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Mean-risk Analysis of Radio Frequency Identification Application in Retail Stores with Inventory Misplacement

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Abstract: Nowadays, the inventory misplacement is a significant issue in the supply chain management. This study analyzes how the managers consider using Radio Frequency Identification (RFID) to effectively eliminate misplacement problems and to improve profitability. A mean-risk framework is carried out to portray this issue and a central semi-deviation model is proposed for risk measurement to analyze the impact of risk attitude on RFID adoption. Both risk neutral and risk aversion cases are discussed in this study. By considering both fixed setup cost and the tag cost, it is proved that retailers do not always benefit more from implementing RFID, unless the level of available products and tag cost are both low enough. Under the risk analysis, it is found that a risk aversion manager will be more unwilling than a risk neutral manager to invest RFID technology. Moreover, the manager will be more unwilling to invest RFID if the manager is more risk-averse.

Key words: Supply chain management, radio frequency identification, inventory misplacement, risk aversion, central semi-deviation, mean-risk analysis

INTRODUCTION

Nowadays, the inventory misplacement is still a significant issue in the retail stores (Raman *et al*., 2001; Kang and Gershwin, 2005; Dehoratius and Raman, 2008). More and more managers take into account the adoption of RFID to eliminate inventory misplacements. Lee and Ozer (2007) provide a literature review and argued that there was great potential of RFID technology in this area. Rekik *et al*. (2009) focused on the theft type errors in a finite-horizon periodic review store and analyzes the impact of RFID technology on the inventory system. Heese (2007) concluded that a decentralized supply chain would benefit more from RFID. Rekik *et al*. (2008) provided the relative insights on the benefit of RFID adoption. Camdereli and Swaminathan (2010) derived the conditions under which the parties can benefit from RFID adoption. However, most of above literatures do not consider the setup cost of RFID implication, which exists in the practice. In addition, this study looks into the problem under a risk-averse environment, while they only consider risk-neutral case.

There is a considerable literature devoted to risk aversion issues in inventory management. This study focuses on reviewing the study on Mean-variance (MV) model. Chen and Federgruen (2000) studied several basic inventory models by a systematic MV analysis to illustrate the optimal order quantity. Choi *et al*. (2008) used MV model to study the newsvendor problem with consideration on different risk preferences. Wu *et al*. (2009) pointed out that the stockout cost has complicated the analysis. Similar to the MV model, the Central Semi-deviation (CSD) is used to describe the risk rather than the variance measurement, which only considers the down side risk of the profit. Another advantage of CSD model is that it is consistent with Second Order Stochastic Dominance (SSD) rules (Ogryczak and Ruszczynski, 2001).

MODEL AND METHODOLOGY

The study considers a single retailer with a newsvendor type of single seasonal product. The retailer determines the order quantity q to cover a random demand D, with an unit cost c. The demand follows a known distribution with the probability density function f(.) and the cumulative density function f(.). The misplacement of inventory is assumed to occur before the demand happens. It can be viewed as the products ordered and received from the supplier are forbidden in the backroom, or misplaced on other shelves in the replenishment process. Therefore, only α $(0\le\alpha\le1)$ proportion of the order is available to satisfy the demand. Every available unit is sold for a price r. The other misplaced proportion $(1-\alpha)$ will be found at the end of

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season and salvaged at a unit price v, together with the unsold inventory. At the end of season, the unmet demand is lost without any penalty cost. To avoid trivial cases, $0<v<c<r$ is assumed.

When RFID is implemented, each product is tagged with an RFID tag, at a certain tag cost t. The retailer adopting RFID incurs a fixed cost K. The misplacement problem is assumed to be eliminated if RFID is adopted (i.e., $\alpha\equiv 1$). This assumption is quite common in the related research works (Heese, 2007; Rekik *et al*., 2009; Camdereli and Swaminathan, 2010). For notational convenience, the following notation is used throughout this study: the subscripts "1" and "2" denote for the case without RFID and with RFID, respectively. The superscript "*" denote for the optimal solution. Thus, the optimization problem of retailer is:

$$\begin{aligned} &\max_{q_i} \quad E[\pi_i(q_i)] \\ &\text{s.t.} \quad VP(q_i) \le M \end{aligned} \tag{1}$$

where i = 1, 2 and:

$$E[\pi_1(q_1)] = (r-c)\alpha q_1 - (c-v)(1-\alpha)q_1 - (r-v)\int_0^{\alpha q_1}(\alpha q_1 - x)f(x)dx \tag{2}$$

$$E[\pi_2(q_2)] = (r-c-t)q_2 - K - (r-v)\int_0^{q_2}(q_2 - x)f(x)dx \tag{3}$$

and $VP(q_i)$ is CSD risk measurement. $M\ge 0$ is the risk aversion threshold. A smaller M implies a more conservative retailer. As defined in Ogryczak and Ruszczynski (2001), the k-th CSD is formulated as:

$$VP(x) = \left(E[E[\pi(x)] - \pi(x)]_+^k\right)^{1/k} \tag{4}$$

where, $k\ge 1, (.)_+ = \max(.,0)$. Substituting Eq. 2 and 3 into Eq. 4, respectively, then:

$$VP(q_1) = (r-v)\delta^{1/k}(\alpha q_1) \tag{5}$$

$$VP(q_2) = (r-v)\delta^{1/k}(q_2) \tag{6}$$

Where:

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

RESULTS OF RISK INFLUENCE ON RFID ADOPTION

From Eq. 2 and 3, it is similar to the classical Newsvendor problem. Thus, the corresponding solutions are well known as:

$$q_1^* = (1/\alpha)\cdot F^{-1}[(r-c-(1-\alpha)(c-v)/\alpha)/(r-v)]$$

and $q_2^* = F^{-1}[(r-c-t)/(r-v)]$. From Eq. 5 and 6, the following lemma is obtained.

Lemma 1:

(a) In the case with RFID adoption, $VP(q_2)$ is independent of t and K
(b) In both two cases, $VP(q_i)$ is an increasing function of q_i, i = 1, 2
(c) In the case without RFID adoption, given the order quantity q_1, $VP(q_1)$ is increasing in a

Proof: (a) The result is obviously. The results of (b) and (c) can be yielded by taking the first derivative of $VP(q_i)$ (i = 1, 2).

Given the risk threshold value M, Let $q_i(M)$ (i = 1, 2) denote the retailer's maximum order quantity which satisfies the risk constraint, i.e.:

$$q_i(M) = \arg\max_{q_i}\{VP(q_i)\le M\} \tag{7}$$

Theorem 1: Given the risk threshold value M:

(a) In the case without RFID adoption, if $\bar{\alpha}<\alpha\le 1$, where $\bar{\alpha}$ = (c-v)/(r-v), the optimal ordering quantity is $q_{1,M}^* = \min(q_1^*, q_1(M))$, otherwise $q_{1,M}^* = 0$
(b) In the case with RFID adoption, if $0<t<r-c$, the optimal ordering quantity is $q_{2,M}^* = \min(q_2^*, q_2(M))$, otherwise $q_{2,M}^* = 0$
(c) $q_{i,M}^*$ is non-decreasing in M, where i = 1, 2

Proof: Combining the newsvendor solution and Lemma 1, the result is yielded.

The results of the optimal order quantity are similar to the results by Chen and Federgruen (2000), but quite different from the results by Wu *et al*. (2009), since the stockout cost is not considered. Next, the incentive of the retailer to invest in RFID technology without risk consideration is studied for a benchmark. Let H(t) be the retailer's incentive function, then:

$$\begin{aligned} H(t) &= E[\pi_2(q_2^*)] - E[\pi_1(q_1^*)] \\ &= (r-v)\left[\int_0^{q_2^*} xf(x)dx - \int_0^{\alpha q_1^*} xf(x)dx\right] - K \end{aligned} \tag{8}$$

Theorem 2:

(a) For a given K>0, H(t) is decreasing in α and there exists a threshold value of available proportion $\alpha_K<1$, such that if $\alpha\ge\alpha_K$, $H(t)\le 0$ for all $t\ge 0$

(b) For a given $\alpha \geq \alpha_K$, H(t) is decreasing in tag cost t and there exists an unique value t_k that satisfies $H(t_k) = 0$. If and only if $0 \leq t \leq t_k$, then $H(t) \geq 0$. If K = 0, then $t_k = t_0 = (1-\alpha)(c-v)/\alpha$
(c) t_k is decreasing in available proportion α and increasing in product cost c
(d) For a given α and $t<t_0$, there exists a threshold value of fixed cost $K_t>0$, such that $H(t) \geq 0$, if and only if $K \leq K_t$. Further, K_t is decreasing in t and α. If t = 0 and $\alpha = \bar{\alpha}$, K_t reaches the maximum value K_0

Proof: (a) Since H(t) decreases with αq_1^* and αq_1^* increases with α. Thus, H(t) decreases with α and t. Given $\alpha = 1$, t = 0, then, $H(0)|_{\alpha=1} = -K<0$. Thus, there must exists unique value α_K, that satisfies $H(t)_{\alpha=\alpha_k}$ and the result yields. (b) The proof is similar to (a). Let K = 0, substitute αq_1^* and q_2^* into Eq. 8, the result is yielded. (c) Assume $\alpha_1<\alpha_2<\alpha_K$, from (b), $t_{k,1}$ and $t_{k,2}$ can be obtained, respectively. Then:

$$H(t_{K,1})\big|_{\alpha=\alpha_2} < H(t_{K,1})\big|_{\alpha=\alpha_1} = H(t_{K,2})\big|_{\alpha=\alpha_2}$$

thus, $t_{k,2}<t_{k,1}$. The proof of monotonicity respective to c is similar. (d) Since H(t) decreases with K, let H(t) = 0, the threshold value is straightforwardly yielded as:

$$K_t = (r-v)\left[\int_0^{q_2^*(t)} xf(x)dx - \int_0^{\alpha q_1^*} xf(x)dx\right]$$

According to the proof of part (a), K_t is decreasing in t and α, respectively.

Part (a) of Theorem 2 gives an upper bound value of the available proportion, above which the retailer will never gain benefits from RFID. If the available proportion value is below the threshold, part (b) gives the threshold value of tag cost, below which retailer will gain more in the case with RFID investment. Part (c) indicates that, given the product cost, there is a tendency that the retailer is more willing to adopt RFID technology when the problem of misplacement is more serious. Furthermore, the retailer will more prefer to adopt RFID if the product is more valuable. The result of Part (d) is straightforward, since the retailer's optimum profit in the case with RFID adoption is deceasing in K. A lower fixed cost is necessary for inducing retailer to adopt RFID.

In the risk-averse case, there will be four cases of the optimal order quantities:

(a) $q_{1,M}^* = q_1^*,\ q_{2,M}^* = q_2^*$
(b) $q_{1,M}^* = q_1(M),\ q_{2,M}^* = q_2^*$
(c) $q_{1,M}^* = q_1(M),\ q_{2,M}^* = q_2(M)$
(d) $q_{1,M}^* = q_1^*,\ q_{2,M}^* = q_2(M)$

Case (a) is reduced to the risk neutral problem. The results are proposed in Theorem 2. In case (b), $q_2^* < q_2(M) = \alpha q_1(M) < \alpha q_1^*$. Then, from Theorem 1, it is concluded that the retailer will never adopt RIFD, Therefore, the study only need to consider case (c) and (d). Let G(t, M) denote the incentive function of the retailer, such as:

$$G(t,M) = (r-v)\left\{\begin{array}{l}\left[\dfrac{r-c-t}{r-v}q_2(M) - \displaystyle\int_0^{q_2(M)} F(x)dx - \dfrac{K}{r-v}\right] \\ -\left[\dfrac{r-c-\dfrac{1-\alpha}{\alpha}(c-v)}{r-v}\alpha q_{1,M}^* - \displaystyle\int_0^{\alpha q_{1,M}^*} F(x)dx\right]\end{array}\right\} \quad (9)$$

where, $q_2(M)$ is given by Eq. 7. Similar to Theorem 2, the following theorem is obtained.

Theorem 3:

(a) Given $K<K_0$, t and α, G(t, M) is increasing in M and there exists an unique value M_L, such that $G(t, M) \geq 0$ if and only if $M \geq M_L$
(b) Given $K<K_0$, t and M, G(t, M) is decreasing in α and there exists α threshold value α_L, such that if $\alpha \geq \alpha_L$, G(t, M) for all $t \geq 0$ and where $\alpha_L<\alpha_K$
(c) Given $K<K_0$ and α, M, G(t, M) is decreasing in t. There exists an unique value $t_L \leq t_K$ that satisfies $G(t_L, M) \geq 0$ if and only if $0 \leq t \leq t_L$, where t_L is decreasing in α and increasing in M
(d) Given α, t and M, there exist a threshold value of fixed cost $K_L \leq K_L$, such that $G(t, M) \geq 0$, if and only if $K \leq K_L$. Further, K_L is decreasing in t and α, respectively and increasing in M

Proof: (a) First, proof G(t, M) is increasing in M. It only need to consider two cases: (i) $q_{1,M}^* = q_1(M),\ q_{2,M}^* = q_2(M)$ (ii) $q_{1,M}^* = q_1^*,\ q_{2,M}^* = q_2(M)$. For case (I), $aq_1(M) = q_2(M)$. $\partial G(t, M)/\partial q_2(M) = t-(1-\alpha)(c-v)/\alpha \geq 0$. Therefore, G(t, M) is increasing in $q_2(M)$. Since $q_2(M)$ increases with M. Thus, G(t, M) is increasing in M. For case (ii). Since $q_{1,M}^* = q_1^*$, $q_{1,M}^*$ is independent of M. $\partial G(t, M)/\partial q_2(M) = (r-v)[F(q_2^*)-F(q_2(M))] \geq 0$. Thus, G(t, M) increases with $q_2(M)$. (b) The proofs of monotonicity and existence of unique value are similar to the proof of Theorem 2(a). (c) Since $q_2(M)$ is independent of t, $\partial G(t, M)/\partial q_2(M)/\partial t = -q_2(M)<0$. The proof of existence of unique value t_L is similar to the proof of Theorem 2(b). Now, proof the result $t_L \leq t_K$. Since $G(t_K, M)<G(t_K, \infty) = H(t_K) = 0 = G(t_L, M)$, G(t, M) is decreasing in t, thus $t_L \leq t_K$. The proof of monotonicity of t_L respect to α and M is similar to the proof of Theorem 2(c). The proof of $\alpha_L<\alpha_K$ is similar to the proof of $t_L<t_K$. (d) The proof of $K_L \leq K_t$ is similar to the proof of $t_L<t_K$. And the proof of the other results is similar to the proof of Theorem 2(d).

Theorem 3(a) implies that, the risk aversion retailer will achieve more benefits from RFID if the retailer is less risk-averse. If $M<M_L$, the risk-averse retailer will never

adopt RFID, since the benefits from RFID are significantly constrained by limited order quantity. As indicated by Part (b), the threshold value of available proportion is lower than that in risk neutral case. It means that, a risk aversion retailer is more tolerant with inventory misplacement. Part (c) indicates that if the tag cost is low enough, the retailer will always benefits more from RFID adoption even in a risk-averse case. The smaller threshold value of tag price in risk-averse case indicates that the risk-averse investors will be more careful to invest in new technology than the ones who are risk-neutral. Similarly, part (d) gives the threshold value of the fixed cost K in risk-averse case.

A numerical study is provided to illustrate the above analysis results. Considering that the demand is normally distributed with mean 1000 and standard deviation 400, the other parameter are : r = 25, c = 15, v = 5, K = 2400 and k = 2 (i.e., standard semi-deviation). Let α vary from 0 to 1, let tag cost vary from 0 to 10 and let risk threshold vary from 0 to 6000. The optimal order quantities without and with RFID are illustrated in Fig. 1.

Figure 1 illustrates that the optimal order quantities in both cases are non-decreasing in M. From Fig. 1a, the retailer will not order if $\alpha \in (0, 0.5]$, due to the serious misplacement. When $\alpha > 0.5$, $q^*_{1,M}$ first increases and then decreases with α for a given M. In fact, the available proportion creates two-fold effects on order quantity. It is easily obtained that the increase of available proportion leads to newsboy-ratio increases. However, the order quantity is not necessary to increase, due to more and more products are available. As illustrated in Fig. 1b, for a given M, $q^*_{2,M}$ is non-increasing in t. Since there exists a fixed cost K, the retailer only order the products when the expected profit will be cover the fixed cost. Therefore, the order quantity $q^*_{2,M}$ will be zero if the tag cost is high enough (t>5.1) or the risk threshold value is small enough (M≤500), although the newsboy ratio is positive.

Next, it studies how changes in the misplacement level and risk attitude affect the threshold value of tag cost (given K = 2400) and fixed cost (given t = 2). The result is illustrated in Fig. 2.

Figure 2 gives the maximum value of tag cost and fixed cost that the retailer can afford, which are both

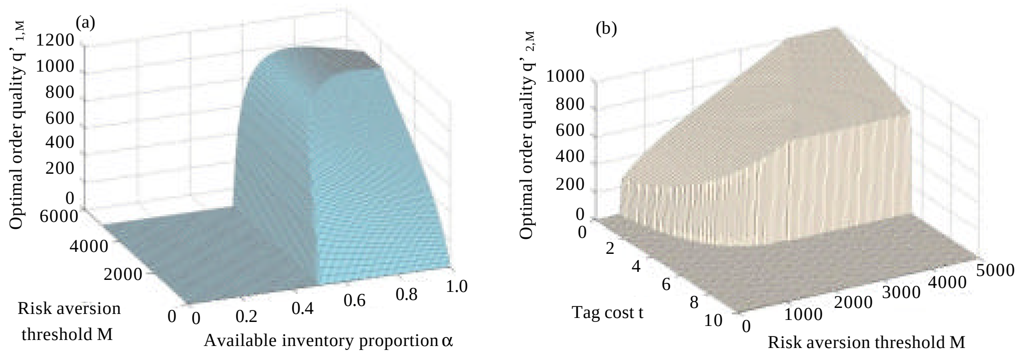

Fig. 1(a-b): Optimal order quantity (a) Without RFID adoption and (b) With RFID adoption in the risk-averse case

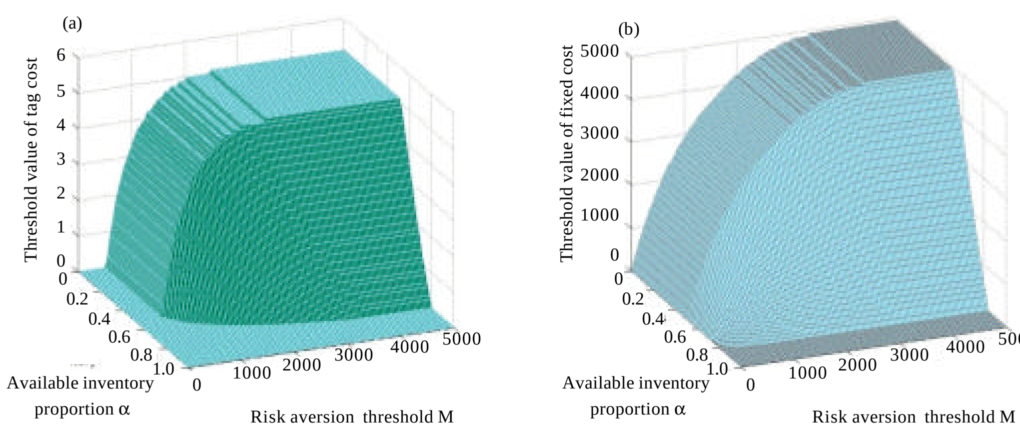

Fig. 2(a-b): Threshold value of the (a) Tag cost and (b) Fixed cost with different value of α and M non- decreasing in M and non-increasing in α. It means that the more risk-averse retailer is more tolerant of inventory misplacement and less willing to adopt RFID. As illustrated in Fig. 2a, when $M \leq 500$, the maximum tag cost is always zero when α varies from 0 to 1, which means that the retailer will never adopt RFID if the retailer is conservative enough. The result is quite different from the results in Rekik *et al*. (2008) and Camdereli and Swaminathan (2010), since the authors did not consider the retailer's risk preference. A similar result can be found that there exists a threshold value α_0, such that t is zero if $\alpha \geq \alpha_0$, for a given M. Furthermore, α_0 increases with M and reaches the maximum 0.8 when M>3400. It means that, when the misplacement problem is not serious enough, the benefit from RFID adoption is not much enough to cover the additional investment cost. Therefore, the optimal policy for retailer is not to adopt RFID. The similar results of the maximum fixed cost can be also found in Fig. 2b.

CONCLUSION

This study analyzes the impact of retailer's risk attitude on the benefits from RFID adoption and on the investment incentives of risk aversion retailers. Three main results are found. Firstly, the optimal orders must be not more than that of risk neutral case in both with or without RFID. Secondly, the acceptable area of tag cost is much smaller for risk-averse managers. Finally, the critical value of available proportion for risk-averse retailer to refuse to adopt RFID technology must be lower than that in risk neutral case. The above results indicate that a risk aversion retailer is more cautious on RFID investment decision. The more risk averse is, the more cautious the risk-averse retailer is. For the future study of the works, it will be a challenging but useful extension of the risk-averse model between the supply chain members.

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