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Inventory misplacement and demand forecast error in the supply chain: profitable RFID strategies under wholesale and buy-back contracts

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We investigate RFID adoption strategies under wholesale price and buy-back contracts in a supply chain with one manufacturer and one retailer who faces inventory misplacement and demand forecast error. RFID can alleviate the misplacement problem, and can reduce demand forecast error by shortening order lead time. By a newsvendor model, we characterise the optimal contract terms in the supply chain without and with RFID adoption, respectively. We further analyse how the contract terms depend on RFID-related parameters (e.g. salable rate and demand forecast error). We find that both without and with RFID, the wholesale price contract will lead to the double marginalisation problem, while the buy-back contract can coordinate the supply chain. We show that the supply chain adopts RFID if and only if the tagging cost is below a threshold; the threshold is in negative correlation to the demand forecast error. The supply chain is more willing to adopt RFID under the buy-back contract than under the wholesale price contract. RFID adoption can sometimes lessen the double marginalisation problem under the wholesale price contract, improving the supply chain efficiency. A smaller RFID tagging cost or a reduced forecast error do not necessarily lead to higher supply chain efficiency.

Keywords: RFID; inventory misplacement; demand forecast error; supply chain contracts; coordination

1. Introduction

Inventory misplacement is widely discussed in the supply chain context (Sahin, Buzacott, and Dallery 2008; Bai, Szmerekovsky, and Zhang 2009; Sahin and Dallery 2009; Rekik and Sahin 2012). It leads to significant losses of profits in retail supply chains (Thiel, Hovelaque, and Hoa 2010; Rekik 2011). Meanwhile, the market demand is always random and the demand forecast accuracy is very important to supply chain operations. A short order lead time can improve the demand forecast accuracy (Rohr and Correa 1998). The empirical study by Iyer and Bergen (1997) shows that if a supply chain reduces the lead-time from 8 to 4 months, then the demand forecast error can be improved from 65 to 35%.

Radio-frequency identification (RFID) technology helps firms identify, track and transmit inventory information (Ben-Daya, Hassini, and Bahroun 2017) and has been a most effective tool to solve the inventory misplacement problem (Hardgrave, Aloysius, and Goyal 2013). RFID can also increase the automation operational process, reduce the time of manual operations and increase the efficiency of manufacturing, transportation, storage and other links; thus it can reduce lead-time (Wang et al. 2010), and increase the demand forecast accuracy. Several retailers (i.e. Wal-Mart, Target and Metro) have strongly promoted – or even mandated – RFID adoption by their suppliers (Szmerekovsky and Zhang 2008; Wang et al. 2010) and have achieved significant results with RFID adoption (OECD 2008; Feng et al. 2014).

Supply chain contracts and coordination has long been a topic of practical and academic importance. Researchers propose various contracts that can improve supply chain efficiency, incorporating different market conditions and operational factors. However, there is little research on how RFID – a new element fundamentally influencing supply chain operations – and supply chain contracts interact with each other. It is unclear how the two consequences of RFID adoption (i.e. reducing misplacement and reducing demand forecast error) jointly impact the supply chain contracts and operations.

To fill this gap, we consider a supply chain with a manufacturer and a newsvendor retailer. The demand is uncertain and the retailer makes his order quantity decision based on the demand forecast. The retailer has a misplacement problem where some of his ordered units cannot be found in time to satisfy the demand in the selling season. RFID can alleviate the misplacement problem; it can also shorten the order lead time and thus improve the forecast accuracy. By comparing two supply chain contracts, wholesale price and buy-backs, we investigate the RFID adoption strategies and

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their impacts on the contract terms. We address the following questions: What are the optimal contract terms without and with RFID and their impacts on the firms' profitability? How will the RFID-related parameters (e.g. salable rate and demand forecast error) affect the two contracts and optimal order quantities? How do the supply chain's RFID adoption strategies depend on contracts? How does the supply chain efficiency change without and with RFID? The logic flow of our study is shown in Figure 1.

Our paper is related to the adoption of RFID in supply chain. Lee and Özer (2007) provided an excellent overview of the current RFID-related research in operations management and suggested additional directions for further strengthening the contributions of operations management to help industries realise the full potential of RFID. Gaukler, Seifert, and Hausman (2007) developed an analytical model of item-level RFID in a retail supply chain. They assumed that the demand is normally distributed and found that RFID adoption improves demand visibility. Rekik, Sahin, and Dallery (2007), (2008) employed the model to analyse a supply chain in which a manufacturer sells a single product to a retailer that suffers from inaccuracies in inventory. The researchers identified misplaced items, damage and spoilage and supply errors as the factors that cause inventory inaccuracy and analysed the effects of RFID technology on each of the factors. Camdereli and Swaminathan (2010) used the newsvendor model to delve into inventory misplacement in a supply chain in which one manufacturer sells a short-life cycle product through one retailer. They explored the feasibility of RFID adoption when a supply chain is operated under centralised and decentralised conditions. Rekik and Sahin (2012) model a set of scenarios depending on the technology available to track shrinkage in the store with/without RFID. They assume that an inspection process is performed at a regular frequency of N selling periods. The deployment of RFID produces two benefits: total visibility of the shrinkage rate and the elimination of shrinkage errors. A comparison of the scenarios enables them to evaluate the economic impact of inventory record inaccuracies, which can be significant, particularly in systems with a poor estimation of the error parameter as well as with a high inspection cost. Chen et al. (2014) used the newsvendor model to investigate the application of RFID as a means of eliminating misplacement problems in a supply chain that comprises a risk-neutral manufacturer and a risk-averse retailer. Considering the fixed and tagging costs of RFID, the authors investigated the agents' incentives for adopting RFID in uncoordinated and coordinated supply chains. They proposed the use of a risk-sharing contract that protects retailers from risks to achieve channel coordination. Rekik, Syntetos, and Jemai (2015) showed that RFID adoption harms a manufacturer and benefits an e-retailer but such effects depend on the discrepancy between an inventory information system and physical inventory. Wang et al. (2016) derived the tagging price threshold under which RFID adoption is beneficial to firms in conditions wherein demand depends on inventory level. However, the studies discussed above assumed that RFID read rates are perfect up to 100% and disregarded that RFID can shorten lead-time and thereby reduce the demand forecast error.

There also exist some articles considering the imperfect RFID read rate. Xu et al. (2012) considered a two-echelon supply chain consisting of a Stackelberg manufacturer and a retailer that suffers from inventory misplacement. Their analysis was based on a single-period newsvendor model and considered four cases of order decisions. The authors then derived a critical tagging price for RFID implementation as a technological remedy for inventory inaccuracy. Fan et al. (2015) considered a supply chain that consists of one supplier and one retailer that sells a single product to customers. They assumed that demand is uniformly distributed and examined the factors that influence RFID fixed costs, tagging prices and shrinkage recovery rates. Our study differs from the above papers on two aspects. On one hand, we incorporate RFID's effect of reducing forecast error, in addition to the misplacement problem; in contrast, they do not consider the improvement in forecast accuracy brought by RFID. On the other hand, we compare RFID adoption strategies under different contracts, and show how the firms' profitability and contract terms depend on RFID-related parameters.

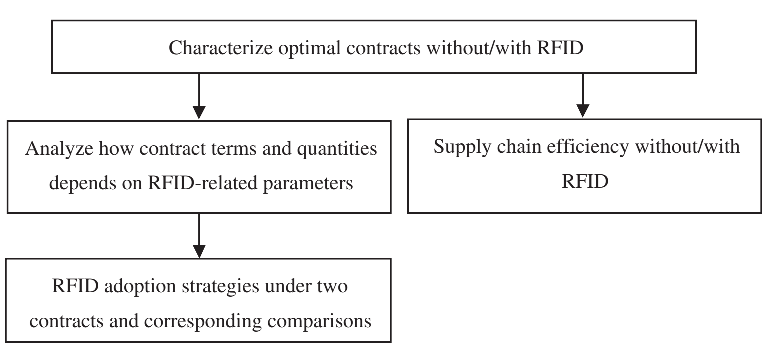


Figure 1. The logic flow of the study.

Our paper also contributes to the literature on supply chain contracts. Cachon (2003) provides a comprehensive review of supply chain contracts. A consensus of supply chain contract research is that the wholesale price contract leads to inefficiencies in channel decisions due to double marginalisation, whereas more complex contracts, such as revenue sharing contracts and two-part tariffs, achieve system optimality. Yoo, Kim, and Park (2015) investigated three commonly used supply contracts, i.e. wholesale price, buy-back and quantity discount contracts, to discuss the retailer's decision on pricing and return policies which affect consumers' demand and return behaviours. Zhang, Donohue, and Cui (2016) showed that a loss-averse supplier's preference over revenue-sharing and a buyback contract depends on the ratio of production cost and retail price. Unlike the above literature, we compare the two firm's profits under the supply chain contracts, i.e. wholesale price contract and buy-back contract, with (non-)adoption of RFID. Camdereli and Swaminathan (2010) investigated the contracts to coordinate the supply chain with RFID adoption, while we analyse how the contract parameters change with/without RFID adoption.

The remainder of the paper is organised as follows. In Section 2, we describe our model assumptions and notations. In Section 3, we establish the profit models. By providing numerical examples, Section 4 identifies some implications and managerial insights, and in Section 5 we summarise the results and present directions for future research. All proofs are provided in the Appendix 1.

2. Model assumptions and notation

Consider a two-level supply chain comprised of a manufacturer (she) and a retailer (he). The manufacturer produces goods at a unit production cost c_m and sells them to the retailer through a contract that will be specified later. The retailer in turn sells the goods to the end market over a short selling season. The demand during the selling season is uncertain, captured by the random variable X. At time 0, the retailer determines his order quantity q. At time T (the time length T is called the order lead time), the retailer receives the ordered products and the selling season starts. During the selling season $[T, T_e]$, the retailer sells at regular price p per unit and the demand X is realised at T_e. After time T_e, the leftover inventories are salvaged at s per unit; if the demand is more than the available items, the retailer incurs g per each unit of excess demand, i.e. a penalty cost for lost sales.

The retailer makes his order quantity decision q based on the forecast about the uncertain demand X. At time 0, the demand forecast is that X follows a distribution $F(x, 0)$ with mean μ and variance σ_0^2. The retailer suffers from the misplacement problem where some of his ordered units cannot be found in time to satisfy the demand during the selling season. Only a proportion α of the ordered units (i.e. αq units) are available for selling, while $(1-\alpha)\ q$ units are misplaced and unavailable for selling during the selling season. The parameter α is called *the salable rate*. We assume the misplaced items can eventually be found after the selling season and thus can be salvaged with the leftovers, at the same salvage price s per unit. Nevertheless, different salvage prices for misplaced items and leftovers can easily be incorporated into our model.

RFID technology can help supply chain decisions in two ways. First, RFID alleviates the misplacement problem, making more of the ordered units available during the selling season. In particular, by adopting RFID, the misplacement problem is alleviated and the salable rate becomes $\beta(\beta \in [\alpha, 1])$.[1] The change in salable rate from adopting to not adopting RFID is shown in Figure 2. Second, RFID facilitates a shorter lead time for ordering, which enables the supply chain to better forecast the demand. Specifically, by adopting RFID, the order lead-time is shortened to T–t and the retailer is able to postpone his order decision from time 0 to time t, because RFID can reduce the time of manual opera-

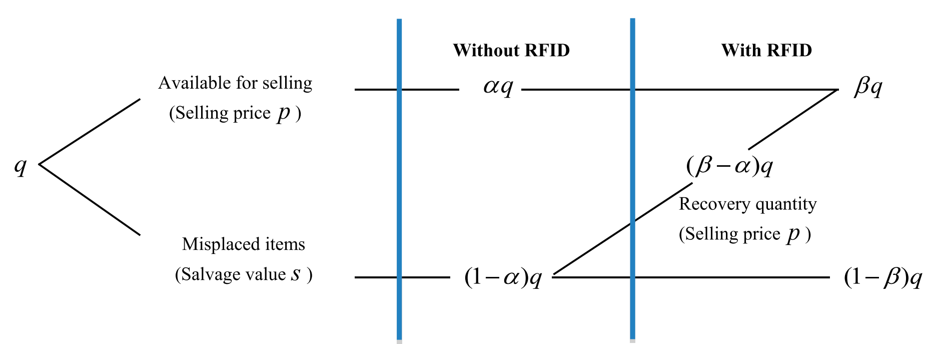


Figure 2. Salable rates with and without RFID.

tions (Wang et al. 2010). The compressed lead time gives rise to a more accurate demand forecast. At time t, the demand forecast is that X follows a distribution $F(x,t)$ with mean μ and variance σ_t^2 ($\sigma_t \leq \sigma_0$). That is, with compressed lead time, the variance of the forecast is smaller, indicating a more accurate demand forecast. The sequence of events is shown in Figure 3, where the case with RFID is depicted above the time axis, while the case without RFID is depicted below the time axis.

We focus on two types of supply chain contracts, wholesale price and buybacks. Under a wholesale price contract w, the retailer pays the manufacturer a fixed wholesale price w per unit ordered. Under a buy-back contract (w, b), the retailer pays the manufacturer w per unit ordered but receives from the manufacturer b (b is called the buyback price) for each unsold unit after the selling season. In actual operations of retail supply chains, an RFID tag is always attached to the product package and this work is often done by the manufacturer, so we assume the manufacturer pays for the technology expenses and attaches an RFID tag onto each unit of product. It costs the manufacturer c_t for attaching each RFID tag. In this paper, we do not explicitly model the fixed cost of adopting RFID (reader systems, basic application and integration, maintenance and support and over-head). This is because, compared to the RFID tag cost, the fixed cost is a small proportion of the total cost of investing in RFID. Moreover, Sahin (2004) and Rekik, Sahin, and Dallery (2008) have provided that these fixed costs will not vary with the model parameters.

Let $i = 0$ and $i = t$ denote the cases with and without RFID, respectively. The demand forecast distributions in the two cases can thus be written as $F(x, i)$, ($i = 0, t$). Denote the corresponding density functions by $f(x, i)$. The failure rate is $h(x) = f(x)/(1 - F(x))$ and the generalised failure rate is $z(x) = xh(x)$. We assume $F(x, i)$ is differentiable and has a strict increasing generalised failure rate (IGFR), i.e. $z'(x) > 0$. As Zhou and Groenevelt (2007) claim, it can be verified that many commonly applied distributions, e.g. uniform, exponential, power and Weibull with the shape parameter greater than or equal to two, and truncated normal, meet the assumption.

We summarise the main notation mentioned above in Table 1.

3. Profit models

In this section, we will analyse two different scenarios with random market demand in general distribution: Non-RFID adoption and RFID adoption.

3.1 *Non-RFID adoption*

In the non-RFID scenario, we will analyse three settings and obtain optimal contract parameters and order quantities without RFID adoption.

3.1.1 *Centralised supply chain without RFID*

We study a centralised supply chain where the manufacturer owns the retailer. The centralised firm's expected profit $\pi_{C(q,0)}$ without RFID adoption is as follows:

$$\begin{aligned}\pi_{C(q,0)} &= p\left[\int_0^{\alpha q} xf(x,0)\mathrm{d}x + \int_{\alpha q}^{+\infty} \alpha q f(x,0)\mathrm{d}x\right] + s\int_0^{\alpha q} (\alpha q - x)f(x,0)\mathrm{d}x - \\ &\quad g\int_{\alpha q}^{+\infty} (x - \alpha q)f(x,0)\mathrm{d}x + s(1-\alpha)q - c_m q\end{aligned} \tag{1}$$

The profit function is concave in the order quantity as it has the general form of a newsvendor function. The optimal order quantity is $\alpha Q_{C0}^* = F^{-1}\left[1 - \frac{c_m - s}{\alpha(p+g-s)}\right]$. In order to ensure $\pi^*_{C(Q^*_{C0},0)} > 0$, we have $F(\alpha Q^*_{C0}, 0) = 1 - \frac{c_m - s}{\alpha(p+g-s)} > 0$.

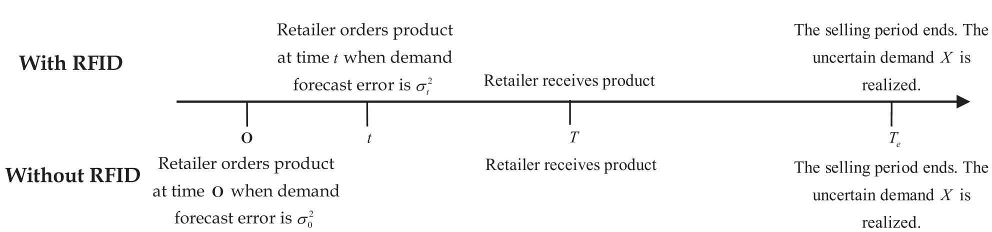


Figure 3. The reduction of demand forecast error with RFID.

Table 1. Notations and explanations.

Notation	Explanation
p	Market price per unit of product sold in the selling season
c_m	The manufacturer's unit production cost
w_i	The manufacturer's unit wholesale price in condition i, where the cases with and without RFID are denoted by subscripts $i = 0$ and $i = t$, respectively
b_i	The Manufacturer's unit wholesale price in condition i
q	The retailer's order quantity
s	Salvage value per unit of leftover inventories and misplaced products at the end of the selling season
g	The unit penalty cost for lost sales.
α	The retailer's salable rate without RFID adoption, where $\alpha \in (0, 1)$
β	The retailer's salable rate with RFID adoption, where $\beta \in [\alpha, 1]$
c_t	The unit price of RFID tag
π	Expected profit
$f(x, i)$	The probability density function of demand in condition i
$F(x, i)$	The cumulative density function of demand in condition i
μ	The mean value of demand
σ_i^2	The variance of demand in condition i
T	The lead-time of supply chain without RFID adoption
t	The amount of lead-time compression with RFID adoption, where $t \in [0, T]$

Thus, we derive $\alpha > (c_m - s)/(p + g - s) = V_{C0}$. This means that there exists a threshold value $\alpha \in (V_{C0}, 1)$ such that the firm's profit $\pi^*_{C(Q^*_{C0},0)} > 0$. Then the optimal order quantity is

$$Q^*_{C0} = \begin{cases} \dfrac{F^{-1}\left[1 - \frac{c_m - s}{\alpha(p+g-s)}\right]}{\alpha}, & V_{C0} < \alpha < 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Then substituting αQ^*_{C0} into Equation (1), we can get the maximal expected profit $\pi^*_{C(Q^*_{C0},0)}$ as follows:

$$\pi^*_{C(Q^*_{C0},0)} = \begin{cases} (p + g - s)\int_0^{\alpha Q^*_{C0}} xf(x, 0)\mathrm{d}x, & V_{C0} < \alpha < 1 \\ 0 & \\ & \text{otherwise} \end{cases} \tag{3}$$

Lemma 1. (i) $\partial Q^*_{C0}/\partial\alpha > 0$ if and only if $\alpha \in (V_{C0}, \overline{\alpha_{C0}}]$, while $\partial Q^*_{C0}/\partial\alpha < 0$ if and only if $\alpha \in (\overline{\alpha_{C0}}, 1)$, where $\overline{\alpha_{C0}} = \arg_{\alpha}\{\overline{\alpha_{C0}}Q^*_{C0}z'(\overline{\alpha_{C0}}Q^*_{C0}, 0)/\left(1 - z(\overline{\alpha_{C0}}Q^*_{C0}, 0)\right)^2 = 1\}$;

(ii) $\partial Q^*_{C0}/\partial s > 0$; $\partial Q^*_{C0}/\partial g > 0$;

(iii) When the demand follows a uniform distribution on $[0, \lambda]$, we have $\partial Q^*_{C0}/\partial\sigma_0 > 0$.

In the centralised supply chain without RFID, the optimal order quantity increases when (i) the salvage value s increases, (ii) the lost sales penalty cost g increases and (iii) the demand information becomes more accurate (i.e. larger σ_0). However, the optimal order quantity is not monotonic in the salable rate α. This is because of the two counteracting effects of increasing α on the optimal order quantity. In fact, the overage cost for the newsvendor-type consolidated firm is c_m–s and the underage cost is $\alpha(p + g - c_m) - (1 - \alpha)(c_m - s) = \alpha(p + g - s) - (c_m - s)$. Apparently, a larger α implies a greater underage cost, pushing the centralised firm to order more. However, an increase in salable rate α gives the firm more units available during the selling season. When α is small (i.e. $\alpha \in (V_{C0}, \overline{\alpha_{C0}}]$), the former effect of enlarging underage cost dominates the latter effect of providing more available units, and hence the optimal order quantity increases in α. When α is large (i.e. $\alpha \in (\overline{\alpha_{C0}}, 1)$), the reverse is true.

3.1.2 *Wholesale price contract without RFID*

In this setting, the manufacturer sets a wholesale price w_{W0}. The optimal decision among the players in the supply chain is a dynamic process game. The expected profits of the retailer and the manufacturer, i.e. $\pi_{Wr(q,0)}$ and $\pi_{Wm(q,0)}$, are given by:

$$\begin{aligned}\pi_{Wr(q,0)} &= p[\int_0^{\alpha q} xf(x,0)\mathrm{d}x + \int_{\alpha q}^{+\infty} \alpha q f(x,0)\mathrm{d}x] + s\int_0^{\alpha q}(\alpha q - x)f(x,0)\mathrm{d}x - \\ &\quad g\int_{\alpha q}^{+\infty}(x-\alpha q)f(x,0)\mathrm{d}x + s(1-\alpha)q - w_{W0}q\end{aligned} \tag{4}$$

$$\pi_{Wm(q,0)} = (w_{W0} - c_m)q \tag{5}$$

In Equation (4), the first and second terms are the retailer's expected revenue, the third term is salvage value of left-over inventories, the fourth term is the lost customer goodwill, the fifth term is salvage value of misplaced items and the last term is the wholesale cost. Doing first- and second-order differentials on q in Equation (4), it can be derived that:

$$\frac{\partial \pi_{Wr(q,0)}}{\partial q} = \alpha(p+g-s) - \alpha(p+g-s)F(\alpha q,0) + s - w_{W0}$$

$$\frac{\partial^2 \pi_{Wr(q,0)}}{\partial q^2} = -\alpha^2(p+g-s)f(\alpha q,0) < 0 \tag{6}$$

After the optimization of Equation (6), the retailer's optimal order quantity is $\alpha Q_{W0} = F^{-1}\left[1 - \frac{w_{W0}-s}{\alpha(p+g-s)}\right]$, which can be rewritten as $w_{W0} = \alpha(p + g - s)(1 - F(\alpha Q_{W0}, 0)) + s$. Hence, the manufacturer's optimization problem depends on Q_{W0}. Therefore, the manufacturer's profit can be rewritten as $\pi_{Wm(Q_{W0},0)} = [\alpha(p+g-s)(1-F(\alpha Q_{W0},0)) + s - c_m]Q_{W0}$. Taking the first-order derivative of $\pi_{Wm(Q_{W0},0)}$ with respect to w_{W0}, we can derive

$$\begin{aligned}\frac{\partial \pi_{Wm(Q_{W0},0)}}{\partial w_{W0}} &= \frac{\partial \pi_{Wm(Q_{W0},0)}}{\partial(\alpha Q_{W0})} \cdot \frac{\partial F(\alpha Q_{W0},0)}{\partial w_{W0}} \Big/ \frac{\partial F(\alpha Q_{W0},0)}{\partial(\alpha Q_{W0})} \\ &= \left(\frac{w_{W0}-c_m}{\alpha} + Q_{W0}\cdot\frac{\partial w_{W0}}{\partial(\alpha Q_{W0})}\right)\cdot\left(-\frac{1}{\alpha(p+g-s)}\right)\Big/ f(\alpha Q_{W0},0) \\ &= -\left(\frac{w_{W0}-c_m}{\alpha} - \frac{(w_{W0}-s)}{\alpha}\cdot\frac{\alpha Q_{W0} f(\alpha Q_{W0},0)}{1-F(\alpha Q_{W0},0)}\right)\cdot\left(\frac{1}{\alpha(p+g-s)f(\alpha Q_{W0},0)}\right) \\ &= -\left(\frac{w_{W0}}{\alpha}(1 - z(\alpha Q_{W0},0)) - \frac{c_m - sz(\alpha Q_{W0},0)}{\alpha}\right)\cdot\left(\frac{1}{\alpha(p+g-s)f(\alpha Q_{W0},0)}\right)\end{aligned}.$$

Let $\frac{\partial \pi_{Wm(Q_{W0},0)}}{\partial w_{W0}} = 0$, and we get the optimal wholesale price $w^*_{W0} = (c_m - sz(\alpha Q_{W0},0))/\left(1 - z(\alpha Q^*_{W0},0)\right)$. In addition, in order to ensure $\pi^*_{Wr(Q^*_{W0},0)} > 0$, we get $F(\alpha Q^*_{W0}) = 1 - \frac{w^*_{W0}-s}{\alpha(p+g-s)} > 0$. Thus, we derive $\alpha > \frac{w^*_{W0}-s}{p+g-s} = V_{W0}$, otherwise the retailer does not gain any profit. Then, the optimal order quantity is:

$$Q^*_{W0} = \begin{cases} \dfrac{F^{-1}\left[1 - \frac{C_m - S}{\alpha(p+g-s}(1 - z(\alpha Q^*_{W0},0)\right]}{\alpha}, & V_{W0} < \alpha < 1 \\ 0, & \text{otherwise}\end{cases} \tag{7}$$

Substituting the optimal wholesale price w^*_{W0} and the optimal order quantity Q^*_{W0} into Equations (4) and (5), the maximal expected profits $\pi^*_{Wr(Q^*_{W0},0)}$ and $\pi^*_{Wm(Q^*_{W0},0)}$ under a wholesale price contract can be written as follows:

$$\pi^*_{Wr(Q^*_{W0},0)} = \begin{cases}(p+g-s)\int_0^{\alpha Q^*_{W0}} xf(x,0)\mathrm{d}x, & V_{W0} < \alpha < 1 \\ 0 & \text{otherwise}\end{cases} \tag{8}$$

$$\pi^*_{Wm(Q^*_{W0},0)} = \begin{cases}(c_m - s)z(\alpha Q^*_{W0},0)Q^*_{W0}/\left(1 - z(\alpha Q^*_{W0},0)\right), & V_{W0} < \alpha < 1 \\ 0 & \text{otherwise}\end{cases} \tag{9}$$

Lemma 2. (i) $\partial Q^*_{W0}/\partial\alpha > 0$ if and only if $\alpha \in (V_{W0}, \overline{\alpha}_{W0}]$, while $\partial Q^*_{W0}/\partial\alpha < 0$ if and only if $\alpha \in (\overline{\alpha}_{W0}, 1)$, where $\overline{\alpha}_{W0} = \arg\{\overline{\alpha}_{W0}Q^*_{W0}z'(\overline{\alpha}_{W0}Q^*_{W0},0)/\left(1 - z(\overline{\alpha}_{W0}Q^*_{W0},0)\right) = 1\}$; $\partial w^*_{W0}/\partial\alpha < 0$ if and only if $z(\alpha Q^*_{W0},0) \in (1, \overline{z}(\alpha Q^*_{W0},0))$, while $\partial w^*_{W0}/\partial\alpha > 0$ otherwise, where $\overline{z}(\alpha Q^*_{W0},0) = (w^*_{W0} - s)/(w^*_{W0} - c_m)$;

(ii) $\partial Q^*_{W0}/\partial g > 0$; $\partial w^*_{W0}/\partial g > 0$;

(iii) $\partial Q^*_{W0}/\partial s > 0$;$\partial w^*_{W0}/\partial s > 0$ if and only if $z(\alpha Q^*_{W0},0) \in (0, \overline{\overline{z}}(\alpha Q^*_{W0},0]$, while $\partial w^*_{W0}/\partial s < 0$ otherwise;

(iv) When the demand follows a uniform distribution on [0, λ], we have $\partial Q^*_{W0}/\partial\sigma_0 > 0$ and $\partial w^*_{W0}/\partial\sigma_0 < 0$.

In the decentralised supply chain, the impacts of the salable rate α, the salvage value$s$, the lost sales penalty cost g, and the demand information accuracy $\sigma_0$on the optimal order quantity are similar to their impacts in the centralised supply chain. As the price p is fixed, the profit of the decentralised supply chain only depends on the optimal order quality. With Equations (2) and (7), because $w^*_{W0} > c_m$ and $F(x, 0)$ is a monotonically increasing function, we have $Q^*_{W0} < Q^*_{C0}$, as shown in the following Corollary.

Corollary 1. *The wholesale price contract will lead to 'double marginalisation' in the supply chain which is subject to misplacement and demand forecast error without adoption of RFID.*

3.1.3 *Buy-back contract without RFID*

We analyse a buyback contract where the manufacturer buys back any remaining items (including the retailer's leftover inventory and misplaced product) from the retailer for a price b_0 per unit (see Figure 4). In order to prevent the retailer from arbitraging by ordering as much as possible, we assume that $b_0 < w_{B0}$ (e.g. Pasternack 1985). $b_0 > s$ is necessary so that the retailer sells it back rather than salvaging it. We also assume $b_0 < p$ so that the retailer sells to customers first and then return the remaining items to the manufacturer. Denote by w_B 0 the wholesale price under a buyback contract without RFID.

The expected profits of the retailer and manufacturer under a buy-back contract without RFID, $\pi_{Br(q,0)}$ and $\pi_{Bm(q,0)}$, are given by:

$$\begin{aligned}\pi_{Br(q,0)} &= p\left[\int_0^{\alpha q} xf(x,0)\mathrm{d}x + \int_{\alpha q}^{+\infty} \alpha q f(x,0)\mathrm{d}x\right] + b_0\int_0^{\alpha q}(\alpha q - x)f(x,0)\mathrm{d}x - \\ &\quad g\int_{\alpha q}^{+\infty}(x-\alpha q)f(x,0)\mathrm{d}x + b_0(1-\alpha)q - w_{B0}q\end{aligned} \tag{10}$$

$$\pi_{Bm(q,0)} = (w_{B0} - c_m)q - (b_0 - s)\int_0^{\alpha q}(\alpha q - x)f(x,0)\mathrm{d}x - (b_0 - s)(1-\alpha)q \tag{11}$$

Obviously, $\pi_{Br(q,0)}$ is a concave function of q and we get the order quantity: $\alpha Q_{B0} = F^{-1}\left[1 - \frac{w_{B0}-b_0}{\alpha(p+g-b_0)}\right]$. In addition, in order to ensure $F(\alpha Q^*_{B0}) = 1 - \frac{w_{B0}-b_0}{\alpha(p+g-b_0)} > 0$, we derive $\alpha > \frac{w_{B0}-b_0}{p+g-b_0} = V_{B0}$. Then the optimal order quantity is:

$$Q^*_{B0} = \begin{cases} \dfrac{F^{-1}\left[1-\frac{w_{B0}-b_0}{\alpha(p+g-b_0)}\right]}{\alpha}, & V_{B0} < \alpha < 1 \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

Substituting αQ^*_{B0} into Equations (10) and (11), the conclusion can be drawn that the maximal expected profits $\pi^*_{Br(Q^*_{B0},0)}$ and $\pi^*_{Bm(Q^*_{B0},0)}$ with a buy-back contract are as follows:

$$\pi^*_{Br(Q^*_{B0},0)} = \begin{cases} (p+g-b_0)\int_0^{\alpha Q^*_{B0}} xf(x,0)\mathrm{d}x, & V_{B0} < \alpha < 1 \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$\pi^*_{Bm(Q^*_{B0},0)} = \left(w^*_{B0} + (1-\alpha)(b_0 - s) - c_m\right)Q^*_{B0} - (b_0 - s)\int_0^{\alpha Q^*_{B0}} F(x,0)\mathrm{d}x \tag{14}$$

Next, we analyse the coordination of the buy-back contract. For system coordination, the investment decisions must be the same and the order quantities must be equal for the centralised and decentralised systems. With Equations (2), (3) and (12), (14), we can derive two propositions as follows:

Proposition 1. *The profits of the decentralised non-RFID supply chain under a buy-back contract are the same as that of the centralised non-RFID supply chain if and only if the contract term satisfies* $(w^*_{B0}, b^*_0) \in C_{B0}$, *where* $C_{B0} = \{(w^*_{B0}, b^*_0) | w^*_{B0} = \frac{(p+g-c_m)b^*_0}{p+g-s} + \frac{(p+g)(c_m-s)}{p+g-s}\}$.

Proposition 2. *In a supply chain without RFID, there exists two thresholds* $\underline{b_0}$ *and* $\overline{b_0}$ *such that, for any* $\underline{b_0} \le b^*_0 \le \overline{b_0}$, *a buyback contract* $(w^*_{B0}, b^*_0) \in C_{B0}$ *makes both the retailer and the manufacturer better off compared to*

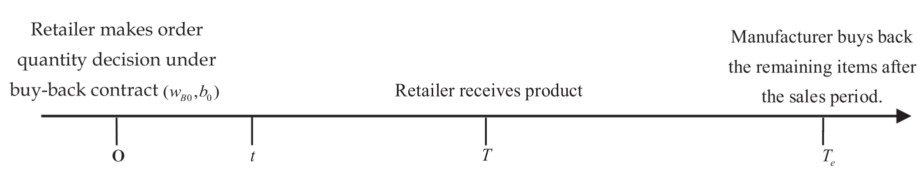


Figure 4. Firms' actions under the buy-back contract without RFID.

the wholesale price contract, where $\overline{b_0} = p + g - \frac{(p+g-s)\int_0^{\alpha Q^*_{W0}} xf(x,0)\mathrm{d}x}{\int_0^{\alpha Q^*_{B0}} xf(x,0)\mathrm{d}x}$ *and*

$$\underline{b_0} = \frac{\left(c_m z(\alpha Q^*_{W0})-s\right)Q^*_{W0}-(1-z(\alpha Q^*_{W0}))\left(w^*_{B0}-c_m-s(1-\alpha)\right)Q^*_{C0}-(1-z(\alpha Q^*_{W0}))s\int_0^{\alpha Q^*_{C0}} F(x,0)\mathrm{d}x}{\left((1-\alpha)Q^*_{C0}-\int_0^{\alpha Q^*_{C0}} F(x,0)\mathrm{d}x\right)\left(1-z(\alpha Q^*_{W0})\right)}.$$

From the above two propositions, we get corollary 2 as follows.

Corollary 2. *The buy-back contract can coordinate a supply chain which is subject to misplacement and demand forecast inaccuracy without adoption of RFID.*

3.2 *RFID adoption*

In the RFID adoption scenario, we will analyse three settings and get optimal contract parameters and order quantities with RFID.

3.2.1 *Centralised supply chain with RFID*

In this setting, we calculate the optimal order quantity Q_{Ct} of the vertically integrated supply chain. The centralised firm's expected profit $\pi_{C(q,t)}$with RFID is:

$$\begin{aligned} \pi_{C(q,t)} &= p\left[\int_0^{\beta q} xf(x,t)\mathrm{d}x + \int_{\beta q}^{+\infty} \beta q f(x,t)\mathrm{d}x\right] + s\int_0^{\beta q} (\beta q - x)f(x,t)\mathrm{d}x \\ &\quad -g\int_{\beta q}^{+\infty} (x-\beta q)f(x,t)\mathrm{d}x + s(1-\beta)q - (c_m + c_t)q \end{aligned} \tag{15}$$

We can easily derive the optimum order quantity $\beta Q^*_{Ct} = F^{-1}\left[1 - \frac{c_m+c_t-s}{\beta(p+g-s)}\right]$ and the maximal expected profit $\pi^*_{C(Q^*_{Ct},t)} = (p+g-s)\int_0^{\beta Q^*_{Ct}} xf(x,t)\mathrm{d}x$.

Proposition 3. *The centralised supply chain benefits from adopting RFID, if and only if* $c_t < U_C$, *where* $U_C = \begin{cases} U_{C0} = \beta(p+g-s) - c_m + s, \ \text{for } \alpha \in (0, V_{C0}] \\ U_{C\pi} = \arg\limits_{c_t}\{\int_0^{\beta Q^*_{Ct}} xf(x,t)\mathrm{d}x = \int_0^{\alpha Q^*_{C0}} xf(x,0)\mathrm{d}x\}, \ \text{for } \alpha \in (V_{C0}, 1] \end{cases}\cdot$

Proposition 3 states that the centralised supply chain adopts RFID when the unit tagging cost is below the threshold U_C. Note that $c_t < U_{C0}$ if and only if $\beta > (c_m + c_t - s)/(p+g-s) = V_{Ct}$. Thus, the optimal order quantity is

$$Q^*_{Ct} = \begin{cases} \dfrac{F^{-1}\left[1-\frac{c_m+c_t-s}{\beta(p+g-s)}\right]}{\beta}, & V_{Ct} < \beta \le 1 \\ Q^*_{C0}, & \text{otherwise} \end{cases} \tag{16}$$

The maximal expected profit is:

$$\pi^*_{C(Q^*_{Ct},t)} = \begin{cases} (p+g-s)\int_0^{\beta Q^*_{Ct}} xf(x,t)\mathrm{d}x, & V_{Ct} < \beta \le 1 \\ \pi^*_{C(Q^*_{C0},0)}, & \text{otherwise} \end{cases} \tag{17}$$

Lemma 3. (i) $\partial Q^*_{Ct}/\partial\beta > 0$ *if and only if* $\beta \in (V_{Ct}, \overline{\beta_{Ct}}]$, *while* $\partial Q^*_{Ct}/\partial\beta < 0$ *if and only if* $\beta \in (\overline{\beta_{Ct}}, 1]$, *where* $\overline{\beta_{Ct}} = \arg\limits_{\beta}\{\overline{\beta_{Ct}}Q^*_{Ct}z'(\overline{\beta_{Ct}}Q^*_{Ct}, t)/\left(1 - z(\overline{\beta_{Ct}}Q^*_{Ct}, t)\right)^2 = 1\}$;

(ii) $\partial Q^*_{Ct}/\partial c_t < 0$;$\partial Q^*_{Ct}/\partial s > 0$;$\partial Q^*_{Ct}/\partial g > 0$;

(iii) *When the demand follows a uniform distribution on* $[\varepsilon, \lambda - \varepsilon]$, *we have* $\partial Q^*_{Ct}/\partial\sigma_t > 0$.

When the centralised supply chain adopts RFID, the impacts of salable rate $\beta\beta$, salvage value$s$, lost sales penalty cost g and the demand information accuracy σ_t are akin to their impacts without RFID (Lemma 1). Lemma 3 further shows that the optimal order quantity decreases with the unit tagging cost c_t, because a greater unit tagging cost causes higher average cost for the centralised supply chain.

3.2.2 *Wholesale price contract with RFID*

Denote by w_{Wt} the wholesale price in a decentralised supply chain with RFID. The expected profit of the retailer and the manufacturer under a wholesale price contract with RFID, $\pi_{Wr(q,t)}$ and $\pi_{Wm(q,t)}$, are given by:

$$\begin{aligned}\pi_{Wr(q,t)} &= p[\int_0^{\beta q} xf(x,t)\mathrm{d}x + \int_{\beta q}^{+\infty} \beta q f(x,t)\mathrm{d}x] + s\int_0^{\beta q}(\beta q - x)f(x,t)\mathrm{d}x - \\ &\quad g\int_{\beta q}^{+\infty}(x-\beta q)f(x,t)\mathrm{d}x + s(1-\beta)q - w_{Wt}q\end{aligned} \tag{18}$$

$$\pi_{Wm(q,t)} = (w_{Wt} - c_m - c_t)q \tag{19}$$

Following a similar procedure and logic as in Section 3.1.2, we obtain the retailer's and manufacturer's maximal expected profits $\pi^*_{Wm(Q^*_{Wt},t)} = (p+g-s)\int_0^{\beta Q^*_{Wt}} xf(x,t)\mathrm{d}x$ and $\pi^*_{Wm(Q^*_{Wt},t)} = (c_m + c_t - s)z(\beta Q_{Wt},t)Q^*_{Wt}/\left(1 - z(\beta Q^*_{Wt},t)\right)$.

RFID imposes a cost on the manufacturer, but helps the retailer alleviate his misplacement problem and improve his forecast accuracy. However, under a wholesale price contract, the manufacturer is able to transfer some of the RFID tagging cost to the retailer by appropriately increasing her wholesale price. This makes RFID a double-edge sword to the retailer. The following proposition shows that the retailer benefits from RFID if and only if the unit tagging cost is below a threshold.

Proposition 4. *The retailer benefits from adopting RFID, if and only if* $c_t < U_W$, *where* $U_W = \begin{cases} U_{W0} = (s + \beta(p+g-s))(1 - z(\beta Q^*_{Wt},t)) + sz(\beta Q^*_{Wt},t) - c_m, & \text{for } \alpha \in (0, V_{W0}] \\ U_{W\pi} = \arg_{c_t}\{\int_0^{\beta Q^*_{Wt}} xf(x,t)\mathrm{d}x = \int_0^{\alpha Q^*_{W0}} xf(x,0)\mathrm{d}x\}, & \text{for } \alpha \in (V_{W0}, 1] \end{cases}$.

Thus, the optimal order quantity is

$$Q^*_{Wt} = \begin{cases} \dfrac{F^{-1}\left[1 - \frac{c_m + c_t - s}{\beta(p+g-s)\left(1 - z(\beta Q^*_{Wt},t)\right)}\right]}{\beta}, & V_{Wt} < \beta \le 1 \\ Q^*_{W0}, & \text{otherwise} \end{cases} \tag{20}$$

Substituting the optimal wholesale price w^*_{Wt} and the optimal order quantity Q^*_{Wt} into Equations (18) and (19), the maximal expected profits $\pi^*_{Wr(Q^*_{Wt},t)}$ and $\pi^*_{Wm(Q^*_{Wt},t)}$ under a wholesale price contract are as follows:

$$\pi^*_{Wr(Q^*_{Wt},t)} = \begin{cases} (p+g-s)\int_0^{\beta Q^*_{Wt}} xf(x,t)\mathrm{d}x, & V_{Wt} < \beta \le 1 \\ \pi^*_{Wr(Q^*_{W0},0)}, & \text{otherwise} \end{cases} \tag{21}$$

$$\pi^*_{Wm(Q^*_{Wt},t)} = \begin{cases} \left((c_m + c_t)z(\beta Q^*_{Wt},t) - s\right)Q^*_{Wt}/\left(1 - z(\beta Q^*_{Wt},t)\right), & V_{Wt} < \beta \le 1 \\ \pi^*_{Wm(Q^*_{W0},0)}, & \text{otherwise} \end{cases} \tag{22}$$

Lemma 4. (i) $\partial Q^*_{Wt}/\partial\beta < 0$ *if and only if* $\beta \in (\overline{\beta}_{Wt}, 1]$, *while* $\partial Q^*_{Wt}/\partial\beta > 0$ *if and only if* $\beta \in (V_{Wt}, \overline{\beta}_{Wt}]$, *where* $\overline{\beta}_{Wt} = \arg_{\beta}\{\overline{\beta}_{Wt}Q^*_{Wt}z'(\overline{\beta}_{Wt}Q^*_{Wt},t)/\left(1 - z(\overline{\beta}_{Wt}Q^*_{Wt},t)\right) = 1\}$; $\partial w^*_{Wt}/\partial\beta < 0$ *if and only if* $z(\beta Q^*_{Wt},t) \in (1, \overline{z}(\beta Q^*_{Wt},t))$, *while* $\partial w^*_{Wt}/\partial\beta > 0$ *otherwise, where* $\overline{z}(\beta Q^*_{Wt},t) = (w^*_{Wt} - s)/(w^*_{Wt} - c_m - c_t)$;

(ii) $\partial Q^*_{Wt}/\partial c_t < 0$ *if and only if* $z(\beta Q^*_{Wt},t) \in (0,1)$, *while* $\partial Q^*_{Wt}/\partial c_t > 0$ *otherwise;* $\partial w^*_{Wt}/\partial c_t > 0$ *if and only if* $z(\beta Q^*_{Wt},t) \in (0,1)$, *while* $\partial w^*_{Wt}/\partial c_t < 0$ *otherwise;*

(iii) $\partial Q^*_{Wt}/\partial g > 0$; $\partial w^*_{Wt}/\partial g > 0$;

(iv) $\partial Q^*_{Wt}/\partial s > 0$; $\partial w^*_{Wt}/\partial s > 0$ *if and only if* $z(\beta Q^*_{Wt},t) \in (0, \overline{\overline{z}}(\beta Q^*_{Wt},t))$, *while* $\partial w^*_{Wt}/\partial s < 0$ *otherwise;*

(v) *When the demand follows a uniform distribution on* $[\varepsilon, \lambda - \varepsilon]$, *we have* $\partial Q^*_{Wt}/\partial\sigma_t > 0$ *and* $\partial w^*_{Wt}/\partial\sigma_t < 0$.

In the decentralised supply chain with RFID, the impact of unit tagging cost is different from its impact in the centralised supply chain with RFID (refer to Lemma 3). In particular, Lemma 4 shows that, with the decentralisation of the supply chain, the optimal order quantity is no longer monotonically decreasing in the unit tagging cost. This is because, by appropriately choosing a wholesale price, the manufacturer balances between letting the retailer bear more tagging cost and incentivising him to order more.

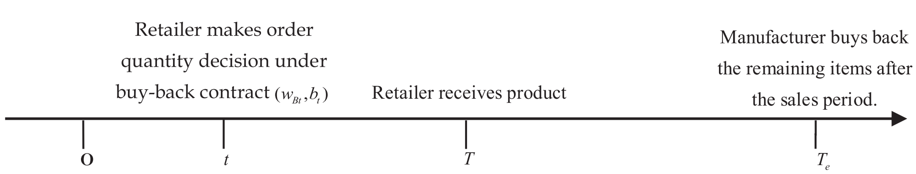


Figure 5. Firms' actions under a buy-back contract with RFID.

With Equations (16) and (20), because $w^*_{Wt} > c_m + c_t$ and $F(x)$ is a monotonically increasing function, we get $Q^*_{Wt} < Q^*_{Ct}$.

Corollary 3. *The wholesale price contract will lead to 'double marginalisation' in a supply chain with adoption of RFID.*

3.2.3 *Decentralised supply chain with buy-back contract*

Here, we analyse a buy-back contract where the manufacturer buys back from the retailer remaining items (including the retailer's leftover inventory and misplacement) at a price b_t per unit (see Figure 5). Similar to Section 3.1.3, we assume that $b_t < w_{Bt}$, $b_t > s$ and $b_t < p$. The wholesale price under a buy-back contract with RFID is represented by w_{Bt}.

The expected profit of the retailer and the manufacturer under a buy-back contract with RFID, $\pi_{Br(q,t)}$ and $\pi_{Bm(q,t)}$ are given by:

$$\begin{aligned}\pi_{Br(q,t)} &= p[\textstyle\int_0^{\beta q} xf(x,t)\mathrm{d}x + \int_{\beta q}^{+\infty} \beta q f(x,t)\mathrm{d}x] + b_t \int_0^{\beta q} (\beta q - x)f(x,t)\mathrm{d}x \\ &\quad -g \textstyle\int_{\beta q}^{+\infty} (x-\beta q)f(x,t)\mathrm{d}x + b_t(1-\beta)q - w_{Bt}q\end{aligned} \tag{23}$$

$$\pi_{Bm(q,t)} = (w_{Bt} - c_m - c_t)q - (b_t - s)\int_0^{\beta q} (\beta q - x)f(x,t)\mathrm{d}x - (b_t - s)(1-\beta)q \tag{24}$$

The retailer's profit $\pi_{Br(q,t)}$ is a concave function of q and we derive the order quantity: $\beta Q_{Bt} = F^{-1}\left[1 - \frac{w_{Bt}-b_t}{\beta(p+g-b_t)}\right]$. In addition, in order to ensure $F(\beta Q^*_{Bt}) = 1 - \frac{w_{Bt}-b_t}{\beta(p+g-b_t)} > 0$, we derive $\beta > \frac{w_{Bt}-b_t}{p+g-b_t} = V_{Bt}$. Then, the optimal order quantity is:

$$Q^*_{Bt} = \begin{cases} \dfrac{F^{-1}\left[1-\frac{w_{Bt}-b_t}{\beta(p+g-b_t)}\right]}{\beta}, & V_{Bt} < \beta \le 1 \\ Q^*_{B0}, & \text{otherwise} \end{cases} \tag{25}$$

Substituting Q^*_{Bt} into Equations (23) and (24), the maximal expected profits $\pi^*_{Br(Q^*_{B0},0)}$ and $\pi^*_{Bm(Q^*_{B0},0)}$ under a buy-back contract are as follows:

$$\pi^*_{Br(Q^*_{Bt},t)} = \begin{cases} (p+g-b_t)\int_0^{\beta Q^*_{Bt}} xf(x,t)\mathrm{d}x, & V_{Bt} < \beta \le 1 \\ \pi^*_{Br(Q^*_{B0},0)}, & \text{otherwise} \end{cases} \tag{26}$$

$$\pi^*_{Bm(Q^*_{Bt},t)} = \left(w^*_{Bt} + (1-\beta)(b_t - s) - c_m - c_t\right)Q^*_{Bt} - (b_t - s)\int_0^{\beta Q^*_{Bt}} F(x,t)\mathrm{d}x \tag{27}$$

We consider a buy-back contract and investigate coordination issues under this contract in this subsection. To coordinate the system, the investment decisions must be the same and the order quantities must be equal for the centralised and decentralised systems. With Equations (16), (17) and (25), (27), we can derive two propositions as below:

Proposition 5. *The profits of the decentralised RFID-adoption supply chain under a buy-back contract are the same as that of the centralised RFID-adoption supply chain if and only if the contract satisfies* $(w^*_{Bt}, b^*_t) \in C_{Bt}$, *where* $C_{Bt} = \{(w^*_{Bt}, b^*_t) | w^*_{Bt} = \frac{(p+g-c_m-c_t)b^*_t}{p+g-s} + \frac{(p+g)(c_m+c_t-s)}{p+g-s}\}$.

Proposition 6. *In a supply chain with RFID, there exists two thresholds* $\underline{b_t}$ *and* $\overline{b_t}$ *such that, for any* $\underline{b_t} \le b^*_t \le \overline{b_t}$, *a buy-back contract* $(w^*_{Bt}, b^*_t) \in C_{Bt}$ *makes both the retailer and the manufacturer better off compared to the wholesale price contract, where* $\overline{b_t} = p + g - \frac{(p+g-s)\int_0^{\beta Q^*_{Wt}} xf(x,t)\mathrm{d}x}{\int_0^{\beta Q^*_{Wt}} xf(x,t)\mathrm{d}x}$ *and*
$\underline{b_t} = \frac{\left((c_m+c_t)z(\beta Q^*_{Wt})-s\right)Q^*_{Wt} - (1-z(\beta Q^*_{Wt}))\left(w^*_{Bt}-c_m-c_t-s(1-\beta)\right)Q^*_{Ct} - (1-z(\beta Q^*_{Wt}))s\int_0^{\beta Q^*_{Ct}} F(x,t)\mathrm{d}x}{\left((1-\beta)Q^*_{Ct} - \int_0^{\beta Q^*_{Ct}} F(x,t)\mathrm{d}x\right)\left(1-z(\beta Q^*_{Wt})\right)}$.

From the above two propositions, we get Corollary 4 as follows.

Corollary 4. *The buy-back contract can coordinate the supply chain with adoption of RFID.*

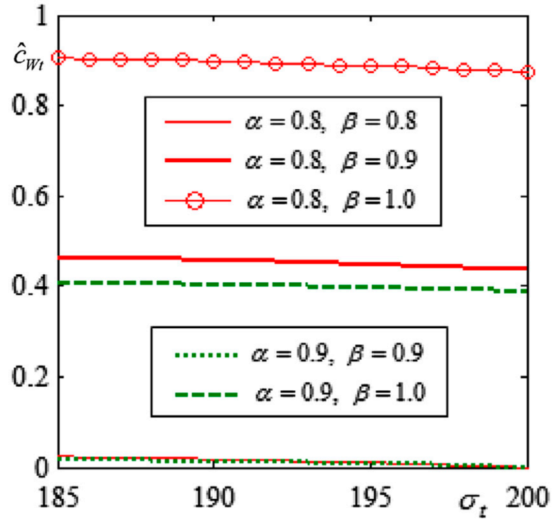


Figure 6a. The RFID cost threshold of a decentralised supply chain under a wholesale price contract.

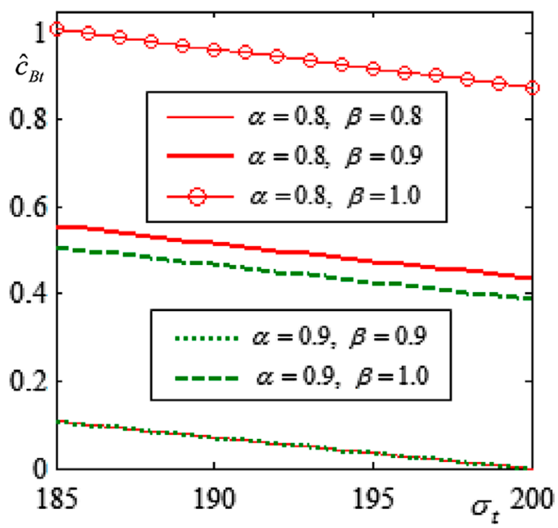


Figure 6b. The RFID cost threshold of a decentralised supply chain under a buy-back contract.

4. Numerical study

To illustrate the proposed models, we give numerical examples as follows. According to Camdereli and Swaminathan (2010), we suppose $\mu = 500$ units, $\sigma_0 = 200$ units, $p = 25$ dollars/per unit, $c_m = 5$ dollars/per unit, $g = 4$ dollar/per unit and $s = 1.5$ dollars/per unit. The simulation data used for carrying out these numerical computations are intended to represent real-world conditions as closely as possible.

4.1 *Decision-making with RFID adoption under the two contracts*

In this section, we only consider the situation of $\alpha \in [V_{W0}, 1]$ because in reality the retailer's salable rate will not be too small. Let $\hat{c}_{Wt}$ and $\hat{c}_{Bt}$ be the thresholds below which adopting RFID is profitable to the decentralised supply chain, under wholesale price and buy-back contracts, respectively. Figures 6a and 6b are drawn with the same set of parameters α, β and σ_t. Comparison of the two figures generates three insights.

First, for any parameter pair (α, β), $\hat{c}_{Wt} < \hat{c}_{Bt}$ holds in most cases. This suggests that the supply chain is more willing to adopt RFID under the buy-back contract than under the wholesale price contract. Intuitively, the buy-back contract

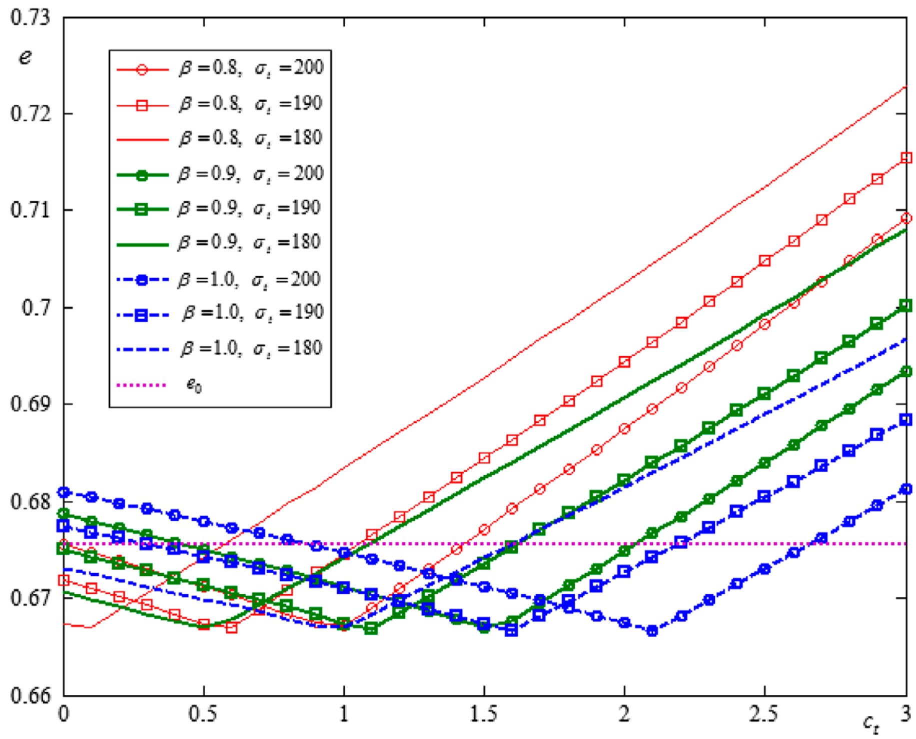


Figure 7. Supply chain efficiency with/without RFID under wholesale price contract ($\alpha = 0.8$).

can generally bring more profit to the supply chain than the wholesale price contract, making it more tolerant to costly RFID tags.

Second, the thresholds $\hat{c}_{Wt}$ and $\hat{c}_{Bt}$ are both in negative correlation to demand forecast error σ_t. The more accurate the signal brought by adopting RFID (i.e. smaller σ_t), the more tolerant the supply chain is to an expensive tagging cost, regardless of the contract type. Moreover, the buy-back contract is more sensitive to the forecast error than the wholesale price contract, as it is observed that the decreasing rates in Figure 6b are bigger than in Figure 6a.

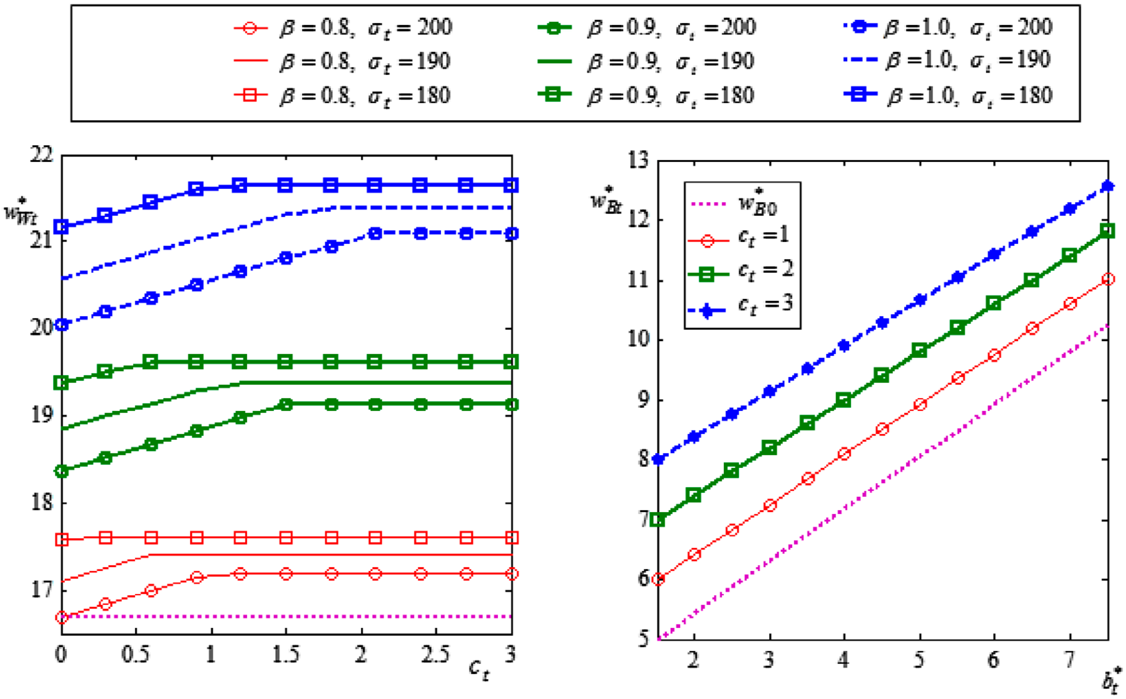
Third, for any fixed α, both $\hat{c}_{Wt}$ and $\hat{c}_{Bt}$ are increasing in β, the improved salable rate brought by RFID. Intuitively, the more effective RFID is at alleviating misplacement problems (i.e. greater β), the more willingly the supply chain adopts RFID, regardless of contract type.

4.2 *Supply chain efficiency with/without RFID under the two contracts*

Following Cachon (2003), we define supply chain efficiency as the ratio of decentralised supply chain profit to centralised supply chain profit. From Corollary 2 and Corollary 4, the buy-back contract can co-ordinate the supply chain with/without RFID, so both of the efficiencies with and without RFID under buy-back contract are 100%. From Corollary 1 and Corollary 3, the wholesale price contract will lead to 'double marginalisation' in a supply chain with/without RFID, and so the efficiencies with and without RFID under the wholesale price contract are both less than 100%. Thus, for the wholesale price contract, we analyse the RFID supply chain efficiency e and the non-RFID supply chain efficiency e_0. Figure 7 reveals several results regarding supply chain efficiencies.

First, RFID adoption can sometimes lessen the double marginalisation problem and improve the supply chain efficiency. Without RFID, c_t does not impact any supply chain decisions and e_0 is invariant with c_t (the dotted line in Figure 7). With RFID, the efficiency e can be greater than e_0, especially when c_t is large. When the tagging cost c_t is large, the manufacturer has to reduce her margin to prevent the retailer from ordering too little.

Second, the efficiency of RFID supply chain e first decreases and then increases in the tagging cost c_t. This indicates that a smaller tagging cost cannot necessarily lead to a better supply chain efficiency, as the manufacturer can adjust the wholesale price to her own interest in response to a reduction of tagging cost, hurting the supply chain performance. In fact, the non-monotonicity property of e with respect to c_t originates from the non-monotonicity properties of order quantity Q^*_{Wt} and wholesale price w^*_{Wt} with respect to c_t (Lemma 4).



a. The change of wholesale price contract parameter with RFID cost **b.** The change of buy-back contract parameter with RFID cost

Figure 8. (a) The change of wholesale price contract parameter with RFID cost. (b) The change of buy-back contract parameter with RFID cost.

Third, a reduced demand forecast error σ_t may not lead to an increase in the supply chain efficiency. Focus on the curves with the same β. If the tag cost c_t is low (high), the demand forecast error σ_t is positively (negatively) related to the supply chain efficiency e. This result is driven by the impacts of σ_t on order quantity Q^*_{Wt} and wholesale price w^*_{Wt} (Lemma 4). In Section 4.1, we have shown that the supply chain is more tolerant to a high tagging cost when the demand error is smaller. In this section, we further reveal that, when the RFID tagging cost is low, the supply chain should not invest too much in reducing the demand forecast error which will enable the manufacturer to charge a higher wholesale price (w^*_{Wt} increases as σ_t increases) and will exacerbate double marginalisation.

Fourth, an increased salable rate β does not necessarily translate into increased supply chain efficiency. Focus on the curves with the same σ_t. If the tag cost c_t is low (high), the salable rate β is positively (negatively) related to the supply chain efficiency e. In Section 4.1, we have shown that the supply chain is more willing to adopt RFID when the salable rate is higher. In this section, we further comment that, to keep high supply chain efficiency, the decentralised supply chain should not always pursue a perfect salable rate when RFID has already been adopted with a high tagging cost.

4.3 *The change in contract parameters with RFID*

Recall that RFID technology influences the supply chain on two respects, raising the salable rate and shortening order lead time that facilitates a more accurate demand forecast. Figure 8(a) shows how a manufacturer's optimal wholesale price w^*_{Wt} changes with salable rate β and demand forecast error σ_t. For any fixed β, the wholesale price w^*_{Wt} decreases with forecast error σ_t. With a more accurate demand forecast (lower σ_t), the retailer faces a less uncertain market and can order less, and thus the manufacturer raises the wholesale price to keep a relatively high margin. This coincides with Lemma 4. For any fixed σ_t, the wholesale price increases with the salable rate (this numerical study corresponds to the case of $z(\beta Q^*_{Wt}, t) \in (0, 1)$ in Lemma 4).

In addition, Figure 8(a) also shows that the manufacturer stops raising her wholesale price when the tagging cost is above a certain threshold for every parameter pair (β, σ_t), as it is observed that for each curve in Figure 8(a) there is an inflexion point after which the wholesale price becomes a constant. This is because a too high wholesale price will make it non-profitable for the retailer to place orders in a market with uncertain demand.

Figure 8(b) shows how the RFID tagging cost impacts coordinating buy-back contracts. By Proposition 5, for any buyback price b^*_t, there is a corresponding wholesale sale price w^*_{Bt} in the coordinating buy-back contract set (i.e. C_{Bt}

defined in Proposition 5). Figure 8(b) reveals that the wholesale price w_{Bt}^{*} in a buy-back contract increases as the RFID tagging cost increases.

5. Conclusion

From a perspective of supply chain management, the Internet of Things (IoT) will allow machine-enabled decision-making with minimum or even no human intervention. As a new and core technology of IoT, RFID can solve many problems in supply chain management. RFID not only can reduce misplacement but can also help reduce forecast error by shortening order lead time. It is unclear how the supply chain contracting and RFID strategies interact with each other. This paper proposes a newsvendor type model and analyses a supply chain's RFID adoption strategies and its impacts on firms' decision variables, as well as contract parameters. By our analytical and numerical studies, several results are presented.

We find how the misplacement problem (i.e. the salable rate α) impacts the non-RFID supply chain decisions. For a centralised supply chain, the optimal order quantity is not monotonic in the salable rate α. When α is small (large), the optimal order quantity increases (decreases) in α. The optimal order quantity of the centralised supply chain increases when (i) the salvage value s increases, (ii) the lost sales penalty cost g increases and (iii) the demand information becomes more accurate (i.e. larger σ_0). The decentralised supply chain has similar results. The wholesale price contract will lead to double marginalisation, while the buy-back contract can coordinate the supply chain.

When the supply chain adopts RFID, the unit tagging cost plays a key role in supply chain quantity decisions. In a centralised supply chain, the optimal order quantity decreases with the unit tagging cost c_t, because a greater unit tagging cost causes higher overage cost. In contrast, in a decentralised supply chain, the optimal order quantity is no longer monotonically decreasing in the unit tagging cost. This is because, by appropriately choosing a wholesale price, the manufacturer balances between letting the retailer bear more tagging cost and incentivising him to order more. RFID adoption can sometimes lessen the double marginalisation problem and improve supply chain efficiency. The buy-back contract can also coordinate a supply chain with RFID adoption.

For each type of contract, we derive the tagging cost threshold below which RFID adoption is profitable. The more accurate the signal brought by adopting RFID (i.e. smaller forecast error), the more tolerant the supply chain is to an expensive tagging cost, regardless of the contract type. The more effective RFID can alleviate misplacement problems (i.e. greater salable rate), the more willingly the supply chain adopts RFID, regardless of contract type. Furthermore, the contract type of a supply chain impacts its RFID adoption strategy. The supply chain is more willing to adopt RFID under a buy-back contract than under a wholesale price contract. If RFID has already been adopted in a supply chain, an improvement of salable rate may hurt the supply chain efficiency.

For further research, there are two main directions. First, it would be very interesting to extend the model to one retailer (manufacturer) with multiple competing manufacturers (retailers). Second, our model assumes the manufacturer is the Stackelberg leader, it is also interesting to analyse the RFID adoption decision considering the cases where the retailer is the leader or the manufacturer and the retailer play a bargaining game in which the firms bilaterally negotiate contract terms via a process of alternating offers.

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Note

1. While the salable rate with RFID can be up to 100% ($\beta = 1$) in some cases, it can be as low as 30% reported for massive identification of several daily consumer products that contain liquids or metal (France 2006). In fact, the technical constraints (e.g. tag collisions, tag detuning and absorption of radio waves) might influence RFID tags' readability and thus lead to unexpected failed reads (Condea, Thiesse, and Fleisch 2012). In this paper, we allow an imperfect salable rate ($\beta \leq 1$) with RFID to reflect this and to generate insights into how the salable rate impacts supply chain operations after RFID has been adopted.

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Appendix 1

Proof of Lemma 1: As $\frac{\partial(\alpha Q_{C0}^*)}{\partial\alpha}=\frac{\partial(\alpha Q_{C0}^*)}{\partial\alpha}+\frac{\partial(\alpha Q_{C0}^*)}{\partial Q_{C0}^*}\cdot\frac{\partial Q_{C0}^*}{\partial\alpha}=\frac{\left(1-z(\alpha Q_{C0}^*,0)\right)\alpha Q_{C0}^*}{\left(1-z(\alpha Q_{C0}^*,0)\right)\cdot z(\alpha Q_{C0}^*,0)+\alpha Q_{C0}^*\cdot z'(\alpha Q_{C0}^*,0)}$, we have $\frac{\partial Q_{C0}^*}{\partial\alpha}=\frac{Q_{C0}^*}{\alpha}\cdot\left[\frac{1-z(\alpha Q_{C0}^*,0)}{\left(1-z(\alpha Q_{C0}^*,0)\right)\cdot z(\alpha Q_{C0}^*,0)+\alpha Q_{C0}^*\cdot z'(\alpha Q_{C0}^*,0)}-1\right]=\frac{\left[\left(1-z(\alpha Q_{C0}^*)\right)^2-\alpha Q_{C0}^*\cdot z'(\alpha Q_{C0}^*,0)\right]Q_{C0}^*}{\left[\left(1-z(\alpha Q_{C0}^*,0)\right)\cdot z(\alpha Q_{C0}^*,0)+\alpha Q_{C0}^*\cdot z'(\alpha Q_{C0}^*,0)\right]\alpha}$. Let $\partial Q_{C0}^*/\partial\alpha=0$, then we get $\overline{\alpha_{C0}}Q_{C0}^*z'(\overline{\alpha_{C0}}Q_{C0}^*,0)/\left(1-z(\overline{\alpha_{C0}}Q_{C0}^*,0)\right)^2=1$. Thus, we have $\partial Q_{C0}^*/\partial\alpha>0$ if and only if $\alpha\in(0,\overline{\alpha_{C0}}]$, while $\partial Q_{C0}^*/\partial\alpha<0$ otherwise, where $\overline{\alpha_{C0}}=\arg_{\alpha}\{\overline{\alpha_{C0}}Q_{C0}^*z'(\overline{\alpha_{C0}}Q_{C0}^*,0)/\left(1-z(\overline{\alpha_{C0}}Q_{C0}^*,0)\right)^2=1\}$.

Doing the first-order differential on s, we obtain $\frac{\partial Q_{C0}^*}{\partial s}=\frac{\partial F(\alpha Q_{C0}^*,0)}{\partial s}\Big/\frac{\partial F(\alpha Q_{C0}^*,0)}{\partial Q_{C0}^*}=\frac{\alpha(p+g-s)-(c_m-s)}{\alpha^3(p+g-s)^2f(\alpha Q_{C0}^*,0)}$. With the condition $\alpha>(c_m-s)/(p+g-s)$, thus $\partial Q_{C0}^*/\partial s>0$.

Doing the first-order differential on g, we obtain $\frac{\partial Q_{C0}^*}{\partial g}=\frac{\partial F(\alpha Q_{C0}^*,0)}{\partial g}\Big/\frac{\partial F(\alpha Q_{C0}^*,0)}{\partial Q_{C0}^*}=\frac{c_m-s}{\alpha^3(p+g-s)^2f(\alpha Q_{C0}^*,0)}>0$. With the condition $c_m>s$, thus $\partial Q_{C0}^*/\partial g>0$.

When the demand follows a uniform distribution on $[0,\lambda]$, the mean is $\mu=\lambda/2$ and the variance (the demand forecast error) is $\sigma_0=\lambda/2\sqrt{3}$. Thus, we can get the optimal order quantity $Q_{C0}^*=\frac{2\sqrt{3}\sigma_0}{\alpha}\left[1-\frac{(c_m-s)}{\alpha(p+g-s)}\right]$. Doing the first-order differential on σ_0, we obtain $\frac{\partial Q_{C0}^*}{\partial\sigma_0}=\frac{2\sqrt{3}}{\alpha}\left[1-\frac{(c_m-s)}{\alpha(p+g-s)}\right]$. With the condition $\alpha>(c_m-s)/(p+g-s)$, we have $\partial Q_{C0}^*/\partial\sigma_0>0$.

Proof of Lemma 2:As $\frac{\partial F(\alpha Q_{W0}^*)}{\partial\alpha}=\frac{(w_{W0}^*-s)-\alpha\cdot\frac{\partial w_{W0}^*}{\partial\alpha}}{\alpha^2(p+g-s)}=\frac{(c_m-s)-\left(1-z(\alpha Q_{W0}^*,0)\right)\alpha\cdot\frac{\partial w_{W0}^*}{\partial\alpha}}{\alpha^2(p+g-s)\left(1-z(\alpha Q_{W0}^*,0)\right)}$. Doing the first-order differential on α, we obtain: $\frac{\partial Q_{W0}^*}{\partial\alpha}=\frac{\partial F(\alpha Q_{W0}^*)}{\partial\alpha}\Big/\frac{\partial F(\alpha Q_{W0}^*)}{\partial Q_{W0}^*}=\frac{(c_m-s)-\left(1-z(\alpha Q_{W0}^*,0)\right)\alpha\cdot\frac{\partial w_{W0}^*}{\partial\alpha}}{\alpha^3(p+g-s)\left(1-z(\alpha Q_{W0}^*,0)\right)f(\alpha Q_{W0}^*)}$. We then take the first-order derivative of w_{W0}^* with respect to $\boldsymbol{\alpha}$ and derive $\frac{\partial w_{W0}^*}{\partial\alpha}=\frac{(c_m-s)\left[Q_{W0}^*z'(\alpha Q_{W0}^*,0)+\alpha z'(\alpha Q_{W0}^*,0)\frac{\partial Q_{W0}^*}{\partial\alpha}\right]}{\left(1-z(\alpha Q_{W0}^*,0)\right)^2}$, thus, we can obtain $\frac{\partial Q_{W0}^*}{\partial\alpha}=\frac{(c_m-s)\left(1-z(\alpha Q_{W0}^*,0)\right)-\alpha Q_{W0}^*z'(\alpha Q_{W0},0)(c_m-s)}{\alpha^3(p+g-s)\left(1-z(\alpha Q_{W0}^*,0)\right)^2f(\alpha Q_{W0}^*)+\alpha^2(c_m-s)z'(\alpha Q_{W0}^*,0)}$. Let $\frac{\partial Q_{W0}^*}{\partial\alpha}=0$, we get $\overline{\alpha}_{W0}Q_{W0}^*z'(\overline{\alpha}_{W0}Q_{W0}^*,0)/\left(1-z(\overline{\alpha}_{W0}Q_{W0}^*,0)\right)=1$. At this point, we have Q_{W0}^* increases in α if $\alpha\in(V_{W0},\overline{\alpha}_{W0}]$, while it decreases in α if$\alpha\in(\overline{\alpha}_{W0},1)$, where $\overline{\alpha}_{W0}=\arg_{\alpha}\{\overline{\alpha}_{W0}Q_{W0}^*z'(\overline{\alpha}_{W0}Q_{W0}^*,0)/\left(1-z(\overline{\alpha}_{W0}Q_{W0}^*,0)\right)=1\}$. We then substitute the expression for $\frac{\partial Q_{W0}^*}{\partial\alpha}$ into $\frac{\partial w_{W0}^*}{\partial\alpha}=\frac{(c_m-s)\left[Q_{W0}^*z'(\alpha Q_{W0}^*,0)+\alpha z'(\alpha Q_{W0}^*,0)\frac{\partial Q_{W0}^*}{\partial\alpha}\right]}{\left(1-z(\alpha Q_{W0}^*,0)\right)^2}$ and derive $\frac{\partial w_{W0}^*}{\partial\alpha}=\frac{\alpha^2(p+g-s)(c_m-s)Q_{W0}^*z'(\alpha Q_{W0}^*,0)\left(1-z(\alpha Q_{W0}^*,0)\right)f(\alpha Q_{W0}^*)+(c_m-s)^2z'(\alpha Q_{W0}^*,0)}{\left(1-z(\alpha Q_{W0}^*,0)\right)\left[\alpha^2(p+g-s)\left(1-z(\alpha Q_{W0}^*,0)\right)^2f(\alpha Q_{W0}^*)+\alpha(c_m-s)z'(\alpha Q_{W0}^*,0)\right]}$. Let $\frac{\partial w_{W0}^*}{\partial\alpha}=0$, we get $\bar{z}(\alpha Q_{W0}^*,0)=(w_{W0}^*-s)/(w_{W0}^*-c_m)$. At this point, we have w_{W0}^* decreases in α if $z(\alpha Q_{W0}^*,0)\in(1,\bar{z}(\alpha Q_{W0}^*,0))$, while it increases in α otherwise.

Doing the first-order differential on g, we obtain $\frac{\partial Q_{W0}^*}{\partial g}=\frac{\partial F(\alpha Q_{W0}^*,0)}{\partial g}\Big/\frac{\partial F(\alpha Q_{W0}^*,0)}{\partial Q_{W0}^*}=\frac{w_{W0}^*-s-(p+g-s)\frac{\partial w_{W0}^*}{\partial g}}{\alpha^2(p+g-s)^2f(\alpha Q_{W0}^*,0)}$. As $\frac{\partial w_{W0}^*}{\partial g}=\frac{\alpha(c_m-s)z'(\alpha Q_{W0}^*,0)}{\left(1-z(\alpha Q_{W0}^*,0)\right)^2}\cdot\frac{\partial Q_{W0}^*}{\partial g}$, we have $\frac{\partial Q_{W0}^*}{\partial g}=\frac{(w_{W0}^*-s)\left(1-z(\alpha Q_{W0}^*,0)\right)^2-\alpha(p+g-s)(c_m-s)z'(\alpha Q_{W0}^*,0)\cdot\frac{\partial Q_{W0}^*}{\partial g}}{\alpha^2(p+g-s)^2f(\alpha Q_{W0}^*,0)\left(1-z(\alpha Q_{W0}^*,0)\right)^2}$. Thus, $\frac{\partial Q_{W0}^*}{\partial g}=\frac{(w_{W0}^*-s)\left(1-z(\alpha Q_{W0}^*,0)\right)^2}{\alpha^2(p+g-s)^2f(\alpha Q_{W0}^*,0)\left(1-z(\alpha Q_{W0}^*,0)\right)^2+\alpha(p+g-s)(c_m-s)z'(\alpha Q_{W0}^*,0)}>0$. Furthermore, $\frac{\partial w_{W0}^*}{\partial g}>0$.

Doing the first-order differential on s, $\frac{\partial Q_{W0}^*}{\partial s}=\frac{\partial F(\alpha Q_{W0}^*,0)}{\partial s}\Big/\frac{\partial F(\alpha Q_{W0}^*,0)}{\partial Q_{W0}^*}=\frac{-(p+g-s)(\frac{\partial w_{W0}^*}{\partial s}-1)-(w_{W0}^*-s)}{\alpha^2(p+g-s)^2f(\alpha Q_{W0}^*,0)}$. As $\frac{\partial w_{W0}^*}{\partial s}=\frac{-z(\alpha Q_{W0},0)\left(1-z(\alpha Q_{W0}^*,0)\right)+\alpha z'(\alpha Q_{W0}^*,0)\cdot\frac{\partial Q_{W0}^*}{\partial s}(c_m-s)}{\left(1-z(\alpha Q_{W0}^*,0)\right)^2}$, we derive $\frac{\partial Q_{W0}^*}{\partial s}=\frac{(p+g-c_m)\left(1-z(\alpha Q_{W0}^*,0)\right)^2}{\alpha^2(p+g-s)^2f(\alpha Q_{W0}^*,0)\left(1-z(\alpha Q_{W0}^*,0)\right)^2+\alpha(c_m-s)z'(\alpha Q_{W0}^*,0)}>0$. We then substitute the expression for $\frac{\partial Q_{W0}^*}{\partial s}$ into $\frac{\partial w_{W0}^*}{\partial s}=\frac{-z(\alpha Q_{W0},0)\left(1-z(\alpha Q_{W0}^*,0)\right)+\alpha z'(\alpha Q_{W0}^*,0)\cdot\frac{\partial Q_{W0}^*}{\partial s}(c_m-s)}{\left(1-z(\alpha Q_{W0}^*,0)\right)^2}$ and then derive

$\frac{\partial w^*_{W0}}{\partial s}=\frac{(c_m-s)(p+g-c_m-z(\alpha Q_{W0},0))z'(\alpha Q^*_{W0},0)-\alpha(p+g-s)^2 f(\alpha Q^*_{W0},0)z(\alpha Q_{W0},0)\left(1-z(\alpha Q^*_{W0},0)\right)}{\alpha(p+g-s)^2 f(\alpha Q^*_{W0},0)\left(1-z(\alpha Q^*_{W0},0)\right)^2+(c_m-s)z'(\alpha Q^*_{W0},0)}$. Let $\frac{\partial w^*_{W0}}{\partial s}=0$, then $\overline{\overline{z}}(\alpha Q^*_{W0},0)=1-\frac{(c_m-s)(p+g-c_m-z(\alpha Q_{W0},0))z'(\alpha Q^*_{W0},0)}{\alpha(p+g-s)^2 f(\alpha Q^*_{W0},0)z(\alpha Q_{W0},0)}$. At this point, we have w^*_{W0} increases in s if $z(\alpha Q^*_{W0},0)\in(0,\overline{\overline{z}}(\alpha Q^*_{W0},0)]$, while it decreases in s otherwise.

When the demand follows a uniform distribution on $[0,\lambda]$, we can get the optimal order quantity $w^*_{W0}=\frac{\alpha(\mu+\sqrt{3}\sigma_0)(p+g-s)}{4\sqrt{3}\sigma_0}+\frac{c_m+s}{2}$ and $Q^*_{W0}=\frac{\mu+\sqrt{3}\sigma_0}{\alpha}-\frac{\sqrt{3}\sigma_0(c_m-s)}{\alpha^2(p+g-s)}$. Doing the first-order differential on σ_0, we obtain $\frac{\partial w^*_{W0}}{\partial\sigma_0}=-\frac{\alpha\mu(p+g-s)}{4\sqrt{3}\sigma_0^2}<0$. With the condition $\alpha>\frac{w^*_{W0}-s}{p+g-s}$, thus $\frac{\partial Q^*_{W0}}{\partial\sigma_0}=\frac{\sqrt{3}}{\alpha}[1-\frac{c_m-s}{\alpha(p+g-s)}]>0$.

Proof of proposition 1: When the price p is a fixed parameter, the performance of the decentralised supply chain only depends on the optimal order quantity. With Equations (9) and (13), we need to ensure $Q^*_{B0}=Q^*_{C0}$, so $\frac{F^{-1}\left[\frac{\alpha(p+g-b_0)+b^*_0-w^*_{B0}}{\alpha(p+g-b_0)}\right]}{\alpha}=\frac{F^{-1}\left[\frac{\alpha(p+g-s)+s-c_m}{\alpha(p+g-s)}\right]}{\alpha}$ and we get $w^*_{B0}=\frac{(p+g-c_m)b^*_0}{p+g-s}+\frac{(p+g)(c_m-s)}{p+g-s}$.

Proof of proposition 2: The retailer and the manufacturer under a buy-back contract must get no less profits than that under a wholesale price contract. Also, the players need to achieve a win–win situation. Thus, we need $\pi^*_{Br(Q^*_{B0},0)}\geq\pi^*_{Wr(Q^*_{W0},0)}$, $\pi^*_{Bm(Q^*_{B0},0)}\geq\pi^*_{Wm(Q^*_{W0},0)}$ and get $\underline{b_0}\leq b^*_0\leq\overline{b_0}$, where $\underline{b_0}=\frac{\left(c_m z(\alpha Q^*_{W0})-s\right)Q^*_{W0}-(1-z(\alpha Q^*_{W0}))\left(w^*_{B0}-c_m-s(1-\alpha)\right)Q^*_{C0}-(1-z(\alpha Q^*_{W0}))s\int_0^{\alpha Q^*_{C0}}F(x,0)\mathrm{d}x}{\left((1-\alpha)Q^*_{C0}-\int_0^{\alpha Q^*_{C0}}F(x,0)\mathrm{d}x\right)\left(1-z(\alpha Q^*_{W0})\right)}$ and $\overline{b_0}=p+g-\frac{(p+g-s)\int_0^{\alpha Q^*_{W0}}xf(x,0)\mathrm{d}x}{\int_0^{\alpha Q^*_{B0}}xf(x,0)\mathrm{d}x}$.

Proof of Proposition 3: Compared to the profit of the centralised supply chain without RFID, (i) when $\alpha\in(0,V_{C0}]$, the firm benefits from RFID if and only if $F(\beta Q^*_{Ct},t)=1-\frac{c_m+c_t-s}{\beta(p+g-s)}>0$, that is $c_t<\beta(p+g-s)-c_m+s=U_{C0}$ (or $\beta>(c_m+c_t-s)/(p+g-s)=V_{Ct}$); (ii) when $\alpha\in(V_{C0},1)$, the firm benefits from RFID if and only if $\pi^*_{C(Q^*_{Ct},t)}>(p+g-s)\int_0^{\alpha Q^*_{C0}}xf(x,0)\mathrm{d}x$, that is $c_t<U_{C\pi}$, where $U_{C\pi}=\arg_{c_t}\{\int_0^{\beta Q^*_{Ct}}xf(x,t)\mathrm{d}x=\int_0^{\alpha Q^*_{C0}}xf(x,0)\mathrm{d}x\}$. Otherwise, the firm loses from RFID adoption.

Proof of Lemma 3: As $\frac{\partial(\beta Q^*_{Ct})}{\partial\beta}=\frac{\partial(\beta Q^*_{Ct})}{\partial\beta}+\frac{\partial(\beta Q^*_{Ct})}{\partial Q^*_{Ct}}\cdot\frac{\partial Q^*_{Ct}}{\partial\beta}=\frac{\left(1-z(\beta Q^*_{Ct},t)\right)\beta Q^*_{Ct}}{\left(1-z(\beta Q^*_{Ct},t)\right)\cdot z(\beta Q^*_{Ct},t)+\beta Q^*_{Ct}\cdot z'(\beta Q^*_{Ct},t)}$, we have $\frac{\partial Q^*_{Ct}}{\partial\beta}=\frac{Q^*_{Ct}}{\beta}\cdot\left[\frac{1-z(\beta Q^*_{Ct},t)}{\left(1-z(\beta Q^*_{Ct},t)\right)\cdot z(\beta Q^*_{Ct},t)+\beta Q^*_{Ct}\cdot z'(\beta Q^*_{Ct},t)}-1\right]=\frac{\left[\left((1-z(\beta Q^*_{Ct})\right)^2-\beta Q^*_{Ct}\cdot z'(\beta Q^*_{Ct},t)\right]Q^*_{Ct}}{\left[\left(1-z(\beta Q^*_{Ct},t)\right)\cdot z(\beta Q^*_{Ct},t)+\beta Q^*_{Ct}\cdot z'(\alpha Q^*_{Ct},t)\right]\beta}$. Let $\partial Q^*_{Ct}/\partial\beta=0$, then we get $\overline{\beta_{Ct}}Q^*_{Ct}z'(\overline{\beta_{Ct}}Q^*_{Ct},t)/\left(1-z(\overline{\beta_{Ct}}Q^*_{Ct},t)\right)^2=1$. Thus, we have $\partial Q^*_{Ct}/\partial\beta>0$ if and only if $\beta\in(V_{Ct},\overline{\beta_{Ct}}]$, while $\partial Q^*_{Ct}/\partial\beta<0$ otherwise, where $\overline{\beta_{Ct}}=\arg_{\beta}\{\overline{\beta_{Ct}}Q^*_{Ct}z'(\overline{\beta_{Ct}}Q^*_{Ct},t)/\left(1-z(\overline{\beta_{Ct}}Q^*_{Ct},t)\right)^2=1\}$.

Doing the first-order differential on c_t, we obtain $\frac{\partial Q^*_{Ct}}{\partial c_t}=\frac{\partial F(\beta Q^*_{Ct},t)}{\partial c_t}/\frac{\partial F(\beta Q^*_{Ct},t)}{\partial Q^*_{Ct}}=-\frac{1}{\beta^2(p+g-s)f(\beta Q^*_{Ct},t)}<0$.

Doing the first-order differential on s, we obtain $\frac{\partial Q^*_{Ct}}{\partial s}=\frac{\partial F(\beta Q^*_{Ct},t)}{\partial s}/\frac{\partial F(\beta Q^*_{Ct},t)}{\partial Q^*_{Ct}}=\frac{\beta(p+g-s)-(c_m+c_t-s)}{\beta^3(p+g-s)^2 f(\beta Q^*_{Ct},t)}$. Given the condition $\beta>(c_m+c_t-s)/(p+g-s)$, thus $\partial Q^*_{Ct}/\partial s>0$.

Doing the first-order differential on g, we obtain $\frac{\partial Q^*_{Ct}}{\partial g}=\frac{\partial F(\beta Q^*_{Ct},t)}{\partial g}/\frac{\partial F(\beta Q^*_{Ct},t)}{\partial Q^*_{Ct}}=\frac{c_m+c_t-s}{\beta^3(p+g-s)^2 f(\beta Q^*_{Ct},t)}>0$. With the condition $c_m+c_t>s$, thus $\partial Q^*_{Ct}/\partial g>0$.

RFID adoption will lower the demand forecast error, so the demand will change to a uniform distribution on $[\varepsilon,\lambda-\varepsilon]$ and $0\leq\varepsilon\leq\lambda$, the mean is $\mu=\lambda/2$ and the variance is $\sigma_t=(\lambda-2\varepsilon)/2\sqrt{3}$. It is very easy to see $\sigma_t\leq\sigma_0$. We can get the optimal order quantity $Q^*_{Ct}=\frac{2\sqrt{3}\sigma_t}{\beta}\left[1-\frac{(c_m+c_t-s)}{\beta(p+g-s)}\right]$. Doing the first-order differential on σ_t, we obtain $\frac{\partial Q^*_{Ct}}{\partial\sigma_t}=\frac{2\sqrt{3}}{\beta}\left[1-\frac{(c_m+c_t-s)}{\beta(p+g-s)}\right]$. With the condition $\beta>(c_m+c_t-s)/(p+g-s)$, thus $\partial Q^*_{Ct}/\partial\sigma_t>0$.

Proof of Lemma 4: We have $\frac{\partial F(\beta Q^*_{Wt})}{\partial\beta}=\frac{(w^*_{Wt}-s)-\beta\cdot\frac{\partial w^*_{Wt}}{\partial\beta}}{\beta^2(p+g-s)}=\frac{(c_m+c_t-s)-\left(1-z(\beta Q^*_{Wt},t)\right)\beta\cdot\frac{\partial w^*_{Wt}}{\partial\beta}}{\beta^2(p+g-s)\left(1-z(\beta Q^*_{Wt},t)\right)}$. Doing the first-order differential on β, we obtain: $\frac{\partial Q^*_{Wt}}{\partial\beta}=\frac{\partial F(\beta Q^*_{Wt})}{\partial\beta}/\frac{\partial F(\beta Q^*_{Wt})}{\partial Q^*_{Wt}}=\frac{(c_m+c_t-s)-\left(1-z(\beta Q^*_{Wt},t)\right)\beta\cdot\frac{\partial w^*_{Wt}}{\partial\beta}}{\beta^3(p+g-s)\left(1-z(\beta Q^*_{Wt},t)\right)f(\beta Q^*_{Wt})}$. We then take the first-order derivative of w^*_{Wt} with respect to β and derive $\frac{\partial w^*_{Wt}}{\partial\beta}=\frac{(c_m+c_t-s)\left[Q^*_{Wt}z'(\beta Q^*_{Wt},t)+\beta z'(\beta Q^*_{Wt},t)\frac{\partial Q^*_{Wt}}{\partial\beta}\right]}{\left(1-z(\beta Q^*_{Wt},t)\right)^2}$, thus, we can obtain $\frac{\partial Q^*_{Wt}}{\partial\beta}=\frac{(c_m+c_t-s)\left(1-z(\beta Q^*_{Wt},t)\right)-\beta Q^*_{Wt}z'(\beta Q_{Wt},t)(c_m+c_t-s)}{\beta^3(p+g-s)\left(1-z(\beta Q^*_{Wt},t)\right)^2 f(\beta Q^*_{Wt})+\beta^2(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}$. Let $\frac{\partial Q^*_{Wt}}{\partial\beta}=0$, we get $\overline{\beta}_{Wt}Q^*_{Wt}z'(\overline{\beta}_{Wt}Q^*_{Wt},t)/\left(1-z(\overline{\beta}_{Wt}Q^*_{Wt},t)\right)=1$. At this point, we have Q^*_{Wt} increases in β if $\beta\leq\overline{\beta}_{Wt}$, while it decreases in β if $\beta>\overline{\beta}_{Wt}$, where $\overline{\beta}_{Wt} = \arg_{\beta}\{\overline{\beta}_{Wt}Q^*_{Wt}z'(\overline{\beta}_{Wt}Q^*_{Wt},t)/\big(1-z(\overline{\beta}_{Wt}Q^*_{Wt},t)\big)=1\}$. We then substitute the expression for $\frac{\partial Q^*_{Wt}}{\partial \beta}$ into $\frac{\partial w^*_{Wt}}{\partial \beta} = \frac{(c_m+c_t-s)\left[Q^*_{Wt}z'(\beta Q^*_{Wt},t)+\beta z'(\beta Q^*_{Wt},t)\frac{\partial Q^*_{Wt}}{\partial \beta}\right]}{\left(1-z(\beta Q^*_{Wt},t)\right)^2}$ and derive:

$$\frac{\partial w^*_{Wt}}{\partial \beta} = \frac{\beta^2(p+g-s)(c_m+c_t-s)Q^*_{Wt}z'(\beta Q^*_{Wt},t)\big(1-z(\beta Q^*_{Wt},t)\big)f(\beta Q^*_{Wt})+(c_m+c_t-s)^2z'(\beta Q^*_{Wt},t)}{\big(1-z(\beta Q^*_{Wt},t)\big)\left[\beta^2(p+g-s)\big(1-z(\beta Q^*_{Wt},t)\big)^2f(\beta Q^*_{Wt})+\beta(c_m+c_t-s)z'(\beta Q^*_{Wt},t)\right]}.$$

Let $\frac{\partial w^*_{Wt}}{\partial \beta}=0$, then we get $\bar{z}(\beta Q^*_{Wt},t)=(w^*_{Wt}-s)/(w^*_{Wt}-c_m-c_t)$. At this point, we have w^*_{Wt} decreases in β if $z(\beta Q^*_{Wt},t)\in(1,\bar{z}(\beta Q^*_{Wt},t))$, while it increases in β otherwise.

Doing the first-order differential on c_t, we obtain $\frac{\partial Q^*_{Wt}}{\partial c_t}=\frac{\partial F(\beta Q^*_{Wt},t)}{\partial c_t}\Big/\frac{\partial F(\beta Q^*_{Wt},t)}{\partial Q^*_{Wt}}=\frac{-(p+g-s)\left(1-z(\beta Q^*_{Wt},t)\right)-(c_m+c_t-s)\beta^2(p+g-s)z'(\beta Q^*_{Wt},t)\cdot\frac{\partial Q^*_{Wt}}{\partial c_t}}{\beta^3(p+g-s)^2\left(1-z(\beta Q^*_{Wt},t)\right)^2f(\beta Q^*_{Wt},t)}$, then we derive $\frac{\partial Q^*_{Wt}}{\partial c_t}=\frac{z(\beta Q^*_{Wt},t)-1}{\beta^3(p+g-s)\left(1-z(\beta Q^*_{Wt},t)\right)^2f(\beta Q^*_{Wt},t)+\beta^2(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}$. Let $\frac{\partial Q^*_{Wt}}{\partial c_t}=0$, then we get $z(\beta Q^*_{Wt},t)=1$. At this point, we have Q^*_{Wt} decreases in c_t if and only if $z(\beta Q^*_{Wt},t)\in(0,1)$, while it increases in c_t otherwise. Doing the first-order differential on c_t, we can derive: $\frac{\partial w^*_{Wt}}{\partial c_t}=\frac{(1-z(\beta Q_{Wt},t))\cdot\frac{\partial Q^*_{Wt}}{\partial c_t}+\beta(c_m+c_t-s)z'(\beta Q^*_{Wt},t)\cdot\frac{\partial Q^*_{Wt}}{\partial c_t}}{\left(1-z(\beta Q^*_{Wt},t)\right)^2}=\frac{1-z(\beta Q_{Wt},t)+\beta(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}{\left(1-z(\beta Q^*_{Wt},t)\right)\left[\beta^3(p+g-s)\left(1-z(\beta Q^*_{Wt},t)\right)^2f(\beta Q^*_{Wt},t)+\beta^2(c_m+c_t-s)z'(\beta Q^*_{Wt},t)\right]}$. Thus, we have w^*_{Wt} increases in c_t if and only if $z(\beta Q^*_{Wt},t)\in(0,1)$, while it decreases in c_t otherwise.

Doing the first-order differential on g, we obtain $\frac{\partial Q^*_{Wt}}{\partial g}=\frac{\partial F(\beta Q^*_{Wt},t)}{\partial g}\Big/\frac{\partial F(\beta Q^*_{Wt},t)}{\partial Q^*_{Wt}}=\frac{w^*_{Wt}-s-(p+g-s)\frac{\partial w^*_{Wt}}{\partial g}}{\beta^2(p+g-s)^2f(\beta Q^*_{Wt},t)}$. As $\frac{\partial w^*_{Wt}}{\partial g}=\frac{\beta(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}{\left(1-z(\beta Q^*_{Wt},t)\right)^2}\cdot\frac{\partial Q^*_{Wt}}{\partial g}$, we have

$$\frac{\partial Q^*_{Wt}}{\partial g}=\frac{(w^*_{Wt}-s)\big(1-z(\beta Q^*_{Wt},t)\big)^2-\beta(p+g-s)(c_m+c_t-s)z'(\beta Q^*_{Wt},t)\cdot\frac{\partial Q^*_{Wt}}{\partial g}}{\beta^2(p+g-s)^2f(\beta Q^*_{Wt},t)\big(1-z(\beta Q^*_{Wt},t)\big)^2}.$$

Thus, $\frac{\partial Q^*_{Wt}}{\partial g}=\frac{(w^*_{Wt}-s)\left(1-z(\beta Q^*_{Wt},t)\right)^2}{\beta^2(p+g-s)^2f(\beta Q^*_{Wt},t)\left(1-z(\beta Q^*_{Wt},t)\right)^2+\beta(p+g-s)(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}>0$. Furthermore, $\frac{\partial w^*_{Wt}}{\partial g}>0$.

Doing the first-order differential on s, we obtain $\frac{\partial Q^*_{Wt}}{\partial s}=\frac{\partial F(\beta Q^*_{Wt},t)}{\partial s}\Big/\frac{\partial F(\beta Q^*_{Wt},t)}{\partial Q^*_{Wt}}=\frac{-(p+g-s)(\frac{\partial w^*_{Wt}}{\partial s}-1)-(w^*_{Wt}-s)}{\beta^2(p+g-s)^2f(\beta Q^*_{Wt},t)}$. As $\frac{\partial w^*_{Wt}}{\partial s}=\frac{-z(\beta Q_{Wt},t)\left(1-z(\beta Q^*_{Wt},t)\right)+\beta(c_m+c_t-s)z'(\beta Q^*_{Wt},t)\cdot\frac{\partial Q^*_{Wt}}{\partial s}}{\left(1-z(\beta Q^*_{Wt},t)\right)^2}$, we have $\frac{\partial Q^*_{Wt}}{\partial s}=\frac{(p+g-c_m-c_t)\left(1-z(\beta Q^*_{Wt},t)\right)^2}{\beta^2(p+g-s)^2f(\beta Q^*_{Wt},t)\left(1-z(\beta Q^*_{Wt},t)\right)^2+\beta(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}>0$.We then substitute $\frac{\partial Q^*_{Wt}}{\partial s}$ into $\frac{\partial w^*_{Wt}}{\partial s}=\frac{(c_m+c_t-s)(p+g-c_m-c_t-z(\beta Q_{Wt},t))z'(\beta Q^*_{Wt},t)-\beta(p+g-s)^2f(\beta Q^*_{Wt},t)z(\beta Q_{Wt},t)\left(1-z(\beta Q^*_{Wt},t)\right)}{\beta(p+g-s)^2f(\beta Q^*_{Wt},t)\left(1-z(\beta Q^*_{Wt},t)\right)^2+(c_m+c_t-s)z'(\beta Q^*_{Wt},t)}$. Let $\frac{\partial w^*_{Wt}}{\partial s}=0$, then $\bar{\bar{z}}(\beta Q^*_{Wt},t)=1-\frac{(c_m+c_t-s)(p+g-c_m-c_t-z(\beta Q_{Wt},t))z'(\beta Q^*_{Wt},t)}{\beta(p+g-s)^2f(\beta Q^*_{Wt},t)z(\beta Q_{Wt},t)}$. At this point, we have w^*_{Wt} increases in s if $z(\beta Q^*_{Wt},t)\in(0,\bar{\bar{z}}(\beta Q^*_{Wt},t))$, while it decreases in s otherwise.

When the demand follows a uniform distribution on $[\varepsilon,\lambda-\varepsilon]$, we can get the optimal wholesale price $w^*_{Wt}=\frac{\beta(\mu+\sqrt{3}\sigma_t)(p+g-s)}{4\sqrt{3}\sigma_t}+\frac{c_m+c_t+s}{2}$ and the optimal order quantity $Q^*_{Wt}=\frac{\mu+\sqrt{3}\sigma_t}{\beta}-\frac{\sqrt{3}\sigma_t(c_m+c_t-s)}{\beta^2(p+g-s)}$. Doing the first-order differential on σ_0, we obtain $\frac{\partial w^*_{Wt}}{\partial \sigma_t}=-\frac{\beta\mu(p+g-s)}{4\sqrt{3}\sigma_t^2}<0$. With the condition $\beta>\frac{w^*_{Wt}-s}{p+g-s}$, thus $\frac{\partial Q^*_{Wt}}{\partial \sigma_t}=\frac{\sqrt{3}}{\beta}[1-\frac{c_m+c_t-s}{\beta(p+g-s)}]>0$.

Proof of Proposition 4: Compared to the profit under a wholesale price contract without RFID: when $\alpha\in(0,\ V_{W0}]$, the retailer benefits from RFID if and only if $F(\beta Q_{Wt},t)=1-\frac{(c_m+c_t-s)/\left(1-z(\beta Q^*_{Wt},t)\right)-s}{\beta(p+g-s)}>0$, that is $c_t<(s+\beta(p+g-s))\big(1-z(\beta Q^*_{Wt},t)\big)+sz(\beta Q_{Wt},t)-c_m=U_{W0}$ (or $\beta>z^{-1}\left(1-\frac{c_t-sz(\beta Q_{Wt},t)+c_m}{s+\beta(p+g-s)}\right)/Q^*_{Wt}=V_{Wt}$); when $\alpha\in(V_{W0},\ 1)$, the retailer benefits from RFID if and only if $\pi^*_{Wr(Q^*_{W0},0)}>(p+g-s)\int_0^{\alpha Q^*_{W0}}xf(x,0)\mathrm{d}x$, that is $c_t<U_{W\pi}$, where $U_{W\pi}=\arg_{c_t}\{\int_0^{\beta Q^*_{Wt}}xf(x,t)\mathrm{d}x=\int_0^{\alpha Q^*_{W0}}xf(x,0)\mathrm{d}x\}$. Otherwise, the retailer loses from RFID adoption.

Proof of proposition 5: The proof is similar to that of Proposition 1 and hence is omitted.
Proof of proposition 6: The proof is similar to that of Proposition 2 and hence is omitted.