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Mean-risk analysis of radio frequency identification technology in supply chain with inventory misplacement: Risk-sharing and coordination

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ABSTRACT

This paper investigates the application of radio frequency identification (RFID) technology to eliminate the misplacement problems in the supply chain, which consists of a risk-neutral manufacturer and a risk-averse retailer. By considering both fixed cost and tag cost of RFID implementation, we study the agents' incentives to adopt RFID in both uncoordinated and coordinated cases. We focus on analyzing the impact of risk attitudes on the agents' incentives and on the supply chain coordination. The central semi-deviation is adopted to measure the retailer's risk attitude. In the uncoordinated case, we find that, in order to induce the retailer to adopt RFID, the manufacturer must assume more fixed cost if the retailer is more risk-averse. In the coordinated case, we first show that the standard revenue sharing contract does not always coordinate the channel. If the channel is coordinated, we observe that the agents' incentives will be perfectly aligned and independent of the risk attitudes, if the revenue sharing ratio equals the fixed cost sharing ratio. Then we propose a risk-sharing contract that offers the risk protection to the retailer, to achieve the channel coordination. An interesting finding is that the manufacturer's incentive will not decrease with the tag cost, if she takes much risk from the retailer. The corresponding impacts of RFID adoption on the two contracts are also analyzed in this paper. Finally, a case study in a tobacco industry is presented to show the real RFID cost in practice.

1. Introduction

Nowadays, the inventory misplacement is still a significant issue in the retail stores. Raman et al. [1] claimed that the lost sales due to misplaced products caused the retailer's profits reduced by 25%. Kang and Gershwin [2] note inaccuracies in 51% of the records used by one retail firm and claim that the proportion of inaccurate records ranges from 30% to 80% across stores. Dehoratius and Raman [3] report that 65% of the inventory records in retail stores were inaccurate by examining about 370,000 inventory records. Thus, more and more managers take into account the adoption of radio frequency identification (RFID) to eliminate inventory misplacements, based on the benefits of its ability to improve visibility in supply chains [4,5].

Academic research on RFID has proliferated significantly over the last few years. Much of the research has assumed the agents in the supply chain are risk neutral; i.e., they maximize their respective expected profits without risk consideration. However, the risk of failure may appear, such as the benefits obtained by RFID implementation cannot balance the increased cost. Thus, the results in the risk-neutral case may be viewed as unrealistic by the risk-averse decision makers.

This paper considers the RFID application in a supply chain consisting of a risk-neutral manufacturer and a risk-averse retailer, who faces the inventory misplacement issue. The retailer considers investing in RFID technology to eliminate misplacements. For a risk-averse person, he will be reluctant to accept a bargain with an uncertain payoff rather than another bargain with a more certain, but possibly lower, expected payoff. The retailer should balance the gain from improving inventory management and the increased investment cost, with further consideration on his risk aversion tolerance. However, the manufacturer only considers how to maximize the expected profit without risk consideration, since the manufacturer is risk-neutral. On the other hand, in order to induce both agents to adopt RFID for more profits, the manufacturer should propose the effective coordination mechanisms for the win–win

Abbreviations: RFID, radio frequency identification; MV, mean–variance; CSD, central semi-deviation; SSD, second-order stochastic dominance; PDF, probability density function; CDF, cumulative density function

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cooperation. The risk neutrality assumption on the part of the manufacturer is reasonable. Gan et al. [6] indicated that the manufacturer was able to diversify his risk by serving a number of independent retailers, which was quite often in practice. Since the retailers are independent, the supply chain can be divided into a number of sub-chains, each consisting of one manufacturer and only one retailer. In this case, it is enough to study a supply chain consisting of one manufacturer and one retailer.

Even though substantial literature has been developed on both the improvement of inventory management with RFID application (see [7], and references therein) and risk-averse analysis of channel coordination (see [6,8–10], and references therein), very little effort has been spent in analyzing the impact of agents' risk attitude on RFID application and on the coordination contracts with RFID adoption. Actually, this paper is motivated by a case of RFID application in a tobacco industry in China (the case study will be detailed discussed in Section 6). In that case, the agents were more concerned with the loss than the gain from the innovation. The significant problem faced by them is, how to share the investment cost and profits. Hence, a mean-risk framework is proposed to capture this issue. The mean-risk framework is similar to the traditional mean–variance (MV) model, while the risk is measured by the central semi-deviation (CSD), which is widely used in the financial operation research. Different from MV model, the upside of variance is not taken into account as the retailer's risk in CSD model. Intuitively, the upside of variance can be viewed as the surprising gains from investment. The most investors only care about the downside losses rather than upside gains. Thus, CSD is more intuitive and comprehensive to reflect investor's risk attitude. Ogryczak and Ruszczynski [11] and Ahmed et al. [12] also discussed the difference between CSD and the other risk measurement models, such as Value at Risk (VaR) and Conditional Value at Risk (CVaR). They pointed out that only CSD and CVaR can be consistent with second-order stochastic dominance (SSD) rules. In addition, from the following discussion in Section 2, it is shown that CSD will be more flexible since the value of the model's parameter can be adjusted for different risk measurements. However, our concern is not to argue how much better CSD is than the other models. Rather, we just use CSD for risk measurement. Actually, our model is also suitable for the traditional variance measurement.

The first contribution is that we take a few steps in analyzing the impact of the agent's risk attitude on the incentives to adopt RFID technology, which is the gap in the existing literature. Another contribution lies in the proposed risk-sharing contract to coordinate the supply chain, which is suitable for CSD model. This contract could be viewed as an improvement of the work in [6]. In this paper, the major research questions we try to address are:

1. Do the agents have incentives to invest in RFID technology in a decentralized supply chain?
2. How to propose a cost sharing contract to align the agents' incentives in the risk-averse case?
3. How to propose an effective coordination mechanism to coordinate the supply chain?
4. How does the risk attitude affect the coordination mechanism and the agents' incentives?

The above problems and the corresponding sections can be summarized in the following Fig. 1.

The recent academic literature review on RFID technology can be found in [7,13,14]. We limit ourselves to reviewing the papers studying the impact of RFID technology on reduction of inventory inaccuracies. Kok et al. [15] indicate that the price of an RFID tag is highly related with the value of the items lost. Rekik et al. [16] focuses on the theft type errors in a finite-horizon periodic review store, and analyzes the impact of theft errors and the value of the RFID technology on the inventory system. Using single-period model, Heese [17] concluded that a decentralized supply chain would benefit more with RFID adoption. Uçkun et al. [18] concluded that if the market is characterized by highly uncertain demand, making an investment in RFID to decrease inventory inaccuracy may be ill advised. Rekik et al. [19,20] discussed the RFID adoption strategy with coordination contract to improve the performance of supply chain under inventory inaccuracy. Camdereli and Swaminathan [21] study the benefits of RFID in a two-stage supply chain experiencing misplaced inventory. The authors find that the incentives of the parties for implementing RFID are not perfectly aligned if the fixed cost is not ignored. A threshold on variable tagging cost is analyzed in their work.

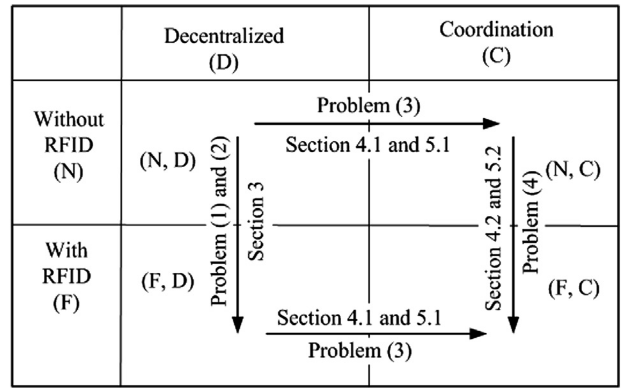

Fig. 1. Summary of the structure of the mean-risk analysis.

Our work differs from the above articles in its focus on risk analysis of RFID adoption in supply chain and on how to propose a risk-sharing contract among the supply chain members. Gaukler [22,23] also investigated the problem of sharing RFID costs among the supply chain members. However, the author focused on the improvement of the replenishment process by RFID adoption in a retailer under the assumption of multiple replenishment and sales periods, which is quite different from our research issue. Furthermore, the author assumed that the demand followed a normal distribution with known parameters, while our model does not have this assumption.

For the study on the effects of sharing the tagging cost between supply chain members, Ustundag [24] proposed a simulation model to calculate the impact of RFID benefits on different supply chain cost factors and indicated that the different RFID implementation levels cause different benefits. However, in order to carry out more quantitative analysis and more analytical solutions, we limit our investigation in the impact of RFID benefits on the misplacement problem and take into account the decision maker's risk attitude, which is different from all the previous papers. For more research efforts to use simulation model for integrated analysis of RFID benefits, refer to [25–27].

Risk aversion issues in inventory and capacity management have received a lot of attention in the past decades. The analysis approaches are including MV model, utility functions, VaR, etc. Since our mean-risk framework is inspired by MV approach, we next focus on reviewing this stream of the literature. For the research to use other risk aversion models, refer to [28–31] and references therein. Chen and Federgruen [32] study a MV tradeoff analysis on several basic inventory models, and found that the optimal order quantity is less than or equal to the newsboy point if the decision maker is risk-averse. Choi et al. [33] carry out a mean–variance model for the newsvendor problem in the risk seeking case, and found that the optimal order quantity will be larger than that in the risk-neutral case. Then, Choi and Chow [34] study Quick Response Problem via a MV approach, and illustrate how to achieve the win–win situation. Wu et al. [35] study the risk-averse newsvendor model with stockout cost consideration. They point out that the risk-averse newsvendor does not necessarily order less than the risk-neutral newsvendor.

Although MV model has been widely used in risk management research, Ogryczak and Ruszczynski [11] point out that, if variance is used to measure the risk, the model is not consistent with stochastic dominance rules. Choi and Chiu [36] explored mean-downside-risk (MDR) model to show that the analytical solution schemes for both the MDR and MV problems are the same. Following these ideas, we use CSD for risk measurement in our model, instead of variance. Moreover, different from the above papers, we use the risk measurement as a constraint condition rather than objective function. Our model is more realistic in practice, since most of the decision makers are unable to announce their risk-averse coefficient, but only give the threshold value of the risk they can tolerate. Moreover, this change will not affect the results of the risk analysis, but is highly beneficial for gaining more management insights. For more justifications and logic of using CSD for risk measurement, refer to [37–39].

By considering different risk attitudes, Choi et al. [40,41] study the channel coordination under return policy and wholesale price contract respectively. Wei and Choi [9] explore the use of a wholesale pricing and profit sharing scheme for coordinating supply chains under the MV framework. However, in the above papers, the supply chain coordination is defined as the agents' decisions equal to the supply chain's global optimal decision. It means that the contracts studied in the above papers do not guarantee the achievability of the win–win coordination. This is one of the differences between our work and theirs. There are also some literatures devoted to coordination contracts under different risk measurements, such as downside risk measurement (see [6]) and loss-aversion utility function (see [42]). Note that the above literatures do not consider the inventory inaccuracy problem and the impact of RFID adoption on coordination contracts, which is the key difference between our works and theirs.

The remainder of the paper is organized as follows: in Section 2, the discussion of the supply chain structure and assumptions is presented. Section 3 focuses on analyzing the RFID application under the wholesale price contract in the decentralized supply chain, and discussing the corresponding risk attitude influence. In Section 4, we study the traditional revenue sharing contract for channel coordination in our model. The risk analysis of agents' incentives is also discussed in this section. In Section 5, we propose a risk-sharing contract for the win–win channel coordination, and discuss the corresponding risk attitude influence. The agent's truth-telling issue and the unreliable RFID case are also discussed in this section. Section 6 presents a case study of RFID application in a tobacco company in China. Finally, we conclude with a summary of main management insights and discussions of future research in Section 7.

2. Model and assumptions

For notational convenience, we use the following notation:

α: the available inventory proportion, that is, only α proportion of the order is available to satisfy the customer's demand, $0<\alpha<1$.
θ: the sharing proportion of the RFID fixed cost, that is, the retailer pays θ proportion of the RFID fixed cost, while the manufacturer pays $(1-\theta)$ proportion, $0<\theta<1$.
λ_i: the sharing proportion of the supply chain's revenue under revenue sharing contract in the case i, that is, the retailer keeps λ_i proportion of the revenue that he earns from the sales and salvage, and shares the remaining portion $(1-\lambda_i)$ with the manufacturer, $0<\lambda_i<1$, $i=N, F$.
b_i: the buy-back price of a unit unsold available item under risk-sharing contract in the case i, $i=N, F$.
c: unit product cost.
D: random variable that represents the demand at the end of the selling season.
$EP_{i,j}(\cdot)$: the expected profit of the supply chain member i in the case j, $i=R, M, SC$, $j=N, F$.
$f(\cdot)$: the probability density function (PDF) of the demand distribution.
$F(\cdot)$: the cumulative distribution function (CDF) of the demand.
$inc_i^*(\cdot)$: the incentive function of the supply chain member i for RFID adoption, $i=R, M, SC$.
k: the parameter of the CSD model, that is, the different value of k presents the different risk measurement.
K: the fixed cost of RFID.
M_R: the risk aversion threshold of the retailer, which represents the retailer's risk attitude. A smaller M_R implies a more conservative retailer, $M_R\geq 0$.
$P_{i,j}(\cdot)$: random variable that represents the profit of the supply chain member i in the case j, $i=R, M, SC$, $j=N, F$.
$q_{i,j}$: the order quantity of the supply chain member i in the case j, $i=R, SC$, $j=N, F$.
$q_{R,i}^0$: the optimal order quantity of the retailer with the risk constraint under the initial contract of the risk-sharing contract in the case i, $i=N, F$.
r: the fixed price of a unit available product.
t: the unit tag cost.
v: the salvage value of the unsold product.
$VP_i(\cdot)$: the risk measurement of the retailer in the case i, $i=N, F$.
w_i: the wholesale price of a unit product that the manufacturer sells to the retailer in the case i, $i=N, F$.
$w_{SC,i}$: the wholesale price of a unit product that the manufacturer sells to the retailer under the wholesale price contract in the case i, $i=N, F$.
$\tilde{w}_i$: the wholesale price of a unit product that the manufacturer sells to the retailer under the risk-sharing contract in the case i, $i=N, F$.
$(\cdot)_+=\max(\cdot,0)$.
"$*$": superscript that represents optimal decisions and corresponding outcomes.
"R, M, SC": subscripts that denote for the "retailer, manufacturer, Supply Chain" respectively.
"N, F": subscripts that denote for the case without RFID and with RFID, respectively.
"MV": subscripts that represents the decisions or outcomes with risk constraint.
"UN,CO": subscripts that denote the case before and after supply chain coordination.

Consider a supply chain consisting of one risk-averse retailer and one risk-neutral manufacturer, the retailer sells a newsvendor type of fashionable product with a fixed price r. The manufacturer is assumed to be the Stackelberg leader, and produces the product at a unit cost c and sells the product to the retailer at a unit wholesale price w. Before the season begins, the retailer needs to determine the purchase quantity to cover the uncertain market demand, while the manufacturer needs to determine the optimal wholesale price according to gain more profit. We assume that the misplacement of inventory occurs before the demand happens (this assumption is quite common in the research works, see [20,21,43]). It can be viewed as the products ordered and received from the supplier are forbidden in the backroom, or misplaced on the other shelves in the replenishment process. This situation is quite common in supermarkets. The items picked up by the customers may be left at the other shelves when the customers decide not to buy them. Some of the misplaced items would be found after the shelf life. Therefore, as soon as the order is complete, we assume only α $(0<\alpha<1)$ proportion of the order is available to satisfy the customer's demand. The other misplaced part $(1-\alpha)$ is assumed to be found at the end of selling season, and salvaged at a unit price v, together with the unsold inventory. The available ratio α could be obtained by the statistical analysis of the historical data (see [44] for the details). We assume there is no additional cost (e.g., loss of goodwill) on unsatisfied demand. The variance of profit with stockout cost should be much more complex and the analysis of the risk-averse problem should be carried out under some special distributed demands [32,35]. In order to gain more generalized insights, we do not consider the stockout cost. To avoid trivial cases, we assume $v<c<r$.

We consider two cases: one case without implementing RFID and the other with RFID technology. When RFID is implemented, we assume that each product is tagged with an RFID tag. The fixed cost K of RFID is shared between the agents. The retailer pays θK, while the manufacturer pays $(1-\theta)K$. As pointed out by Camdereli and Swaminathan [21], when the manufacturer shares the tag cost, she can adjust the wholesale price as the case that the retailer pays all tag cost. Hence, without loss of generality, we assume that the retailer pays all the tag costs (see detailed discussion in Section 3.2). The misplacement problem is assumed to be eliminated if RFID is enabled (i.e., $\alpha\equiv 1$), which means that RFID is 100% reliable. This assumption is quite common in the related research works (see [16,17,21]). This assumption is a limitation in practice. However, our research emphasis is on analyzing the cost sharing and risk-sharing contract between supply chain agents. This limiting assumption will not affect the most of results, but facilitate gaining more intuitive management insights. In addition, the case of misreading by RFID can also be incorporated into our model easily by assuming that the availability goes to $\alpha<1$ instead of 1, see discussion in Section 5.5 for more details.

The optimization problems for both supply chain members are formulated in (P1) and (P2):

The retailer's problem (P1):

$$\max_{q_{R,i}} \quad EP_{R,i}(q_{R,i})$$
$$\text{s.t.} \quad VP_i(q_{R,i}) \le M_R$$

where $i=N,\ F$,

$$EP_{R,N}(q_{R,N}) = (r-w)\cdot \alpha q_{R,N} - (w-v)\cdot(1-\alpha)q_{R,N} - (r-v)\cdot \int_0^{\alpha q_{R,N}} F(x)\,dx \tag{1}$$

$$EP_{R,F}(q_{R,F}) = (r-w-t)\cdot q_{R,F} - (r-v)\cdot \int_0^{q_{R,F}} F(x)\,dx - \theta K \tag{2}$$

and $VP_i(q_{R,i})$ is the CSD risk measurement. M_R is the risk aversion threshold of the retailer. A smaller M_R implies a more conservative retailer.

As defined in [11], the kth CSD is formulated as

$$VP(x) = (E[[EP(x)-P(x)]_+^k])^{1/k}$$

where $k\ge 1$. If $k=1$, it is the absolute semi-deviation, and $k=2$, described as standard semi-deviation. Therefore, we have

$$VP_N(q_{R,N}) = (r-v)\delta^{1/k}(\alpha q_{R,N}) \tag{3}$$

$$VP_F(q_{R,F}) = (r-v)\delta^{1/k}(q_{R,F}) \tag{4}$$

Where

$$\delta(x) = \int_0^{x-n(x)} [x-n(x)-u]^k f(u)\,du \quad \text{and} \quad n(x) = \int_0^x F(u)\,du.$$

The manufacturer's problem (P2):

Without RFID:

$$EP_{M,N}(q_{R,N}) = (w_N-c)\cdot q_{R,N} \tag{5}$$

With RFID:

$$EP_{M,F}(q_{R,F}) = (w_F-c)\cdot q_{R,F} - (1-\theta)K \tag{6}$$

In the following analysis, we assume that the parameters α and M_R can be observed by manufacturer. The truth-telling issue of the retailer's risk attitude will be discussed in Section 5.3.

3. Wholesale price contract with cost sharing

3.1. The optimal policies for retailer

In the decentralized case, the manufacturer and the retailer concern their own profit, and play the Stackelberg game under the wholesale price contract with sharing fixed cost. From (1) and (2), they are the classic newsvendor type model, and the solutions satisfy

$$F(\alpha q_{R,N}^*) = \frac{r-w_N-\frac{(1-\alpha)}{\alpha}(w_N-v)}{r-v} \tag{7}$$

$$F(q_{R,F}^*) = \frac{r-w_F-t}{r-v} \tag{8}$$

where $(w_N-v)/(r-v)<\alpha\le 1$, and $0\le t<r-w_F$.

From (3) and (4), we have the properties of the retailer's risk as illustrated in Proposition 3.1 (all the proofs are given in Appendix A).

Proposition 3.1.

(a) *$VP_i(q_{R,i})$ is independent of t, K and θ, $i=N,F$.*
(b) *$VP_i(q_{R,i})$ is an increasing function of $q_{R,i}$, $i=N,F$.*

It means that, in both cases, the retailer's risk only depends on the order quantity. Denote by $q_{R,MV,i}$ the retailer's maximum order quantity which satisfies the risk constraint $VP_i(q_{R,i})\le M_R$ $(i=N,F)$, i.e.,

$$q_{R,MV,i} = \arg\max_{q_{R,i}}\{VP_i(q_{R,i})-M_R\le 0\}.$$

Proposition 3.2. *Under the wholesale pricing contract,*

(a) *If $w_N-v/r-v<\alpha\le 1$ and $0\le t<r-w_F$, the retailer's optimal ordering quantity is $q_{R,MV,i}^* = \min(q_{R,i}^*, q_{R,MV,i})$, where $q_{R,i}^*$ $(i=N,F)$ satisfy expressions (7) and (8) respectively, otherwise, $q_{R,MV,i}^* = 0$.*
(b) *$q_{R,MV,N}^*$ is non-increasing in w_N and non-decreasing in M_R; $\alpha q_{R,MV,N}^*$ is non-decreasing in α.*
(c) *$q_{R,MV,F}^*$ is non-increasing in w_F and t, and non-decreasing in M_R.*

Proposition 3.2 implies that the optimal order quantity is less than or equal to the newsboy point which is similar to the results in [32]. In addition, part (a) implies that, for a given wholesale price $w_i(i=N,F)$, there exists a threshold value $\overline{\alpha}=(w_N-v)/(r-v)$ and $\overline{t}=r-w_F$, such that the order quantity will be positive if the α and t lie in the identified area. As the expression of $\overline{\alpha}$, it can be viewed as the probability of stocking out in a newsvendor problem where no misplacement occurs. If the available products under this threshold, no matter what the ordering quantity is, the marginal profit gained from the sales cannot balance the marginal cost generated by misplacement, so the optimal policy is no order. Similarly, if the tag price does not lie in the area $[0, r-w_F)$, the marginal profit cannot balance the marginal cost.

3.2. The optimal policies for manufacturer

For the analysis of manufacturer's policy, we assume that the distribution of demand as a special class of distribution has an increasing generalized failure rate (IGFR) (see [45] for more details). The generalized failure rate is defined as

$$h(x) = xf(x)/\overline{F}(x)$$

If $h'(x) \geq 0$, then IGFR holds. It is known that the IGFR assumption is not restrictive because it captures most common distributions, such as Uniform, Exponential, Normal (as well as truncated Normal at zero), Beta (with parameters ≥ 1), Gamma (with shape parameter $s \geq 1$), and Weibull distribution (with shape parameter ≥ 1) [45].

Proposition 3.3. *Given* $\alpha \in (\overline{\alpha}, 1]$ $(\overline{\alpha} = (c-v)/(r-v))$, *and* $t \in [0, r-c)$, *if* $F(\cdot)$ *is IGFR:*

(a) *The manufacturer's first-order condition under two cases can be written as*

$$\overline{F}(\alpha q_{R,N})[1-h(\alpha q_{R,N})] = \frac{c-v}{\alpha(r-v)} \tag{9}$$

$$\overline{F}(q_{R,F})[1-h(q_{R,F})] = \frac{c-v+t}{(r-v)} \tag{10}$$

(b) $EP_{M,i}(q_{R,i})$ *is concave in* $q_{R,i} \in [0, q^0_{R,i}]$, *and decreasing on* $(q^0_{R,i}, \infty)$, *where* $q^0_{R,i}$ *is the least upper bound on the set of points such that* $h(\cdot) \leq 1$, *and* $0 \leq q^0_{R,i} < \infty$, *and the solution* $q^*_{R,i}$ *is unique and must lie in the interval* $[0, q^0_{R,i}]$, $i = N, F$.

The condition that $\alpha \in (\overline{\alpha}, 1]$ given in Proposition 3.3 is necessary. Because, from (9), if $\alpha < \overline{\alpha}$, the first derivative of the manufacturer's expected profit is smaller than 0. That is, the misplaced problem is serious enough and the optimal policy is no ordering. Therefore, we assume that $\alpha \in (\overline{\alpha}, 1]$ in the following analysis. Proposition 3.3 gives the optimal order quantity for manufacturer without risk attitude consideration. Then we can obtain the corresponding optimal wholesale prices for manufacturer as

$$w^*_N = \alpha(r-v)\overline{F}(\alpha q^*_{R,N}) + v \tag{11}$$

$$w^*_F = (r-v)\overline{F}(q^*_{R,F}) + v - t \tag{12}$$

where $q^*_{R,i}$ $(i = N, F)$ satisfies (9) and (10) respectively.

From the above analysis, we can see that if we assume that the tag cost is shared among the supply chain members with a sharing ratio γ (the retailer pays γt, and the manufacturer pays $(1-\gamma)t$), it is easy to obtain the corresponding optimal wholesale price from expression (12) by replacing t with γt. It means, regardless of how much tag cost the manufacturer shares, she can adjust the wholesale price by $(1-\gamma)t$ as compared with the wholesale price in the scenario where the retailer pays t. Thus, the assumption that the retailer pays for the whole tag cost is reasonable and does not affect the results.

Denote $q'_{R,N} = \alpha q_{R,N}$ and $w'_F = w_F + t$, where $q'_{R,N}$ can be viewed as the available quantity for satisfying the demand, and w'_F can be viewed as the wholesale price announced by the manufacturer when she pays for the tagging expenses.

Proposition 3.4. *If* $F(\cdot)$ *is IGFR, then*

(a) *The optimal solution* $q^*_{R,i}$ *for manufacturer is independent of* K, $i = N, F$.
(b) $q'^*_{R,N}$, w^*_N, $EP_{R,N}(q^*_{R,N})$ *and* $EP_{M,N}(q^*_{R,N})$ *are increasing in* α.
(c) $q^*_{R,F}$ *is decreasing in* t, *and* w'^*_F *is increasing in* t; $EP_{R,F}(q^*_{R,F})$ *and* $EP_{M,F}(q^*_{R,F})$ *are decreasing in* t.
(d) $\forall \alpha \in (\overline{\alpha}, 1]$ *and* $t \in [0, r-c)$, $w'^*_F > w^*_N$.

Part (c) and (d) imply that the unit cost adjusted by the tag cost for the retailer under RFID adoption is increasing in t and always larger than that without RFID adoption. Define $w_{MV,N}$ and $w_{MV,F}$ as the corresponding wholesale prices such that

$$w_{MV,N} = \alpha(r-v)\overline{F}(\alpha q_{R,MV,N}) + v \tag{13}$$

$$w_{MV,F} = (r-v)\overline{F}(q_{R,MV,F}) + v - t \tag{14}$$

Proposition 3.5.

(a) *The optimal wholesale price is* $w^*_{MV,i} = \max(w^*_i, w_{MV,i})$, $i = N, F$.
(b) $w^*_{MV,i}$ *is non-increasing in* M_R, $i = N, F$.

Proposition 3.5 implies that if the retailer's order quantity is constrained by his risk attitude, the optimal policy for the manufacturer is to raise the wholesale price to satisfy (13) and (14). We have the following properties of the agents' optimal expected profits when $VP_i(q^*_{R,i}) \geq M_R$.

Proposition 3.6. *If* $F(\cdot)$ *is IGFR and* $VP_i(q^*_{R,i}) \geq M_R$, $i = N, F$:

(a) $EP_{R,i}(q^*_{R,MV,i})$ $(i = N, F)$ *are independent of* α *and* t, *and increasing in* M_R.
(b) $EP_{M,i}(q^*_{R,MV,i})$ *is increasing in* M_R, $EP_{M,N}(q^*_{R,MV,N})$ *is increasing in* α, *and* $EP_{M,F}(q^*_{R,MV,F})$ *is decreasing in* t.

Proposition 3.6 implies that if the retailer is risk-averse enough, his expected profit only depends on the value of M_R. This is because the manufacturer has found out the retailer's risk attitude and raises the wholesale price in advance. From the perspective of the manufacturer, when RFID is adopted, her expected profit depends not only on the risk attitude, but also on the tag cost, even though the tag cost is paid by the retailer. Since the retailer's order quantity is independent of tag cost under the case $VP_i(q^*_{R,i}) \geq M_R$, from formula (14), it is obviously that, a higher tag cost results in a lower optimal wholesale price for the manufacturer to get less profit. As a result, from formula (6), we can see that the manufacturer's expected profit decreases when tag cost increases.

3.3. The impact of risk on agents' incentives

In this section, we investigate the impact of the risk aversion on the incentives of both agents for adopting RFID. Denote the incentive function of the agents as

$$inc^*_i(\theta) = EP_{i,F}(q^*_{R,MV,F}) - EP_{i,N}(q^*_{R,MV,N})$$

where $i = R, M$. It is well known that the agents are willing to adopt RFID if and only if $inc^*_i(\theta) \geq 0$. From (1) and (2), (5) and (6) and Proposition 3.5, we have

$$inc_R^*(\theta) = (r-v)\int_{\alpha q_{R,MV,N}^*}^{q_{R,MV,F}^*} xf(x)\,dx - \theta K \tag{15}$$

$$inc_M^* = [(w_{MV,F}^* - c)q_{R,MV,F}^* - (w_{MV,N}^* - c)q_{R,MV,N}^*] - (1-\theta)K \tag{16}$$

Proposition 3.7.

(a) *If $M_R > VP_i(q_{R,i}^*)$ $(i = N,\ F)$, for given the values of α, K and θ, $inc_R^*(\theta) \ge 0$ if and only if $t \le t_R^*$. Moreover, $\partial t_R^*/\partial\alpha < 0$, $\partial t_R^*/\partial\theta < 0$. If $M_R < VP_F(q_{R,F}^*)$, $inc_R^*(\theta)$ is independent of t.*
(b) *For given the values of α, t and θ, $inc_R^*(\theta) \ge 0$ if and only if $K \le K_R^*$. Moreover, $\partial K_R^*/\partial\alpha < 0$, $\partial K_R^*/\partial\theta < 0$, and $\partial K_R^*/\partial M_R \ge 0$.*
(c) *$inc_R^*(\theta)$ is non-decreasing in M_R. If $M_R \le VP_i(q_{R,i}^*)$, $inc_R^*(\theta) = -\theta K \le 0$.*

Proposition 3.8.

(a) *For given the values of α, K and θ, $inc_M^*(\theta) \ge 0$ if and only if $t \le t_M^*$. Moreover, $\partial t_M^*/\partial\alpha < 0$, $\partial t_M^*/\partial\theta > 0$, and $\partial t_M^*/\partial M_R \ge 0$.*
(b) *For given values of α, t and θ, $inc_M^*(\theta) \ge 0$ if and only if $K \le K_M^*$. Moreover, $\partial K_M^*/\partial\alpha < 0$, $\partial K_M^*/\partial\theta > 0$, and $\partial K_M^*/\partial M_R \ge 0$.*
(c) *$inc_M^*(\theta)$ is non-decreasing in M_R. If $M_R \le VP_i(q_{R,i}^*)$, then $inc_M^*(\theta) = [t_1 - t]q_{R,MV,F}^* - (1-\theta)K$, where $t_1 = ((1-\alpha)/\alpha)(c-v)$.*

The values of t_i^* and K_i^* $(i = R,\ M)$ in Propositions 3.7 and 3.8 can be obtained from formulas (15) and (16) by setting $inc_i^*(\theta) = 0$. Although the retailer is risk averse, as implied in Proposition 3.7(a), the critical value of t_R^* is not affected by his risk attitude. Moreover, if M_R is small enough, such that $M_R < VP_F(q_{R,F}^*)$, $inc_R^*(\theta)$ depends only on M_R. In other words, for a more risk-averse retailer, a lower tag cost is not an effective incentive for him to adopt RFID. This is because, under the wholesale price contract, the unit cost of the products for the retailer depends not only on the tag cost but also on the wholesale price announced by the manufacturer. Hence, the unit cost for retailer will be adjusted by a higher wholesale price when the tag cost decreases. As a result, the retailer will not benefit from a lower tag cost. In contrast, since $EP_{M,F}(q_{R,MV,F}^*)$ is decreasing in t and increasing in M_R (see the discussion of Proposition 3.6), the critical value of tag cost for manufacturer will increase with retailer's risk threshold. Moreover, Proposition 3.7(c) implies that if the retailer is much more risk averse (i.e., the order quantities in two cases are both constrained by risk attitude), the retailer will never benefit from RFID adoption. In other words, the retailer will never adopt RFID in this case, unless the fixed cost is paid by the manufacturer (i.e., the cost sharing ratio must satisfy $\theta^* = 0$). Therefore, we only consider the case that $M_R > VP_N(q_{R,N}^*)$ in the remainder of this section.

According to the above discussion, the agents' incentives are not aligned in general. Thus, the supply chain comes to an agreement with RFID adoption if and only if $t \le \min(t_R^*, t_M^*)$ or $K \le \min(K_R^*, K_M^*)$. As illustrated by Propositions 3.7 and 3.8, the relations between t_i^* or K_i^* $(i = R, M)$ depend on the value of θ and M_R. The following proposition illustrates that there exists a unique value of θ, under which the agents' incentives are perfectly aligned.

Proposition 3.9.

(a) *If $M_R \ge VP_F(q_{R,F}^*)$, given K (or t), there exists an unique value θ_t^* (or θ_K^*) such that*

$$t_R^* \text{ is } \begin{cases} < t_M^* & \text{if } \theta > \theta_t^* \\ > t_M^* & \text{if } \theta < \theta_t^* \\ = t_M^* & \text{otherwise} \end{cases} \quad \left(\text{or} \quad K_R^* \text{ is } \begin{cases} < K_M^* & \text{if } \theta > \theta_K^* \\ > K_M^* & \text{if } \theta < \theta_K^* \\ = K_M^* & \text{otherwise} \end{cases} \right)$$

(b) *If $M_R < VP_F(q_{R,F}^*)$, for a given t, there exists an unique value $\theta_{K,MV}^*$ such that*

$$K_R^* \text{ is } \begin{cases} < K_M^* & \text{if } \theta > \theta_{K,MV}^* \\ > K_M^* & \text{if } \theta < \theta_{K,MV}^* \\ = K_M^* & \text{otherwise} \end{cases}$$

where θ_t^* (or $\theta_K^*, \theta_{K,MV}^*$) can be obtained by solving the following set of equations:

$$\begin{cases} (r-v)\int_{\alpha q_{R,N}^*}^{q_{R,MV,F}^*} xf(x)\,dx - \theta^* K = 0 \\ (w_{MV,F}^* - c)q_{R,MV,F}^* - (w_N^* - c)q_{R,N}^* - (1-\theta^*)K = 0 \end{cases} \tag{17}$$

From Proposition 3.9(b), there is not a corresponding value of $\theta_{t,MV}^*$ to align the agents' incentives, since $inc_R^*(\theta)$ is independent of t when $M_R < VP_F(q_{R,F}^*)$. Under the wholesale price contract, if the risk constraint is not active, the agents' incentives will be aligned if and only if $\theta = \theta_t^*$ (or $\theta = \theta_K^*$). Moreover, from (17) and Proposition 3.3, we have $(j = t, K)$

$$\theta_j^* = (1/3) - \left[(r-v)\int_{\alpha q_{R,N}^*}^{q_{R,F}^*} x^2 f'(x)\,dx \right] / 3K \tag{18}$$

It is easily to be observed that θ_j^* must be more (less) than $1/3$ if $f'(x) < 0$ $(f'(x) > 0)$. This is because, under the wholesale pricing contract, the retailer will benefits more (less) than one-third of the supply chain overall profit if $F(\cdot)$ is concave (convex) [46]. It is evident that as the retailer gains more (less) than one-third of the whole supply chain's profit, he will afford more (less) than one-third of the fixed cost. In addition, it should be pointed out that this result is more generalized than that in [21], where the demand is assumed to be uniformly distributed.

3.4. Numerical example

Example 3.1. This example illustrates the impact of the retailer's risk attitude on the agents' incentives. Assume that the demand is exponentially distributed with a mean value 1000, and the other parameter values are (the measurement unit can be viewed as RMB, which does not affect the analysis results): $r = 40$, $c = 15$, $v = 5$, $\alpha = 0.6$ and $K = 1500$. Since the RFID equipment can be used for a long time, the value of K assumed here can be viewed as the average cost of depreciation in each selling season. The risk is measured by the standard semi-deviation (i.e., $k = 2$). We calculate the optimal solutions and the agents' incentives with different tag costs and different risk settings. The results are listed in Table 1. We find that as t increases, the $w_{MV,F}^*$ decreases. Moreover, if the retailer's order quantity is constrained by his risk attitude (such as

Table 1
The optimal solutions and incentives for varying t and M_R with $\theta = 0.2$.

M_R	t	$q_{R,MV,N}^*$	$q_{R,MV,F}^*$	$w_{MV,N}^*$	$w_{MV,F}^*$	$EP_{R,F}^*$	$EP_{M,F}^*$	inc_R^*	inc_M^*
∞	0	557.7	519.6	20.0	25.8	3067.5	4420.3	1495.9	1616.3
∞	2	557.7	457.8	20.0	25.1	2418.6	3443.7	847.0	639.7
∞	4	557.7	402.0	20.0	24.4	1873.3	2584.6	301.8	−219.5
∞	6	557.7	350.8	20.0	23.6	1409.4	1832.4	−162.1	−971.6
3900	0	557.7	420.4	20.0	28.0	2048.8	4260.0	477.2	1456.0
3900	2	557.7	420.4	20.0	26.0	2048.8	3419.1	477.2	615.1
3900	4	557.7	402.0	20.0	24.4	1873.3	2584.6	301.8	−219.5
3900	6	557.7	350.8	20.0	23.6	1409.4	1832.4	−162.1	−971.6
2100	0	424.7	254.8	21.3	32.1	659.1	3163.6	−300.0	498.3
2100	2	424.7	254.8	21.3	30.1	659.1	2654.1	−300.0	−11.2
2100	4	424.7	254.8	21.3	28.1	659.1	2144.6	−300.0	−520.7

$M_R=2100$), the decrement of $w^*_{MV,F}$ equals the increment of t. This is evident as $q^*_{R,MV,F}$ only depends on the retailer's risk attitude, the manufacturer must reduce the wholesale price according to the increment of tag cost to ensure an invariant of the order quantity. Table 1 also illustrates that, for a given K and θ, the incentives of the agents may not be aligned. If M_R is small enough, such as 2100, inc^*_R is always negative, even if tag cost is zero.

We further calculate the optimal cost sharing ratio θ^*_K by varying tag cost from 0 to 6 in different risk settings. The result is illustrated in Fig. 2. An interesting finding is that as tag cost increases, θ^*_K increases if the risk constraint is active, but decreases when the risk constraint is not active. That is, in order to align the agents' incentives, a risk-averse retailer must take a greater portion of the fixed cost, if he faces a larger tag cost. There are two reasons. First, the retailer's expected profit is constrained by his risk attitude, and independent of tag cost. For a given risk threshold, the retailer's incentive to adopt RFID is unchanged by tag cost. However, as illustrated in Table 1, the manufacturer will reduce the wholesale price if tag cost increases. As a result, the manufacturer's expected profit will be reduced, and her incentive is also reduced. Therefore, the retailer must take a greater portion of fixed cost to align their incentives. The decreasing property of θ^*_K in the case without risk constraint states that although both agents' expected profits decrease with t, the reduced amount of the retailer's expected profit is larger than that of the manufacturer's. From Fig. 2, we also find that θ^*_K increases with M_R if tag cost is given. It means that the retailer's expected profit increases faster with M_R than the manufacturer's profit.

4. Risk analysis of revenue sharing contract for coordination

In this section, we study the revenue sharing contract for coordination, which is widely studied in the risk-neutral case (see [46–48] and references therein). It is well known that in the risk-neutral case, the revenue sharing contract can coordinate the supply chain and arbitrarily allocate profit among agents by setting an appropriate wholesale price. However, we will show that this result does not always hold in the risk-averse case. In the following discussion, we focus on proposing the necessary and sufficient conditions for channel coordination and analyzing the impact of risk aversion and RFID adoption on the revenue sharing contract.

It should be pointed out that another widely used contract, buy-back contract, can also be incorporated into the following analysis easily, since it can provide the same profit allocation as

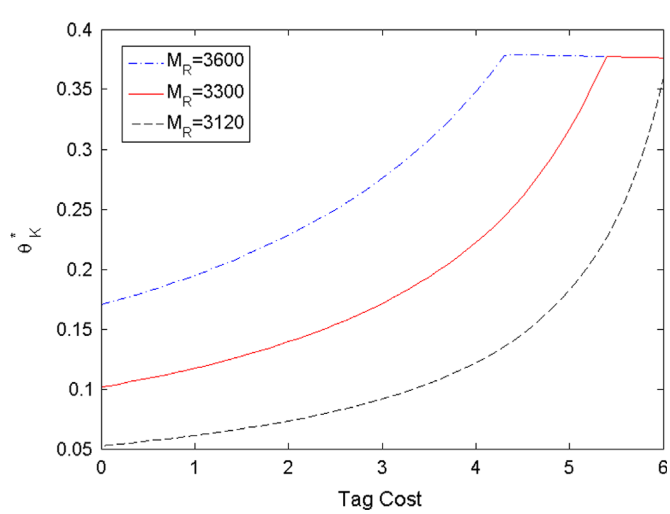

Fig. 2. The optimal cost sharing ratio with different tag costs and risk attitudes.

that in the revenue sharing contract by setting appropriate parameters [46].

Before our discussion, we adopt and rewrite the following definition of coordination proposed in [8] as follows: (i) the retailer and the manufacturer get payoffs not less than their respective reservation payoffs; (ii) the retailer's risk constraint is satisfied; (iii) the supply chain's expected profit is maximized. In the above definition, part (i) is necessary to guarantee that both agents are willing to adopt this contract. In this paper, we adopt the agents' profits gained in the wholesale price contract as their reservation payoffs.

4.1. The necessary and sufficient condition for coordination

Under the revenue sharing contract, the retailer keeps λ portion of the revenue that he earns from sales and salvage, and shares the remaining portion $(1-\lambda)$ with the manufacturer, The manufacturer sets a new wholesale price, denoted by $w_{SC,i}$, to maximize the supply chain's expected profit (where $0<\lambda<1$ and $i=N,\ F$).

We first consider the case that without RFID adoption. Under this contract, the expected profits of the retailer, manufacturer and supply chain, and the risk of the retailer are listed below

$$EP_{R,N}(q_{SC,N},\lambda_N)=\lambda_N\cdot\left\{r\cdot\alpha q_{SC,N}+v\cdot(1-\alpha)q_{SC,N}-(r-v)\cdot\int_0^{\alpha q_{SC,N}}F(x)\,dx\right\}-w_{SC,N}q_{SC,N} \quad (19)$$

$$EP_{M,N}(q_{SC,N},\lambda_N)=(w_{SC,N}-c)q_{SC,N}+(1-\lambda_N)\cdot\left\{r\cdot\alpha q_{SC,N}+v\cdot(1-\alpha)q_{SC,N}-(r-v)\times\int_0^{\alpha q_{SC,N}}F(x)\,dx\right\} \quad (20)$$

$$EP_{SC,N}(q_{SC,N})=(r-c)\cdot\alpha q_{SC,N}-(c-v)\cdot(1-\alpha)q_{SC,N}-(r-v)\cdot\int_0^{\alpha q_{SC,N}}F(x)\,dx \quad (21)$$

$$VP_N(q_{SC,N},\lambda_N)=\lambda_N(r-v)\delta^{1/k}(\alpha q_{SC,N}) \quad (22)$$

From (21), the optimal order quantity for the supply chain, denoted by $q^*_{SC,N}$, must satisfy

$$F(\alpha q^*_{SC,N})=\left(r-c-\left(\frac{1-\alpha}{\alpha}\right)(c-v)\right)/(r-v)\ (\overline{\alpha}<\alpha\le 1)$$

Notice that the retailer's order quantity is limited by M_R. If M_R is large enough, that is, $M_R\ge(r-v)\delta^{1/k}(\alpha q^*_{SC,N})$, the situation is reduced to the risk-neutral case. Then, it is well known that if $w^*_{SC,N}=\lambda^*_N c$ ($\lambda^*_N\in(0,1)$), the revenue sharing contract coordinates the supply chain. There certainly exists an appropriate λ^*_N such that both agents' profits are at least as much as those before the coordination. The value of λ^*_N is negotiated by the bargaining power of each agent. Under this contract, the retailer obtains λ^*_N portion of the supply chain's profit, while the manufacturer takes the $(1-\lambda^*_N)$ portion. However, in the risk-averse case, if $\lambda^*_N(r-v)\delta^{1/k}(\alpha q^*_{SC,N})>M_R$, the retailer will order less than $q^*_{SC,N}$ to guarantee his risk below the risk threshold. Therefore, the coordination is not achieved. The same result will be found in the case with RFID adoption.

In the remainder of this section, without loss of generality, we assume that M_R is small enough such as $M_R<(r-v)\delta^{1/k}(\alpha q^*_{SC,N})$. Denote by $\lambda^*_{MV,N}$ the revenue sharing ratio satisfying $\lambda^*_{MV,N}(r-v)\delta^{1/k}(\alpha q^*_{SC,N})=M_R$. According to the above definition of coordination, the following theorem gives the necessary and sufficient conditions for supply chain coordination.

Theorem 4.1. *In the risk-averse case without RFID adoption, the supply chain is coordinated under the revenue sharing contract if and* *only if the optimal wholesale price $w^*_{SC,N}$ and the optimal revenue sharing ratio λ^*_N satisfy (a) $w^*_{SC,N}=\lambda^*_N c$, (b)$\lambda^*_N \in (0,\lambda^*_{MV,N}]$ and (c) $\int_0^{\alpha q^*_{R,MV,N}} xf(x)\,dx / \int_0^{\alpha q^*_{SC,N}} xf(x)\,dx \le \lambda^*_N \le 1-EP_{M,N}(q^*_{R,MV,N})/(r-v)\int_0^{\alpha q^*_{SC,N}} xf(x)\,dx$, where $q^*_{R,MV,N}$ and $EP_{M,N}(q^*_{R,MV,N})$ are the optimal order quantity and the optimal expected profit of manufacturer under the wholesale price contract.*

In the case with RFID adoption, the expected profits of the retailer, manufacturer and supply chain, and the risk of the retailer are

$$EP_{R,F}(q_{SC,F},\lambda_F)=\lambda_F\cdot\left\{r\cdot q_{SC,F}-(r-v)\cdot\int_0^{q_{SC,F}}F(x)\,dx\right\} -(w_{SC,F}+t)\cdot q_{SC,F}-\theta K \tag{23}$$

$$EP_{M,F}(q_{SC,F},\lambda_F)=(w_{SC,F}-c)\cdot q_{SC,F} +(1-\lambda_F)\cdot\left\{r\cdot q_{SC,F}-(r-v)\cdot\int_0^{q_{SC,F}}F(x)\,dx\right\}-(1-\theta)K \tag{24}$$

$$EP_{SC,F}(q_{SC,F})=(r-c-t)q_{SC,F}-(r-v)\cdot\int_0^{q_{SC,F}}F(x)\,dx-K \tag{25}$$

$$VP_F(q_{SC,F},\lambda_F)=\lambda_F(r-v)\delta^{1/k}(q_{SC,F}) \tag{26}$$

Denote by $\lambda^*_{MV,F}$ the revenue sharing ratio satisfying $\lambda^*_{MV,F}(r-v)\delta^{1/k}(q^*_{SC,F})=M_R$, where $q^*_{SC,F}$ satisfies $F(q^*_{SC,F})=(r-c-t)/(r-v)$. From the similar analysis, we have the following theorem.

Theorem 4.2. *In the risk-averse case with RFID adoption, the chain is coordinated under the revenue sharing contract if and only if the optimal wholesale price $w^*_{SC,F}$ and the optimal revenue sharing ratio λ^*_F satisfy (a) $w^*_{SC,F}=\lambda^*_F c-(1-\lambda^*_F)t$, (b)$\lambda^*_F\in(0,\lambda^*_{MV,F}]$ and (c) $\int_0^{q^*_{R,MV,F}} xf(x)\,dx/\int_0^{q^*_{SC,F}} xf(x)\,dx \le \lambda^*_F \le 1-[EP_{M,F}(q^*_{R,MV,F})+(1-\theta)K]/(r-v)\int_0^{q^*_{SC,F}} xf(x)\,dx$, where $q^*_{R,MV,F}$ and $EP_{M,F}(q^*_{R,MV,F})$ are the optimal order quantity and the optimal expected profit of the manufacturer under the wholesale price contract.*

Comparing with the risk-neutral case, the feasible revenue sharing ratio for the retailer is limited in a smaller interval $(0,\lambda^*_{MV,i}]$ rather than $(0,1)$. It means that the retailer's bargaining power is significantly constrained by his risk aversion attitude in both cases. The condition (c) in Theorem 4.1 or 4.2 is important to ensure that the retailer has incentive to enter into the revenue sharing contract. However, this condition is not always satisfied in different risk settings. The following example shows this result.

Example 4.1. Assume that the demand is uniformly distributed in [500, 1500], and the supply chain adopts RFID. The other parameter are: $r=40$, $c=15$, $v=5$, $t=3$ and $k=2$. Let M_R varies from 0 to 1000. Assume that the retailer pays the same fixed cost after coordination (i.e., θ is not changed). Without loss of generality, we assume $K=0$. The maximum expected profits of the retailer before and after coordination are illustrated in Fig. 3. Obviously, if $0\le M_R\le 380$, the retailer will get more payoffs under the wholesale price contract than under the channel coordination. He has no incentive to enter into the revenue sharing contract.

Lemma 4.1. *If the demand is uniformly distributed in $[0,\beta]$ (β can be any positive value), the condition (c) in both Theorems 4.1 and 4.2 are satisfied for any value of M_R.*

Lemma 4.1 implies that if the demand follows the uniform distribution on the interval $[0,\beta]$, there always exists a value of λ, such that ensuing both agents will get more payoffs in the revenue sharing contract under coordination.

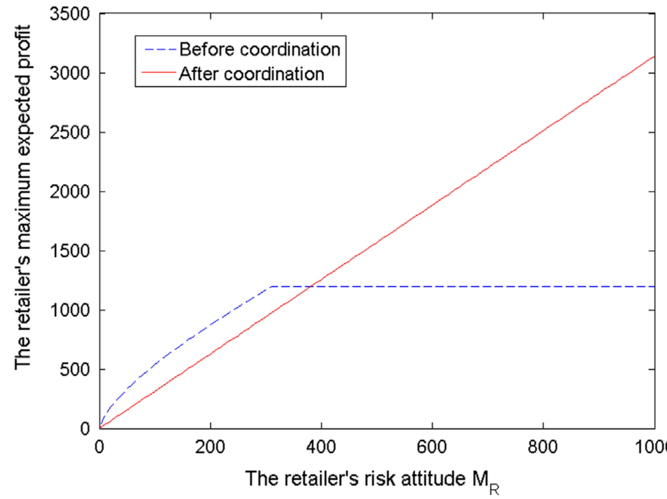

Fig. 3. An example of the supply chain uncoordinated in the revenue sharing contract.

4.2. Risk analysis and the impact of RFID adoption

We first investigate the agents' incentives to adopt RFID in the case that the supply chain is coordinated. If the supply chain is coordinated, let λ_i ($i=N, F$) be the corresponding revenue sharing ratio in the case without and with RIFD adoption, the supply chain's optimal expected profit can be rewritten as

$$EP_{SC,N}(q^*_{SC,N})=(r-v)\cdot\int_0^{\alpha q^*_{SC,N}} xf(x)\,dx \tag{27}$$

$$EP_{SC,F}(q^*_{SC,F})=(r-v)\cdot\int_0^{q^*_{SC,F}} xf(x)\,dx-K \tag{28}$$

Comparing (27) and (28), we have the following proposition.

Proposition 4.1.

(a) *For a given $\alpha>\overline{\alpha}$ and $K\ge 0$, $EP_{SC,F}(q^*_{SC,F})\ge EP_{SC,N}(q^*_{SC,N})$ if and only if $t\le t^*_{SC}$, where $t^*_{SC}\le t_1$.*
(b) *For a given $\alpha>\overline{\alpha}$ and $t\le t_1$, $EP_{SC,F}(q^*_{SC,F})\ge EP_{SC,N}(q^*_{SC,N})$ if and only if $K\le K^*_{SC}$,where t^*_{SC} and K^*_{SC} can be easily obtained by solving $EP_{SC,F}(q^*_{SC,F})-EP_{SC,N}(q^*_{SC,N})=0$.*
(c) *If $\lambda_N=\lambda_F=\theta$, then $t^*_R=t^*_M=t^*_{SC}$, $K^*_R=K^*_M=K^*_{SC}$.*

Proposition 4.1 implies that the supply chain can only benefit from RFID adoption if and only if the tag cost or fixed cost is low enough. The result of part (c) is straightforward, since the allocation of the supply chain's revenue between two agents is perfectly consistent with the allocation of the supply chain's cost. Moreover, in this case, the agents' incentives will not be constrained by the retailer's risk attitude.

Next, we investigate the impact of RFID adoption and cost sharing ratio on the revenue sharing contract. From the definition of $\lambda^*_{MV,i}(i=N,F)$, we have the following lemma.

Lemma 4.2. *$\lambda^*_{MV,i}$ increases with M_R. For a given M_R, $\lambda^*_{MV,F}$ increases with t. Moreover, if $t\le t_1$, then $\lambda^*_{MV,F}\le\lambda^*_{MV,N}$.*

The increasing monotone properties of $\lambda^*_{MV,i}$ with respect to M_R implies that a more risk-averse retailer has weaker bargaining power to get more payoffs under coordination. From Proposition 4.1, we see that $t\le t_1$ is the necessary condition for the supply chain to benefit from RFID adoption under coordination. Therefore, Lemma 4.2 states that under coordination, the more the supply chain benefits from RFID adoption, the weaker the retailer's bargaining power is. However, the final benefit of the retailer from RFID adoption depends not only on the revenue sharing ratio λ^*, but also on the fixed cost sharing ratio θ. Until now, we have assumed that the cost sharing ratio θ is not changed after coordination. Next, we study the impact of the cost sharing mechanism on revenue sharing contract.

Let θ_i^* $(i=UN, CO)$ denote the corresponding cost sharing ratio before and after coordination respectively. We rewrite the retailer's optimal expected profits before and after coordination respectively, such as

$$EP_{R,F,UN}(q^*_{R,MV,F}) = (r-v)\int_0^{q^*_{R,MV,F}} xf(x)\,dx - \theta^*_{UN}K \tag{29}$$

$$EP_{R,F,CO}(q^*_{SC,F}) = \lambda(r-v)\int_0^{q^*_{SC,F}} xf(x)\,dx - \theta^*_{CO}K \tag{30}$$

Then, the condition (c) in Theorem 4.2 can be rewritten as

$$\lambda^*_{MV,F}(r-v)\int_0^{q^*_{SC,F}} xf(x)\,dx \ge (r-v)\int_0^{q^*_{R,MV,F}} xf(x)\,dx - (\theta^*_{UN}-\theta^*_{CO})K \tag{31}$$

From (31), it is obviously to see that, even though the profit allocated to the retailer is limited by his risk attitude, he can improve his profit by paying less fixed cost (i.e., a smaller θ^*_{CO}) under coordination. In other words, the manufacturer can improve the retailer's interest in coordination by affording more fixed cost if RFID is adopted. In a sense, the cost sharing contract will improve the achievement of supply chain coordination under the revenue sharing contract. However, the improvement by cost sharing contract is also limited, and depends on the agents' bargaining power. If formula (31) is not satisfied, the revenue sharing contract cannot accomplish the channel coordination. In light of this, we discuss how to propose a risk-sharing contract to coordinate the supply chain in the next section.

5. Risk-sharing contract

In this section, we propose a risk-sharing contract to coordinate the supply chain, which is similar to the contract proposed in [6]. However, our risk measurement is completely different from the risk measurement proposed in [6], the contract proposed by Gan et al. is not feasible in our model. We focus on proposing an effective risk-sharing contract to coordinate the supply chain and discussing the impact of RFID adoption on this contract.

5.1. Design of the risk-sharing contract

From the discussion of Sections 3 and 4, the retailer's risk attitude is the main constraint for the channel coordination. Let $EP^0_{j,i}(q_{R,i})$ be the agent's expected profit in the initial contract $(j=R,\ M,\ i=N,\ F)$, and let $q^0_{R,i}$ be the optimal order quantity of the retailer with the risk constraint under the initial contract. If $q^0_{R,i}=q^*_{SC,i}$ ($q^*_{SC,i}$ is the optimal order quantity of the supply chain), the channel is already coordinated. Without loss of generality, in the remainder of this section, we assume that $q^0_{R,i}<q^*_{SC,i}$. The requirement on the initial contract is that the retailer's risk and his expected profit increase with the order quantity $q_{R,i}$, when $q^0_{R,i}\le q_{R,i}\le q^*_{SC,i}$. The initial contract can be the wholesale price contract or revenue sharing contract. In the following discussion, we assume that the initial contract is the wholesale price contract, i.e., $q^0_{R,i}=q^*_{R,MV,i}$, where $q^*_{R,MV,i}$ is obtained by Proposition 3.2.

Under the above assumption, Gan et al. [6] construct a risk-sharing contract by adding a return policy to coordinate the supply chain. They find that this contract will increase the retailer's profit without risk increasing. However, this result does not hold in our model. Thus, we propose an improved risk-sharing contract. The constructions of the risk-sharing contract are as follows:

1. If the retailer's order quantity $q_{R,i}\le q^0_{R,i}$, the initial contract is executed.
2. If $q^0_{R,i}<q_{R,i}\le q^*_{SC,i}$, then in addition to the initial contract with an order quantity $q^0_{R,i}$, the retailer pays the wholesale price $\tilde{w}_i$ for each unit in excess of $q^0_{R,i}$. On the other hand, the manufacturer must buy the unsold available items (i.e., excluding the misplaced items in the case without RFID) back from the retailer by a price b_i per unit at the end of selling season, and she can salvage these items by v per unit. The number of the items bought by the manufacturer cannot exceed $\alpha(q_{R,N}-q^0_{R,N})$ (or $(q_{R,F}-q^0_{R,F})$). To avoid trivial cases, we assume $v<b_i<r$.
3. If $q_{R,i}>q^*_{SC,i}$, the terms of the contract are the same as that in (2), except that the unsold items bought back by the manufacturer cannot exceed $\alpha(q^*_{SC,N}-q^0_{R,N})$ (or $(q^*_{SC,F}-q^0_{R,F})$).

Under the above contract, we obtain the agents' profits as follows:

1. If $q_{R,i}<q^0_{R,i}$, then the agent's expected profit is $EP^0_{j,i}(q^0_{R,i})$, $(j=R,\ M)$, and the retailer's risk function is $VP_i(q^0_{R,i})$.
2. If $q^0_{R,i}\le q_{R,i}\le q^*_{SC,i}$, then the agents' expected profit are

$$EP_{R,N}(\tilde{w}_N,q_{R,N},b_N) = EP^0_{R,N}(q^0_{R,N}) + [r-(1-\alpha)(r-v)-\tilde{w}_N] \times (q_{R,N}-q^0_{R,N}) - (r-b_N)\int_{\alpha q^0_{R,N}}^{\alpha q_{R,N}} F(x)\,dx \tag{32}$$

$$EP_{M,N}(\tilde{w}_N,q_{R,N},b_N) = EP^0_{M,N}(q^0_{R,N}) + (\tilde{w}_N-c)(q_{R,N}-q^0_{R,N}) - (b_N-v)\int_{\alpha q^0_{R,N}}^{\alpha q_{R,N}} F(x)\,dx \tag{33}$$

$$EP_{R,F}(\tilde{w}_F,q_{R,F},b_F) = EP^0_{R,F}(q^0_{R,F}) + (r-\tilde{w}_F-t)(q_{R,F}-q^0_{R,F}) - (r-b_F)\int_{q^0_{R,F}}^{q_{R,F}} F(x)\,dx \tag{34}$$

$$EP_{M,F}(\tilde{w}_F,q_{R,F},b_F) = EP^0_{M,F}(q^0_{R,F}) + (\tilde{w}_F-c)(q_{R,F}-q^0_{R,F}) - (b_F-v)\int_{q^0_{R,F}}^{q_{R,F}} F(x)\,dx \tag{35}$$

3. If $q_{R,i}>q^*_{SC,i}$, then the retailer's profit is

$$EP_{R,N}(\tilde{w}_N,q_{R,N},b_N) = EP^0_{R,N}(q^0_{R,N}) + [r-(1-\alpha)(r-v)-\tilde{w}_N](q_{R,N}-q^0_{R,N}) - (r-b_N)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx - (r-v)\int_{\alpha q^*_{SC,N}}^{\alpha q_{R,N}} F(x)\,dx \tag{36}$$

$$EP_{M,N}(\tilde{w}_N,q_{R,N},b_N) = EP^0_{M,N}(q^0_{R,N}) + (\tilde{w}_N-c)(q_{R,N}-q^0_{R,N}) - (b_N-v)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx \tag{37}$$

$$EP_{R,F}(\tilde{w}_F,q_{R,F},b_F) = EP^0_{R,F}(q^0_{R,F}) + (r-\tilde{w}_F-t)(q_{R,F}-q^0_{R,F}) - (r-b_F)\int_{q^0_{R,F}}^{q^*_{SC,F}} F(x)\,dx - (r-v)\int_{q^*_{SC,F}}^{q_{R,F}} F(x)\,dx \tag{38}$$

$$EP_{M,F}(\tilde{w}_F,q_{R,F},b_F) = EP^0_{M,F}(q^0_{R,F}) + (\tilde{w}_F-c)(q_{R,F}-q^0_{R,F}) - (b_F-v)\int_{q^0_{R,F}}^{q^*_{SC,F}} F(x)\,dx \tag{39}$$

First, we investigate the retailer's risk function under the risk-sharing contract. It is obviously that $VP_i(q_{R,i}^0) \le M_R$ when $q_{R,i} < q_{R,i}^0$. If $q_{R,i}^0 \le q_{R,i} \le q_{SC,i}^*$, from (32) and (34), we have the following proposition.

Proposition 5.1. *Under the risk-sharing contract, if* $q_{R,i}^0 \le q_{R,i} \le q_{SC,i}^*$, *the retailer's risk function decreases with* b_i, *i.e.,* $\partial VP_i(\tilde{w}_i, q_{R,i}, b_i)/\partial b_i \le 0$.

Proposition 5.1 implies that the manufacturer can reduce the retailer's risk by increasing the buy-back price b_i. Under the case that $q_{R,i}^0 \le q_{R,i} \le q_{SC,i}^*$, if $b_i = v$ and $q_{R,i} = q_{SC,i}^*$, the retailer's risk will be $VP_i(\tilde{w}_i, q_{SC,i}^*, v)$. If $VP_i(\tilde{w}_i, q_{SC,i}^*, v) \le M_R$, the situation is reduced to the risk-neutral case. Thus, without loss of generality, we assume that $VP_i(\tilde{w}_i, q_{SC,i}^*, v) > M_R$. If $b_i = r$, the retailer's risk is $VP_i(q_{R,i}^0)$. From the analysis of Section 3, we have $VP_i(q_{R,i}^0) \le M_R$ under the initial contract. If $VP_i(q_{R,i}^0) < M_R$, there exists a unit value of b_i^*, such that satisfies

$$VP_i(\tilde{w}_i, q_{SC,i}^*, b_i^*) = M_R \tag{40}$$

Then, if $b_i = b_i^*$ and $q_{R,N} > q_{SC,N}^*$, we have

$$\begin{aligned} VP_N &= (E[(EP_{R,N}-P_{R,N})_+^k|_{0 \le D \le \alpha q_{SC,N}^*} + (EP_{R,N}-P_{R,N})_+^k|_{D > \alpha q_{SC,N}^*}])^{1/k} \\ &> \left(E\left\{ \left[\begin{array}{l} EP_{R,N}(\tilde{w}_N, q_{SC,N}^*, b_N^*) - P_{R,N}(\tilde{w}_N, q_{SC,N}^*, b_N^*) \\ +(r-v)\cdot \left[\alpha(q_{R,N}-q_{SC,N}^*) - \int_{\alpha q_{SC,N}^*}^{\alpha q_{R,N}} F(x)dx\right] \end{array} \right]_+^k \Bigg|_{0 \le D \le \alpha q_{SC,N}^*} \right\} \right)^{1/k} \\ &> (E\{[EP_{R,N}(\tilde{w}_N, q_{SC,N}^*, b_N^*) - P_{R,N}(\tilde{w}_N, q_{SC,N}^*, b_N^*)]_+^k \Big|_{0 \le D \le \alpha q_{SC,N}^*}\})^{1/k} \\ &= M_R \end{aligned} \tag{41}$$

Similarly, we have $VP_F(\tilde{w}_F, q_{R,F}, b_F^*) > M_R$. Therefore, the retailer will not order a quantity $q_{R,N}$ larger than $q_{SC,N}^*$, because his risk constraint is not satisfied in the case $q_{R,N} > q_{SC,N}^*$.

From (32) to (35), it is obviously that the agents have incentives to enter into the risk-sharing contract if and only if $EP_{j,i}(\tilde{w}_i, q_{R,i}, b_i) \ge EP_{j,i}^0(q_{R,i}^0)$ $(i = N,\ F,\ j = R,\ M)$. Denote by $\underline{w}_i$ and $\overline{w}_i$ as

$$\underline{w}_N = c + (b_N^* - v)\int_{\alpha q_{R,N}^0}^{\alpha q_{SC,N}^*} F(x)\,dx/(q_{SC,N}^* - q_{R,N}^0) \tag{42}$$

$$\overline{w}_N = r - (1-\alpha)(r-v) - \alpha(r-b_N^*)F(\alpha q_{SC,N}^*) \tag{43}$$

$$\underline{w}_F = c + (b_F^* - v)\int_{q_{R,F}^0}^{q_{SC,F}^*} F(x)\,dx/(q_{SC,F}^* - q_{R,F}^0) \tag{44}$$

$$\overline{w}_F = r - t - (r-b_F^*)F(q_{SC,F}^*) \tag{45}$$

Thus, we have the following theorem.

Theorem 5.1. *If* $VP_i(q_{R,i}^0) < M_R$, *and the manufacturer buy the unsold available items back from the retailer with a price* b_i^*, *the supply chain is coordinated under the risk-sharing contract if and only if* $\underline{w}_i \le \tilde{w}_i \le \overline{w}_i$, $(i = N,\ F)$.

Theorem 5.1 implies that if $VP_i(q_{R,i}^0) < M_R$, the supply chain can be coordinated by the corresponding risk-sharing contract with an appropriate parameter $\tilde{w}_i$ $(i = N,\ F)$, which depends on the agents' bargaining power. If the order quantity is constrained by the risk in the initial contract, i.e., $VP_i(q_{R,i}^0) = M_R$, the manufacturer must increase her buy-back price b_i^* to r to ensure that the retailer's risk can be limited at M_R. In this case, from (42) to (45), we have

$$\underline{w}_N = c + (r-v)\int_{\alpha q_{R,N}^0}^{\alpha q_{SC,N}^*} F(x)\,dx/(q_{SC,N}^* - q_{R,N}^0) \tag{46}$$

$$\overline{w}_N = r - (1-\alpha)(r-v) \tag{47}$$

$$\underline{w}_F = c + (r-v)\int_{q_{R,F}^0}^{q_{SC,F}^*} F(x)\,dx/(q_{SC,F}^* - q_{R,F}^0) \tag{48}$$

$$\overline{w}_F = r - t \tag{49}$$

Since the buy-back price is equal to the sales price, we must assume that the retailer has an incentive to sell the items to the customers first and then sell the leftovers to the manufacturer at the end of selling season. In this case, the supply chain will be coordinated in the risk-sharing contract. This assumption is reasonable because the retailer has the incentive to reclaim capital as soon as possible, and the retailer will lose his goodwill if he does not satisfy the demand. Thus, the retailer is willing to sell the items to customers first. One may argue that there also exist selling cost and inventory holding cost in practice. This is beyond our discussion. The focus of this paper is analyzing how the risk attitude and RFID adoption affect the supply chain performance.

5.2. Risk analysis and the impact of RFID adoption

Now, we investigate the agents' incentives to adopt RFID if the supply chain is coordinated in the risk-sharing contract. According to (32) and (33), the incentive functions can be written as

$$\begin{aligned} inc_R^*(\theta, \tilde{w}_N, \tilde{w}_F) &= EP_{R,F}^0(q_{R,F}^0) + [r - t - \tilde{w}_F](q_{SC,F}^* - q_{R,F}^0) \\ &\quad -(r-b_F^*)\int_{q_{R,F}^0}^{q_{SC,F}^*} F(x)\,dx - EP_{R,N}^0(q_{R,N}^0) \\ &\quad -[r-(1-\alpha)(r-v) - \tilde{w}_N](q_{SC,N}^* - q_{R,N}^0) \\ &\quad +(r-b_N^*)\int_{\alpha q_{R,N}^0}^{\alpha q_{SC,N}^*} F(x)\,dx \end{aligned} \tag{50}$$

$$\begin{aligned} inc_M^*(\theta, \tilde{w}_N, \tilde{w}_F) &= EP_{M,F}^0(q_{R,F}^0) + (\tilde{w}_F - c)(q_{SC,F}^* - q_{R,F}^0) \\ &\quad -(b_F^*-v)\int_{q_{R,F}^0}^{q_{SC,F}^*} F(x)\,dx - EP_{M,N}^0(q_{R,N}^0) \\ &\quad -(\tilde{w}_N - c)(q_{SC,N}^* - q_{R,N}^0) + (b_N^*-v)\int_{\alpha q_{R,N}^0}^{\alpha q_{SC,N}^*} F(x)\,dx \end{aligned} \tag{51}$$

The incentives of the agents are not only dependent on the risk attitude and RFID cost, but also dependent on $\tilde{w}_i$ and b_i^*. The analysis of the agents' incentives will be discussed in Section 5.4. However, if $VP_i(q_{R,i}^0) = M_R$, i.e., $b_i^* = r$, we have the following interesting findings.

Lemma 5.1. *If* $VP_i(q_{R,i}^0) = M_R$ *and* $t = [\tilde{w}_N - (1-\alpha)v]/\alpha - \tilde{w}_F$, $inc_i^*(\theta, \tilde{w}_N, \tilde{w}_F)$ $(i = R, M)$ *are independent of the risk threshold* M_R.

The lemma illustrates that if the wholesale prices designed in the risk-sharing contract satisfy $t = [\tilde{w}_N - (1-\alpha)v]/a - \tilde{w}_F$, the retailer has the same incentive to adopt RFID with different risk settings, and the result also holds for the manufacturer. This result is also illustrated in Section 5.4 (see Example 5.1).

Let $M_R^0 = \min\,[VP_N(q_{R,N}^*), VP_F(q_{R,F}^*)]$ and $M_R^1 = \max\,[VP_N(q_{R,N}^*), VP_F(q_{R,F}^*)]$, where $q_{R,i}^*$ is the optimal order quantity under the wholesale price contract, satisfying (9) and (10). Then, we have the following lemma.

Lemma 5.2.

(a) *If* $0 < M_R \le M_R^0$, *the lower bound* $\underline{w}_i$ *increases with* M_R, *while* $\overline{w}_i$ *is independent of* M_R. *Moreover, if* $t \le t_1$, *then* $\underline{w}_F > \underline{w}_N$ *and* $\overline{w}_F > \overline{w}_N$.
(b) *If* $M_R > M_R^1$, $\underline{w}_i$ *and* $\overline{w}_i$ *both decrease with* M_R, *and* $\partial(\overline{w}_i - \underline{w}_i)/\partial M_R \le 0$.

It means that the feasible range of $\tilde{w}_i$ will shrink if M_R increases. When $0<M_R \le M_R^0$, for a less risk-averse retailer, the manufacturer must offer a higher price to the retailer for the additional items $(q_{R,i}-q_{R,i}^0)$ $(i=N,F)$, so as to guarantee that she can get additional payoffs under the risk-sharing contract. Observe that the allocation of the additional profit (i.e., $EP_{SC,i}(q_{SC,i}^*)-EP_{SC,i}(q_{R,i}^0)$, denote by $\Delta EP_{SC,i}$) between two agents depends on the value of $\tilde{w}_i$. The feasible range of $\tilde{w}_i$ will shrink since $\overline{w}_i$ is not changed by M_R. When $M_R > M_R^1$, $\Delta EP_{SC,i}$ will be independent of M_R. The shrinkage of the feasible range of $\tilde{w}_i$ implies that the expected profits of the corresponding agents are more sensitive to $\tilde{w}_i$ when M_R increases.

5.3. Discussion of truth-telling issue

In the previous sections, we have assumed that the manufacturer knows the retailer's risk attitude (i.e., M_R is publicly known). However, in practice, the risk threshold of the retailer is private and unknown to the manufacturer. How to induce the retailer to reveal his real risk preference is a significant issue in the risk analysis of the supply chain management.

From Propositions 3.5 and 3.6, it is obvious to see that the retailer will pay less wholesale price and get more payoffs if he pretends to be less risk averse under the wholesale price contract. The similar results are also observed by [6,9,49]. Wei and Choi [9] found that adding an additional minimum quantity commitment is an effective approach to prevent the retailer from lying under the wholesale price contract. In the risk-sharing contract, we will show that the manufacturer can prevent the retailer from lying if she set $\tilde{w}_i^* = \overline{w}_i$.

Denote M_R^1 and M_R^2 as the retailer's real risk attitude and the declared risk attitude, respectively. From (40), we have the corresponding buy-back price b_i^1 and b_i^2. Since we assume the initial contract is the wholesale price contract, the manufacturer can use the minimum quantity commitment to prevent the retailer from lying. Under this assumption, if $M_R^2 > M_R^1$, there will be three possible cases: (a) $M_R^2 > M_R^1 \ge VP_i(q_{R,i}^*)$; (b) $M_R^2 \ge VP_i(q_{R,i}^*) > M_R^1$; (c) $VP_i(q_{R,i}^*) > M_R^2 > M_R^1$, where $q_{R,i}^*$ is optimal order quantity under the wholesale price contract in the risk-neutral case. In the case of (a) or (b), from Proposition 5.1, we have $b_i^2 < b_i^1$, and $VP_i^2(q_{SC,i}^*, b_i^2) > VP_i^1(q_{SC,i}^*, b_i^1) = M_R^1$. Thus, the retailer's risk constraint is not satisfied. In the case of (c), we have $b_i^2 = b_i^1 = r$, substituting (47) and (49) in (32) and (34) respectively, we have $EP_{R,i}(q_{SC,i}^*, b_i^*) = EP_{R,i}^0(q_{R,i}^0)$, under the minimum quantity commitment, the retailer's risk constraint is not satisfied.

If $M_R^2 < M_R^1$, there will be also three possible cases: (a) $M_R^2 < M_R^1 \le VP_i(q_{R,i}^*)$; (b) $M_R^2 \le VP_i(q_{R,i}^*) < M_R^1$; (c) $VP_i(q_{R,i}^*) < M_R^2 < M_R^1$. In the case (a), we have $b_i^2 = b_i^1 = r$, under the minimum quantity commitment, we have $EP_{R,i}^2(q_{R,MV,i}^2) < EP_{R,i}^1(q_{R,MV,i}^1)$, i.e., the retailer will get less profit if he lies. In the case of (b) and (c), from Proposition 5.1, we have $b_i^2 > b_i^1$, substituting (43) and (45) in (32) and (34) respectively, we have

$$EP_{R,N}(q_{SC,N}^*, b_N^*) = EP_{R,N}^0(q_{R,N}^0) + (r-b_N^*)\int_{\alpha q_{R,N}^0}^{\alpha q_{SC,N}^*} [\alpha q_{SC,N}^* - F(x)]\, dx \tag{52}$$

$$EP_{R,F}(q_{SC,F}^*, b_F^*) = EP_{R,F}^0(q_{R,F}^0) + (r-b_F^*)\int_{q_{R,F}^0}^{q_{SC,F}^*} [q_{SC,F}^* - F(x)]\, dx \tag{53}$$

Then, substituting $b_i^2 > b_i^1$ in (52) and (53), we have $EP_{R,i}^2(q_{SC,i}^*, b_i^2) < EP_{R,i}^1(q_{SC,i}^*, b_i^1)$, i.e., the retailer will get less profit if he lies. Thus, the retailer will declare his real risk attitude.

5.4. Numerical example

Example 5.1. This example illustrates the impact of the retailer's risk attitude on the supply chain coordination. Suppose that the demand follows a normal distribution with mean = 1000 and variance = 400^2. The tag cost $t=3$, and $\lambda=\theta=0.3$. The other parameters are the same as in Example 3.1. Assume that the initial contract mentioned in the risk-sharing contract is the wholesale price contract, and $\tilde{w}_F=30$. Table 2 lists the typical optimal solutions under RFID adoption in different contracts by setting different risk thresholds.

As illustrated in Table 2, the revenue sharing contract cannot coordinate the supply chain if the retailer is much more risk-averse (e.g., $M_R=2000$). However, the coordination will be achieved under the risk-sharing contract, if the order quantity is constrained by the risk attitude in the initial contract.

We further vary the risk threshold and $\tilde{w}_F \in [\underline{w}_F, \overline{w}_F]$ to study the corresponding impacts on the agents' incentive functions (see (40) and (41)). Given $\alpha=0.6$ and $\tilde{w}_N=25$, the incentives of the retailer and the manufacturer are illustrated in Fig. 4. As discussed in Section 5.2, the manufacturer's incentive function increases with $\tilde{w}_F$, and the retailer's decreases with $\tilde{w}_F$ at every risk setting. Fig. 4 shows that in order to induce both agents to invest in RFID technology, the feasible wholesale price $\tilde{w}_F$ designed in the risk-sharing contract must be limited in a smaller interval, which is smaller than the interval proposed in Theorem 5.1. Otherwise, either the retailer or the manufacturer has no incentive to adopt RFID. Moreover, as M_R increases, the feasible interval of $\tilde{w}_F$ becomes larger (see Fig. 4).

Next, we fix $\tilde{w}_F=33$ and vary the tag cost from 0 to 6, to study the impacts of tag cost on the agents' incentives to adopt RFID in different contracts. For notational convenience, denote $C1=$ wholesale price contract, $C2=$revenue sharing contract, $C3=$risk-sharing contract. Then we use (i,j) to denote the incentive function of the agent i in contract j, where $i=R$, M and $j=C1$, $C2$, $C3$. The corresponding results are illustrated in Fig. 5 with setting $M_R=3000$. Under these settings, both $C2$ and $C3$ can coordinate the supply chain. As illustrated in Fig. 5, all the incentives are decreasing with tag cost except $(R, C1)$. However, such monotone property does not hold for $(M, C3)$ in different risk settings. As illustrated in Fig. 6, if $M_R=200$, the incentive of the manufacturer is concave. The reason is a higher tag cost does not only reduce the manufacture's gains from selling products, but also reduce her overage cost taken from the retailer (i.e., the third term in (41)). As a result, whether the manufacturer's incentive increases or decreases is determined by which reduction is significant enough. In addition, from Fig. 6, we see that if $t=5.333$, the incentives of both agents are independent of M_R.

5.5. Discussion of the unreliable RFID case

Although the reliability of RFID is difficult to achieve 100% in practice, we will show that the assumption of 100% reliability does not affect the analysis results. Let α' be the available inventory proportion after RFID adoption. Then, the formula (25) can be rewritten as

$$EP_{SC,F}(q_{R,F}) = (r-c-t)\alpha' q_{R,F} - (c+t-v)(1-\alpha')q_{R,F} - (r-v)\cdot\int_0^{\alpha' q_{R,F}} F(x)\, dx - K \tag{54}$$

Thus, we obtain the supply chain's incentive function:

$$inc_{SC}^*(\alpha') = EP_{SC,F}(q_{R,F}) - EP_{SC,N}(q_{R,N}) \tag{55}$$

Table 2
The optimal order quantities and expected profits under different contracts with different risk settings.

M_R	Wholesale price contract				Revenue sharing contract				Risk-sharing contract			
	$q^*_{R,MV,F}$	$EP^*_{R,F}$	$EP^*_{M,F}$	$EP^*_{SC,F}$	$q^*_{R,MV,F}$	$EP^*_{R,F}$	$EP^*_{M,F}$	$EP^*_{SC,F}$	$q^*_{R,MV,F}$	$EP^*_{R,F}$	$EP^*_{M,F}$	$EP^*_{SC,F}$
2000	431	252	7261	7513	968	4429	10,334	14,763	1131	5153	10,073	15,226
3000	562	1289	8622	9911	1131	4568	10,658	15,226	1131	5274	9952	15,226
∞	648	2410	8910	11,320	1131	4568	10,658	15,226	–	–	–	–

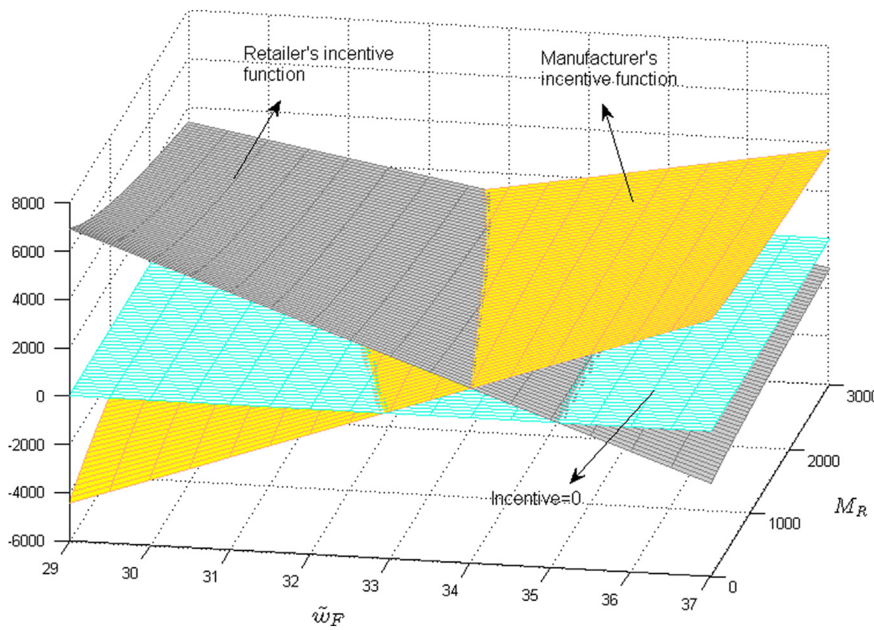

Fig. 4. Incentives of the agents to adopt RFID under coordination in the risk-sharing contract.

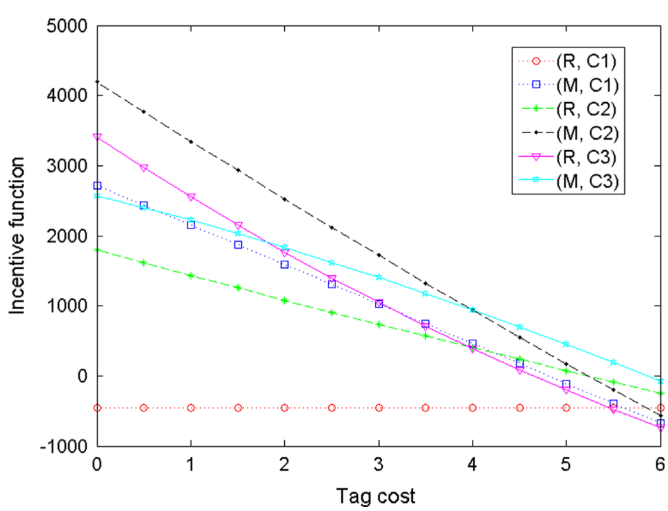

Fig. 5. Incentives of the agents to adopt RFID in different contracts.

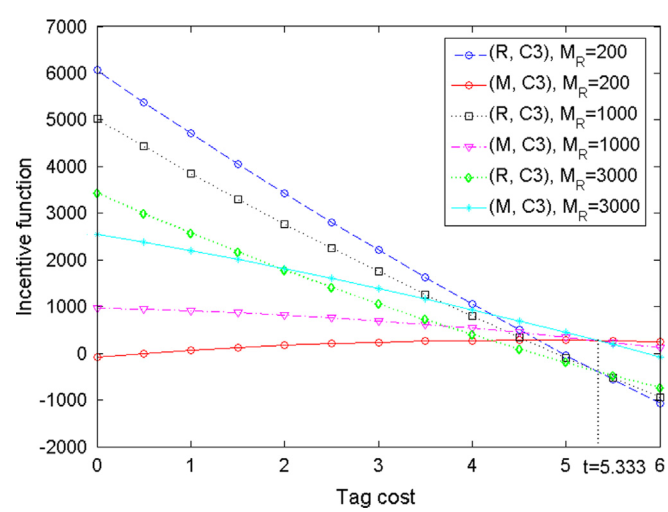

Fig. 6. Incentives of the agents in risk-sharing contract with different risk settings.

where $EP_{SC,N}(q_{R,N})$ can be obtained from (21). Then, let α' varies from 0.9 to 1, the other parameters are the same as in Example 3.1. The result is shown in Fig. 7.

Fig. 7 illustrates that the supply chain's incentive to adopt RFID is positive, although RFID is not 100% reliable. It is obviously that the incentive function increases if RFID reliability is improved. According to the results of this paper, it is easy to conclude that the threshold value of tag cost and fixed cost must be smaller in the unreliable case than that in the 100% reliable case.

6. Case study in a tobacco company

In this section, a case in the tobacco industry is studied to illustrate how the RFID is implemented in practice. We briefly

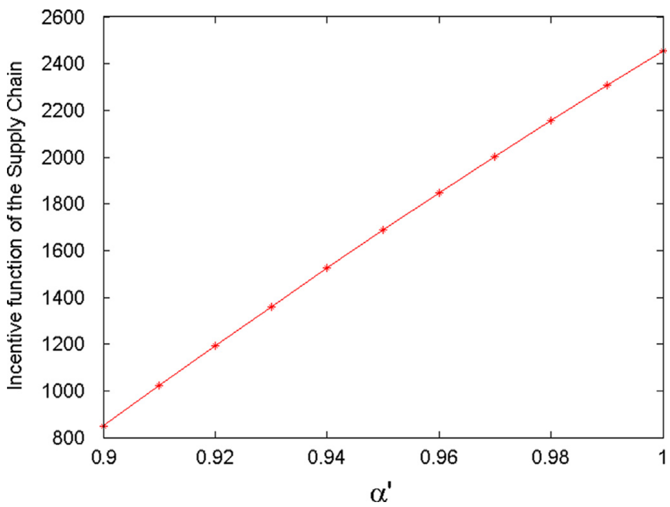

Fig. 7. The impact of RFID reliability on the supply chain's incentive.

describe the background of the tobacco company and focus on discussing the implementation results and how the RFID cost be shared between the agents. For the detailed RFID solutions in this case, refer to [44,50].

1. *Company background*: Wuhan Tobacco Corporation (WTC) has more than 100 warehouses with thousands of different products in different areas. As a short-life-cycle product, tobacco has its own particularities: strict fermentation time requirements, a large number of product variants with very similar appearances, real-time temperature control requirements and small quantities of different varieties to suit certain customer demands. All these properties determine the complexity of warehouse operations in WTC. Due to the disadvantages of the barcodes, the products could not be identified automatically. With greater product variety and increasingly complex customer orders, products were often mixed up, and always placed at the wrong shelves or forgotten in the backroom. As a result, operational efficiency has been greatly reduced, as well as inventory inaccuracy has been increased. Therefore, large-scale manpower is required to reorganize these products and prepare for orders. In the face of these problems, WTC's warehouse managers had decided to enhance their warehouse operations by using RFID technology.
2. *Tagging solutions*: As pointed out by [23], RFID can be used at different levels of granularity, which is the key factor to affect the investment cost. In this case, the pallet-level tagging is used to save the investment cost and be easily implemented in a closed-loop system. That is, a pallet contains 30 tobacco cases, each which is identified by a unique barcode. The 30 barcodes are written in the corresponding pallet tag. The RFID tag and the pallet can be reused between the manufacture and the company. Thus, the tag cost can also be viewed as the fixed cost in this case.
3. *Results discussion*: We conclude the warehousing performance results of the No. 1 tobacco warehouse with and without RFID implementation in Table 3. The comparison illustrates that the number of individuals needed for product loading has been reduced by half, while the average loading time is reduced from 50 min to 18 min with RFID implementation. Since the products are transported in the form of pallets, the loading ratio is only 60% of the previous one. However, the drop in loading ratio can be counteracted by raising loading and unloading efficiency, as well as truck turnover, or by adjusting the size of the pallets or the trucks [51]. Furthermore, the inventory accuracy is increased from 80% to 99%. The 1% inaccuracy is mostly generated by RFID misreading. It is believed that, as RFID readers and tags are improved, the inventory inaccuracy can be avoided.
The inventory inaccuracy was calculated by two aspects: misplacement and transaction errors. Fig. 8 gives the statistic data of the inventory inaccuracy caused by misplacement and transaction errors in each month of the year during our requirements analysis (as shown in (a)), and the first year after implementing RFID (as shown in (b)). It is obviously that the inventory inaccuracy was mainly caused by misplacement. This lied on two main reasons. First, since the storage/retrieval assignment was determined based on operator's memory and experiences, errors would be likely to occur. Second, with the

Table 3
Comparison of warehousing performance results without and with RFID implementation.

Indexes	Without RFID	With RFID
Loading manpower	8 persons	4 persons
Average loading time	50 min	18 min
Loading ratio	800 boxes	480 boxes
Inventory accuracy (%)	80	99

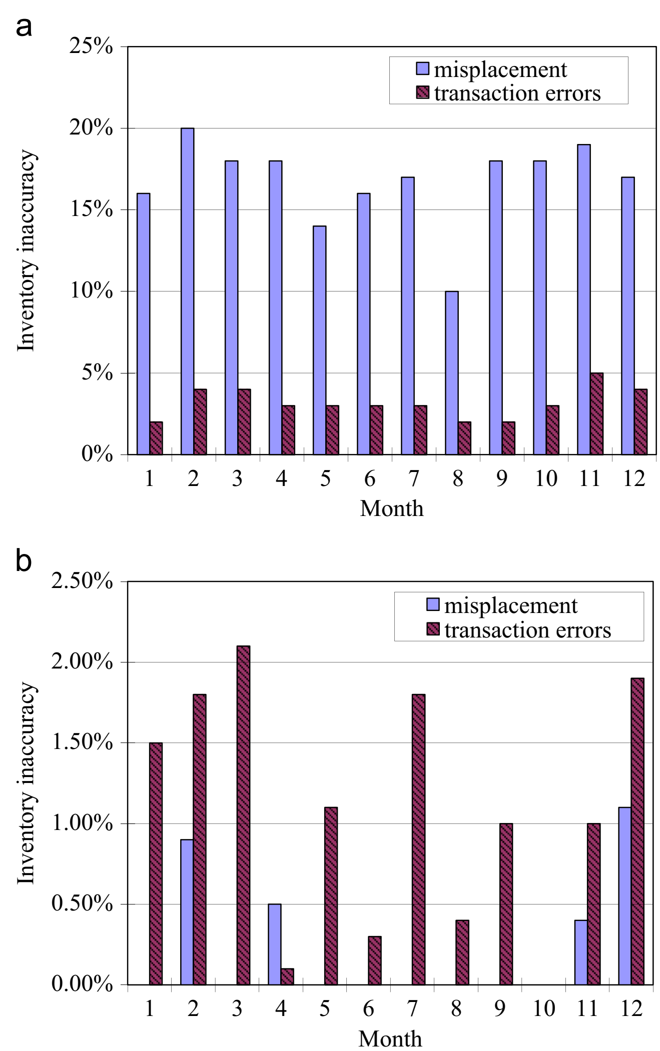

Fig. 8. Comparison of the inventory accuracy. (a) Before RFID implementation and (b) after RFID implementation.

Table 4
The practical cost details of RFID implementation (unit: RMB).

Items	Quantity	Unit price
Shelves	1	300,000
Pallets	5000	500
Tags	5000	20
Software	1	450,000
Computers and servers	6	23,800
Wireless network	1	205,200
RFID fixed cost	2	26,800
Total cost		**3,751,600**

similar appearance of the products, the carriers often made mistakes after receiving the tasks from operators. Fig. 8 (b) shows that the misplacement has been greatly reduced by the automatic Identification of RFID.

4. *Cost analysis*: Since the value of the cigarettes would be significantly reduced with longer storage time, the case can be modeled by a newsvendor model. From Proposition 4.1, it is obviously that the threshold value of the tag increases with the cost of the identified product. Since RFID is used at the pallet-level, we have a greater optional range of the tags in this studied case.
Table 4 gives the detailed cost of the RFID implementation in No. 1 warehouse. Because the pallets and tags are reused in the manufacturer and the downstream company, the tags cost can be viewed as the fixed cost. Let K_R and K_M be the total renovation cost of No. 1 warehouse and the manufacturer respectively, the total cost (K_R+K_M) is shared with a sharing ratio λ, which is determined by the agents' bargaining power. In addition, we use a questionnaire to obtained the warehouse manager's risk attitude M_R, and use the standard semi-deviation to calculate the warehouse manager's risk. We found that M_R is large enough to use revenue sharing contract for coordination.

7. Conclusion

In this paper, we focus on analyzing how the risk attitude affects the supply chain members' incentives to adopt RFID, and the corresponding coordination contract. The central semi-deviation is adopted to measure the retailer's risk attitude. Three kinds of contracts are studied: the wholesale price contract in the decentralized case, the revenue sharing contract and risk-sharing contract for channel coordination. In the decentralized case, we find that both the manufacturer and retailer have their corresponding threshold values of RFID costs. Under the assumption that the retailer pays for the tag cost but shares the fixed cost with the manufacturer, there exists an optimal cost sharing ratio to align the agents' incentives. In order to induce the retailer to adopt RFID, the manufacturer must share more fixed cost if the retailer is more risk-averse.

In order to coordinate the supply chain, we first study the traditional revenue sharing contract, and show that such contract may not coordinate the supply chain in different risk settings. In light of this, we propose a risk-sharing contract to guarantee the achievement of channel coordination. By comparing the contracts, some management insights are found. First, since the retailer's risk attitude is the major constraint for the supply chain coordination, the risk-sharing between the agents is a significant part for designing a coordination contract. Under the assumption that the manufacturer is risk-neutral, the more risk the manufacturer takes, the more feasible to achieve the channel coordination. Second, when the revenue sharing contract coordinates the supply chain, the agents' incentives can be perfectly aligned with the whole supply chain's incentives, if revenue sharing ratio equals the cost sharing ratio. As a result, both the agents' incentives are not affected by the risk constraint. However, this result does not hold for the risk-sharing contract, since the agents' incentives also depends on the wholesale price designed in the contract. Third, under the risk-sharing contract, the manufacturer's incentive may not decrease with tag cost, if she takes much risk from the retailer.

Finally, we present a case study in a tobacco industry, and discuss the corresponding RFID cost. The studied case illustrates that the RFID is not 100% reliable in practice. However, the simulation analysis of unreliable RFID case illustrates that the reliability of RFID only affect the agents' profits. The agents' incentives will increase if the reliability of RFID is improved.

Our research focuses on analyzing the impact of risk aversion attitude on RFID adoption for eliminating inventory misplacement issue. Another important issue is how to extend our analysis with considering different reasons for inventory inaccuracies, such as theft, shrinkage, transaction errors. For the future study of our works, it will be a challenging but useful extension of the risk-averse model for a supply chain consists of different risk preference members. For risk management, how to propose a more realistic risk measurement for RFID investment is another significant research direction.

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Appendix A

Proof of Proposition 3.1. From (4), taking the first-order derivative of $VP_F(q_{R,F})$ with respect to $q_{R,F}$, gives: $\forall k \geq 1$

$$VP_F'(q_{R,F}) = (r-v)\cdot \delta^{(1/k)-1}(q_{R,F})\cdot[1-F(q_{R,F})] \times \int_0^{q_{R,F}-n(q_{R,F})} [q_{R,F}-n(q_{R,F})-x]^{k-1} f(x)\,dx \geq 0$$

Similarly, we have $VP_N'(q_{R,N}) \geq 0$. Then the result yields. □

Proof of Proposition 3.2.

(a) From (7) and (8), $q^*_{R,i}$ is the optimal order quantity which maximizes the retailer's expected profit $(i=N,F)$. If $VP_i(q^*_{R,i}) \leq M_R$, then $q^*_{R,MV,i} = q^*_{R,i}$. By the increasing property of $VP_i(q_{R,i})$, $q^*_{R,i} \leq q_{R,MV,i}$. Otherwise, $q^*_{R,MV,i} = q_{R,MV,i}$.
(b) From (7), by the increasing property of $F(\cdot)$, it suffices to proof that $F(\alpha q^*_{R,N})$ decreases with w_N and $q_{R,MV,N}$ increases with M_R. Since $\partial F(\alpha q^*_{R,N})/\partial w_N = -1/\alpha(r-v) < 0$, and the increasing property of $VP_N(q_{R,N})$, the result is yielded.
(c) Following the similar proof of (b), the result is yielded. □

Proof of Proposition 3.3. We first prove the case $i=N$.

(a) From (5), taking the first-order derivative on $EP_{M,N}$ with respect to $q_{R,N}$ yields

$$\frac{dEP_{M,N}}{dq_{R,N}} = \frac{\partial EP_{M,N}}{\partial q_{R,N}} + \frac{\partial EP_{M,N}}{\partial w_N}\cdot\frac{dw_N}{dq_{R,N}} = (w_N-c) + q_{R,N}\cdot\frac{dw_N}{dq_{R,N}} \quad (A.1)$$

Noticing that $q_{R,N}$ is the retailer's order quantity corresponding to the wholesale price w_N, we thus have: $w_N = \alpha(r-v) - \alpha(r-v)F(\alpha q_{R,N}) + v$ and $dw_N/dq_{R,N} = -\alpha^2(r-v)f(\alpha q_{R,N})$. Substituting them into (A.1) and let $dEP_{M,N}/dq_{R,N} = 0$, the result is yielded.

(b) Taking the second-order derivative on $EP_{M,N}$ with respect to $q_{R,N}$, we have

$$\frac{d^2EP_{M,N}}{dq_{R,N}^2} = -\alpha f(\alpha q_{R,N})[1-h(\alpha q_{R,N})] - \overline{F}(\alpha q_{R,N}) \cdot \alpha h'(\alpha q_{R,N}) \quad (A.2)$$

By the definition of $q_{R,N}^0$, $h(\alpha q_{R,N}) \le 1$ for $q_{R,N} \in [0, q_{R,N}^0]$. Thus, the first term on the right hand side of (A.2) is negative for $q_{R,N} \in [0, q_{R,N}^0]$. In addition, if $F(\cdot)$ is IGFR, $h'(\cdot) \ge 0$. Combining both we have $d^2EP_{M,N}/dq_{R,N}^2 \le 0$, and therefore $EP_{M,N}$ is concave in $[0, q_{R,N}^0]$. Notice that for $q_{R,N} \in (q_{R,N}^0, \infty)$, $h(\alpha q_{R,N}) > 1$. The first-order derivative is less than zero, and the manufacturer's expected profit decreases. Therefore, the optimal order quantity $q_{R,N}^*$ is unique and lies in the interval $[0, q_{R,N}^0]$.

Following the similar proof, the result in the case $i = F$ is yielded. □

Proof of Proposition 3.4.

(a) The result is straightforward.

(b) For $\forall \alpha \in [\overline{\alpha}, 1]$, given any $\alpha_1 < \alpha_2$, assume that $q'^*_{R,N,1}$ and $q'^*_{R,N,2}$ are the corresponding solutions. From (9), we have

$$\overline{F}(q'^*_{R,N,1})[1-h(q'^*_{R,N,1})] = \frac{c-v}{\alpha_1(r-v)} > \frac{c-v}{\alpha_2(r-v)} = \overline{F}(q'^*_{R,N,2})[1-h(q'^*_{R,N,2})],$$

because $F(\cdot)$ is IGFR, the left hand side of (9), $\overline{F}(q'_{R,N})[1-h(q'_{R,N})]$, is decreasing in $q'_{R,N}$ if $q'_{R,N} \in [0, \alpha q_{R,N}^0]$, thus, we have $q'^*_{R,N,1} < q'^*_{R,N,2}$.

In addition, $w_N^* = \alpha(r-v)\overline{F}(q'^*_{R,N}) + v = c - v/[1-h(q'^*_{R,N})] + v$. Since $h'(\cdot) \ge 0$, we have w_N^* is increasing in $q'^*_{R,N}$. Furthermore, we have $EP_{R,N}(q^*_{R,N}) = (r-v)\int_0^{q'^*_{R,N}} xf(x)\,dx$, which is increasing in $q'^*_{R,N}$. Now, we prove the increasing property of $EP_{M,N}(q^*_{R,N})$. Given any $\alpha_1 < \alpha_2$, from IGFR, we have obtained that $q'^*_{R,N,1} < q'^*_{R,N,2}$. Thus,

$$\begin{aligned} EP_{M,N}(q'^*_{R,N,1}) &= [(r-v)\overline{F}(q'^*_{R,N,1}) - (c-v)/\alpha_1] \cdot q'^*_{R,N,1} \\ &\le [(r-v)\overline{F}(q'^*_{R,N,1}) - (c-v)/\alpha_2] \cdot q'^*_{R,N,1} \\ &\le [(r-v)\overline{F}(q'^*_{R,N,2}) - (c-v)/\alpha_2] \cdot q'^*_{R,N,2} \\ &= EP_{M,N}(q'^*_{R,N,2}) \end{aligned}$$

where the second inequality follows from the concavity of $EP_{M,N}$. Thus, the result is yielded.

(c) By the similar discussion and proof of (b), the results are yielded.

(d) From (b) and (c), we have

$$w_N^* \le w_{N,\alpha=1}^* = (r-v)\overline{F}(q^*_{R,N,\alpha=1}) + v = \frac{c-v}{[1-h(q^*_{R,N,\alpha=1})]} + v$$

$$w'^*_F \ge w'^*_{F,t=0} = (r-v)\overline{F}(q^*_{R,F,t=0}) + v = \frac{c-v}{[1-h(q^*_{R,F,t=0})]} + v$$

Then, from Proposition 3.3, we have $q^*_{R,N,\alpha=1} = q^*_{R,F,t=0}$. Thus, $w_F^* > w_N^*$. □

Proof of Proposition 3.5. We first prove the result in the case $i = N$.

(a) To prove the result, it is suffices to show that, if $w_N^* \le w_{MV,N}$, then $EP_{M,N}|_{w^*_{MV,N} = w^*_N} \le EP_{M,N}|_{w^*_{MV,N} = w_{MV,N}}$, otherwise, $EP_{M,N}|_{w^*_{MV,N} = w^*_N} > EP_{M,N}|_{w^*_{MV,N} = w_{MV,N}}$. From Proposition 3.2, if $q^*_{R,N} \ge q_{R,MV,N}$, we have $w_N^* \le w_{MV,N}$ and the order quantity equals $q_{R,MV,N}$. Thus, $EP_{M,N}|_{w^*_{MV,N} = w^*_N} = [w_N^* - c] \cdot q_{R,MV,N} \le [w_{MV,N} - c] \cdot q_{R,MV,N} = EP_{M,N}|_{w^*_{MV,N} = w_{MV,N}}$.

If $q^*_{R,N} < q_{R,MV,N}$, then $w_N^* > w_{MV,N}$ and the order quantity is $q^*_{R,N}$. We have

$$\begin{aligned} EP_{M,N}|_{w^*_{MV,N} = w^*_N} &= [w_N^* - c] \cdot q^*_{R,N} > [w_{MV,N} - c] \cdot q^*_{R,N} \\ &= EP_{M,N}|_{w^*_{MV,N} = w_{MV,N}}. \end{aligned}$$

(b) From Proposition 3.2, we have $q^*_{R,MV,N}$ is non-decreasing in M_R. By the definition of $w^*_{MV,N}$, we have $w^*_{MV,N}$ decreases with $q^*_{R,MV,N}$. Thus, the result is yielded.

Following the similar discussion and proof, the results in the case $i = F$ is also yielded. □

Proof of Proposition 3.6.

(a) If $VP_i(q^*_{R,i}) \ge M_R$, from Propositions 3.2 and 3.5 , we have $q^*_{R,MV,i} = q_{R,MV,i}$ and $w^*_{MV,i} = w_{MV,i}$. Substituting them into (1) and (2), we rewrite the retailer's expected profits as

$$EP_{R,N}(q^*_{R,MV,N}) = (r-v) \cdot \int_0^{q'_{R,MV,N}} F(x)\,dx$$

$$EP_{R,F}(q^*_{R,MV,F}) = (r-v) \cdot \int_0^{q_{R,MV,F}} F(x)\,dx - \theta K$$

It is obviously that $EP_{R,i}$ is independent of α and t, but only depends on the corresponding order quantity, which is increasing with M_R. Thus, the result is yielded.

(b) Given any $\alpha_2 > \alpha_1$ such that satisfy $VP_N(q^*_{R,N}) \ge M_R$. Then, from (3) and Proposition 3.5, we have $\alpha_1 q_{R,MV,N,\alpha=\alpha_1} = \alpha_2 q_{R,MV,N,\alpha=\alpha 2}$ and $w_{MV,N,\alpha=\alpha_1} = w_{MV,N,\alpha=\alpha_2}$, thus

$$\begin{aligned} EP_{M,N}|_{\alpha=\alpha_1} &= [(r-v)\overline{F}(\alpha_1 q_{R,MV,N,\alpha=\alpha_1}) - (c-v)/\alpha_1]\alpha_1 q_{R,MV,N,\alpha=\alpha_1} \\ &= [(r-v)\overline{F}(\alpha_2 q_{R,MV,N,\alpha=\alpha_2}) - (c-v)/\alpha_1]\alpha_2 q_{R,MV,N,\alpha=\alpha_2} \\ &< [(r-v)\overline{F}(\alpha_2 q_{R,MV,N,\alpha=\alpha_2}) - (c-v)/\alpha_2]\alpha_2 q_{R,MV,N,\alpha=\alpha_2} \\ &= EP_{M,N}|_{\alpha=\alpha_2} \end{aligned}$$

Then, $EP_{M,N}(q^*_{R,MV,N})$ is increasing in α. Following the similar proof, the result that $EP_{M,F}(q^*_{R,MV,F})$ is decreasing in t is yielded. From Proposition 3.3, it is known that $EP_{M,i}(q_{R,i})$ concavely increases with $q_{R,i}$ if $q_{R,i} \le q^*_{R,MV,i}$. Since $q_{R,MV,i}$ increases with M_R. Combining both, $EP_{M,i}(q^*_{R,MV,i})$ is increasing in M_R. □

Proof of Proposition 3.7.

(a) From (15), it is obviously that $inc_R^*(\theta)$ increases with $q^*_{R,MV,F}$. If $M_R > VP_i(q^*_{R,i})$, then $q^*_{R,MV,F} = q^*_{R,F}$, which decrease with t. If $t = 0$, $inc_R^*(\theta)$ reaches the maximum: $inc_R^*(\theta)|_{t=0} = (r-v)\int_{\alpha q^*_{R,N}}^{q^*_{R,F,t=0}} xf(x)\,dx - \theta K$. If $K < 1/\theta(r-v)\int_{\alpha q^*_{R,N}}^{q^*_{R,F}} xf(x)\,dx$, there must exists a unique value t_R^* such that $inc_R^*(\theta) \ge 0$ if and only if $t \le t_R^*$. Since $\alpha q^*_{R,MV,N}$ increases with α, and $inc_R^*(\theta)$ decreases with θ, the result that $\partial t_R^*/\partial\alpha < 0$ and $\partial t_R^*/\partial\theta < 0$ are yielded. If $M_R < VP_F(q^*_{R,F})$, $q^*_{R,MV,F} = q_{R,MV,F}$, which depends on the value of M_R. Therefore, $inc_R^*(\theta)$ is independent of t.

(b) It is obviously that $inc_R^*(\theta)$ decreases with K. Noticing that $q^*_{R,MV,F}$ non-decreases with M_R and $\alpha q^*_{R,MV,N}$ increases with α. Combining all, the result is yielded.

(c) If $M_R \le VP_i(q^*_{R,i})$, then $q^*_{R,MV,F} = \alpha q^*_{R,MV,N}$. Thus, from (15), $inc_R^*(\theta) = -\theta K$. If $VP_N(q^*_{R,N}) < M_R \le VP_F(q^*_{R,F})$, noticing that

$\alpha q^*_{R,MV,N}$ is independent of M_R, and $q^*_{R,MV,F}$ is non-decreasing in M_R, combining both, $inc^*_R(\theta)$ is non-decreasing in M_R. □

Proof of Proposition 3.8. From Propositions 3.4 and 3.6, we have $inc^*_M(\theta)$ decreases with α and t, and non-decreases with M_R. Thus, following the similar discussion in the proof of Proposition 3.7, the result of (a) and (b) is yielded. If $M_R \le VP_i(q^*_{R,i})$, we have $q^*_{R,MV,F} = \alpha q^*_{R,MV,N}$, then

$$\begin{aligned} inc^*_M &= [(w^*_{MV,F}-c)q^*_{R,MV,F}-(w^*_{MV,N}-c)q^*_{R,MV,N}]-(1-\theta)K \\ &= \{[(r-v)\overline{F}(q^*_{R,MV,F})+v-t-c]-[(r-v)\overline{F}(\alpha q^*_{R,MV,N}) \\ &\quad -(c-v)/\alpha]\}q^*_{R,MV,F}-(1-\theta)K \\ &= [(1-\alpha)/\alpha(c-v)-t]q^*_{R,MV,F}-(1-\theta)K. \quad \square \end{aligned}$$

Proof of Proposition 3.9. (a) From Propositions 3.7 and 3.8, for a given K, we have that when θ varies from 0 to 1, t^*_R decreases with θ from t_1 to the minimum value, while t^*_M increases in θ from the minimum value to the maximum value t_1. Therefore, there must exist unique value θ^*_t such that satisfies $t^*_R = t^*_M$. By the definition of θ^*_t and t^*_i $(i=R,M)$, they must satisfy (17). By the similar discussion, the result of θ^*_K is also yielded. (b) The proof is similar to (a). □

Proof of Theorem 4.1. We first proof the sufficient part. If $w^*_{SC,N} = \lambda^*_N c$, substituting into (19), we have

$$EP_{R,N}(q_{SC,N},\lambda^*_N) = \lambda^*_N \cdot \left[r\cdot \alpha q_{SC,N} + v\cdot(1-\alpha)q_{SC,N} - cq_{SC,N} - (r-v) \cdot \int_0^{\alpha q_{SC,N}} F(x)\,dx\right] = \lambda^*_N EP_{SC,N}(q_{SC,N})$$

The first-order condition is the same as that of the supply chain. Thus, the condition (iii) of the definition is satisfied. From (22), if $\lambda^*_N \in (0, \lambda^*_{MV,N}]$, the condition (ii) is satisfied. Substituting $q^*_{SC,N}$ into (19), the retailer's expected profit is $\lambda^*_N(r-v)\int_0^{\alpha q^*_{SC,N}} xf(x)\,dx$, and the manufacturer's expected profit is $(1-\lambda^*_N)(r-v)\int_0^{\alpha q^*_{SC,N}} xf(x)\,dx$. From the condition (c), we have $EP_{R,N}(q^*_{SC,N},\lambda^*_N) \ge EP_{R,N}(q^*_{R,MV,N})$ and $EP_{M,N}(q^*_{SC,N},\lambda^*_N) \ge EP_{M,N}(q^*_{R,MV,N})$. Thus, the condition (i) of the definition is satisfied.

Then, we proof the necessary part. From (19), the first-order condition is $F(\alpha q_{SC,N}) = \{r + (1-\alpha/\alpha)v - w_{SC,N}/\alpha\lambda_N\}/(r-v)$, taking some manipulation and collecting similar terms, we have $w^*_{SC,N} = \lambda^*_N \cdot c$. From condition (ii) and the definition of $\lambda^*_{MV,N}$, we have $\lambda^*_N \le \lambda^*_{MV,N}$. From condition (i), we have $EP_{i,N}(q^*_{SC,N},\lambda^*_N) \ge EP_{i,N}(q^*_{R,MV,N})$, $(i=R,M)$. Substituting $q^*_{SC,N}$ into (19) and (20), the result is yielded. □

Proof of Theorem 4.2. The proof is similar to the proof of Theorem 4.1. □

Proof of Lemma 4.1. Without loss of generality, we assume that $F(x) = x (x \in [0,1])$. Then, we first prove result in the case with $i=F$. For a given M_R, according to the risk constraint under wholesale price contract, we have $(r-v)[q^*_{R,MV,F} - (q^*_{R,MV,F})^2/2]^{(k+1)/k}/\ (k+1) \le M_R$. By the definition of $\lambda^*_{MV,F}$, we have $\lambda^*_{MV,F}(r-v)[q^*_{SC,F} - (q^*_{SC,F})^2/2]^{(k+1)/k}/(k+1) = M_R$. Thus, for $\forall k \ge 1$,

$$\begin{aligned} \frac{\lambda^*_{MV,F}\int_0^{q^*_{SC,F}} xf(x)\,dx}{\int_0^{q^*_{R,MV,F}} xf(x)\,dx} &= \frac{(k+1)M_R}{(r-v)[q^*_{SC,F}-(q^*_{SC,F})^2/2]^{(k+1)/k}} \cdot \frac{(q^*_{SC,F})^2/2}{(q^*_{R,MV,F})^2/2} \\ &\ge \frac{[q^*_{R,MV,F}-(q^*_{R,MV,F})^2/2]^{(k+1)/k}}{[q^*_{SC,F}-(q^*_{SC,F})^2/2]^{(k+1)/k}} \cdot \frac{(q^*_{SC,F})^2}{(q^*_{R,MV,F})^2} \\ &= \left[\frac{2-q^*_{R,MV,F}}{2-q^*_{SC,F}}\right]^{(k+1)/k} \cdot \left[\frac{q^*_{SC,F}}{q^*_{R,MV,F}}\right]^{(k-1)/k} \ge 1 \end{aligned}$$

The second inequality follows from $q^*_{R,MV,F} \le q^*_{SC,F}$. □

Proof of Proposition 4.1. The proof of part (a) and (b) is similar to the proof of Proposition 3.7.

c) If the supply chain is coordinated and $\lambda_N = \lambda_F = \theta_N = \theta_F$, we have

$$\begin{aligned} inc^*_R(\theta) &= \lambda_F(r-v)\cdot\int_0^{q^*_{SC,F}} xf(x)\,dx - \lambda_N(r-v)\cdot\int_0^{\alpha q^*_{SC,N}} xf(x)\,dx - \theta K \\ &= \lambda_F[EP_{R,F}(q^*_{SC,F}) - EP_{R,N}(q^*_{SC,N})] \end{aligned}$$

$$\begin{aligned} inc^*_M(\theta) &= (1-\lambda_F)\cdot(r-v)\cdot\int_0^{q^*_{SC,F}} xf(x)\,dx - (1-\lambda_N)\cdot(r-v) \\ &\quad \times \int_0^{\alpha q^*_{SC,N}} xf(x)\,dx - (1-\theta)K \\ &= (1-\lambda_F)\cdot[EP_{R,F}(q^*_{SC,F}) - EP_{R,N}(q^*_{SC,N})] \end{aligned}$$

Thus, according to part (a) and (b), the result is yielded. □

Proof of Lemma 4.2. From (21) and (25), we have that $q^*_{SC,N}$ and $q^*_{SC,F}$ satisfy the following expressions respectively: $F(\alpha q^*_{SC,N}) = (r-c-((1-\alpha)/\alpha)(c-v))/(r-v)$ and $F(q^*_{SC,F}) = (r-c-t)/(r-v)$. If $t \le t_1$, we have $\alpha q^*_{SC,N} \le q^*_{SC,F}$. Thus, by the increasing property of VP_i, we have

$\lambda^*_{MV,F} = M_R/[(r-v)\delta^{1/k}(q^*_{SC,F})] \le M_R/[(r-v)\delta^{1/k}(\alpha q^*_{SC,N})] = \lambda^*_{MV,N}$. □

Proof of Proposition 5.1. Denote by $EP_{R,i}$ and $P_{R,i}$ as the expected profit and random profit of the retailer, we have

$$\frac{\partial VP_i(\tilde{w}_i, q_{R,i}, b_i)}{\partial b_i} = \{E[(EP_{R,i}-P_{R,i})^k_+]\}^{(1/k)-1} \cdot E[(EP_{R,i}-P_{R,i})^{k-1}_+] \times \frac{\partial[(EP_{R,i}-P_{R,i})_+]}{\partial b_i}$$

In the case $i=N$, from (32), we have

$$\begin{aligned} \frac{\partial[(EP_{R,N}-P_{R,N})_+]}{\partial b_N} &= \frac{\partial}{\partial b_N}\cdot\left[\begin{matrix}(r-b_N)\left[(\alpha q_{R,N}-x)_+ - (\alpha q^0_{R,N}-x)_+ - \int_{\alpha q^0_{R,N}}^{\alpha q_{R,N}} F(x)\,dx\right] \\ +(r-v)[(\alpha q^0_{R,N}-x)_+ - n(\alpha q^0_{R,N})]\end{matrix}\right]_+ \\ &= \frac{\partial}{\partial b_N}\cdot\left[\begin{matrix}(r-b_N)\left[(\alpha q_{R,N}-\alpha q^0_{R,N}) - \int_{\alpha q^0_{R,N}}^{\alpha q_{R,N}} F(x)\,dx\right] \\ +(r-v)[(\alpha q^0_{R,N}-x-n(\alpha q^0_{R,N})]\end{matrix}\right]_+ \Big|_{0\le x\le \alpha q^0_{R,N}} \\ &\quad + \frac{\partial}{\partial b_N}\cdot\left[\begin{matrix}(r-b_N)\left[\alpha q_{R,N}-x-\int_{\alpha q^0_{R,N}}^{\alpha q_{R,N}} F(x)\,dx\right] \\ -(r-v)\cdot n(\alpha q^0_{R,N})\end{matrix}\right]_+ \Big|_{\alpha q^0_{R,N}\le x\le \alpha q_{R,N}-\int_{\alpha q^0_{R,N}}^{\alpha q_{R,N}} F(x)\,dx} \\ &\le 0 \end{aligned}$$

Similarly, we have $\partial[(EP_{R,F}-P_{R,F})_+]/\partial b_F \le 0$. Thus, the result is yielded. □

Proof of Theorem 5.1. We first proof the sufficient part. If $i=N$, from (32), we have

$$\partial EP_{R,N}/\partial q_{R,N} = r-(1-\alpha)(r-v)-\tilde{w}_N - \alpha(r-b^*_N)F(\alpha q_{R,N}) \tag{C.1}$$

If $q^0_{R,N} \le q_{R,N} \le q^*_{SC,N}$ and $\tilde{w}_N \le \overline{w}_N$, we have $\partial EP_{R,N}/\partial q_{R,N} \ge 0$, and the optimal order quantity is $q^*_{SC,N}$, which satisfies the condition (iii). If $\tilde{w}_N \le \overline{w}_N$, from (32), we have

$$\begin{aligned} &EP_{R,N}(\tilde{w}_N, q^*_{SC,N}, b^*_N) - EP^0_{R,N}(q^0_{R,N}) \\ &\quad = [r-(1-\alpha)(r-v)-\tilde{w}_N](q^*_{SC,N}-q^0_{R,N}) - (r-b^*_N)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx \\ &\quad \ge (r-b^*_N)F(\alpha q^*_{SC,N})(\alpha q^*_{SC,N}-\alpha q^0_{R,N}) - (r-b^*_N)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx \\ &\quad \ge 0 \end{aligned}$$

Similarly, if $\tilde{w}_N \ge \underline{w}_N$, we have $EP_{M,N}(\tilde{w}_N, q^*_{SC,N}, b^*_N) - EP^0_{M,N}(q^0_{R,N}) \ge 0$. Thus, the condition (i) is satisfied. In addition, from the definition of b^*_N, it is obviously that the condition (ii) is satisfied. Similarly, the result in the case $i=F$ is also yielded.

Then, we proof the necessary part by contradiction. If $\tilde{w}_N > \overline{w}_N$, from (C.1), we have $\partial EP_{R,N}/\partial q_{R,N} < 0$. Thus, the optimal order quantity is $q^0_{R,N}$, which does not satisfy the condition (iii). If $\tilde{w}_N < \underline{w}_N$, we have

$$EP_{M,N}(\tilde{w}_N, q^*_{SC,N}, b^*_N) - EP^0_{M,N}(q^0_{R,N})$$
$$= (\tilde{w}_N - c)(q^*_{SC,N} - q^0_{R,N}) - (b^*_N - v)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx < 0$$

It does not satisfy the condition (i). Similarly, we have the corresponding result in the case $i = F$. Thus, the results is yielded. □

Proof of Lemma 5.1. Since $q^0_{R,i}$ $(i = N, F)$ is constrained by the risk threshold, from (3) and (4), we have $\alpha q^0_{R,N} = q^0_{R,F}$. Let $T_1 = [r - (1-\alpha)(r-v) - \tilde{w}_N]/\alpha$ and $T_2 = r - t - \tilde{w}_F$, from Proposition 3.7(c), we have

$$inc^*_R(\theta, \tilde{w}_N, \tilde{w}_F) = -\theta K + T_2(q^*_{SC,F} - q^0_{R,F}) - T_1(\alpha q^*_{SC,N} - \alpha q^0_{R,N})$$
$$= T_2 \cdot q^*_{SC,F} - T_1 \cdot \alpha q^*_{SC,N} - \theta K + (T_2 - T_1)\cdot \alpha q^0_{R,N}$$

Obviously, $q^0_{R,N}$ is the only parameter relevant to M_R. If $T_2 = T_1$, $inc^*_R(\theta, \tilde{w}_N, \tilde{w}_F)$ will be independent of M_R. In addition, since

$$inc^*_R(\theta, \tilde{w}_N, \tilde{w}_F) + inc^*_M(\theta, \tilde{w}_N, \tilde{w}_F) = EP_{SC,N}(q^*_{SC,F}) - EP_{SC,N}(q^*_{SC,N}) = inc^*_{SC}(\theta)$$

which is independent of M_R. Thus, if $T_2 = T_1$, $inc^*_M(\theta, \tilde{w}_N, \tilde{w}_F)$ is also independent of M_R. Then the result is yielded. □

Proof of Lemma 5.2.

(a) Consider the case without RFID adoption, taking the first-order derivative of $\underline{w}_N$ with respect to $q^0_{R,N}$, gives

$$\frac{\partial \underline{w}_N}{\partial q^0_{R,N}} = \frac{-\alpha(r-v)F(\alpha q^0_{R,N})}{q^*_{SC,N} - q^0_{R,N}} - \frac{-(r-v)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx}{(q^*_{SC,N} - q^0_{R,N})^2}$$
$$= (r-v)\left[\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx - \alpha(q^*_{SC,N} - q^0_{R,N})F(\alpha q^0_{R,N})\right] / (q^*_{SC,N} - q^0_{R,N})^2 \geq 0$$

Then, since $q^0_{R,N}$ is increasing with M_R (see the requirement on the initial contract), we have $\underline{w}_N$ increases with M_R. The proof of $\underline{w}_F$ is similar to $\underline{w}_N$.
According to the proof of Lemma 4.2, we have $\alpha q^*_{SC,N} \leq q^*_{SC,F}$ if $t \leq t_1$. We rewrite the $\underline{w}_N$ and $\underline{w}_F$ as

$$\underline{w}_N = c + (r-v)\int_{\alpha q^0_{R,N}}^{\alpha q^*_{SC,N}} F(x)\,dx/(q^*_{SC,N} - q^0_{R,N}) \text{ and}$$
$$\underline{w}_F = c + (r-v)\int_{q^0_{R,F}}^{q^*_{SC,F}} F(x)\,dx/(q^*_{SC,F} - q^0_{R,F})$$

Then, we denote $W(q)$ as $W(q) = c + (r-v)\int_{q^0_{R,F}}^{q} F(x)\,dx/(q - q^0_{R,F})$. To prove $\underline{w}_F > \underline{w}_N$, it suffices to show that $W(q)$ increases with q. Taking the first-order derivative

$$\frac{dW(q)}{dq} = \frac{(r-v)F(q)}{q - q^0_{R,F}} - \frac{(r-v)\int_{q^0_{R,F}}^{q} F(x)\,dx}{(q - q^0_{R,F})^2}$$
$$= (r-v)\left[(q - q^0_{R,F})F(q) - \int_{q^0_{R,F}}^{q} F(x)\,dx\right] / (q - q^0_{R,F})^2 \geq 0$$

Rewriting $\overline{w}_N$ and $\overline{w}_F$ as: $\overline{w}_N = r - (1-\alpha)(r-v)$ and $\overline{w}_F = r - t$. If $t \leq t_1$, we have $\overline{w}_F = r - t \geq r - t_1 = r - (1-\alpha)(c-v)/\alpha \geq r - (1-a)(r-v) = \overline{w}_N$. The second inequality follows from $\alpha \in (\overline{\alpha}, 1]$ (see the discussion in Proposition 3.3).

(b) From the Proposition 5.1 and the definition of b^*_i, we have b^*_i decreases with M_R. From (42)–(45), it is obviously to see that $\underline{w}_i$ and $\overline{w}_i$ both increases with b^*_i. Then,

$$\frac{\partial(\overline{w}_F - \underline{w}_F)}{\partial b^*_F} = \left[F(q^*_{SC,F}) - \int_{q^0_{R,F}}^{q^*_{SC,F}} F(x)\,dx/(q^*_{SC,F} - q^0_{R,F})\right]$$
$$= \left[F(q^*_{SC,F})(q^*_{SC,F} - q^0_{R,F}) - \int_{q^0_{R,F}}^{q^*_{SC,F}} F(x)\,dx\right] / (q^*_{SC,F} - q^0_{R,F})$$
$$\geq 0$$

Similarly, the result $\partial(\overline{w}_N - \underline{w}_N)/\partial b^*_N \geq 0$ is yielded. □

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