016

Keywords:
Inventory
RFID effectiveness
Sustainable supply chain
Error reduction

ABSTRACT

Inventory information inaccuracy is one of the main causes to the inventory waste in supply chain operations, which motivates many companies to adopt modern tracing technologies, e.g. radio frequency identification (RFID), to decrease inventory errors and strengthen the cooperation between the supply chain stakeholders. Considering different types of RFID possess unequal technique features in tracing items in more practical environment, for the first time this paper explores the *different effectiveness* of RFID in decreasing the inventory inaccuracies in a supply chain containing one retailer and two suppliers. Firstly, a novel scale factor function is introduced to illustrate the relationships between the variable cost of RFID and the *non-full* abilities of RFID in decreasing inventory inaccuracies. Then, under the stochastic demand and inaccurate inventory, analytical models are formulated to investigate the cost-effectiveness of different RFIDs to the optimal order quantities and the expected profits in different scenarios (uncoordinated and coordinated supply chains), hereby the best coordination strategies are addressed. At last, numerical results obtained from different scenarios on adopting RFID and a practical case-level RFID system for recycling packaging cases indicate that RFID can not only decrease inventory inaccuracies, but also strengthen the supply chain coordination.

1. Introduction

Current supply chain management gradually walks toward to the direction with environment-friendly, operation efficient and cost controllable features, which can be considered as the most typical essentials for the *sustainable supply chain* and the basic requirements to realize supply chain coordination (Hoof and Thiell, 2014; Fahimnia et al., 2015). Inventory inaccuracies, or more specifically, inventory errors are the prime culprits that are caused by undetected item losses, shrinkages, misplacements, out of date storages and inconsistencies between the physical storage and the records in the information system, these phenomenons are even worse in the fast moving product transactions (Bottani and Rizzi, 2008; Xu et al., 2012), which are the main obstacles for the realization of the *sustainable supply chain*. Hence, in 2004, Wal-Mart invited its eight main suppliers, namely, Gillette, Hewlett-Packard, Johnson & Johnson, Kimberly-Clark, Kraft Foods, Nestlé Purina PetCare Co., Procter & Gamble and Unilever, to pilot case and pallet-level RFID during their procurement processions to increase transaction accuracies and decrease inventory errors. Since then, the public has gradually observed the large-scale commercial applications of RFID. The applications and actual effectiveness of such a technology in supply chains have drawn both the researchers' and the practitioners' attention (Gaukler et al., 2007; Cui et al., 2014). Currently, different RFIDs are widely employed in the distribution centers (receiving, picking and sorting), the retail stores (receiving, backroom management and expositive area management), and even the product returns or recycles (Bottani and Rizzi, 2008; Shaharudin et al., 2015), all of which constitute the most basic elements for performing *sustainable supply chain* (Zhu and Sarkis, 2004).

What specific features of RFID can contribute to the *sustainable supply chain*? RFID is a system that consists of tags and readers, application software, computing hardware and midware (Ngai

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http://dx.doi.org/10.1016/j.jclepro.2016.11.081
0959-6526/

et al., 2008). The superior feature of RFID lies in its unique tracing ability. For example, the contactless and anti-interference abilities of RFID make it extremely helpful in monitoring and tracing tagged objects, thereby contributing to profitable labor savings. Lee and Özer (2007) once cited a quotation stating that, in 2004, Metro Group saw a 17% of labor reduction. These researchers also reported two estimations from Accenture (2002) and SAP (2003), in which 100% of labor in physical inventory count was eliminated, whereas 20–30% and 40–50% receiving and picking costs in the retail warehouse were reduced, respectively. Another appealing feature of RFID is that it can realize unique identification, providing the supply chain with less shrinkages and higher visibility. IBM estimated that, after RFID was introduced, inventory shrinkages reduced to 2/3 at manufacturers, and 47% in sales in 2002 (Lee and Özer, 2007). With automatic sensing RFID, information at different organizational levels in can be distributed in real-time (Delen et al., 2007). Due to the contribution of RFID to item level information visibility, Zhou (2009) simulated about 6.7% (1.24/18.76) more units were sold per day. The above-mentioned figures in practical operations are only the partial profiles of RFID's contributions in building the *sustainable supply chain* (by cost decreasing and efficiency increasing) (Diabat and Govindan, 2011; Fahimnia et al., 2015; Govindan et al., 2015a), further benefits for performing RFID are still need us to investigate.

Apart from the direct and superficial benefits of RFID in labor saving, shrinkage error diminishing, and visibility improving, also RFID assists in reducing out-of-stock (Szmerekovsky and Zhang, 2008), compressing lead time (Rekik, 2011), and improving transportation efficiency (Lee et al., 2011), which help firms achieve a *smooth supply chain*. However, one of the remarkable challenges in supply chain management is the *inventory inaccuracies*, which involve imperfect quality products (Sana, 2011a), mismatches between the physical flow and the information flow (Rekik, 2011), and invisibility of inventory storage (Lee and Özer, 2007). Among those researches, the contribution of RFID on the order lead-time and safety inventory level has already been addressed, but it leaves spaces to investigate the role of RFID in dealing the inventory inaccuracies. Generally, there usually have difficulties in calibrating the effectiveness of a new technology to an old supply chain system (Ribeiro et al., 2015), even numerous researchers have developed diverse strategies for modeling the improvement abilities or effects of new technologies like RFID in the supply system and their investment scales. Thus, Xu et al. (2012) believed that before investigating RFID investment effectiveness, the causes and types of inventory inaccuracies should be identified. They, correspondingly, differentiated inventory errors as temporary errors (e.g., the misplacement), and permanent shrinkages (e.g., theft). Meanwhile, Rekik (2011) noted four kinds of errors (i.e., transaction errors, misplacement, shrinkage, and product quality) in the yield and supply process. From the perspective of the inventory holding levels, inventory errors exhibit positive and negative features (Heese, 2007). This viewpoint, however, has not been taken into account in constructing research models.

Constructing the *analytical model* is a feasible and practical means for investigating the effectiveness of new technologies on the supply chain system. However, Dubey et al. (2016) admitted that the dynamic nature of the *sustainable supply chain* system makes it difficult in connecting practical qualitative observations with quantitative analysis. Hence, it is meaningful to see Lee et al. (2011) summarized three means for assessing a novel technology: (1) obtaining empirical estimation from experts or practitioners, (2) conducting in-depth case studies and (3) employing analytical models. At present, inventory record inaccuracies in the supply chain are normally modeled on the premise that either the inventory is independent of the customer demand or not. Uçkun et al. (2008) adopted a normally distributed, demand independent random variable to represent the errors of the inventory record. Xu et al. (2012) once specified that parameterized RFID investment should be assumed to introduce 0%, 50% and 100% effects on modeling errors, but in current models, RFID is all assumed to have 100% ability to eliminate inventory errors. Furthermore, inventory errors were simplified as two fixed ratios and are proportional to demand, which could be easily in processing the errors, but some randomness in the practical application might be lost.

The game model has been testified as a convenient and reasonable model in modeling the complex relationships of different stakeholders in cleaning production and *sustainable supply chain* system (Huang et al., 2016; Liang et al., 2016; Ouyang and Shen, 2017). If taking a look at the supply chain coordination models, we can easily draw that the two-level supply chain with a supplier/manufacturer and a buyer/retailer is the most prevailing modeling structure (Aljazzar et al., 2016; Sana, 2013; Li et al., 2015), while the purpose of formulating the two-level supply chain with a supplier and two buyers (Roy et al., 2015) or two suppliers and one buyer (Hu et al., 2013) is to set the extra supplying member as the comparison counterpart. Of all constructed models, customers' demand is usually assumed as stochastic (Sana, 2011b; Roy et al., 2016). Besides, the other most commonly mentioned uncertainty factors, such as stochastic lead-time (Hayya et al., 2009) or stochastic selling price (Sana, 2011b) are usually discreetly assumed in different models, it would be very intractable when considering two random variables simultaneously Hayya et al. (2009). Moreover, related researches on the uncertainty factor like inventory inconsistencies in operations, are rare, our research would provide supplements to the literature of this realm.

When considering implement new technologies, different stakeholders in supply chain usually harbor different stands. Thus, such an undertaking induces numerous risks, such as security (Lee et al., 2011), investment scale (Uçkun et al., 2008) and credibility of information technology (Dutta et al., 2007). However, there have no clear discussions on the role of RFID in smoothing the supply chains. The coordination of stakeholders for collaborative investment in new technology is a proper means of achieving more benefits and decreasing risks (Lee et al., 2011). Hence, the implementation of RFID is largely affected by the actual attitude of the other stakeholder, hence, the considerable coordination work is evidently required, e.g. the buy-back price strategy, to deal with uncertainties in transactions (Dutta et al., 2016; Hou et al., 2010; Hu et al., 2013). Moreover, in the two-echelon supply chain established by Xu et al. (2012), four cases (i.e. shrinkage ignorance, error elimination, information sharing and RFID adoption) are compared to depict the different efforts that supply chain partners spend in reality to improve the supply chain cooperation level. Our research would provide a supplement research based on above outcomes.

Accordingly, by drawing the predecessors' implications on investigating inventory inaccuracy and new technologies adoptions, this research would contribute related literature in below aspects:

(1) Considering the inventory error plays a significant role in causing inventory waste, this research constructs analytical models to uncover the secrets of different scale RFID investment endeavors in decreasing the stochastic inventory errors under different supply chain coordination scenarios assuming the stochastic customer demand.

(2) In this study, in light of residual degrees of errors exist in practical RFID data collection (e.g. recognition failure), and the cost and effectiveness of different RFIDs (e.g. LF, HF and UHF RFID), a scale factor function is firstly introduced to illustrate the relationships of the variable cost of RFID and the *non-full* abilities of RFID in decreasing inventory errors.
(3) Numerical results are presented to provide a good illustration of the different impacts of RFID on smoothing the supply chain and decreasing inventory errors under different scenarios.
(4) A real case is introduced to demonstrate the benefits of adopting a RFID information system in recycling the plastic cases between a manufacturer and a retailer of a tobacco supply chain.

The remainder of this paper is organized as follows. Section 2 presents the basic notations of the problem and necessary parameters. Section 3 describes the RFID investment models under the uncoordinated supply chain scenarios. Section 4 introduces four strategies considering substantial coordination with the emphasis on RFID investment. Numerical examples and computational results are provided in Section 5, a practical RFID implementation case is presented in Section 6, and Section 7 cites the conclusions and recommendations for future research.

2. Notations and parameters description

In this section, a two-echelon single-period supply chain consisting of one retailer and two suppliers, is considered. Demand $D(\geq 0)$ is presented as a random variable with *pdf* $f(D)$ and *cdf* $F(D)$. For brevity, this study temporarily defines the domain of the errors as $(0,\infty)$.[1] The retailer (denoted by r) sells the items to customers at the price p per unit, where Q is the total order quantity of r. Supplier i (denoted by sp_i) manufacturers the item at the cost c_i per unit and then sells it to r at a wholesale price w_i ($i = 1{,}2$), obviously, $p > w_i > c_i$. All unsold items are salvaged at the value of s per unit. If the order quantity is larger than the demand of customers, holding cost (noted by h) is caused in the market leader's place, $s > h$ is assumed. The lost sale cost is l per unit once the available storage cannot satisfy the demand of customers.

When considering the inventory errors, the combined inventory expressions are illustrated as two cases, namely, the additive and multiplicative settings (Rekik, 2011), which are favored by researchers. In particular, Rekik (2011) adopted the additive setting to denote the physical and information system errors. Meanwhile, Xu et al. (2012) used two additive ratios α and β to model the inventory shrinkages. By referring to the expression of Heese (2007), this study adopts the multiplicative settings. Assuming random variable $e(>0)$ denote the multiplier of inventory errors in the supply chain with mean μ_e, the non-negative *pdf* and the *cdf* can be defined as $g(e)$ and $G(e)$, respectively. The domain of error multiplier is $(0,\infty)$.[2] Since inventory error exists, the stocks available for the customer are expressed as $\widehat{Q}$ and $\widehat{Q} = eQ$ (If $\widehat{Q} < D$, lost sale cost is caused, whereas if $\widehat{Q} > D$, the salvage cost is caused).

The results of predecessors' research on inventory operations reveal that the causes of inventory errors are differ. An instance is the inventory shrinkages in the cloth transactions: some types of cloth are procured by weight or batches, but sold by size, discretely. In such case, inventory inconsistency errors come out during these transactions and cannot be eliminated, even with RFID implemented. By contrary, other errors, (e.g., misplacement and data errors in system), can be perfectly rectified with RFID. In most cases, however, researchers usually assume that inventory errors are completely eliminated with RFID ($\widehat{Q} = Q$ or $e = 1$), e.g. Heese (2007), Uçkun et al. (2008), and Rekik (2011). Meanwhile, some other researchers consider that the inventory accuracy improvement through RFID is obtainable between 0 and 1, e.g. Gaukler et al. (2007) and Xu et al. (2012). By sharing these experience, in our study, $\delta(\delta > 0)$ is assumed as the scale factor for reducing inventory errors. Hence, the inventory available for sale changes from $\widehat{Q}$ to $\delta\widehat{Q}$, implying that if $\widehat{Q} < D$ or $\widehat{Q} > D$, $\widehat{Q} < \delta\widehat{Q} < D$ or $\widehat{Q} > \delta\widehat{Q} > D$ is obtained after adopting RFID. In the proposed system, r orders Q items from two sp_i s, and sp_i ($i = 1{,}2$) supplies r with Q_i, and $Q = Q_1 + Q_2$.

Let π, π_r and π_{spi} be the expected profits of the supply chain, r and sp_i, respectively. This study assumes RFID investment without considering the fixed cost, since these cost is usually audited in the long run, e.g. the hardware cost and the software cost. Similar to the discussions of Heese (2007), the cost of item-level RFID is largely driven by the cost of RFID tag, this study uses t to denote the cost of one piece of RFID tag. The leader of the supply chain generally shares the cost of RFID to promote its quick adoption. Let $\alpha(0 \leq \alpha \leq 1)$ be the fraction of the shared RFID cost at the retailer, which can be considered a kind of technology investment subsidy, and $(1-\alpha)t$ be the cost shared by two suppliers. If $\alpha = 0$, the suppliers are expected to endure the entire cost t. Contrarily, if the retailer bears the entire cost, then $\alpha = 1$.

In constructing RFID investment effective model, the relations of δ and t are usually neglected. In the current research, coarse relations of δ and t are assumed, but how to express of expressing such relationships has not been extensively explored by researchers. In practical applications, RFID is deployed with the capable of reducing inventory uncertainties. Nevertheless, the ability of RFID mainly depends on its deployment level (e.g., SKU, plate and item level investments). Hence, an exponential expression is designed to express the relations of δ and t: $\delta(t) = 1 - (\mu_e - 1)/\mu_e exp^{-\beta c/t}$, where exp is the exponent number, β is the expansion coefficient, a positive constant number, and c is the unit production cost of an item. The above expression demonstrates that, as a monotonic function, if no RFID investment is performed, $t = 0$. Subsequently, the scale factor is $\delta \to 1$, $\delta\mu_e \to \mu_e$, implying that no RFID contribution takes effect; if RFID tag cost $t \to \infty$, is $\delta \to \frac{1}{\mu_e}$, $\delta\mu_e \to 1$, which means that RFID contributes to 100% inaccuracy reduction.

On whether the similar expression has ever been adopted by other researchers, this study identifies that the exponential expression has been adopted by Lee and Lee (2010), in which the RFID efficiency improvement factor was considered a function of RFID investment. Based on the magnitude of μ_e is larger than 1 or not, the role of scale factor δ is shown in Fig. 1, and $\beta = 0.5$, $c = 5$.

3. RFID investment in the uncoordinated supply chain

3.1. Centralized situation

In the centralized situation (denoted by I), different parties are collectively integrated, compelling all of them into the same company (He and Zhang, 2008). Thus, the only objective of the supply chain is to maximize its entire profit. Let π^I and π_R^I denote the expected profits before and after RFID implementation, and by applying the Leibniz's formula, the optimal order quantity can be obtained by taking the first and second derivatives of expected profit π^I with respect to Q and let it equal to 0. If the two suppliers

[1] This domain can be replaced by the domain of the actual distribution.
[2] The same to 1.

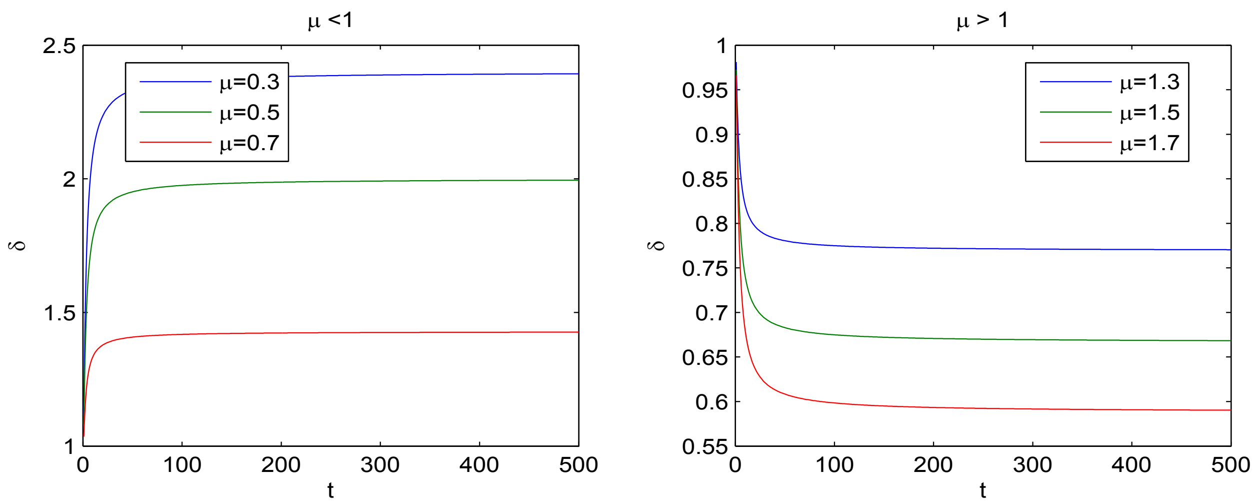

Fig. 1. Role of scale factor δ

are assumed to have the same production cost $c(c_1 = c_2 = c)$, then below expressions are achieved:

$$\pi^I = pE_{e,D}\left[min\left(\widehat{Q},D\right)\right] + sE_{e,D}\left[\left(\widehat{Q}-D\right)^+\right] - hE_{e,D}\left[\left(\widehat{Q}-D\right)^+\right] - lE_{e,D}\left[\left(D-\widehat{Q}\right)^+\right] - cQ \tag{1}$$

$$\pi_R^I = pE_{e,D}\left[min\left(\delta\widehat{Q},D\right)\right] + sE_{e,D}\left[\left(\delta\widehat{Q}-D\right)^+\right] - hE_{e,D}\left[\left(\delta\widehat{Q}-D\right)^+\right] - lE_{e,D}\left[\left(D-\delta\widehat{Q}\right)^+\right] - (c+t)Q \tag{2}$$

In Eq. (1), the first term is the expected profit, the second represents the expected salvaged value dues to over procurement, the third signifies the holding cost for over-supplying, and the fourth corresponds to the lost sales cost, and the last denotes the production cost. The terms in Eq. (2) are similar to those in Eq. (1) by adding RFID tag cost t and scale factor δ.

Lemma 1. *In the centralized supply chain, under the demand uncertainty and inventory record accuracy, the expected profit function, no matter RFID invest or not, is concave on Q.*

Proof Based on min(a,b) $= a-(a-b)^+$, the plus (+) notation denotes the formula equal to or greater than zero. Equation (1) can be written as:

$$\pi^I = pE_e[eQ] - (p-s+h)E_{e,D}\left[(eQ-D)^+\right] - lE_{e,D}\left[(D-eQ)^+\right] - cQ \tag{3}$$

By taking the first and second derivatives of Eq. (1) with respect to Q, the below formulas are acquired.

$$\frac{\partial\pi^I}{\partial Q} = p\mu_e - (p+h+l-s)\int_0^\infty eF(eQ)g(e)de - c \tag{4}$$

$$\frac{\partial^2\pi^I}{\partial Q^2} = -(p+h+l-s)\int_0^\infty e^2f(eQ)g(e)de \tag{5}$$

$f(x) > 0$ and $(p+h+l-s) > 0$. In this event, $\frac{\partial^2\pi^I}{\partial Q^2} < 0$, the expected profit function is concave on Q, an optimal value of expected profit exists. Similarly, the expected profit π_R^I under the RFID investment is concave on Q (the first and the second derivatives of π_R^I with respect to Q are $\delta p\mu_e - (p+h+l-s)\int_0^\infty \delta eF(\delta eQ)g(e)de - (c+t)$ and $-(p+h+l-s)\int_0^\infty (\delta e)^2 f(\delta eQ)g(e)de$, respectively).

π^N is evidently described as the expected profit function of the classic newsvendor or newsboy problem (Sana, 2012). The optimal order quantity is subsequently expressed as $Q^N = F^{-1}[(p-c)/(p+h+l-s)]$. This case is not considerably emphasized in the investigation. Based on Lemma 1, Corollary 1 presents the optimal order quantity before and after the implementation of RFID.

Corollary 1. In the centralized supply chain under the conditions of demand uncertainty and inventory record inaccuracy, if $p\mu_e \geq c$ and $p\delta\mu_e \geq c+t$, the optimal order quantity can be derived as $Q^* = H^{-1}[(p\mu_e-(c+t))/(p+h+l-s)]$ without RFID invested and $Q_R^{I*} = H_R^{-1}[(p\delta\mu_e-(c+t))/(p+h+l-s)]$ with RFID invested, where $H(Q) = \int_0^\infty eF(eQ)g(e)de$ and $H_R(Q) = \int_0^\infty \delta eF(\delta eQ)g(e)de$.

Proof. Based on the proof of Lemma 1, if $Q = 0$, Eq. (4) becomes $p\mu_e - c \geq 0$, specifying that the profit function is increasing; if $Q \to \infty$, Eq. (4) is less than zero, implying that the profit function is decreasing. Let Eq. (4) be equal to zero, obtaining $H(Q) = \int_0^\infty eF(eQ)g(e)de = (p\mu_e - c)/(p+h+l-s)$, from which the optimal order quantity Q^* is derived. Moreover, if $p\delta\mu_e \geq (c+t)$, the first derivative of π_R^I is taken with respect to Q under Eq. (2). Let this derivative be zero, acquiring $H_R(Q) = \int_0^\infty \delta eF(\delta eQ)g(e)de = (p\delta\mu_e-(c+t))/(p+h+l-s)$, from which optimal order quantity Q_R^{I*} is drawn.

Taking the second derivative of the expected profit function, we can find that the marginal profit difference does not only depend on the scale factor δ, but also on RFID tag cost and specific demand distributions, this particular subject must be thoroughly discussed.

3.2. Decentralized situation

In terms of decentralized situation, many coordination investigations have been conducted among different players under a two-echelon supply chain with uncertainty demand, such as the discussions of Inderfurth (2004) and He and Zhang (2008) on random yield problem, and Halati and He (2010) on random demand with fixed incentives. After RFID is introduced into the supply chain, researchers have tried to investigate the relationships of supplier and retailer under decentralized situations, such as the allocation of RFID tag cost between manufacturer and retailer (Gaukler et al., 2007) and RFID investment in a decentralized supply chain to improve inventory accuracy (Uçkun et al., 2008). Nevertheless, only a few researchers have examined the coordination of one retailer and two suppliers (Li et al., 2010; Hu et al., 2013), also the mechanism of collaborative investment in RFID to reduce inventory errors has not been explored yet.

Therefore, this study discusses the situations of the retailer dominates and does not dominate the relationships of all players. Correspondingly, the two suppliers play as either followers or leaders in the system. We also assume that if the two suppliers have exceedingly close market powers, they equally share the profits of the market. Contrarily, if the two suppliers have different market powers, the coordination strategies of the entire supply chain are quite different. Therefore, the coordination strategies of the supply chain under the specified situations should be discussed.

3.2.1. Two suppliers with close market powers

We assume that, when the two sp_i s (market followers) have close market powers, they own the same production cost c and equally share the profits (noted by *II*). Consequently, r provides the same wholesale price w and asks the two sp_i s to adopt RFID. For example, Wal-Mart, retained the sufficient power in the retailing market, requires its main suppliers to adopt RFID. In this situation, the leftover inventory is owned by the retailer, likes the VMI system, who receives the salvaged value s, but the leftover inventory induces holding cost h.

Therefore, the decision process consists of two steps: First, r offers the wholesale price w to two sp_i s, and orders Q items within the specified cost w. In the second stage, two sp_i s provide the r with the ordered items if the price can cover the production cost of them, otherwise, no supplying is offered. Thus, the expected profits of sp_i s and r after RFID (R) implementation are expressed as follows:

$$\pi^{II}_{sp,R} = \pi^{II}_{sp_1,R} + \pi^{II}_{sp_2,R} = [w - c - (1-\alpha)t]Q \tag{6}$$

$$\begin{aligned}\pi^{II}_{r,R} = {} & pE_{e,D}\left[min\left(\delta\widehat{Q},D\right)\right] + sE_{e,D}\left[\left(\delta\widehat{Q}-D\right)^{+}\right] \\ & - lE_{e,D}\left[\left(D-\delta\widehat{Q}\right)^{+}\right] - hE_{e,D}\left[\left(\widehat{Q}-D\right)^{+}\right] - (w+\alpha t)Q\end{aligned} \tag{7}$$

where $\widehat{Q} = eQ$. When $t = 0$ and $\delta = 1$, Eqs (6) and (7) are the situations that no RFID is adopted. Eq. (6) signifies the expected profits of two sp_i s. Meanwhile, the five given terms in Eq. (7) are the sales profit, the salvaged value, the lost sales cost, the holding cost and the purchasing cost. Corollary 2 provides the condition on the optimal order quantity.

Corollary 2. In the decentralized and retailer dominated supply chain with RFID invested situations, under the demand uncertainty and inventory record inaccuracy, if $p\delta\mu_e \ge w + \alpha t$, $w{-}c{-}(1{-}\alpha)t \ge 0$, and two suppliers have close market powers, the optimal order quantity can be derived as $Q^{*II}_R = H^{-1}_R((p\delta\mu_e - w - \alpha t)/(p+h+l-s))$ with RFID invested.

Proof. Similar to the proof of Corollary 1, the first derivative of Eq. (7) is taken with respect to Q, and is set as 0. If $p\delta\mu_e \ge w + \alpha t$ and $w{-}c{-}(1{-}\alpha)t \ge 0$, the best inventory level Q^{*II}_R is obtained with RFID investment $H(Q) = \int_0^\infty \delta eF(\delta eQ)g(e)de = (p\delta\mu_e - w - \alpha t)/(p+h+l-s)$ and $Q^{*II}_R = H^{-1}_R((p\delta\mu_e - w - \alpha t)/(p+h+l-s))$. Meanwhile, if $p\mu_e \le w + \alpha t$, the marginal profit of r is negative, implying that r will order nothing from the two suppliers, and if $w{-}c{-}(1{-}\alpha)t \le 0$, the marginal profits of two sp_i s are negative, indicating that supplying is not offered.

From the myopic view, r intends to provide a wholesale price slightly higher than the production cost ($w > c{-}(1{-}\alpha)t$), and each sp_i shares half of the profit $\pi^{II}_{sp,R}$. In the long run, however, their profits decrease to zero, r acquires the entire profit of the supply chain, conforming to the result of Eq. (2). In terms of the share of RFID cost, r obviously bears the entire RFID cost.

The results of the analyses on the marginal profits are quite different between the centralized and decentralized cases with RFID invested, which attests that in a short span of time, the only influential factor in the two situations is w. Under the decentralized situation, w is relatively higher than that in the centralized situation. Henceforth, Q in the decentralized situation is *smaller* than that in the centralized situation. In due course, when the market leader is r, who has the power in item pricing, w in the decentralized situation continuously drops to $c + \alpha t$, and r acquires the whole supply chain profits. When Q decreases, in terms of the total supply chain profits, the following expression can be drawn $\pi^{II}_R \le \pi^{I}_R$, where $\pi^{II}_R = \pi^{II}_{sp,R} + \pi^{II}_{r,R}$.

3.2.2. Two suppliers with different market powers

When the suppliers have different market powers (denoted by *III*), a main sp_1 and a backup sp_2 are assumed. These suppliers both receive the orders from the market leader r, who does not make a long-term contract with the two suppliers but sets the wholesale price as w. Accordingly, the expected profits are as follows:

$$\pi^{III}_{sp_i,R} = [w - c_i - (1-\alpha_i)t]Q_i \tag{8}$$

$$\begin{aligned}\pi^{III}_{r,R} = {} & pE_{e,D}\left[min\left(\delta\widehat{Q},D\right)\right] + sE_{e,D}\left[\left(\delta\widehat{Q}-D\right)^{+}\right] \\ & - lE_{e,D}\left[\left(D-\delta\widehat{Q}\right)^{+}\right] - hE_{e,D}\left[\left(\widehat{Q}-D\right)^{+}\right] - (w+\alpha_1 t)Q_1 \\ & - (w+\alpha_2 t)Q_2\end{aligned} \tag{9}$$

where $Q = Q_1 + Q_2$, $i = 1,2$. Based on Corollary 2, if $c_1 \le c_2$, Corollary 3 provides further discussions, in which r dominated the market and two sp_i s have different market powers.

Corollary 3. Based on the conditions in Corollary 2, in which two suppliers have different market powers, the below propositions can be drawn.

1)The total order quantity Q decided by r and the expected profit of the supply chain.

2)If $\alpha_1 Q_1 + \alpha_2 Q_2 \ge \alpha Q$, the expected profit of r is decreased as indicated in situation II, otherwise, the expected profit of r is increased.

3)If $w{-}c_1{-}(1{-}\alpha_1)t \ge w{-}c_2{-}(1{-}\alpha_2)t \ge 0$ the order quantity of sp_1 is larger than that of sp_2; otherwise, $w{-}c_2{-}(1{-}\alpha_2)t \ge w{-}c_1{-}(1{-}\alpha_1)t \ge 0$, it is smaller than that of sp_2; if $w{-}c_1{-}(1{-}\alpha_1)t \ge 0 \ge w{-}c_2{-}(1{-}\alpha_2)t$, the order quantity of sp_1 is Q, and that of sp_2

is 0; if $w-c_1-(1-\alpha_1)t \le 0 \le w-c_2-(1-\alpha_2)t$, the order quantity of sp_1 is 0, and that of sp_2 is Q; if $w-c_1-(1-\alpha_1)t \le 0$ and $w-c_2-(1-\alpha_2)t \le 0$, the order quantities of both suppliers are 0.

Proof. 1) Following the proof of Corollary 2, the first derivative of Eq. (9) is estimated with respect to Q. Consequently, the first conclusion is derived, $Q_R^{*II} = Q_R^{*III}$ is obtained; 2) By computing the differences of Eqs. (7) and (9), the result can be easily derived; 3) Based on Eq. (8), the marginal cost of sp_i (i = 1,2) is $w-c_i-(1-\alpha_i)t$, if the marginal cost of the two sp_i s is positive, the lower marginal cost who owns, the leading role who acquires in the supplying process, or who acquires more profit in the supplying side. The supplier, who faces the negative marginal cost, will lose the offer.

Corollary 3 demonstrates that the profits of suppliers largely depend on their own market powers. The marginal profits of sp_1 and sp_2 are $w-c_1-(1-\alpha_1)t$ and $w-c_2-(1-\alpha_2)t$, respectively. If the two results are equal, then $t=(c_1-c_2)/(\alpha_1-\alpha_2)$, because $t \ge 0$ and $c_1 \le c_2$, $\alpha_1 < \alpha_2$. These results indicate that: a) In the short run, the profit of each sp_i will be positively related to the order quantity required by *r*. b) In the long run, the main sp_1 will win the entire supplying 'contract'. c) Because *r* is the leader, benefits of the main sp_i are eventually close to zero when *w* continues to decrease down to the production cost.

3.2.3. The retailer is not the market leader

The characteristics of this system are: a) Suppliers provide *r* with the items by setting the proper w_i, while *r* decides to purchase the items from a particular supplier or both. b) Suppliers, as the system leader, receive the most profits and bear the risks of losing sales and holding cost. c) Inventory errors information of suppliers may be transparent to *r*, they can make some forecast on demand of customers according to historical data. Thus, the motivations for adopting RFID are mainly from the suppliers, who seek the equality between the benefits obtained from errors reduction and the cost of RFID tags.

In a competitive market, the two sp_i s' decisions on adopting RFID are primarily based on their market powers. Accordingly, this study investigates two sp_i s with different market influences (denoted by *IV*). In this case, *r* knows the strategies of suppliers in setting w_i s, and therefore decides the order quantity of the items. Meanwhile, the supplying quantities made by the two sp_i s largely depend on their own negotiation abilities. Based on these instances, the expected profit functions of *r* and two sp_i s are expressed as follows:

$$\pi_{r,R}^{IV} = pE_{e,D}[min(Q,\delta eQ,D)] - \sum_{i=1}^{2}(w_i+\alpha t)E_e[min(\delta eQ_i,Q_i)] \tag{10}$$

$$\pi_{sp_i,R}^{IV} = w_iE_e[min(\delta eQ_i,Q_i)] - h_iE_e\left[(\delta eQ_i-Q_i)^+\right] - l_iE_e\left[(Q_i-\delta eQ_i)^+\right] - [c_i+(1-\alpha_i)t]E_e[\delta eQ_i] \tag{11}$$

where $i=1,2$. Eq. (10) contains two terms, namely, the revenue of sales, and the ordering cost. Eq. (11) incorporates four terms, which are the sales profit, the holding cost, the lost sale cost, and the item and shared item-level RFID costs. The analyses of this study are facilitated with the introduction of the average wholesale price $\overline{w}$, then, $\overline{w} = (\sum_{i=1}^{2} w_iQ_i)/Q$, and $Q=\sum_{i=1}^{2}Q_i$. Consequently, the below Lemma 2 is achieved.

Lemma 2. $\pi_{r,R}^{IV}$ is concave on Q if and only if $(\delta e)^2 f(\delta eQ) > f(Q)$, and $\pi_{sp_i,R}^{IV} = KQ_i$, where K is determined not only by the marginal cost in III, but also by the inventory error distributions.

Proof. For $min(Q,\delta eQ,D) = Q-[Q-min(\delta eQ,D)]^+$, $min(\delta eQ,D) = \delta eQ-(\delta eQ-D)^+$, then $E_{e,D}[min(Q,\delta eQ,D)] = Q-E_{e,D}[(Q-(\delta eQ-(\delta eQ-D)^+))^+] = Q-E_{e,D}[(Q-\delta eQ+ \ (\delta eQ-D)^+)^+]$; for $E_e[min(\delta eQ_i,Q_i)] = Q_i[\delta\mu_e - \int_{1/\delta}^{\infty}(\delta e-1)g(e)de]$. Thus, Eqs (10) and (11) are derived as follows:

$$\pi_{r,R}^{IV} = p\left\{Q - \int_0^{1/\delta}\left(\int_0^{\delta eQ}(Q-D) + \int_{\delta eQ}^{\infty}(Q-\delta eQ)\right)f(D)dDg(e)de - \int_{1/\delta}^{\infty}\int_0^{Q}(Q-D)f(D)dDg(e)de\right\} - \sum_{i=1}^{2}(w_i+\alpha t)Q_i\left\{\delta\mu_e - \int_{1/\delta}^{\infty}(\delta e-1)g(e)de\right]\right\} \tag{12}$$

$$\pi_{sp_i,R}^{IV} = Q_i\left\{w_i\left(\delta\mu_e - \delta\int_0^{1/\delta}G(e)de\right) + \delta(h_i+l_i)\left(\int_0^{1/\delta s}G(e)de\right) - (c_i+(1-\alpha)t)\delta\mu_e\right\} \tag{13}$$

Initially, the first and second derivatives of $\pi_{r,R}^{IV}$ are taken with respect to Q, Subsequently, $\pi_{r,R}^{IV}$ is concave on Q if and only if $(\delta e)^2 f(\delta eQ) > f(Q)$. In this case, $K_0 = \delta\mu_e - \int_{1/\delta}^{\infty}(\delta e-1)g(e)de$, where the marginal profit of sp_i is $K = w_iK_0 - \ (h_i+l_i)(\delta\mu_e - K_0) - (c_i+(1-\alpha)t)\delta\mu_e$.

$$\frac{\partial\pi_{r,R}^{IV}}{\partial Q} = p\left\{1 - \int_0^{1/\delta}\left[F(\delta eQ) + Q(1-\delta e)\delta ef(\delta eQ) - (1-\delta e)F(\delta eQ) - Q(1-\delta e)\delta ef(\delta eQ)\right]g(e)de + \int_0^{1/\delta}F(Q)g(e)de\right\}\overline{w}K_0 - \alpha t$$
$$= p\left\{1 - \int_0^{1/\delta}\delta eF(\delta eQ)g(e)de + \int_0^{1/\delta}F(Q)g(e)de\right\} - \overline{w}K_0 - \alpha t$$

$$\frac{\partial^2\pi_{r,R}^{IV}}{\partial Q^2} = -p\left\{\int_0^{1/\delta}\left[(\delta e)^2 f(\delta eQ) - f(Q)\right]g\left(e\right)de\right\}$$

Corollary 4. In the situations of decentralized and retailer non-monopolized supply chain with RFID invested, under conditions of demand uncertainty and inventory record inaccuracy, based on the conditions in Lemma 2, if $p \ge \overline{w}K_0$, the optimal order quantity is

$Q^* = (H^{IV})^{-1}\left(\frac{p-\overline{w}K_0-\alpha t}{p}\right)$, where $H^{IV}(Q) = \int_0^{1/\delta}[\delta eF(\delta eQ) - F(Q)]g(e)de$, $K_0 = \delta\mu_e - \delta\int_0^{1/\delta}G(e)de$, $\overline{w} = (\sum_{i=1}^{2} w_iQ_i)/Q$, and $Q = Q_1 + Q_2$.

Proof. The proof is similar to that of Lemma 2.

After the optimal order quantity of the supply chain is determined, the optimal expected profits of r and two sp_i s can be obtained. Two sp_i s are expected to maintain a stable supplying if the marginal profit K is larger than zero. Moreover, two sp_i s may have the impetus to adopt new technology if the marginal cost can be decreased. Meanwhile, retailer r asks sp_i to supply Q_i items according to his forecast on the demand of customers and the inventory errors knowledge of sp_i. If the market leader is sp_i, who only knows his own inventory errors information. In this event, the supplying arrangement of sp_i is prepared according to this information. Therefore, sp_i makes his decisions according to his judgment on the inventory errors. Accordingly, investment in RFID to reduce these uncertainties is the driving force for the supplier to make investment decisions.

4. RFID investment in the coordinated supply chain

Numerous researchers have studied the supply chain coordinations (Qu et al., 2015), particularly the one concerning multi-suppliers (Minner, 2003). In particular, Li et al. (2010) discussed the sourcing strategies with a single retailer and two unreliable suppliers and modeled the order up to level policy and the best responses of the two suppliers in the centralized supply chain when common cause failures were considered. In the current research, when a supply chain endures uncertain demand and inventory errors, different coordination strategies are adopted to enhance the partnerships between the retailer and the two suppliers. RFID, as the core technology of supply chain of things and terminal technology in data collection, is adopted to decrease the risks of uncertainties in supply chain management. Subsequently, four supply chain coordination strategies are introduced to examine RFID investment effects.

4.1. Main supplier strategy

In this part, r is assumed to make a contract with sp_1 (a cheaper, but unreliable main supplier), but not with sp_2 (a reliable, but more expensive supplier for backup). This strategy is depicted as the main supplier strategy, noted by MS. Retailers generally pursue a long-term contract with their best supplier to maintain a stable supply chain, especially when inventory errors exist. This issue has been assessed by researchers, such as He and Zhang (2008), Hou et al. (2010), and Hu et al. (2013). In these models, an emergency order from the spot market or its original back-up supplier are usually assumed.

The information on the retailing process is transparent between r and sp_1 when they compose a long-term contract. The main supplier sp_1 makes his own decisions according to the uncertain demand and his own inventory position and subsequently faces the under- and over-supplying risks. When sp_1 encounters the under-supplying cost, r orders from sp_2 at a higher price ($w_2>w_1$); otherwise, r orders 0 from sp_2. In this case, the decision process is that the order quantity in the system is $Q = Q_1$; if $\delta eQ_1<Q_1$, the order quantity of r from sp_1 is δeQ_1, from sp_2 is $Q_1-\delta eQ_1$; otherwise, if $\delta eQ_1\geq Q_1$, the order quantities of r from sp_1 and sp_2 are Q_1 and 0, respectively. The expected profit functions are expressed below.

$$\pi^{MS}_{sp_1,R} = w_1E_e[min(\delta eQ_1, Q_1)] - h_1E_e\left[(\delta eQ_1 - Q_1)^+\right] - l_1E_e\left[(Q_1 - \delta eQ_1)^+\right] - [c_1 + (1-\alpha_1)t]E_e[\delta eQ_1] \quad (14)$$

$$\pi^{MS}_{r,R} = pE_D[min(Q, D)] - (w_1 + \alpha_1 t)E_e[min(\delta eQ_1, Q_1)] - (w_2 + \alpha_2 t)Q_2 \quad (15)$$

$$\pi^{MS}_{sp_2,R} = [w_2 - c_2 - (1-\alpha_2)t]E[Q_2] \quad (16)$$

where $Q = Q_1$ and $Q_2 = Q_1(1-\delta e)^+$. Eq. (14) is derived from Eq. (11), and $E_D[min(Q,D)] = Q - \int_0^Q F(D)dD$. By taking the derivative of Eq. (15) with respect to Q and is set to 0, Corollary 5 is obtained.

Corollary 5. In the main supplier contracted supply chain, the expected profit function $\pi^{MS}_{r,R}$ of r is concave on Q, and the optimal order quantity is $Q^* = F^{-1}\left(\frac{p-K_0(w_1+\alpha_1 t)-(w_2+\alpha_2 t)(\delta\mu_e-K_0)}{p}\right)$ if and only if $p\geq(w_1 + \alpha_1 t)K_0 + (w_2 + \alpha_2 t)(\delta\mu_e-K_0)$, where $K_0 = \delta\mu_e - \int_{1/\delta}^{\infty}(\delta e - 1)g(e)de$.

Proof. The proof is similar to that of Corollary 4.

Based on Corollary 5, the order quantities from the two suppliers are if $\delta e \geq 1$, the order quantity of r from sp_1 is $Q_1 = Q^*$, from sp_2 is 0, otherwise, the order quantity of r from sp_1 is $Q_1 = \delta eQ^*$, from sp_2 is $(1-\delta e)Q^*$. The corresponding expected profits are $\pi^{IV}_{r,R} = p(Q^* - \int_0^{Q^*}F(D)dD) - (w_1 + \alpha_1 t)Q^*$, $\pi^{MS}_{sp_1,R} = w_1K_0Q^* - h_1(\delta\mu_e - K_0) - [c_1 + (1-\alpha_1)t]\delta\mu_eQ^*$, $\pi^{MS}_{sp_2,R} = 0$, and $\pi^{IV}_{r,R} = p(Q^* - \int_0^{Q^*}F(D)dD) - (w_1 + \alpha_1 t)K_0Q^* - (w_2 + \alpha_2 t)\delta Q^*(\delta\mu_e - K_0)$, $\pi^{MS}_{sp_1,R} = w_1K_0Q_1^* - l_1Q_1^*\int_0^{1/\delta}(1-\delta e)g(e)de - [c_1 + (1-\alpha_1)t]\delta\mu_eQ_1^*$, $\pi^{MS}_{sp_2,R} = [w_2 - c_2 - (1-\alpha_2)t]Q^*(\delta\mu_e - K_0)$, respectively.

Accordingly, the expected profits depend on the inventory error distribution and RFID effectiveness. The visibility of the supply chain has been improved for providing min(Q,D), but not $min(Q, \widehat{Q}, D)$. However, because the existed risks in inventory errors are rooted from the main supplier, the *supply chain cooperation* still remains at an unstable level. In this case, sp_2 is assumed to adopt RFID. If sp_2 does not adopt RFID, then $\alpha_2 = 0$, which signifies that r solely bears the cost of RFID investment in the retailing sector. Thus, r is preferred to subsidize sp_2 to adopt RFID, in this case, the scaling factor α_2 is considered as the subsidy rate.

Risk sharing is one of the most common strategies for supply chain coordination (Hu et al., 2013). In this study, the coordination processes of under-supplying (US) and over-supplying (OS) cost sharing are modeled by the retailer when underproduction and overproduction occur in the two suppliers because inventory errors exist, particularly after RFID is adopted.

4.2. Main supplier strategy with under-supplying risk sharing

In this case, penalty strategy is applied and is transferred from the lost sales to the penalty cost of the under-supplying suppliers, as discussed by He and Zhang (2008). The under-supplying model presented below is quite similar to that under the MS strategy, except for the added expected profit function into the penalties from the suppliers. In this process, r decides on the number of items he should order from sp_1 and sp_2 with uncertain demand (Q).

Consequently, sp_1 supplies r with the ordered items according to his demand estimations and inventory errors; if under-supplying occurs, sp_1 has to bear the penalty cost.

$$\pi^{US}_{r,R} = pE_{e,D}[min(Q,D)] - (w_1 + \alpha_1 t)E_e[min(\delta eQ_1, Q_1)] - (w_2 + \alpha_2 t)Q_2 + p_e E_e\left[(Q_1 - \delta eQ_1)^+\right] \quad (17)$$

$$\pi^{US}_{sp_1,R} = w_1 E_e[min(\delta eQ_1, Q_1)] - h_1 E_e\left[(\delta eQ_1 - Q_1)^+\right] - p_e E_e\left[(Q_i - \delta eQ_i)^+\right] - [c_1 + (1-\alpha_1)t]E_e[\delta eQ_1] \quad (18)$$

In this research, the penalty cost per unit is set as p_e and $p_e \geq w_1$. Three terms of Eq. (17) are the profit of sales, the purchasing cost and the penalties acquired from sp_1, respectively. The expected profit function of sp_2 is similar to that in Eq. (16). Based on Lemma 2 and Corollary 4, $K_1 = E_e[(Q_1 - \delta eQ_1)^+] = \delta Q_1 \int_0^{1/\delta}(1-\delta e)g(e)de$, Therefore, Corollary 6 is deduced below.

Corollary 6. In the decentralized supply chain with RFID invested, under the similar conditions in Lemma 2, if $p \geq K_0(w_1 + \alpha_1 t) + [(w_2 + \alpha_2 t) - p_e](\delta\mu_e - K_0)$, $Q^* = (F^{US})^{-1}\left(\frac{p - K_0(w_1+\alpha_1 t) - [(w_2+\alpha_2 t)](\delta\mu_e - K_0) + p_e K_1}{p}\right)$, where $K_0 = \delta\mu_e - \int_{1/\delta}^{\infty}(\delta e - 1)g(e)de$, $K_1 = \int_0^{1/\delta}(1-\delta e)g(e)de$, and $F^{US}(Q)$ is the cdf of demand when under-supplying transpires.

Proof. The proof is similar to that of Corollary 4.

The comparative results of Corollaries 5 and 6 demonstrate that, when $p_e = 0$, the optimal order quantity of the supply chain in the latter is similar to that in the former. Nevertheless, when r receives the penalties from sp_1, the expected profit of r is regained. Based on Eq. (18), the marginal profit of sp_1 is $w_1K_0 - h_1(\delta\mu_e - K_0) - p_e K_1 - (c_1 + (1-\alpha_1)t)\delta\mu_e$. By comparing this marginal profit with that specified in Section 3.2.3, this study identifies that the changes of the expected profit of sp_1 are largely reflected in the transformation of opportunity and penalty costs. Therefore, under-supplying risk sharing is realized, depending on the negotiation abilities of the supply chain players. However, under-supplying risks still challenge the stability of the supply chain.

4.3. Main supplier strategy with over-supplying risk sharing

A retailer maintains a stable supplying by generally sharing a part of the cost via procuring the overproduced items from his suppliers at a lower cost w_o. In this case, $w_o < c_1$, which illustrates that the overproduction items are sold by the supplier at a discount price w_o. Meanwhile, w_o is smaller than the maximum production cost c_1, otherwise, the supplier produces unlimited products. The expected profit functions of r and sp_1 are described below.

$$\pi^{OS}_{r,R} = pE_{e,D}[min(Q,D)] - (w_1 + \alpha_1 t)E_e[min(\delta eQ_1, Q_1)] - (w_2 + \alpha_2 t)Q_2 - w_o E_e\left[(\delta eQ_1 - Q_1)^+\right] \quad (19)$$

$$\pi^{OS}_{sp_1,R} = w_1 E_e[min(\delta eQ_1, Q_1)] + w_o E_e\left[(\delta eQ_1 - Q_1)^+\right] - l_1 E_e\left[(Q_1 - \delta eQ_1)^+\right] - [c_1 + (1-\alpha_1)t]E_e[\delta eQ_1] \quad (20)$$

The expected profit function of sp_2 is similar to that in Eq. (14). The first three terms of Eq. (19) are similar to those of Eq. (17), while its last term is the expected discount cost for the retailer. The above two equations indicate that the supply chain profits remained the same, but the profits of suppliers increased because the over holding cost has been transferred to the retailer. Meanwhile, the profit of r is decreased by ordering the overproduced items. For $E_e[(\delta eQ_1 - Q_1)^+] = Q_1(\delta\mu_e - K_0)$, the optimal order quantity of OS can be expressed as follows:

Corollary 7. In the decentralized supply chain with RFID invested, under the similar conditions in Lemma 2, the optimal order quantity is $Q^* = (F^{OS})^{-1}\left(\frac{p - K_0(w_1+\alpha_1 t) - [(w_2+\alpha_2 t) + w_o](\delta\mu_e - K_0)}{p}\right)$, if $p \geq K_0(w_1 + \alpha_1 t) + [(w_2 + \alpha_2 t) + w_o](\delta\mu_e - K_0)$, where $K_0 = \delta\mu_e - \int_{1/\delta}^{\infty}(\delta e - 1)g(e)de$ and $F^{OS}(Q)$ is the cdf of demand when over-supplying occurs.

Proof. Similar to the proof of Corollary 4.

By comparing Corollary 7 and 6, this study determines that, when $w_o = 0$, the optimal order quantity of the supply chain is similar to that in Corollary 4. Nevertheless, the expected profit of r is decreased when he pays the over-supplying cost to sp_1. Based on Eq. (20), the marginal profit of sp_1 is $w_1K_0 - K_1 l_1 + w_0(\delta\mu_e - K_0) - (c_1 + (1-\alpha_1)t)\delta\mu_e$. The comparative result reveals that the expected profits of the players largely depend on the magnitude of holding cost and the discounted wholesale price. Under this condition, if r asks sp_1 to supply enough items according to their capacity, the over-supplying risk is caused due to the over holding inventory in sp_1. Moreover, if the per unit discount price is lower than the item production cost, the under-supplying risk is induced.

Therefore, the overall profit of the supply chain remains constant, and the strategies for processing the under and over-supplying risks affect the profits of the players. Based on the above propositions, this study attests that the above two coordination strategies are mainly constructed on the monopolistic ability of the supplier, who has the market power to transfer his risk to the retailer. However, the premise of the coordination strategies being successfully performed lies in that two main players (r and sp_1) cooperate in the supplying process, given that two suppliers exist. Otherwise, the above-stated strategies cannot maintain a stable supply chain for a long time.

4.4. An integrated coordination strategy

In this section, a new integrated coordination strategy (IS) is proposed, in which the US, OS, and MS are combined. The retailer can develop a more stable partnership by negotiating with a supplier and sharing with the risks of that supplier when over-supplying occurs. Meanwhile, if under-supplying transpires, the retailer receives the penalties from the main supplier and purchases the items from a backup supplier at a higher price. In this case, r and sp_1 are both motivated to adopt RFID to increase their profits. That is, r intends to provide his customers with a stable service, and sp_1 desires to increase his profits and occupy the entire market by eliminating uncertainties.

With RFID (R) investment, sp_1's expected profit is:

$$\pi^{IS}_{sp_1,R} = w_1 E_e[min(\delta eQ_1, Q_1)] + w_o E_e\left[(\delta eQ_1 - Q_1)^+\right] - p_e E_e\left[(Q_1 - \delta eQ_1)^+\right] - [c_1 + (1-\alpha_1)t]E_e[\delta eQ_1] \quad (21)$$

Eq. (21) includes three items, which are the $sp_1^{\prime}s$ profit of sales, the discount profit of over-supplying, and the penalty cost of under-supplying. In this case, $p_e > w_o$ is assumed to guarantee r keep a relatively stable supplying. The expected profit of r is:

$$\pi^{IS}_{r,R} = pE_{e,D}[min(Q,D)] - \{(w_1+\alpha_1 t)E_e[min(\delta e Q_1, Q_1)] + (w_2+\alpha_2 t)Q_2\} - w_o E_e\left[(\delta e Q_1 - Q_1)^+\right] + p_e E_e\left[(Q_1 - \delta e Q_1)^+\right] \tag{22}$$

Eq. (22) incorporates four items, namely, the profit of sales, order cost, discounted ordering cost, and the penalties acquired from sp_1 for under-supplying. And $sp_2's$ expected profit function is equal to Eq. (16). Here $Q = Q_1$ and $Q_2 = Q_1(1-\delta e)^+$. The coordination process of the supply chain is constructed considering the under and over-supplying from sp_1 to r. Based on the former corollaries, the below results can be derived.

Corollary 8. In the integrated supply chain strategy, the expected profit function of r $\pi^{IS}_{r,R}$ is concave on Q, and its optimal order quantity is $Q^* = F^{-1}([p-(w_1+\alpha_1 t)K_0-(w_2+\alpha_2 t+w_o)(\delta\mu_e - K_0)+p_e K_1]/p)$, if and only if $p \geq (w_1+\alpha_1 t)K_0+(w_2+\alpha_2 t+w_o-p_e)(\delta\mu_e - K_0)de)$, where $K_0 = \delta\mu_e - \int_{1/\delta}^{\infty}(\delta e-1)g(e)de$ and $K_1 = \int_0^{1/\delta}(1-\delta e)\, g(e)de$.

Proof. Similar to the proof of Lemma 2 and Corollary 4.

The optimal order quantity Q^* of r from two suppliers is given with the following conditions, if $\delta e \geq 1$, the order quantities of r from sp_1 and sp_2 are $Q_1 = Q^*$, and $Q_2 = 0$, respectively. Otherwise, the order quantities of r from sp_1 and sp_2 are $Q_1 = \delta e Q^*$ and sp_2 is $(1-\delta e)Q^*$, respectively. Consequently, the corresponding expected profit of r is $\pi^{IV}_{r,R} = p(Q^* - \int_0^{Q^*}F(D)dD) - (w_1+\alpha_1 t)Q^* - w_o Q^*(\delta\mu_e - K_0)$, $\pi^{MS}_{sp_1,R} = w_1 Q_1^* + w_o Q^*(\delta\mu_e - K_0) - [c_1+(1-\alpha_1)t]\delta\mu_e Q_1^*$, and $\pi^{MS}_{sp_2,R} = 0$ if $\delta e \geq 1$; otherwise $\delta e < 1$, $\pi^{IV}_{r,R} = p(Q^* - \int_0^{Q^*}F(D)dD) + p_e K_1 Q^* - (w_1+\alpha_1 t)\delta\mu_e Q^* - (w_2+\alpha_2 t)K_0 Q^*$, $\pi_{sp_1,R^{MS}} = w_1 Q^* - p_e K_1 Q^* - [c_1+(1-\alpha_1)t]\delta\mu_e Q^*$, and $\pi^{MS}_{sp_2,R} = [w_2 - c_2 - (1-\alpha_2)t]Q^* K_0$.

5.. Model analysis

5.1. Robustness analysis with different distribution combinations

Different distributions (e.g., the uniform distribution and the exponential distribution in Inderfurth (2004) and Heese (2007)) show varying properties in analytical models with uncertain demand, and the adherence to normal distribution may not be an ideal premise for simulating inventories (Wanke, 2008). Therefore, the specific demand and inventory inaccuracy distributions can affect the actual properties of RFID investment. These are the reasons why this study examines the models under different distribution combinations. However, since many *cdf* and *pdf* functions (e.g., normal and gamma distributions) are not integral ones, the candidate distributions of this study are only limited to the exponential (λ) and uniform distributions (u). Moreover, exponential *pdf* only has a single parameter λ, and uniform *pdf* has no other additional parameters. Thus, the two distributions and their different combinations are adopted to lead the analysis.

The optimal ordering quantities of the proposed models under different combinations are first tested. The adopted *pdf* of the exponential distribution is $f(x;\lambda) = \lambda exp^{-\lambda x}$, $x > 0$. The domains of the demand and the error are set as [$\underline{D}$ and $\overline{D}$] [$\underline{e}$, $\overline{e}$], respectively. Meanwhile, the illustrative combination for the two variables is set as (demand, inventory errors). The remaining parameters are set as follows, $p = 50$, $c = 10$, $s = 5$, $h = 3$, $l = 15$, $w = 20$, $t = 5$, $\alpha = 0.5$, $\beta = 0.5$, $p_e = 25$, $w_o = 8$, w_i(18,22), α_i(0.5,0.5), and c_i(10,10), the numbers in brackets are the initial value of two suppliers. The computation results are shown in Table 1.

Two points can be derived from Table 1: (1) From the overall aspect, RFID investment affects the optimal order quantities. After RFID is adopted, the optimal order quantities with demand combination (u,u) move closer to the mean value of demand when that of inventory errors is less than 1 and vice versa. By contrary, the situation of (u,λ) is relatively different, in which the optimal order quantities are closer to the mean of demand when that of inventory errors is larger than 1 and vice versa. Evidently, the situation of (u,λ) is different from those of (u,u) and (u,λ); yet, all optimal order quantities move closer to the mean value of demand after RFID is adopted regardless whether the mean value of inventory errors is larger than 1 or not. (2) Changes are observed in the optimal order quantities under different combinations. In particular, multiple relations are identified when both the domains of the two variables are doubled.

Another important aspect of implementing RFID lies in that RFID investment can influence the profits of all parties. This study also determines whether the different distribution combinations affect expected profit and if the stability of the models under different distribution combinations shows the same properties. To ease of analyses, the existence of negative profits is allowed. After that the investigations are performed with respect to the above combinations. The computation results are given in Table A.1.

The results in Table A.1 illustrate that implementing RFID can decrease the uncertainties in order quantities. However, the ability of this technology in increasing supply chain profits is rather questionable. The supply chain profit in almost all models is decreased with RFID investment. By thoroughly investigating these results, however, this study determines that the level of the supply chain coordination is improved after RFID is introduced. For example, the profits of sp_1 in (u,u) when [$\underline{D}$, $\overline{D}$] and ($\underline{e}$, $\overline{e}$) are [0, 1000] and (0, 1), respectively. Due to RFID adoption, the profits in MS, US, OS, and IS scenarios are improved from −2870, −9095, −2870, and −6420 to −1971, c5811, −1130, and −2201, respectively. The higher profit of r is shared by sp_1 and sp_2. Therefore, the alleviated cases with RFID investment make the supply chain more stable than those without RFID investment. Moreover, the main reason for the supply chain profit decreasing is that RFID cost is transferred to the selling price since the selling price in the retailer is assumed unchanged.

From the overall aspect, the expected profit under supply chain coordinated situations is larger than that without coordination initiative. When coordination does not exist, the optimal order quantity in the centralized situation is moderately larger than that in the decentralized situation. For the case that the retailer negotiates with a main supplier under the over-supplying strategy, the optimal order quantity is the smallest; otherwise, it is the largest under the under-supplying strategy. Meanwhile, under the integrated strategy, the benefit function formulation absorbs the superiority of the above two strategies, and its optimal order quantity lies between those results under such strategies.

In the next section, the parameter analysis is endeavored to investigate the effectiveness of these elements on each supply chain player.

5.2. Sensitivity analysis

By testing different distribution combinations, this study

Table 1
Optimal order quantity under different distribution combinations.

	$[\underline{D}, \overline{D}]$, $(\underline{e}, \overline{e})$	I		II & III		MS		US		OS		IS	
		Q^*	Q_R^*	Q^*	Q_R^*	Q^*	Q_R^*	Q^*	Q_R^*	Q^*	Q_R^*	Q^*	Q_R^*
(u,u)	[0,1000],(0,1)	714	488	238	298	820	714	1070	906	820	715	1070	898
	[0,1000],(1,2)	442	449	374	383	420	437	420	422	340	366	340	370
	[0,2000],(0,1)	1429	977	476	595	1640	1428	2140	1812	1640	1430	2140	1796
	[0,2000],(1,2)	884	898	748	765	840	875	840	845	680	732	680	740
$(u,\lambda$: 0.5, 1.5, 0.5, 1.5)	[0,1000],(0,∞)	179	198	159	176	159	235	265	361	0	44	23	170
	[0,1000],(0,∞)	417	312	238	216	757	674	998	891	751	669	992	886
	[0,2000],(0,∞)	357	397	317	352	317	471	530	723	0	89	45	341
	[0,2000],(0,∞)	833	623	476	432	1514	1348	1996	1781	1502	1339	1984	1772
(λ: 0.001, 0.001, 0.002, 0.002, u)	[0,∞),[0,1]	–	–	–	–	1715	1257	∞	2286	1715	1230	∞	2212
	[0,∞),[1,2]	–	–	–	–	545	570	223	578	415	482	415	489
	[0,∞),[0,1]	–	–	–	–	857	628	∞	1143	857	615	∞	1106
	[0,∞),[1,2]	–	–	–	–	272	285	272	288	208	241	208	245

Scenario IV and '–' means no value exists.

identifies that the combination of (u,u) slightly shows intuitive results and can be easily calculated and evaluated. Moreover, this particular combination has been preferred by Heese (2007) and He and Zhang (2008) in their papers to obtain analytically tractable and crisp results. The analysis of this study presented below is conducted under the (u,u) combination. The parameters selling price, wholesale price, holding cost, unit under-supplying penalty, and over-supplying discount price are expected to influence the optimal order quantity and corresponding expected profit. The effectiveness of these parameters on the performance of supply chain must be examined.

The direct and substantial effect of RFID investment is the decreasing of inventory errors, which is eventually reflected in the optimal order quantity. Camdereli and Swaminathan (2010) and Hosoda and Disney (2012) initially focused on the optimal ordering quantities and not on the expected profit because several parameters induce combined influences. The profit analysis of the current research on RFID investment effectiveness is mainly elucidated in the next part. In particular, the analysis is expedited by classifying the above-constructed scenarios as coordinated and uncoordinated scenarios. The tested parameters are those with global effects, including the selling price and mean value of the inventory errors, RFID cost, and RFID investment effectiveness related parameters, α and β.

5.2.1. Parameter analysis: selling price

Table 1 depicts that the optimal order quantity becomes larger after RFID is adopted in the uncoordinated scenarios. Is this situation similarly occurring in the coordinated scenarios? The expected profit function is a linear function of price; hence, its properties can be predicted from the price. In this case, the optimal quantity is exhaustively explored instead of the expected profit. The initial price is set as $p = w = 20$, the largest price is 100, and the other parameters are kept unchanged. The relations of the optimal order quantity are changed, and the selling price is increased, as indicated in Fig. 2.

The optimal order quantity is greatly influenced by the two kinds of inventory errors. When $\mu_e < 1$, which implies that inventory errors (e.g., misplacement) exist, the inventory record is larger than the actual inventory supplying ability because misplaced items cannot be immediately identified. Moreover, if the order quantity in another ordering cycle is reallocated according to the estimation of inventory errors and demand, serious over-Tuesday, November 8, 2016 5:30 pmholding risk is induced in the warehouse. Till then, inventory errors may $\mu_e > 1$. The results of the research model reveal that the optimal order quantity is higher when the selling price is higher, particularly when prices are increasing.

Therefore, the actual order quantity in the current ordering cycle should be decreased after RFID adopted, see the uncoordinated situation (the left two small figures) in Fig. 2 when μ_e<1 and μ_e>1. Specifically, in the coordinated supply chain, the optimal order quantity in the case of $\mu_e < 1$ is quite different from that when $\mu_e \geq 1$. When $\mu_e < 1$, the optimal order quantity with RFID implemented is larger than that without RFID implemented, but the optimal order quantities in different coordination strategies approach to a stable value. When $\mu_e \geq 1$, the optimal order quantity without RFID implemented is smaller than that with RFID implemented. These results testify that RFID investment ease the over and under inventory situation.

With the linear function of p, this study determines that the changes of expected profit are quite similar to those of price. For example, the directly perceived changes are acquired from the uncoordinated decentralized supply chain, and the expected profits of r, sp_1, and sp_2 as well as the supply chain are altered from 5119, 1190, 1190, and −2378 to −2705, 1116, 1116, and −472, respectively with the combinations of [0, 1000] and [0,1]. In the coordinated situation, the expected profits of r, sp_1, sp_2, and the supply chain in IS strategy before and after RFID is implemented are modified from 28,623, to 6420, 0, and 22,203 to 19,822, −2201, 422, and 18,043, respectively. Accordingly, the expected profits are realized reallocation among different players.

This study also investigates the effects of the wholesale price. In particular, the wholesale price ($c \leq w \leq p$) of the two suppliers is assumed changed from 10 to 50. The findings specify that, when wholesale price increases, the optimal order quantities linearly decrease in all scenarios, except in the centralized situation. The only differences of the optimal order quantities before and after RFID implementation lie in the changing curve slopes.

5.2.2. Parameter analysis: mean value of inventory errors

Some results presented above signify that inventory errors affect the results of the optimal order quantity. Consequently, a new question emerges as that 'how do the changing inventory errors influence the optimal order quantities?'. As the most important characteristic parameter in representing inventory inaccuracy, the changes of mean value of the inventory errors are shown in Fig. 3, where the domain of μ_e is [0, 2].

In the uncoordinated supply chain (the left sub-figure in Fig. 3), all the optimal order quantities show slightly different features because μ_e increases when $\mu_e < 1$. Nevertheless, when μ_e goes beyond 1.5, all optimal order quantities attain a fixed value (0) regardless if RFID is implemented or not. When $\mu_e < 1$, the optimal order quantity in the centralized supply chain first experiences a

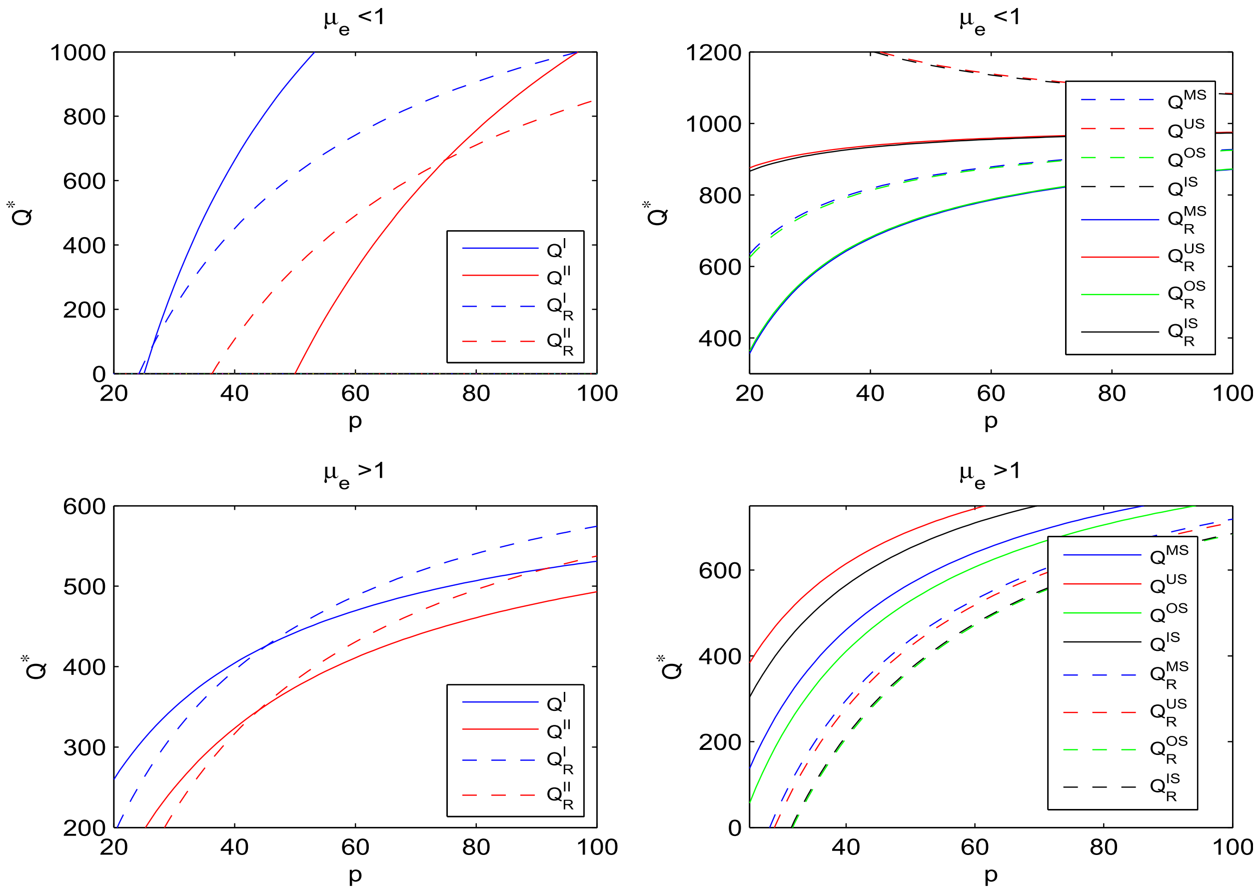

Fig. 2. Effects of price fluctuations on the optimal order quantity.

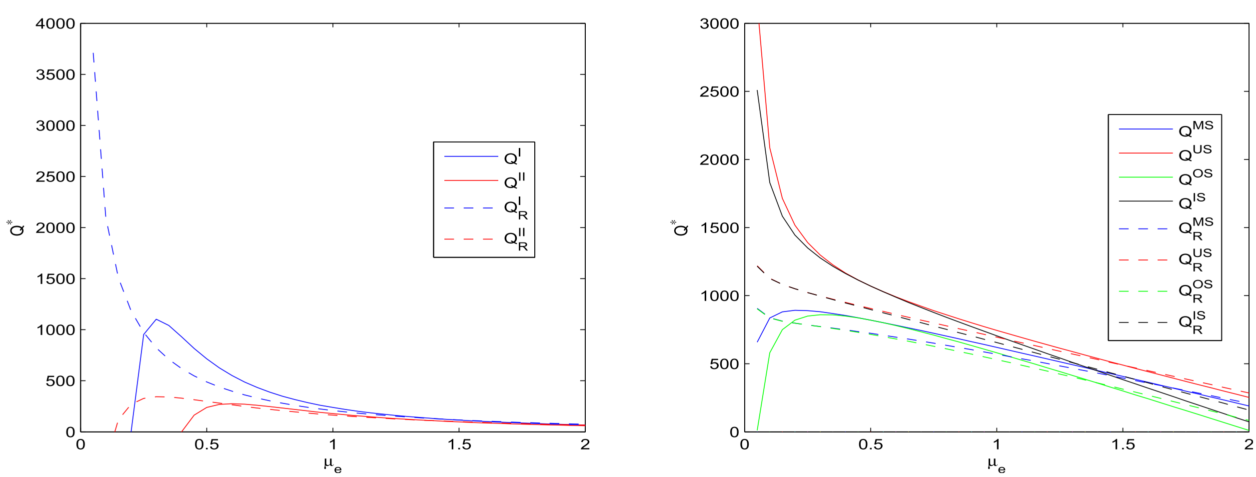

Fig. 3. Fluctuations of mean value on the optimal order quantity.

sharp increase before RFID is implemented. Subsequently, this order quantity slowly decreases. These trends are also observed in the decentralized case. After RFID is implemented, the optimal order quantity smoothly decreases. From the uncoordinated supply chain (the left small figure in Fig. 3), the extreme situation is alleviated with RFID implementation. In more extreme situations, particularly when $\mu_e \rightarrow 0$, the optimal order quantity without RFID is 0. The system receives a positive order after RFID is implemented.

Fig. 3 demonstrates that one of the most important features of implementing RFID is that it relieves the pressures of the supply chain in extreme situations by decreasing inventory errors. Moreover, Fig. 3 specifies that the implementation of RFID in decreasing inventory errors does not induce 100% of effects, but relates to the magnitude of the mean value of inventory errors. For example, when the mean value of inventory error μ_e is larger than 2, the investment effects are not so extremely obvious.

In the coordinated supply chain (right small image in Fig. 3), when $\mu_e > 0.5$ as μ_e attains or go beyond 2, the optimal order quantities in different strategies also approach 0. When $\mu_e < 0.5$, the order quantities show disparities. Before RFID is implemented, the optimal order quantities of US and IS are decreasing, while those of MS and OS are sharply increasing, then slowly decreasing. By contrary, after RFID is implemented, the optimal order quantities in IS and OS decrease faster than those in US and MS, respectively. The cross points in the small image on the right side of Fig. 3 show the effective thresholds of different coordination strategies and the effective thresholds of RFID investment.

5.2.3. Parameter analysis: α and β

In this section, how the parameters, α and β, affect the optimal order quantity and their corresponding expected profits is investigated. The discussion is simplified by analyzing only the IS strategy. Table 2 presents the computation results with different α and β. The other parameter settings are as follows: the domains of demand and error are [0, 1000] and [0, 1], respectively, and $p = 50$, $c = 10$, $w_1 = 18$, $w_2 = 25$, $t = 5$, and $p_e = 20$.

The magnitude of α expresses the extent or percentage of RFID investment repayment from the retailer to the supplier. If $\alpha = 0$, the retailer does not repay the supplier, who then bears the entire RFID tag cost. By contrary, when $\alpha = 1$, the retailer bears the entire RFID tag cost. The results in Table 2 imply that when α increases, the optimal order quantity decreases. The most important changes is transpired in the expected benefits transfer, which is realized from r to sp_1 and sp_2. The total expected benefits of the supply chain are also increased. In this situation, the retailer must bear more RFID tag costs to strengthen its cooperation. Thus, the role of α influences the expected profits allocation and coordination of the supply chain.

The magnitude of β influences the ability of the scale factor in eliminating inventory errors. If β is large, RFID cannot efficiently eliminate inventory errors, and vice versa. Thus, the results in Table 2 show that, when β increases, the optimal order quantity increases far away from its mean value, whereas the expected benefits show disparities. In particular, the expected benefits of r and supply chain are increased, but the expected profits of the two suppliers become worse, increasing the instability of the supply chain.

5.3. RFID investment effectiveness

As noted above, the RFID investment effects are mainly reflected at two aspects, namely, the direct effects on eliminating inventory errors and the indirect effects on the expected profits. These aspects are reexamined in the following analyses.

5.3.1. RFID investment effectiveness on the optimal ordering quantity

In this section, the effects of RFID on the optimal order quantity are examined. RFID implementation directly influences the optimal order quantity (≥ 0). The relationship of RFID cost and optimal order quantity changes are exhibited in Fig. 4 (negative results are adopted to facilitate the illustration).

When $\mu_e < 1$ as RFID cost increases, the optimal order quantity decreases faster in the centralized situation than that in the decentralized situation. In the uncoordinated situation, the optimal order quantity first increases then slowly decreases to 0 in the decentralized situation. The implicated information in Fig. 4 reveals that the optimal order quantity in the centralized situation is larger than that in the decentralized situation, but RFID investment can convert this situation to some extent. Similar effects are also observed when $\mu_e < 1$. Moreover, when $t = 0$, the optimal order quantity is larger than that when t is exceedingly small (see the marked rings in Fig. 4). Meanwhile, in the coordinated situation, the optimal order quantities in US and IS scenarios are higher than those in MS and OS scenarios. However, when RFID cost increases, the optimal order quantities in IS and OS scenarios decrease faster than those in US and MS, respectively. From the overall observation, the changing curves of these optimal ordering quantities all exhibit convex shapes when $\mu_e < 1$.

When $\mu_e > 1$ as RFID tag cost increases, the optimal ordering quantity in the uncoordinated supply chain contradicts the ordering quantity when $\mu_e < 1$. In both the centralized and the decentralized situations, the two optimal order quantities show declining trends, but the one in the former state decreases faster. In the coordinated situation, the optimal ordering quantity is slightly higher when $t = 0$ than that when t is small (see the marked circles in Fig. 4). It testifies that the contribution of RFID in eliminating inventory errors has taken effect though the investment is small. The optimal ordering quantity first increases, then decreases when RFID cost increases. From the overall observation, when $\mu_e < 1$, the changing curves of these optimal ordering quantities display approximately concave shapes.

5.3.2. RFID effects on the expected profits

The analysis on this subject is simplified by investigating only the expected profits of integrated, decentralized, and IS supply chains. The range of RFID tag cost is set to [0, 50], and the changing trends of the expected profits are shown in Fig. 5.

In general, no close link is observed between the optimal ordering quantity and expected profit. Nevertheless, when RFID tag cost increases, the general trends of all different scenarios follow

Table 2
Effects of α and β

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Q^*	895	888	881	875	868	861	855	848	841	835	828
π_r^{IS}	19,718	19,415	19,115	18,817	18,522	18,228	17,937	17,649	17,363	17,079	16,797
$\pi_{sp_1}^{IS}$	−5147	−4805	−4468	−4135	−3807	−3483	−3164	−2849	−2539	−2234	−1933
$\pi_{sp_2}^{IS}$	310	329	349	368	386	405	423	441	458	475	492
π_T^{IS}	14,880	14,939	14,996	15,050	15,101	15,150	15,196	15,240	15,281	15,320	15,356
β	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Q^*	733	755	782	810	837	861	883	901	917	931	942
π_r^{IS}	9660	11,907	13,843	15,523	16,977	18,228	19,298	20,206	20,974	21,619	22,160
$\pi_{sp_1}^{IS}$	−1465	−1766	−2142	−2568	−3022	−3483	−3934	−4361	−4756	−5114	−5432
$\pi_{sp_2}^{IS}$	1740	1321	999	748	554	405	292	209	148	104	72
π_T^{IS}	9935	11,463	12,701	13,703	14,509	15,150	15,656	16,054	16,366	16,609	16,800

T: the total cost.

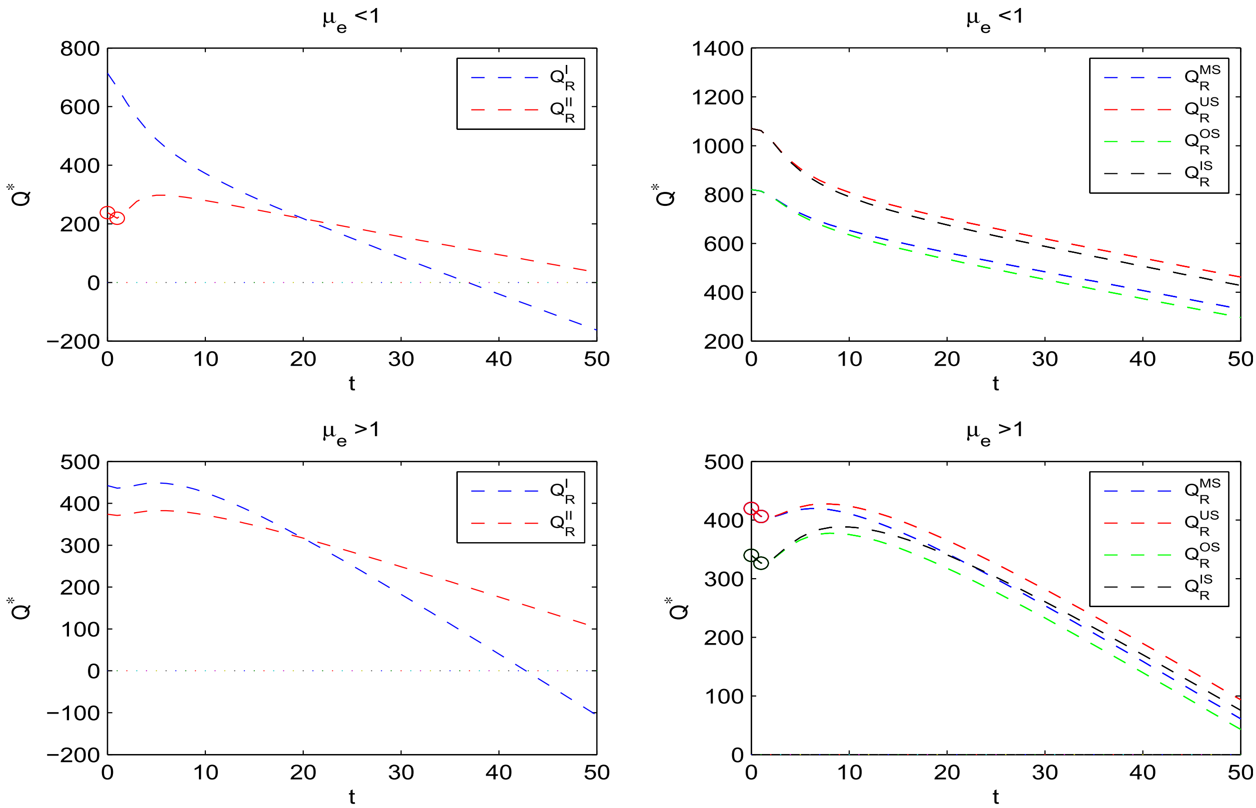

Fig. 4. The impacts of RFID tag cost to the optimal order quantity.

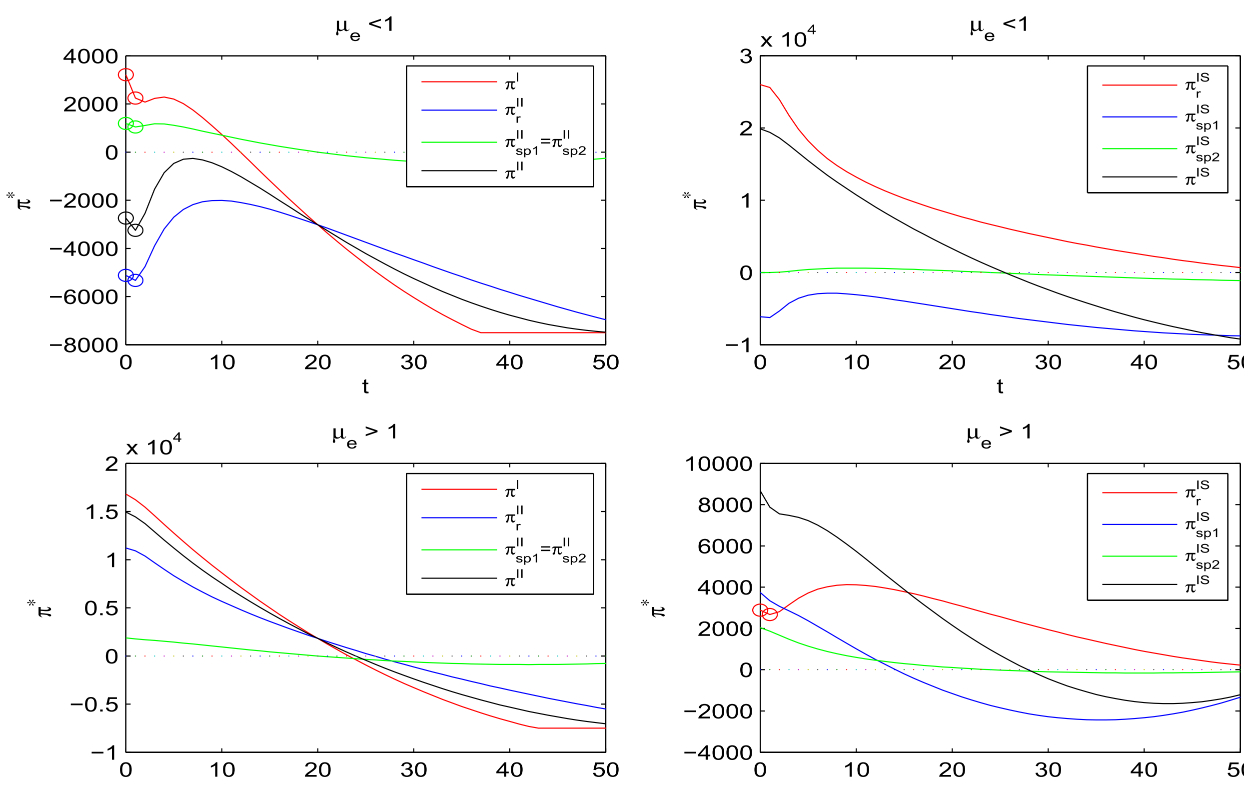

Fig. 5. Effects of RFID tag cost on the expected profits.

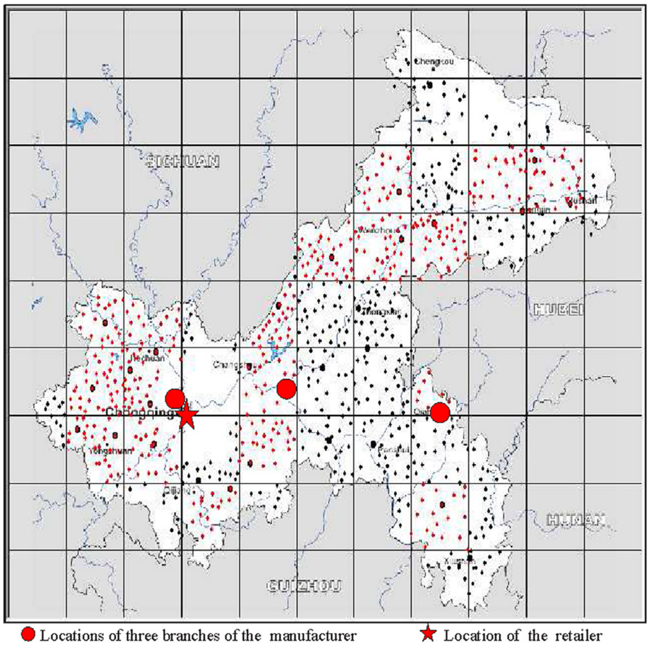

Fig. 6. Geographical positions of the manufacturer and the retailer.

the declining trends. Thus, the RFID cost is a decisive factor in adopting RFID, but the effects of such technology are quite specific and must be further explored. Numerical results also specify that the effects of RFID investment in $\mu_e < 1$ are usually more complicated than those in $\mu_e > 1$. In general, in the uncoordinated supply chain, the expected profits of all players are smaller when $\mu_e < 1$ than those when $\mu_e > 1$, but in the coordinated supply chain, the results are on the contrary.

The focus of RFID investment can be identified according to the specific supply chain status. For example, if one intends to make RFID investment and emphasis the maximal profits of the supply chain, the best state is in $\mu > 1$ and with IS strategy. Meanwhile, if the emphasis is allotted on the profit of *r*, when $\mu < 1$, the IS supply chain is the ideal candidate investment supply chain.

When $\mu_e < 1$, in the uncoordinated situation, the expected profits are moderately higher when $t = 0$ than those when t is exceedingly small (see marked rings in Fig. 5 when $\mu_e < 1$). When t increases, the total expected profits of scenarios *I* and *II* and the expected profits of *r*, sp_1, and sp_2 in scenario *II* first increase then decrease. That is to say, a threshold exists for each supply chain player to invest in RFID. Moreover, when $t \geq 38$, the expected profit of the supply chain in scenario I attains a fixed value (-7500, in which the order quantity is 0), whereas those of the other players continuously decrease. In the coordinated supply chain, when t increases, the expected profits of *r* and supply chain decrease. In this case, the profits of sp_1 first increase then decrease, whereas those of sp_2 are stable (approaches 0).

When $\mu_e > 1$, in the uncoordinated situation, the expected profits of all players decrease to negative as RFID investment increases. The expected profits of *r* and sp_1 are more sensitive to RFID cost, whereas those of sp_2 are not. If the optimal order quantities are considered simultaneously, the optimal order quantity first increases, then decreases when RFID cost augments. Moreover, when $t > 44$, the expected profit of the supply chain in scenario *I* attains a fixed value (-7500, in which the order quantity is 0), while those of the other players continuously decrease.

In the coordinated situation, when $\mu_e > 1$, all the expected profits of the other players and supply chain decrease, except for *r*, whose profits first increase, then decrease. When $t = 0$, the expected profit of *r* is larger than that when *t* is small (see the two marked circles in Fig. 5). Moreover, the expected profit of sp_1 decreases faster than that of sp_2. In other words, sp_1 is more sensitive to expected profit than sp_2. The results of this study also testify the assumption that 'item-level tagging seems to hold the most potential for the retailer, but is the costliest solution for the manufacturer' in managing practical operations (Gaukler et al., 2007) when $\mu_e > 1$.

6. An investigation of a RFID-based case recycling system

6.1. The background of the cigarette case recycling supply chain

To reveal the effectiveness of RFID system to decreasing inventory errors in the supply chain, a case-level RFID project performed in Chongqing tobacco supply chain is investigated. The tobacco supply chain comprises a local cigarette manufacturer in Chongqing that supplying cigarettes to different regional retailers all over the Chinese mainland, and an exclusive retailer in Chongqing district replenishing cigarettes from different manufacturers (including the local manufacturer) all over the country and selling cigarettes monopoly within the region of Chongqing. Their geographical positions of the manufacturer (owns three branch factories) and the retailer (owns four distribution centers) are shown in below Fig. 6.

The industrial manufacturer and the commercial retailer usually run independently in Chongqing district, but with the economic situation becoming worse in recent years, the two companies harbor the desire to strengthen their coordination level by sharing the selling information to decrease the operational cost. Henceforth, a project is launched to recycle the cigarette cases among different counterparts through performing a case-level RFID system. Case recycling is a typical practice in *reverse logistics*, which is

Fig. 7. Different levels of RFID implementations.

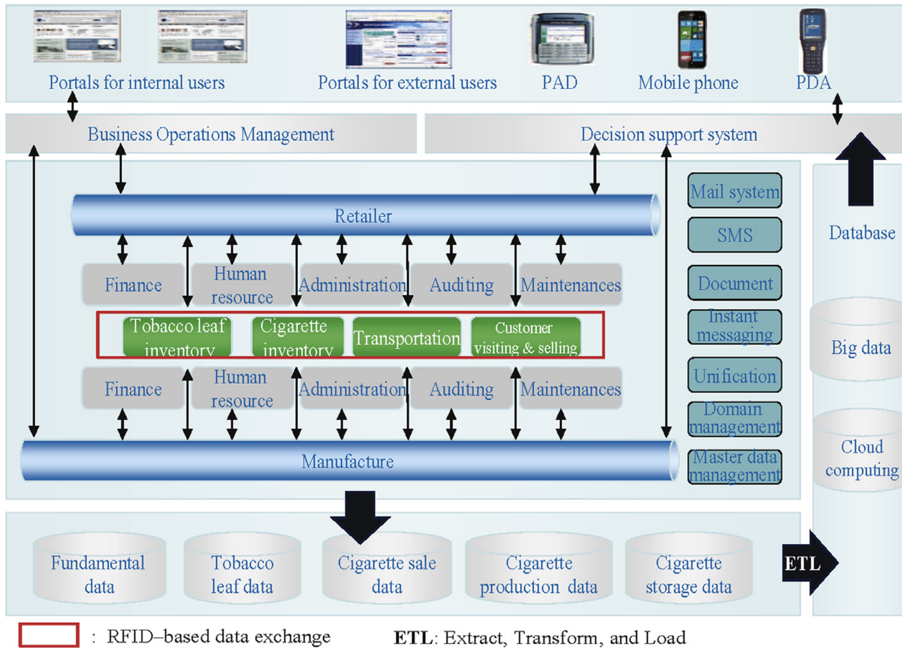

Fig. 8. The implemented case-level RFID system structure.

also a main content in *sustainable supply chain* (Govindan et al., 2015b). Before selling the cigarettes to the customer, 20 cigarettes are standardly packaged into a selling package, then 10 packages are enveloped into a carton, and finally fifty cartons are sealed into a plastic case, 24 or 30 cases are stacked on a pallet to ease of forklift transfer. Package-level, carton-level, case-level and pallet-level of RFID (see Fig. 7) are all planned in the project, however, considering the cost and operational complexities in the two companies' transactions, only the case-level RFID is performed, the system structure of the case-level RFID system is shown in Fig. 8, and the plastic cigarette case recycling process is depicted in Fig. 9.

6.2. Operational data and analysis

The four distribution centers of the retailer collect the cigarette cases in their service areas. There have two types of the cigarette cases in the supply chain, the plastic type cases with RFID tags pasted are exclusively supplied by the manufacturer in Chongqing and the paper case with no RFID tag pasted is supplied by other manufacturers outside Chongqing. The data on the recycled cases

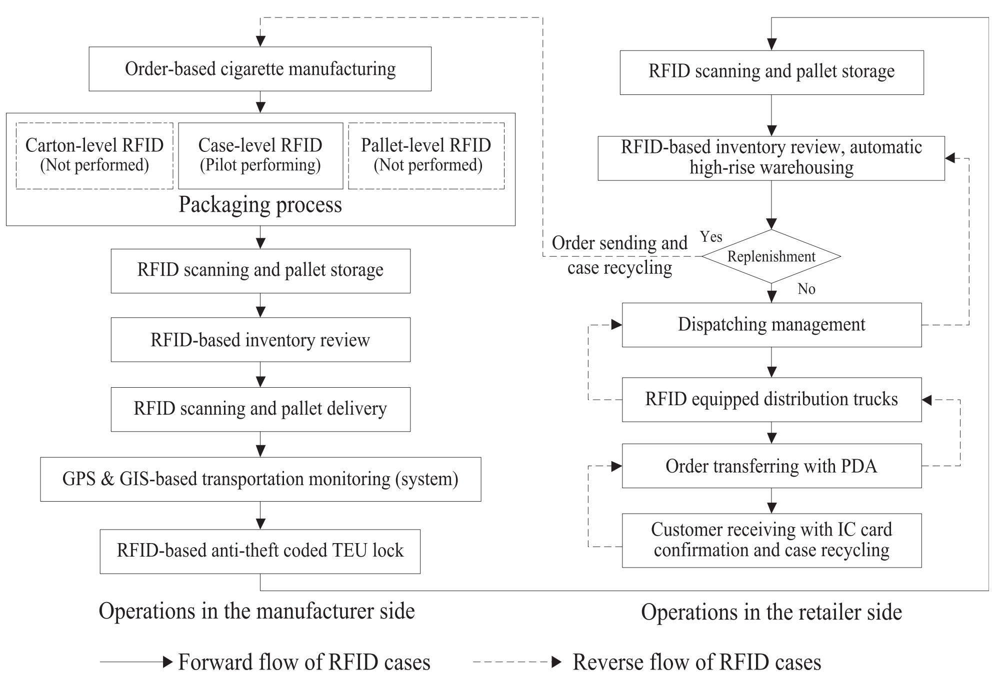

Fig. 9. Recycling process of cigarette cases.

in 2015 is collected and listed in Table A.2.

From the statistical data listed in Table A.2, we can easily draw that.

(1) Case-level RFID implementation is very convenient for large-scale packaging cases recycling, which helps decrease the recycling errors (by reducing the losses of cases) in the tobacco supply chain.
(2) Comparing to the recycled cases without RFID tags, the cases with RFID have higher recycling rate, which means that RFID implementation takes effects in reducing lost cases and bring all the cases into the recycling process.
(3) RFID implementation also makes the cases recycling faster than that without RFID, which means that it saves money for the manufacturer to procure fewer RFID cases.
(4) With RFID implemented, broken packages are identified in time, which decreases the risks, e.g. delivering the damaged cigarettes to customers, for the retailer and helps the retailer make quick rectification.

7. Conclusions

This study explores the effectiveness of RFID in decreasing inventory inaccuracies to build a *sustainable supply chain*. By assuming a supply chain with one retailer and two suppliers, analytical models are constructed and tested under the uncoordinated and coordinated supply chain scenarios considering RFID investment effectiveness and its variable cost. Accordingly, the management insights for investment in RFID at the following aspects:

(1) From the point of the average of inventory errors on the optimal ordering quantity: as the inventory error increases from the under-supplying to the over-supplying, the optimal order quantity decreases at different levels under different circumstances. After RFID is introduced, the decreasing speed of order quantity is intensified at the uncoordinated supply chain, which helps the *supply chain bear lower purchasing cost* at each order. However, there exists an intersection point of the order quantities before and after RFID is introduced, which means that the role of RFID is not only influenced by the cost but also correlated with the coordination strategies of the supply chain.
(2) For both the centralized and decentralized supply chains, the main obstacles for the companies to investment in RFID are interfered by the inventory errors, if the inventory errors cause insufficient inventory (e.g. shrinkages), there exists an optimal threshold at the expected profit, RFID investment becomes the sheer cost. The only differences between the two supply chain coordinations are reflected in the different magnitudes of the expected benefits and the order quantities.
(3) For the coordinated supply chains, the major consideration for the companies' investment in RFID is that, if the inventory errors cause surplus inventory (e.g. misplacement), there exists an optimal value of the order quantity. Thus, it is necessary for companies to consider the inventory error types, the performed coordination strategies, and RFID types before RFID investment.

This study examines the effectiveness of RFID in different supply chain scenarios given that RFID does not only affect inventory errors, but also affects the ordering quantities from different suppliers. These consequences are expected to influence the coordination of the supply chain. RFID simulation models are planned in our future research by jointly considering the shelf-space and price-dependent demand disruptions, to particularly investigate the effects of RFID invested by the retailers and/or the suppliers to the selling prices and supply chain coordination strategies.

Acknowledgements

This research is partially supported by National Natural Science Foundation of China (71602015; 71371080; 71471024), Humanities and Social Sciences Foundation of the Chinese Ministry of Education (16YJC630014), Social Science Planning Project of Chongqing (2015YBGL117; 2015BS027), Scientific and Technological Research Program of Chongqing Municipal Education Commission (KJ1500523), and Fundamental and Frontier Research Project of Chongqing (cstc2016jcyjA0530).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.11.081.

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