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Warehouse efficiency improvement using RFID in a humanitarian supply chain: Implications for Indian food security system

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ABSTRACT

This paper investigates the impact of RFID adoption in a non-profit supply chain scenario to study the effect of *available rate of ordering* and *shrinkage recovery rate* on overall costs at the warehouse level. We model the situation as a Newsvendor problem with the objective to minimize the total expected cost and compare two scenarios with and without RFID for managing the inventory subjected to shrinkage and misplacement. We apply the model to Indian food security system and the results show that, incentive to deploy RFID depends on the deprivation cost, the severity of error and the shrinkage recovery rate.

1. Introduction

Efficiency improvement in humanitarian supply chain has been a major challenge due to involvement of complex list of stakeholders and has drawn the attention of both academics and not-for-profit organizations (Chandes and Paché, 2010; Christopher and Tatham, 2014; Kovács and Spens, 2009). Such supply chains can be broadly classified into two categories: *short-term ones* those operate during disasters such as earthquake or hurricane, or slow-onset, such as drought or famine, and the *long-term* ones those provide consistent assistance to a group of socially deprived community (Çelik et al., 2012). Examples of some long-term humanitarian issues include food insecurity, high mortality from diseases and gender inequality, which are mostly covered under the Millennium Development Goals (UN, 2017). Though, most of the literature on humanitarian supply chain revolves around short-term disaster management; long-term developmental supply chain covering a gamut of human life issues like food security, health care, education and gender equality deserves equal attention. For example, the United Nations acknowledges hunger and malnutrition as the greatest risk to world health. Accordingly, eradication of extreme poverty and hunger remains the first of the eight objectives defined under the Millennium Development Goals (UN, 2017).

Performance in the context of such supply chains is predominantly measured in terms of *cost* and a combination of cost and *customer responsiveness* (Beamon, 1999). Cost components primarily include inventory costs, operational costs and deprivation costs (Holguín-Veras et al., 2012) whereas lead-time, stockout probability, and fill rate are the measure of customer responsiveness. Lack of skilled human resource, low recognition of logistics, inadequate infrastructure, and resource wastages are some of the leading challenges of both short-term and long-term humanitarian supply chain (Kovács and Spens, 2009). Specifically, in food security systems such as Indian Targeted Public Distribution System (TPDS), wastage of resources through spoilage, leakage, and theft are the primary cause of concern (CAG, 2013; Drèze and Khera, 2015).

The spoilage and misplacement of stocks never get reconciled on a real-time basis, which is the source of inventory inaccuracy in such supply chains. Inventory inaccuracy refers to the discrepancies that exist between actual inventory available and what is on the record of the information system. This primarily arises from three main sources namely shrinkage, misplacement, and transaction

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errors (Atali et al., 2009; Fan et al., 2015). Shrinkage includes theft of inventory, spoilage, obsolescence, supplier fraud, and damage resulting in reduced actual inventory as compared with system record. Misplacement errors occur when a part of the inventory is not available to satisfy customer demand although physically present (Rekik et al., 2008).

Radio Frequency Identification (RFID) technology is considered as a promising solution to address the problem of inventory inaccuracy. This is an Automatic Identification and Data Capture (AIDC) technology, which enables real-time communication with numerous objects simultaneously from a distance without line of sight (García et al., 2007). This unique and advanced tracking capability enables RFID in reducing inventory shrinkage, directly by preventing theft and fraud through accurate monitoring, and indirectly by enhancing accuracy of information and improved visibility (de Kok et al., 2008; Lee and Özer, 2007; Pero and Rossi, 2014; Rekik et al., 2009). RFID technology can be used to improve efficiency and responsiveness both in *short-term* and *long-term* humanitarian supply chain. During disaster, responding quickly to the need of the victims is the prime concern and the ability of RFID technology to track the critical resources like food, medicine, equipments and human resource would greatly reduce the response time (Yang et al., 2011, 2013). It can also improve the security and management aspects of the relief supply chain (Baldini et al., 2012). Similarly in long-term humanitarian supply chain the situation is comparatively stable and efficiently achieving the social mission is the prime concern (Baruch and Ramalho, 2006; Holguín-Veras et al., 2012, 2013). Application of RFID technology can improve operational efficiency in terms of lower inventory, reduced stock out, and better utilization of resources.

Although RFID technology has gained traction in the for-profit sector, the same cannot be claimed for the non-profit supply chain. Most of the technology projects in such supply chains are donor funded, and without realistic estimation of the benefits it is difficult to get the go ahead for the project (Maiers et al., 2005). The traditional modeling approach while estimating value of RFID may not give accurate result in a humanitarian scenario. This is because, along with operational efficiency, the reduction in human suffering due to technology intervention should also be suitably accounted for in the objective function for realistic estimation of the value of RFID (Holguín-Veras et al., 2013). The models used in the existing literature do not consider this aspect.

In this paper, we explore the possibility of deploying RFID technology in warehouses operating under non-profit scenario and facing inventory inaccuracy issues. We model the situation as a newsvendor problem to quantify the benefits by comparing two scenarios – with and without RFID. This generic setting is further analysed under uniformly distributed demand to derive the closed-form expression for optimal order quantity and total expected costs for both the scenarios and tag cost under which RFID deployment is feasible. We apply the model in the context of Indian food security system collecting the data from different resources and field visits. We perform sensitivity analysis on the parameters for which exact values are not available from any source. Our observations show that RFID is not beneficial when the shrinkage and misplacement level in the warehouse is less than a critical value. The critical tag price below which the system with RFID becomes viable is dependent on level of shrinkage and misplacement, shrinkage recovery rate and deprivation cost factor. When the shrinkage in the warehouse is high, RFID is viable even at higher tag price. Similarly a better shrinkage recovery rate justifies higher tag cost. We also estimate the potential cost saving for a 50,000 MT warehouse with RFID.

Our work is motivated by Fan et al. (2014) and (2015). However, we differ from them in many ways. Fan et al. (2014) model inventory inaccuracy by considering only the shrinkage. They neither consider inventory misplacement nor do they incorporate the fixed cost of RFID implementation. Although, these two issues are addressed later in Fan et al. (2015), they study the impact of RFID in a profit maximization scenario. While their model applies to for-profit organizations, it is restrictive in a humanitarian supply chain context due to the following reasons. First, the warehouses under non-profit scenarios need to suitably account for the reduction in human suffering along with operational efficiency (Holguín-Veras et al., 2013). Second, procurement cost in a non-profit scenario does not make much sense as the cost is directly reimbursed by the donor. Hence, procurement cost does not contribute to total operational cost of the warehouse. Third, they calculate shrinkage based on the selling price. However, in non-profit scenario warehouse is only responsible for distribution. Hence, sales price is not meaningful. The model proposed in this paper fills this void.

We make three significant contributions. *First*, our model is unique in that, we incorporate deprivation cost to account for the human suffering due to delay in delivery of critical items. *Second*, we jointly consider shrinkage and misplacement in a cost minimization scenario and derive closed-form solutions for *the critical tag cost* and *threshold value of shrinkage recovery rate* under uniform demand distribution. The solutions developed in the earlier literature are not applicable due to the unique nature of our model. *Third*, while most of the papers have numerical illustrations using hypothetical data, we consider the data for Public Distribution System of India and interpret the result. To sum it up we are the first to quantify the benefits of RFID in a not-for-profit scenario considering shrinkage, misplacement and deprivation cost in the model.

The rest of the paper is organized as follows. In Section 2, we review the related literature on humanitarian supply chain, RFID application in humanitarian supply chain and the application of RFID to address inventory inaccuracy issue. In Section 3, we model the inventory inaccuracy issue in a warehouse under two different scenarios with and without RFID. In Section 4, we apply the model in the context of Indian food security system and analyze the effect of available rate of ordering, shrinkage recovery rate after RFID implementation, and the tag price respectively. We also provide an analytical expression of the tag cost, which makes the deployment of RFID a viable option. In Section 5, we discuss the managerial implications and finally, in Section 6, we conclude the study and show direction for future research.

2. Related literature

2.1. Humanitarian supply chain

Disasters and *Long-term development issues* are the two key terms in the context of humanitarian supply chain. Disaster is an event that causes hundred deaths or hundred injuries or damage worth US$ 1 million (Apte, 2010). Long-term development issues lead to human suffering in a prolonged term, and generally, their causes cannot be traced back to a single catastrophic event (Çelik et al., 2012). In recent times, the academic community has shown renewed interest in this topic due to increased number of both natural and man-made disasters around the world. Accordingly there are some recent survey papers categorizing the literature in terms of different modeling approaches, solution methodologies and the technologies used in different stages of the disaster life cycle (Caunhye et al., 2012; Galindo and Batta, 2013; Luis et al., 2012; Özdamar and Ertem, 2015). One stream of literature discuss about the unique characteristics and challenges of humanitarian supply chain. Kovács and Spens (2009) find that challenges of humanitarian logisticians depend upon both the type of disaster and local presence of their employer. The authors identify coordination of logistical activities as the major challenge. Tatham et al. (2009) investigate whether for-profit, stable supply chain techniques are applicable in the not-for-profit humanitarian supply chain setting. They find that SCM tools and techniques created in for-profit context, especially for partnership formation and performance measurements could be applied in the humanitarian supply chain context. Beamon and Balcik (2008) review the key differentiating characteristics between the for-profit and non-profit supply chain in terms of sources of fund, goals of the organization, performance measurement criteria and the stakeholders involved. To identify a few, the for-profit sectors earn their money by selling product or services to customers whereas non-profit organizations depend on government funding and donations(Moore, 2000). Financial return to the shareholders is the prime objective in for-profit scenarios but in non-profit, it is to efficiently achieve the social purpose and mission (Baruch and Ramalho, 2006; Holguín-Veras et al., 2013).

Literature concerning the long-term humanitarian supply chain is limited as study on humanitarian supply chain is more focused towards disaster. Mohan et al. (2013) simulate the warehouse operations in a non-profit food supply chain and show how improved efficiency in terms of handling extra volume can be achieved without investing in additional warehouse space. Natarajan and Swaminathan (2014) study inventory management in humanitarian operations under budget constraints over a finite planning period and find the optimal procurement policy. Some literature consider the application of OR to improve the efficiency of the system in long-term humanitarian supply chain like in food security and health care (Epstein et al., 2002; Rahman and Smith, 2000; White et al., 2011). Our study is concerned with efficiency improvement in a long-term humanitarian supply chain through Technology intervention. We discuss RFID application *to eliminate shrinkage and misplacement in food security system* which has not been discussed earlier in the literature.

2.2. RFID in humanitarian supply chain

Although RFID application in long-term developmental supply chain has not been discussed much in the literature, its application in Disaster supply chain has been proposed by some of the authors. Ozguven and Ozbay (2015) propose an emergency management framework integrating *RFID based online tracking mechanism* with offline *multi-commodity stochastic humanitarian inventory control* (*MC-SHIC*) *model*. Through the on-line tracking the authors intend to synchronise the critical delivery and consumption process whereas they use the off-line MC-SHIC model to determine the optimal safety stock level for un-interrupted service. Yang et al. (2011) propose a Hybrid Zigbee RFID sensor network for monitoring the critical resources like rescue equipments, vehicle, people as well as local environment during emergency situation. Baldini et al. (2012) propose the application of secure RFID technology to improve the management and security aspects of the relief supply chain. The authors use the cryptographic algorithm for the secured RFID system along with system architecture and deployment workflow. Ganz et al. (2015) use DIORAMA based systems to triage patients embedded with active RFID tags and also to mark the trapped patients and point of interest. Wang et al. (2014) explore the possibility of deploying RFID technology in post disaster reconstruction to track movement and location of materials, antitheft systems, and automatic ordering of inventory. None of the above research works discuss about the viability of using RFID technology in the humanitarian supply chain. This may be because in disaster situations the prime objective is quick and uninterrupted service to save human life. However, in long-term humanitarian supply chain scenario that we consider, the situation is comparatively stable and efficiently achieving the social purpose and mission is also a concern (Baruch and Ramalho, 2006; Çelik et al., 2012; Holguín-Veras et al., 2013). In this paper, we discuss the efficiency improvement in a long-term humanitarian supply chain by using RFID and evaluate the conditions under which this technology is beneficial.

2.3. Inventory inaccuracy and value of RFID

Although studies related to RFID application in a humanitarian supply chain is relatively new and limited, RFID application in commercial supply chain is not. Recent review papers highlight the applications of RFID in various industries (Zhu et al., 2012); benefits and obstacles faced when used in warehouse operations (Lim et al., 2013); and the supply chain problems addressed through RFID (Sarac et al., 2010). Sarac et al. (2010) classify the supply chain problems addressed through RFID as *inventory inaccuracy* due to theft and misplacements, *bullwhip effect* due to information delay and *ineffective replenishment policy* due to imperfect information. The authors highlight, *analytical approach*, *simulation approach*, and *case studies and experiments* as the methodologies used while quantifying the benefits of RFID. In this paper, we model inventory inaccuracy issue through analytical approach.

Several authors have used analytical approach to model inventory inaccuracy in supply chain. In the single period models, Newsvendor framework is used considering a short life cycle product under stochastic demand (Heese, 2007; Sahin and Dallery, 2009; Xu et al., 2012). Heese (2007) consider a single period, two-level supply chain and compare the impact of inventory record inaccuracy on optimal profit under centralized and decentralized setting. Their analysis shows that RFID adoption could be more suitable to decentralized supply chain suffering from double marginalization. Sahin and Dallery (2009) consider the case of a wholesaler who is unaware of inventory inaccuracy and evaluate efficiency loss due to errors compared to error free situations. They quantify the economic impact of inventory inaccuracy and assess possibility of deploying new data capture technology to address this issue. Xu et al. (2012) analyze a supply chain consisting of a manufacturer who is a Stackelberg leader and a retailer who is dealing with inventory inaccuracy due to shrinkage. While comparing different strategies to tackle inventory inaccuracy, they find that non-technological approach like information sharing is inefficient as compared to technological strategy like RFID implementation. Camdereli and Swaminathan (2010) model inventory misplacement in study incentives to different players in the supply chain to adopt RFID technology as a remedy to inventory misplacement. They consider both coordinated and uncoordinated environment to show that investing in RFID is beneficial when the fixed cost of implementation and tag prices are comparatively low.

Among the multi-period models, Atali et al. (2009) consider a finite time horizon, single item, and periodic review inventory control policy to quantify the value of RFID. However, they assume RFID as perfect technology and do not incorporate reading/tracking errors in their model. DeHoratius and Raman (2008) provide a detailed empirical characterization of inventory record inaccuracy in a retail context. By applying hierarchical linear modeling (HLM) technique, the authors identify the factors to be incorporated into the inventory planning tools to reduce the presence of inventory record inaccuracy. Ustundag and Tanyas (2009) simulate a three-echelon supply chain under multi-period scenario and quantify the expected benefit of RFID integration. The authors further investigate the effect of product costs, lead time and uncertain demand on cost at the echelon level. Kök and Shang (2014) study how to design an effective cycle count program for a multi-stage supply chain while considering inventory inaccuracy at different locations. They analyze the impact of optimal cycle counts on RFID investment decisions. While presenting an analytical model to quantify the value of RFID, Dai and Tseng (2012) consider both tangible and intangible benefits of RFID like shrinkage reduction and improvement in information flow in a multi-echelon supply chain.

There is some recent work on the impact of improved visibility due to RFID, on supply chain performance. Cannella et al. (2015) assess the impact of inventory record inaccuracy both on operational performances and customer service level considering a collaborative supply chain scenario. Through numerical simulation, the authors show that inventory record inaccuracy strongly compromises the stability when moving towards the upstream of the supply chain. Considering the amount of safety stock required as the KPI, Chan et al. (2012) analyze the performance of RFID and Barcode systems. They find that ratios between the two systems' stock-taking costs and error variations are the deciding factors while determining which system outperforms the other. Contrary to the above papers, we model inventory inaccuracy problem in a non-profit scenario and incorporate deprivation cost in the model. We apply the model to a real case and perform numerical analysis using actual data to draw meaningful insights.

3. The modeling framework

We consider a non-profit supply chain consisting of a warehouse, getting supplies for a single seasonal product from some upstream suppliers at regulated unit cost v. The warehouse is required to maintain the inventory for distributing to the intended beneficiaries or downstream warehouses, and during storage; it is subjected to misplacement and shrinkage. Excess demand is back ordered and resolved through emergency procurement. We model the total expected cost at the warehouse under a newsvendor framework and wish to minimize it. In a humanitarian supply chain, one major objective is to minimize the human suffering brought about by the deprivation of critical supplies and services (Holguín-Veras et al., 2016). So in our model, we consider both operational costs and deprivation cost while calculating the total expected cost under newsvendor framework. Deprivations costs are economic value of the human suffering and a function of deprivation time and socio-economic characteristic of the beneficiaries (Holguín-Veras et al., 2013, 2016). Accurately representing the deprivation cost function is very complex and the readers are referred to Holguín-Veras et al. (2013) for a detailed discussion on this. We consider deprivation time as the key variable and take a proxy approach to account for the deprivation cost which works reasonably well in a long-term humanitarian scenario (Holguín-Veras et al., 2012). In a similar context, earlier literature also consider that after a disaster, the psychological penalty cost perceived by the victims requiring evacuation, medical treatments or other critical resources is a function of waiting time (Hu and Sheu, 2013; Hu et al., 2017). To incorporate the deprivation cost, we assume that the total deprivation time is directly proportional to the backlogged quantity and the beneficiaries incur deprivation cost of ω per unit waiting time.

In classical newsvendor model, one primary assumption is that there is no execution error (Rekik et al., 2008). Therefore, to incorporate misplacement and shrinkage problem in the model, we define one variable η, which reflects the effect of shrinkage on the actual quantity available for distribution. The fraction η is the ratio between *the actually available quantity considering only the effect of shrinkage* to *the initially procured quantity for storing in the warehouse*. Similarly, we define another variable θ, *which reflects the effect of only misplacement and is the ratio between the available quantity considering misplacement and initial procured quantity*.

We consider two situations under which the warehouse manager (hereafter called he) takes his inventory decisions. In the first scenario, he acknowledges that shrinkage and misplacement are happening in the warehouse and makes inventory decisions based on the prior knowledge available on these two types of errors. In the second scenario, he invests in RFID technology along with theft preventing auxiliary equipment like CCTV camera (Dai and Tseng, 2012) and takes inventory decisions under reduced shrinkage and accurate information. The total expected cost in a single period considering an improved newsvendor model differs in the above two scenarios and gives the basis to quantify the value of investing in RFID technology. While considering the base situation to compare the value of RFID, we assume that the manager acknowledges the inventory inaccuracy issue without completely ignoring it. This helps to get a realistic estimation of the benefits obtained from RFID implementation.

3.1. Assumptions

We model the inventory inaccuracy problem in the warehouse under the following assumptions. Table 1 above lists the notations

Table 1
List of notations used in the model.

Notation	Description
Q	The ordering quantity without RFID (Decision variable)
Q^*	The optimal order quantity without RFID
Q_{RF}	The ordering quantity with RFID (Decision variable)
Q_{RF}^*	The optimal order quantity with RFID
$C(Q)$	The total expected cost without RFID
$C_{RF}(Q_{RF})$	The total expected cost with RFID
v	The purchase cost per unit item
h	The holding cost per surplus unit during the period
g	Expedited cost (the per unit additional cost for emergency procurement)
ω	The deprivation cost factor (the cost incurred per unit delay time)
r	The cost of one RFID tag
x	The random demand
t	Time required to replenish one backlogged item
$f(x)$	Probability Density Function (PDF) associated with demand
$F(x)$	Cumulative Distribution Function (CDF) associated with demand
μ	Mean of the demand
η	The available rate of order quantity when we consider only the shrinkage
θ	The available rate of order quantity when we consider only the misplacement
ϕ	The shrinkage recovery rate after RFID implementation
τ_1	The available rate of order quantity when there is no RFID
τ_2	The available rate of order quantity after implementation of RFID
γ	The upper bound of uniformly distributed demand
K	The fixed cost of RFID implementation

used in the model.

i. Excess demand from the beneficiaries or downstream warehouses is backlogged.
ii. Deprivation time is directly proportional to the backlogged quantity. This is because the total time required for processing, packaging, transferring and loading/unloading directly varies with the quantity to be distributed (Lodree et al., 2008).
iii. Deprivation cost is a linear function of deprivation time. This is because we consider deprivation time as the key variable and take the proxy approach to account for the deprivation cost which works reasonably well in a long-term humanitarian scenario (Holguín-Veras et al., 2012)
iv. Passive RFID tags are used at the item level
v. Inventory error happens as the order is placed
vi. Inventory shrinkage (η) and misplacement (θ) are independent of each other
vii. After implementing RFID, the misplaced inventory can be recovered completely but shrinkage cannot be wholly eliminated; although it can be reduced substantially. This is because RFID system can prevent thefts and pilferage easily but it cannot identify a product of degraded quality which is unsuitable for consumption. Shrinkage recovery rate (ϕ) is the proportion of the shrinkage quantity that can be recovered with RFID.
viii. The fractional values of $\eta,\theta and \phi$ are known quantities
ix. $\eta + \theta > 1$. This ensures that some quantity of the product is available for distribution even if we consider both misplacement and shrinkage simultaneously.
x. The procurement price of the product is independent of demand as it is fixed by the regulatory body

3.2. Inventory inaccuracy with and without RFID setting

Table 2 compares the inventory inaccuracy scenarios in both RFID and no RFID setting. When the warehouse orders Q quantity of products, $(1-\eta)$ fraction of the order undergoes shrinkage and $(1-\theta)$ fraction of the order gets misplaced. Therefore, without RFID technology the total loss is the sum of these two quantities. Accordingly the *available rate of order quantity under inventory inaccuracies*

Table 2
Inventory inaccuracies in a warehouse with and without RFID.

	Scenario without RFID	Scenario with RFID
Loss due to Shrinkage	$Q(1-\eta)$	$Q(1-\eta)(1-\phi)$
Loss due to Misplacement	$Q(1-\theta)$	0
Total loss	$Q(2-\eta-\theta)$	$Q(1-\eta)(1-\phi)$
Remaining inventory	$Q-Q(2-\eta-\theta) = Q(\eta + \theta-1)$	$Q-Q(1-\eta)(1-\phi) = Q(\eta + \phi(1-\eta))$
Available rate	$\tau_1 = (\eta + \theta-1)$	$\tau_2 = (\eta + \phi(1-\eta))$

without RFID is $\tau_1 = \eta + \theta - 1$. This is the fraction of the order that is available to the end beneficiary during the distribution period. The situation is depicted in column 2 of Table 2. It may be noted that only the misplacement portion $(1-\theta)$ of the inventory is recoverable at the end of the period, which contributes towards additional holding cost. Column 3 of Table 2 shows the scenario under RFID. Since, shrinkage recovery rate (ϕ) is the proportion of the shrinkage quantity that can be recovered with RFID, $(1-\eta)(1-\phi)$ proportion is not available for distribution. But with RFID, the misplaced products can be fully recovered. So finally, the portion of the quantity available for distribution with RFID is $\tau_2 = \eta + \phi(1-\eta)$. Here, τ_2 is *the available rate of order quantity under inventory inaccuracy with RFID* situation.

3.3. Ordering policy without RFID

Under this scenario, the warehouse manager orders Q quantity of products. But as depicted in Table 2, considering shrinkage and misplacement the available order quantity is $\tau_1 Q$. Therefore, under the Newsvendor framework, the total expected cost $C(Q)$ considering inventory inaccuracy can be modeled as follows.

$$C(Q) = h\int_0^{\tau_1 Q}(\tau_1 Q - x)f(x)dx + g\int_{\tau_1 Q}^{\infty}(x-\tau_1 Q)f(x)dx + h(1-\theta)Q + v(1-\eta)Q + \int_{\tau_1 Q}^{\infty}\omega t(x-\tau_1 Q)f(x)dx \quad (1)$$

On the right-hand side of the Eq. (1), there are five terms. The first term refers to the expected holding cost of the leftover quantity after fulfilling the demand; the second term refers to the expected expedited cost of procurement when demand exceeds the available quantity $\tau_1 Q$ for distribution. The third term represents the holding cost incurred for the misplaced quantity and the fourth term is the cost of the quantity lost due to shrinkage. The last term represents the deprivation cost which we calculate through the proxy approach and apply the constant penalty-based model to capture it (Holguín-Veras et al., 2013). This is based on a linear waiting cost that is directly proportional to the shortage quantity $(x-\tau_1 Q)$ in which all the shortage quantity is delivered to the beneficiaries $t(x-\tau_1 Q)$ time units after the demand is realized. For tractability, we apply the constant-penalty based model which works reasonably well in a long-tem humanitarian situation (Holguín-Veras et al., 2012). However, other approaches like econometric estimation method (Holguín-Veras et al., 2016) can be applied to estimate the deprivation cost function specifically for food which is beyond the scope of this manuscript. It is important to mention here that, RFID intervention affects the available rate of ordering as explained in Table 2 above, and hence, the deprivation cost component in the model. It may be further noted that unlike earlier models we cannot compute loss due to shrinkage using selling price in a non-profit scenario (Fan et al., 2015). Therefore, we consider the loss in terms of procurement cost to represent the fact that shrinkage is the wastage of the subsidy given to the beneficiary. Since this wastage happens due to negligence of the warehouse owner he is accountable for this and may give appropriate compensation. We also consider that timely delivery of critical items to the beneficiaries is the responsibility of the warehouse manager. So the deprivation cost is chargeable to the warehouse as compensation. It is worth mentioning that, the procurement cost has not been included in the objective function as procurement cost of the materials is directly reimbursed by the donor and not the warehouse. Rearranging Eq. (1), we get

$$C(Q) = h\int_0^{\tau_1 Q}(\tau_1 Q - x)f(x)dx + (g+\omega t)\int_{\tau_1 Q}^{\infty}(x-\tau_1 Q)f(x)dx + h(1-\theta)Q + v(1-\eta)Q$$

Except for the last two terms, the expected cost $C(Q)$ is a well-known newsvendor function which is convex. However, these two terms are linear in terms of quantity, hence; their addition does not change the nature of the function. Applying the first order condition and after further simplification (See Appendix A.1 for details), the optimal order quantity in this setting turns out to be:

$$Q^* = \frac{1}{\tau_1}F^{-1}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right] \quad (2)$$

Here, $Q^* > 0$ if and only if $\tau_1 > 1/(g+\omega t)[h(1-\theta)+v(1-\eta)]$. If we assume that the inventory is accurate and there is no deprivation cost $(\omega = 0)$, then the values of τ_1,η,θ are all unity and the optimal order quantity is $Q_c^* = F^{-1}[g/(g+h)]$ .This verifies our solution with the existing literature for classical newsvendor problem (Taha, 2007). Intuitively, the order quantity under inventory inaccuracy should be more to satisfy the demand; however, the same cannot be said in this case because of the presence of the term $(1/\tau_1)$ in Q^*. So the order quantity while considering inventory inaccuracies may not be always greater than that of the accurate inventory case. The optimal expected cost under inventory shrinkage and misplacement can be derived as follow: (See Appendix A.2 for details)

$$C(Q^*) = (g+\omega t)\mu - (g+\omega t+h)\int_0^{\tau_1 Q^*} xf(x)dx \quad (3)$$

Where, $\mu = \int_0^{\infty} xf(x)dx$

3.4. Ordering policy with RFID and corresponding benefits

In this scenario, we consider that the warehouse improves the inventory system by deploying RFID. As per *Assumption 2,* the available portion of the inventory is $\tau_2 = \eta + \phi(1-\eta)$. Due to deployment of RFID, the warehouse incurs unit variable cost r towards cost of tag, fixed set up cost K which includes installation, operation and maintenance cost of the equipment. So the expected overall cost when RFID is deployed is given by

$$C_{RF}(Q_{RF}) = h\int_0^{\tau_2 Q_{RF}} (\tau_2 Q_{RF}-x)f(x)dx + g\int_{\tau_2 Q_{RF}}^{\infty} (x-\tau_2 Q_{RF})f(x)dx + v(1-\eta)(1-\phi)Q_{RF} + Q_{RF}r + \mathrm{K} + \int_{\tau_2 Q_{RF}}^{\infty} \omega t(x-\tau_2 Q_{RF})f(x)dx \tag{4}$$

On the right-hand side of the Eq. (4), the first two terms represent the expected holding cost and the expected expedited cost of procurement respectively when $\tau_2 Q_{RF}$ is the available quantity for distribution. The third term represents the cost of the quantity lost due to shrinkage. As explained earlier, part of the items lost due to shrinkage cannot be recovered in spite of RFID equipment installation. The fourth and fifth terms represent the variable cost (tag cost) and the fixed cost of RFID implementation respectively. The last term represents the deprivation cost. It may be noted that the fifth term being a constant does not affect the optimal order quantity; but, is important while calculating the benefits due to RFID.

Similar to the previous case, the expected total cost is a variation of the newsvendor function hence convex. Thus, with first order condition and some algebraic calculation, the optimal order quantity and corresponding cost in this scenario are derived as follows (See Appendix A.3 and A.4 respectively for details).

$$Q_{RF}^* = \frac{1}{\tau_2}F^{-1}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right] \tag{5}$$

$$C_{RF}(Q_{RF}^*) = K + (g+\omega t)\mu - (g+\omega t+h)\int_0^{\tau_2 Q_{RF}^*} xf(x)dx \tag{6}$$

Since, $Q_{RF}^* > 0$, the tern within the square bracket in Eq. (5) has to be greater than zero which is possible if and only if the tag cost $r < (g+\omega t)\tau_2 - v(1-\eta)(1-\phi)$. The optimal order quantities in the non-RFID and RFID scenarios as obtained in Eqs. (2) and (5) can be compared assuming a specific distribution function $F(\bullet)$. Intuitively, when RFID is implemented, the inventory can be recovered to some extent and the ordering quantity should be less. However, this conclusion may not be true which is further discussed in the next section.

3.5. Optimal policy under uniform distribution of demand

In this section, we assume that the demand follows uniform distributions. Although this seems somewhat restrictive, it allows us to get closed-form solutions for the optimal policy and helps to get managerial insights on the total expected cost with and without RFID, critical tag cost and threshold value of shrinkage recovery rate (Fan et al., 2014; Inderfurth, 2003). To gain analytical insights through closed-form solutions we assume demand is uniformly distributed in an interval $[0,\gamma]$ .Using Eqs. (2) and (5), the closed-form solutions of the optimal policies are

$$Q^* = \frac{\gamma}{\tau_1}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right] \tag{7}$$

and

$$Q_{RF}^* = \frac{\gamma}{\tau_2}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right] \tag{8}$$

Theorem 1. *Under uniformly distributed demand*

(1) Given that the two order quantities $Q_{RF}^*, Q^* > 0$, there exists a threshold value of the shrinkage recovery rate on RFID ϕ_c, such that $Q_{RF}^* \geqslant Q^*$ if and only if $\phi \geqslant \phi_c$ where ϕ_c is given by

$$\phi_c = \frac{\tau_1^2(v+g+\omega t) + \sqrt{\tau_1^4(v+g+\omega t)^2 - 4\tau_1^2(v+r)[(g+\omega t)\tau_1 - h(1-\theta) - v(1-\eta)}}{2(1-\eta)[(g+\omega t)\tau_1 - h(1-\theta) - v(1-\eta)]} - \frac{\eta}{1-\eta}$$

(2) Given $Q_{RF}^*, Q^* > 0$, there also exists a threshold value of RFID tag price r_c such that $Q_{RF}^* \geqslant Q^*$ if and only if $r \leqslant r_c$ where r_c is given by

$$r_c = (g+\omega t)\tau_2 - \frac{\tau_2^2}{\tau_1^2}[(g+\omega t)\tau_1 - h(1-\theta) - v(1-\eta)] - v(1-\eta)(1-\phi)$$

The above theorem states that, as the ability of the RFID tag to recover shrinkage quantity varies, the values of Q_{RF}^* and Q^* become equal at ϕ_c and $Q_{RF}^* \geqslant Q^*$ when $\phi \geqslant \phi_c$. When compared with non-RFID scenario, some of the shrinkage inventories are recovered when RFID is deployed. Hence, one could expect that under improved inventory availability fewer units will be ordered. However, the order quantity is also a function of tag price and increases with decrease in tag price. Therefore, when the tag price goes down below a critical value, it is optimal to order more quantity under RFID technology, which is indicated by Theorem – 1(2). The proof of the Theorem is given in Appendix A.5.The optimal expected costs with and without RFID setting are as follows:

$$C(Q^*) = \frac{(g+\omega t)\gamma}{2} - \frac{(g+\omega t+h)\gamma}{2}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right]^2 \quad (9)$$

$$C_{RF}(Q_{RF}^*) = K + \frac{(g+\omega t)\gamma}{2} - \frac{(g+\omega t+h)\gamma}{2}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right]^2 \quad (10)$$

Similarly, the deprivation cost component with and without RFID at optimal order quantity can be given by Eqs. (12) and (11) respectively

$$DC = \frac{\omega t}{2\gamma}(\gamma - \tau_1 Q^*)^2 \quad (11)$$

$$DC_{RF} = \frac{\omega t}{2\gamma}(\gamma - \tau_2 Q_{RF}^*)^2 \quad (12)$$

Theorem 2. *Under uniformly distributed demand*

(1) There exists a critical value of the shrinkage recovery rate of RFID $\overline{\phi_c}$, such that when $\phi > \overline{\phi_c}$, $C_{RF}(Q_{RF}^*) < C(Q^*)$, where $\overline{\phi_c}$ is given by

$$\overline{\phi_c} = \frac{(v+r)}{z(g+\omega t+h)(1-\eta)}\left[\sqrt{\left(\frac{g+\omega t+v}{g+\omega t+h}\right)^2 + z} - \frac{g+\omega t+v}{g+\omega t+h}\right] - \frac{\eta}{1-\eta},$$

where $z = \left[\frac{g+\omega t}{g+\omega t+h} - \frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right]^2 + \frac{2k}{\gamma(g+\omega t+h)} - \left(\frac{g+\omega t+v}{g+\omega t+h}\right)^2$

(2) For a given value of K, there exists a threshold value of RFID tag price $\bar{r}_c$, such that when $r \leqslant \bar{r}_c$, $C_{RF}(Q_{RF}^*) < C(Q^*)$,where $\bar{r}_c$ is given by

$$\bar{r}_c = (g+\omega t)\tau_2 - v(1-\eta)(1-\phi) - \tau_2(g+\omega t+h)\sqrt{\frac{2k}{\gamma(g+\omega t+h)} + \left[\frac{g+\omega t}{g+\omega t+h} - \frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right]^2}$$

(3) For a given value of r, there exists a threshold value of RFID fixed setup cost $\overline{K}$,such that when $K < \overline{K}$, $C_{RF}(Q_{RF}^*) < C(Q^*)$ where $\overline{K}$ is given by

$$\overline{K} = \frac{(g+\omega t+h)\gamma}{2}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right]^2 - \frac{(g+\omega t+h)\gamma}{2}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right]^2$$

The proof of the above Theorem is given in Appendix A.6. Theorem 2(1) provides a threshold value of the shrinkage recovery rate (ϕ) with RFID beyond which the warehouse manager could further decrease cost by deploying RFID. The first part of Theorem 2(2) states that, the investment in RFID is viable if the tag price is less than a critical value ($\bar{r}_c$). For a given tag price r, it is beneficial to invest in RFID if and only if the fixed cost is less than $\overline{K}$ which is indicated in part (b) of Theorem 2(2).

4. Numerical illustration: the case of Warehousing in Indian food security system

4.1. The Public distribution system (PDS) of India

In India, the Targeted Public Distribution System (TPDS) is the backbone for ensuring food security to the poor (Khera, 2011). Essential commodities like Rice, Wheat, Pulses, and the like are supplied to approximately 180 million families at subsidized prices. After implementation of National Food Security Act (NFSA) 2013, the system guarantees food for two-thirds of the population with an estimated annual cost in the range of INR 950 billion to INR 1120 billion (Balani, 2013). Although TPDS has shown some progress towards poverty alleviation, the inefficiency in the system is one of the leading causes of concern. It suffers from problems like resource wastage, corruption, leakage and non-transparency (Kumar, 2015). As per a recent report, to transfer the goods worth one Indian rupee (INR) to a beneficiary, the government is spending INR 3.65 (Commission, 2005). A similar study estimates leakages at more than 40 percent at all India level (Drèze and Khera, 2015; Gulati and Saini, 2015). Rotting of food grains, stealing, quality degradation, misplacement, and overstocking at the warehouses are some of the many malaises, which are contributing to the losses.

A schematic diagram of PDS supply chain is shown in Fig. 1. The grains are first collected from farmers either directly or through procurement agency at a minimum support price (MSP) decided by the government every year. This price is decided considering many factors such as cost of production, input output price parity, market conditions and so on. Government designated procurement agencies bring the food grains to warehouses directly under central government. Depending on the demand and supply conditions the grains are further distributed to state owned warehouses for distribution to the beneficiaries through fair-price shops (Balani, 2013). Warehouse constitutes a very important element of this supply chain because food grains are stored at each stage starting from

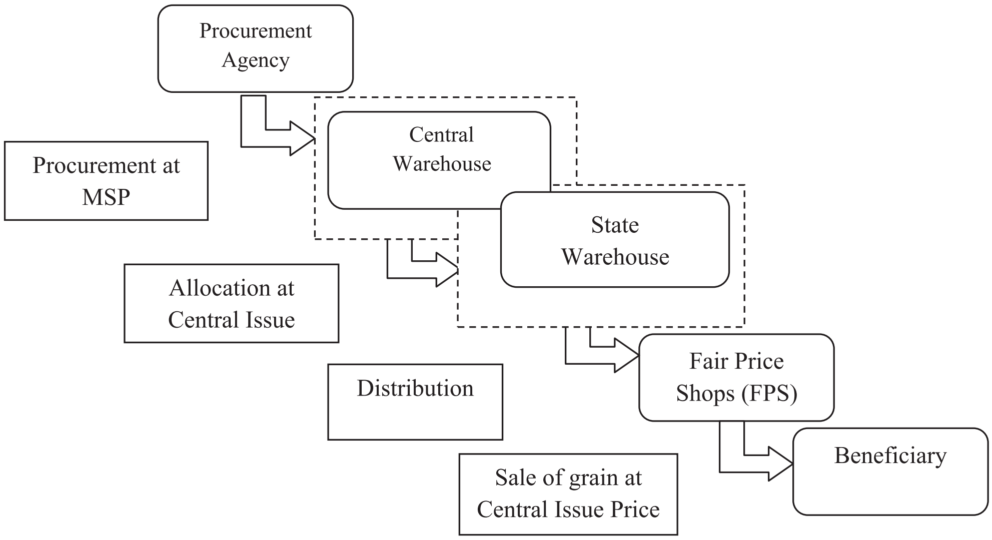

Fig. 1. Warehouses in PDS supply chain.

procurement to the final distribution to the end beneficiary. However, a major portion of the loss happens during storage at the warehouse level through pilferage, and spoilage due to non adherence to First In First Out (FIFO) principle (CAG, 2013). In case, the shrinkage and misplacement of stocks gets reconciled on real-time basis, loss due to inventory inaccuracy in the supply chain can be avoided up to some extent. Though, the procurement and distribution is the responsibility of the *Department of Food and Public Distribution* (dfpd.nic.in), the warehouses are owned by *Central Warehousing Corporation*, *State Warehousing Corporations* and many private agencies; which makes the centralized monitoring quite complicated. Currently, the system is manually monitored and stock data need to be updated in a centralized information system from time to time. As a result, real time stock monitoring is not possible. While based on the suggestion of a high level committee to introduce a completely automated system with minimal human intervention to prevent leakages and other losses in this supply chain (Committee, 2009) and huge amount of investment to realize this (DFPD, 2016), RFID is never considered as a viable technology for online monitoring of the warehouses. This may be due to the fear of high cost. In the following section we apply the proposed model to explore the possibility of RFID adoption in the PDS warehouse.

4.2. A proposal for RFID adoption in warehouses

The various processes concerning the material flow at different level of the PDS supply chain is depicted in Fig. 2. We want to address the problem of inventory inaccuracy by using RFID at the warehouse level. The warehouse may be either central government controlled or state government controlled as shown through the dotted lines in Fig. 1.Grain packets may be suitably tagged by the procurement agency before being dispatched to the warehouse where it is received and stored to meet the demand from the beneficiaries. The basic components and working mechanism of the RFID system is shown in Fig. 3. The RFID antenna shown in the figure is embedded in the entry gate to the warehouse. Whenever a tagged item like grain packet passes through the RFID gate, it gets detected, and the information system record is updated accordingly on real time basis. During storage inside the warehouse, the inventory shrinkage and misplacement can easily be tracked by frequently reconciling the stock through portable handheld RFID

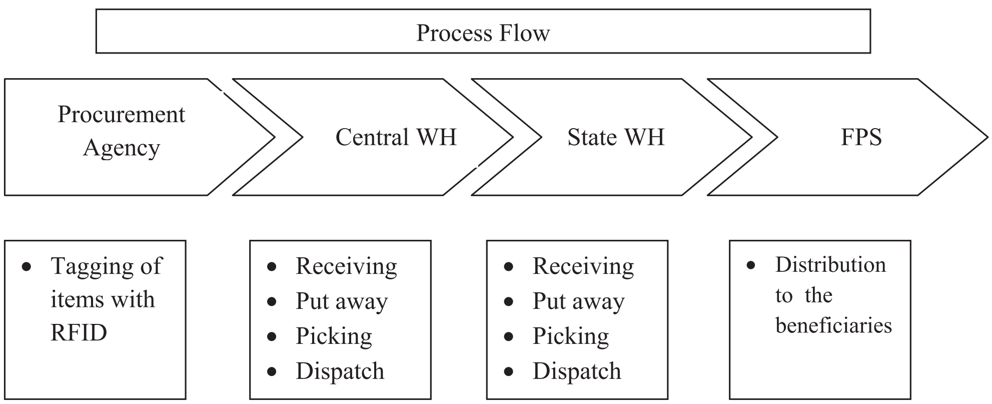

Fig. 2. Process Flow in the PDS supply chain.

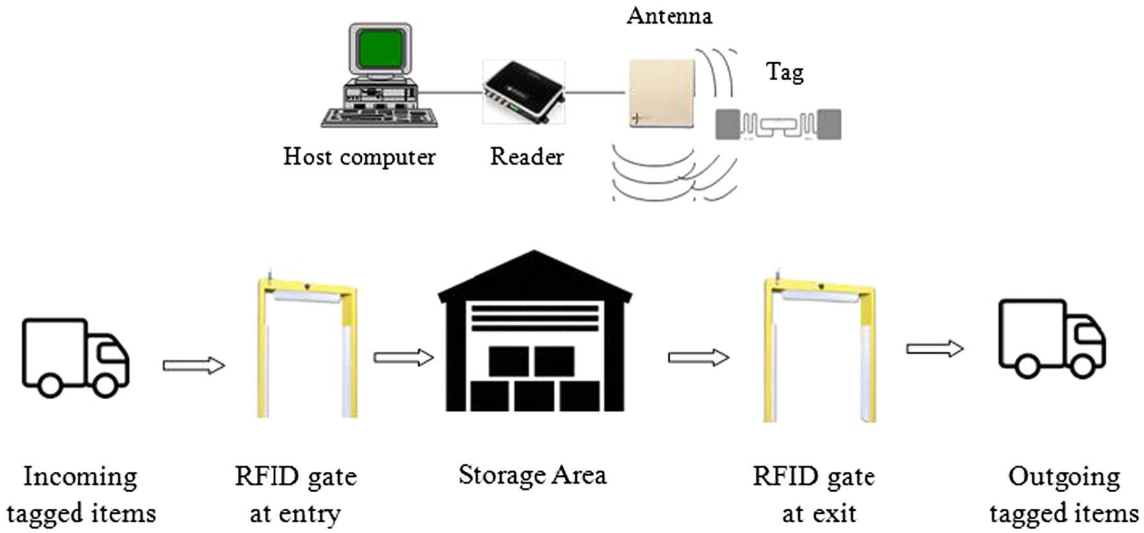

Fig. 3. The proposed RFID systems.

readers or by suitably placing fixed-position RFID readers to cover the entire storage area. We consider the handheld reader scenario while assuming the fixed cost of RFID implementation in our numerical analysis. We further consider that the variable cost (tag cost) and fixed cost of RFID implementation is incurred by the warehouse only.

4.3. The data

We collected data from various reports available from government website, interaction with various stakeholders during several field visits to the warehouses operational under the food security scheme and vendors dealing with RFID equipment in India. We include some of the photographs of our Warehouse visit as Appendix B. The standard SKU available in the warehouse is a 50 kg gunny bag, which is suitable for tagging. Considering the acquisition cost of rice as INR 2410 per quintal and carrying cost of INR 474 per quintal (Kumar, 2015), we set the purchase cost $v = 1205$ and holding cost $h = 474$. We consider that excess demand is back logged and resolved through emergency procurement. We set the range for additional expenditure per unit item due to expedited procurement as twenty percent of the normal purchase cost (v) considering practical scenario ($g = 241$ INR). This is because of the higher material cost and logistic cost during emergency procurement. It is extremely difficult to accurately estimate the deprivation cost per unit time. In regulatory environment, this cost can be interpreted as the compensation paid to the beneficiaries per unit delay time. However in extreme cases, non-availability of food grains in time may cost the human life. So we assign a range (20–2000 INR) and set the upper limit of the deprivation factor comparatively high for doing sensitivity analysis. The time to replenish one backlogged item can be attributed to the time associated with the procurement lead time, processing, locating, retrieving from the warehouse and packaging for shipment. We assume the time to replenish one backlogged item as one day ($t = 1$). Considering the physical condition to which the RFID tag would be exposed during storage and handling in the warehouse, we set the RFID tag price $r = 45$ INR, which is the market price of a laminated tag not prone to damage during material handling process. Warehouses operating under Public Distribution System are generally tagged to cater to certain geographical areas based on the capacity of the warehouse and the number of eligible beneficiaries under that area. So the maximum demand at the warehouse is a finite quantity and cannot be more than a certain value. The data (DFPD, 2017) also suggest that, off-take range varies from zero to the maximum allocation quantity which is a finite value. So this better suits to our earlier assumption of uniformly distributed demand in the model.

The capacity of the six types of warehouses approved by FCI and Central Warehousing Corporation (CWC) is in the range of 5000–50,000 MT (FCI, 2016). Therefore, while assuming the demand as uniformly distributed, we fix the upper bound (γ) to 50,000 MT for evaluating the possibility of implementing RFID in all six types of warehouses. The values of various parameters collected are shown in Table 3.

4.4. Analysis of available rate of ordering

The comparison of the optimal order quantities with and without RFID, as a function of shrinkage and misplacement is shown in Fig. 4. First, we can observe that there exists a critical line, indexed by (η^*,θ^*); if the value of $\eta(\theta)$ is larger than $\eta^*(\theta^*)$, the order quantity without RFID is greater than that of the RFID situation. This is consistent with the findings of Fan et al. (2015) where they investigated the performance of order quantities in a profit maximization scenario. Keeping the other parameters unchanged, as the value of η increases, the difference between the two order quantities decreases and converges to zero when $\eta = \eta^*$. The inference we can draw from this is, at low value of available rate of ordering, the order quantity with RFID is more than that of the non-RFID case.

Table 3
Model parameters.

Parameter	Value
Weight of a rice bag	50 kg
Procurement cost per bag (v)	1205 INR
Holding cost per bag (h)	478 INR
Expedited procurement cost per bag (g)	241 INR
Deprivation cost factor (ω)	20–2000 INR
Time to replenish one back logged item (t)	1 day
Warehouse capacity (γ)	5000–50000 MT
RFID Tag Price (r)	45 INR
Shrinkage recovery rate (ϕ)	0.6–0.9
Shrinkage rate (η)	3–5%
Misplacement rate (θ)	2–4%
Fixed cost (K)	1,200,000 INR

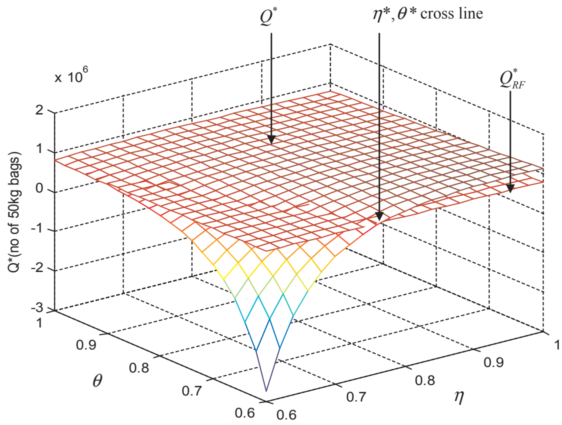

Fig. 4. Comparison of Q^* and Q^*_{RF} with respect to changes in $\eta and \theta$.

One possible reason for this could be, at very high level of misplacement and shrinkage, the cost of unrecovered inventories is more than the cost incurred due to unsatisfied demand.

The sensitivity analysis on the impact of changes in η and θ on the optimal cost under both RFID and non-RFID scenario is shown in Fig. 5. Similar to the earlier case, there exists a critical line indexed by η^*,θ^* such that the optimal cost under both the scenarios is equal. From the figure, we observe that the optimal cost with RFID is lower than that of non-RFID scenario until the value of shrinkage and misplacement recovery rate reach the critical value (η^*,θ^*). In other words, we can say that, as long as the total loss proportion including shrinkage and misplacement is more than $[(1-\eta^*) + (1-\theta^*)]$, it is beneficial to implement RFID. In case of public distribution system this total loss is approximately 5% as can be observed from Fig. 5. Below this, the fixed costs of RFID implementation along with tag costs outweigh the cost saving attributable to reduced shrinkage and accurate inventory records.

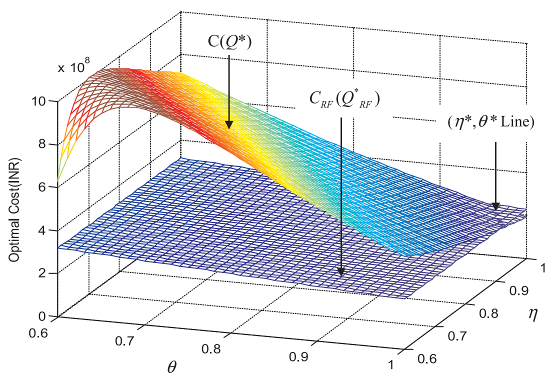

Fig. 5. Comparison of $C(Q^*)$ and $C_{RF}(Q^*_{RF})$ with respect to changes in $\eta and \theta$.

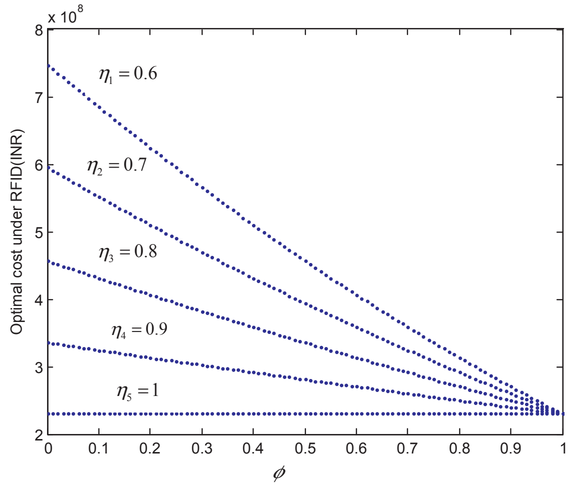

Fig. 6. $C_{RF}(Q_{RF}^*)$ with changes in ϕ for different η.

4.5. Analysis of RFID read rate improvement

Using Eq. (10), we derive the impact of RFID read rate improvement on optimal expected cost. In Fig. 6, we notice that the optimal expected cost is a decreasing function in RFID read rate improvement. This implies, greater the ability of the RFID tag to detect pilferage and theft, the more beneficial it is to implement RFID.

Further, we can observe that, the difference between optimal costs at different values of available rate of ordering converges with improvement in RFID read rate.

4.6. Analysis of RFID tag price

We propose an analytical critical tag cost at which the optimal cost with and without RFID becomes equal and we derive this critical value ($\bar{r}_c$). Any price of the tag below this threshold value makes the RFID system beneficial as compared to the non-RFID system. In Fig. 7, we demonstrate the effect of available rate of ordering (η) and shrinkage recovery rate (ϕ) on critical tag price ($\bar{r}_c$). As it can be observed, the threshold value of RFID tag price is decreasing with the available rate of ordering and increasing with the shrinkage recovery rate. This is because, the cost saving due to RFID is more when the shrinkage proportion ($1-\eta$) before RFID implementation is high in the warehouses and this allows a higher critical tag price. Similarly, higher shrinkage recovery rate implies better ability of the RFID tag to detect pilferage and spoilage; hence the system is viable at higher tag price. The general perception is that, RFID is viable at lower tag price, but we show that it also depends on other factors like the existing loss in the system and the ability of the RFID tag to recover the shrinkage.

The sensitivity analysis of the critical tag price with respect to the deprivation cost factor is shown in Fig. 8 and Table 4 above. As can be observed, the critical tag price is more sensitive to changes in deprivation cost factor (ω) in the beginning and for higher value of ω, it is almost constant. So it can be interpreted that, the marginal benefit of RFID deployment is more when the deprivation cost is

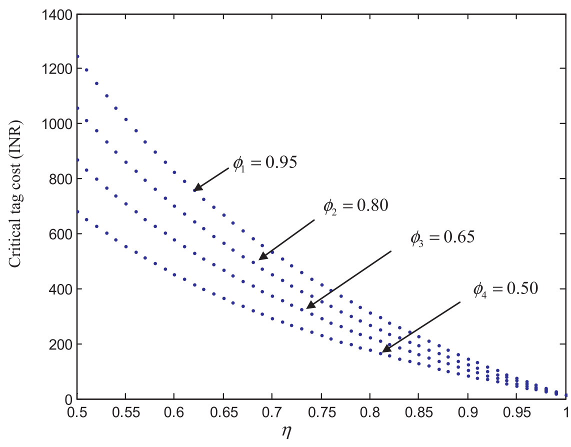

Fig. 7. $\bar{r}_c$ with changes in η for different value of ϕ.

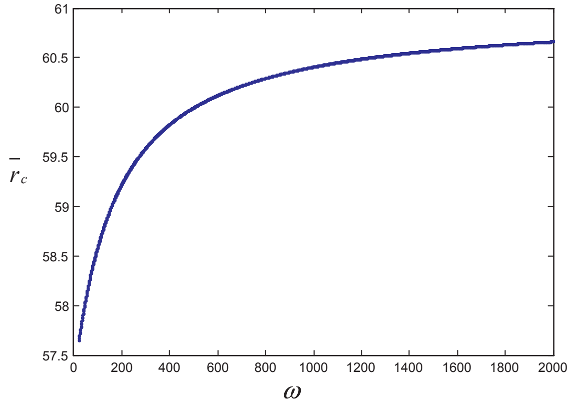

Fig. 8. $\bar{r}_c$ with changes in ω.

Table 4
Values of $\bar{r}_c$ at different ω.

(ω)	($\bar{r}_c$)
20	57.65
200	59.23
400	59.83
600	60.12
800	60.29
1000	60.40
1200	60.48
1400	60.54
1600	60.59
1800	60.63
2000	60.66

low. This is because at higher value of ω, the cost saving from shrinkage and misplacement reduction is outweighed by the deprivation cost.

4.7. Analysis of deprivation costs with and without RFID

The comparison of the deprivation cost with and without RFID, as a function of shrinkage and misplacement is shown in Fig. 9. At higher level of misplacement and shrinkage (lower η and θ) the deprivation cost with RFID is less than that of the non-RFID situation. Further we can observe that, there exists a critical line, indexed by (η_1^*,θ_1^*); if the value of $\eta(\theta)$ is lower than η_1^*,(θ_1^*), the deprivation cost with RFID is less than that of the non-RFID situation. However, beyond (η_1^*,θ_1^*), the trend is reversed and deprivation cost is more

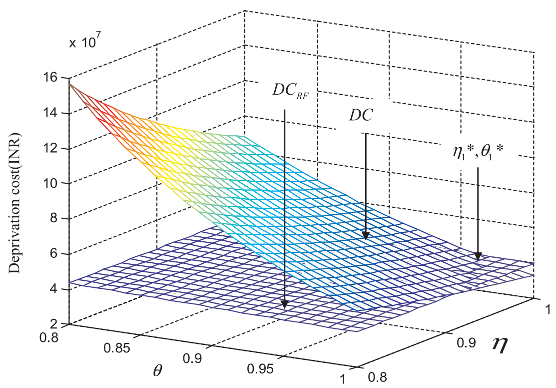

Fig. 9. Comparison of DC and DC_{RF} with respect to changes in $\eta and \theta$.

with RFID. Referring to the mathematical expressions (Eqs. (11) and (12)), the deprivation cost with RFID will reduce ($DC_R \leqslant DC$) only when the net available quantity for distribution with RFID is greater than that of the non-RFID situation i.e. $\tau_2 Q^*_{RF} \geqslant \tau_1 Q^*$. However, as the inventory control policy follows the optimal order quantity based on the overall cost, this situation may not always arise. As depicted though Fig. 4, beyond a certain level, the optimal order quantity with RFID is less than that of the non-RFID situation and hence it affects the net available quantity for distribution.

5. Policy suggestion for TPDS

In the year 2009, the Justice Wadhwa Committee, formed by the Indian government, submitted its report on the end-to-end computerisation of the TPDS operations. They considered the possibility of attaching RFID tags at the packet level for tracking the stock on real time basis. Although there was no mathematical model to validate the claim, the committee was of the opinion that, RFID technology would be too expensive to implement at the packet level.

However, in recent years, the price of the RFID tags and other related system equipment like Readers, Antennas has come down substantially due to rapid advancement in the field of microelectronics. Accordingly, the variable and fixed cost of RFID implementation has come to the acceptable level. Through our mathematical model, we quantify the benefit and show that, for a shrinkage loss of 4% and misplacement of 3% at the warehouse, RFID is beneficial as long as the tag cost is below **INR 57.65** assuming a deprivation factor of INR 200. With the same level of shrinkage and misplacement, for a warehouse of capacity 50,000 MT, the expected savings will be approximately INR **2.7** million in a single season.

Although RFID technology can improve the efficiency in Food Security System, there may arise some potential issues. Employee resistance to changes in already existing system could be a barrier to its implementation. Moreover, it is very difficult for employees to turn off traditional methods of working and learn new ones. This may require formal change management process and adequate amount of training to the employees. In the warehouses used by FCI, CWC and SWC, 50 kg rice bags are vertically stored in rectangular stacks. Under such situations, positioning the optimal numbers of fixed RFID readers and antennas in the existing warehouses to read all the tagged rice bags could be a challenge. However, as we suggest, using handheld readers to cover the storage area could be a solution to this problem. RFID technology uses radio spectrum for signal transmission and is prone to interference from other radio frequency (RF) objects. Presence of metals, liquid and moisture in the storage area could lead to false read and might provide wrong information. Privacy and security of data is also an issue because, RFID can be read by unauthorized entities. Trained personnel and help of private companies that are familiar with the technology could minimize these problems.

Our estimation on cost savings is conservative and can be taken as a lower bound. Packet level RFID tagging has the potential to decrease the loss happening beyond the warehouse. Also in a multi-period scenario, the fixed cost of RFID implementation will be shared over the time horizon. Designing a suitable mechanism to reuse the RFID tags can further reduce the effective tag cost. All the above factors if taken into account will only strengthen the case in favour of RFID implementation in the food security system.

6. Conclusion

In this paper, we study the benefits of RFID to reduce inefficiency in the supply chain attributable to inventory shrinkage and misplacement under a non-profit scenario. We jointly consider misplacement and shrinkage in an improved newsvendor model to analyze its effect on the optimal order quantity and total expected cost. We incorporate deprivation cost in the objective function to account for the human suffering due to delay in delivery of critical items. We consider two scenarios for our analysis. In the first case, the warehouse manager optimizes its operations only acknowledging the inventory inaccuracy in the system. In the second scenario, the manager improves the system by investing in RFID technology along with theft preventing auxiliary equipment. Assuming demand as uniformly distributed, we compare the expected operational costs with/without RFID and derive an analytical critical tag cost for RFID deployment to be viable. Finally, in our numerical analysis we apply our model to the warehouse operating under Indian food security system and analyze the impact of available rate of ordering, shrinkage recovery rate and tag price by using actual data.

We find that the cost saving by deploying RFID in a warehouse depends on the available rate of ordering and the tag price. Lower the value of available rate of ordering and the tag price from a threshold value, more beneficial it is to invest in RFID. The optimal expected cost with system under RFID is a decreasing function of read rate improvement. This implies the effectiveness of the RFID system to prevent possible theft and spoilage of inventory is a deciding factor to the overall cost. We also observe that the marginal benefit of RFID deployment is more when the deprivation cost factor is low. This is because at higher value of the deprivation factor, increase in the deprivation cost outweighs the benefit from RFID. Contrary to the general belief that investment in RFID is not justified under higher tag cost, our analysis shows, when shrinkage and misplacement are severe; RFID creates value even at higher tag price.

Although we get meaningful insights from the model, there are limitations which give opportunities for future research. We assume that deprivation cost is a linear function of deprivation time only. It will be interesting to consider deprivation cost as nonlinear and a function of deprivation time and socio-economic characteristic of the beneficiary (like age, gender, income, physical condition). Although there are many sources of inventory inaccuracy, we consider only shrinkage and misplacement in the model. Our model can be extended to incorporate other types of errors like transactions error and ticket switching. Further we assume that, the warehouse owner bears the entire cost of RFID implementation. Future work may consider a suitable cost sharing mechanism among the supply chain partners. We model inventory inaccuracy and quantify the benefit of RFID under a single period newsvendor framework in a non profit scenario. The problem can be extended to multi-echelon supply chain in a multi-period scenario.

Appendix A

A.1. Derivations of Eq. (2)

$$C(Q) = h\int_0^{\tau_1 Q}(\tau_1 Q-x)f(x)dx + (g+\omega t)\int_{\tau_1 Q}^{\infty}(x-\tau_1 Q)f(x)dx + h(1-\theta)Q + v(1-\eta)Q \tag{1}$$

Differentiating $C(Q)$ wrt Q by applying Leibniz rule and equating it to zero we get, $h\int_0^{\tau_1 Q}\frac{\partial}{\partial Q}(\tau_1 Q-x)f(x)dx + (g+\omega t)\int_{\tau_1 Q}^{\infty}\frac{\partial}{\partial Q}(x-\tau_1 Q)f(x)dx + h(1-\theta) + v(1-\eta) = 0$

$$\Rightarrow h\tau_1\int_0^{\tau_1 Q}f(x)dx-(g+\omega t)\tau_1\int_{\tau_1 Q}^{\infty}f(x)dx + h(1-\theta) + v(1-\eta) = 0$$

$$\Rightarrow h\tau_1\int_0^{\tau_1 Q}f(x)dx-(g+\omega t)\tau_1[1-\int_0^{\tau_1 Q}f(x)dx] + h(1-\theta) + v(1-\eta) = 0$$

$$\Rightarrow [h\tau_1 + (g+\omega t)\tau_1]\int_0^{\tau_1 Q}f(x)dx-(g+\omega t)\tau_1 + h(1-\theta) + v(1-\eta) = 0$$

$$\Rightarrow \tau_1(g+\omega t+h)\int_0^{\tau_1 Q}f(x)dx = (g+\omega t)\tau_1-h(1-\theta)-v(1-\eta)$$

$$\Rightarrow \int_0^{\tau_1 Q}f(x)dx = \frac{g+\omega t}{g+\omega t+h}-\frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}$$

$$\Rightarrow F(\tau_1 Q) = \frac{g+\omega t}{g+\omega t+h}-\frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}$$

$$\Rightarrow \tau_1 Q = F^{-1}\left[\frac{g+\omega t}{g+\omega t+h}-\frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right]$$

$$Q^* = \frac{1}{\tau_1}F^{-1}\left[\frac{g+\omega t}{g+\omega t+h}-\frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right] \tag{2}$$

A.2. Derivations of Eq. (3)

The cost function without implementing RFID is given by

$$C(Q) = h\int_0^{\tau_1 Q}(\tau_1 Q-x)f(x)dx + (g+\omega t)\int_{\tau_1 Q}^{\infty}(x-\tau_1 Q)f(x)dx + h(1-\theta)Q + v(1-\eta)Q$$

At optimal order quantity Q^*, the cost is:

$$C(Q^*) = h\int_0^{\tau_1 Q^*}(\tau_1 Q^*-x)f(x)dx + (g+\omega t)\int_{\tau_1 Q^*}^{\infty}(x-\tau_1 Q^*)f(x)dx + h(1-\theta)Q^* + v(1-\eta)Q^*$$

$$= h\tau_1 Q^*\int_0^{\tau_1 Q^*}f(x)dx-h\int_0^{\tau_1 Q^*}xf(x)dx + (g+\omega t)\int_{\tau_1 Q^*}^{\infty}xf(x)dx-(g+\omega t)\tau_1 Q^*\int_{\tau_1 Q^*}^{\infty}f(x)dx + h(1-\theta)Q^* + v(1-\eta)Q^*$$

$$= h\tau_1 Q^* F(\tau_1 Q^*)-h\int_0^{\tau_1 Q^*}xf(x)dx + (g+\omega t)\int_{\tau_1 Q^*}^{\infty}xf(x)dx-(g+\omega t)\tau_1 Q^*(1-F(\tau_1 Q^*)) + h(1-\theta)Q^* + v(1-\eta)Q^*$$

$$= \tau_1(h+g+\omega t)Q^* F(\tau_1 Q^*)-h\int_0^{\tau_1 Q^*}xf(x)dx + (g+\omega t)\int_{\tau_1 Q^*}^{\infty}xf(x)dx-(g+\omega t)\tau_1 Q^* + h(1-\theta)Q^* + v(1-\eta)Q^*$$

Substituting the value of $F(\tau_1 Q^*)$ as derived earlier, we get,

$$C(Q^*) = \tau_1(h+g+\omega t)Q^*\left(\frac{g+\omega t}{g+\omega t+h}-\frac{h(1-\theta)+v(1-\eta)}{\tau_1(g+\omega t+h)}\right)-h\int_0^{\tau_1 Q^*}xf(x)dx + (g+\omega t)\int_{\tau_1 Q^*}^{\infty}xf(x)dx-(g+\omega t)\tau_1 Q^*$$
$$+ h(1-\theta)Q^* + v(1-\eta)Q^*$$

Except the second and third terms, all others cancel out. So the optimal cost is given by

$$C(Q^*) = -h\int_0^{\tau_1 Q^*} xf(x)dx + (g+\omega t)\int_{\tau_1 Q^*}^{\infty} xf(x)dx$$

$$= -h\int_0^{\tau_1 Q^*} xf(x)dx + \left((g+\omega t)\int_{\tau_1 Q^*}^{\infty} xf(x)dx + (g+\omega t)\int_0^{\tau_1 Q^*} xf(x)dx\right) - (g+\omega t)\int_0^{\tau_1 Q^*} xf(x)dx$$

$$\Rightarrow C(Q^*) = (g+\omega t)\mu - (g+\omega t+h)\int_0^{\tau_1 Q^*} xf(x)dx \tag{3}$$

A.3. Derivations of Eq. (5)

When RFID is implemented, the cost function is given

$$C_{RF}(Q_{RF}) = h\int_0^{\tau_2 Q_{RF}} (\tau_2 Q_{RF}-x)f(x)dx + (g+\omega t)\int_{\tau_2 Q_{RF}}^{\infty} (x-\tau_2 Q_{RF})f(x)dx + v(1-\eta)(1-\phi)Q_{RF} + Q_{RF}r + \mathrm{K} \tag{4}$$

Differentiating wrt Q_{RF} and equating it to zero, we get

$$h\int_0^{\tau_2 Q_{RF}} \frac{\partial}{\partial Q_{RF}}(\tau_2 Q_{RF}-x)f(x)dx + (g+\omega t)\int_{\tau_2 Q_{RF}}^{\infty} \frac{\partial}{\partial Q_{RF}}(x-\tau_2 Q_{RF})f(x)dx + v(1-\eta)(1-\phi) + r = 0$$

$$\Rightarrow h\tau_2\int_0^{\tau_2 Q_{RF}} f(x)dx - (g+\omega t)\tau_2\int_{\tau_2 Q_{RF}}^{\infty} f(x)dx + v(1-\eta)(1-\phi) + r = 0$$

$$\Rightarrow h\tau_2\int_0^{\tau_2 Q_{RF}} f(x)dx - (g+\omega t)\tau_2\left(1-\int_0^{\tau_2 Q_{RF}} f(x)dx\right) + v(1-\eta)(1-\phi) + r = 0$$

$$\Rightarrow (h+g+\omega t)\tau_2\int_0^{\tau_2 Q_{RF}} f(x)dx - (g+\omega t)\tau_2 + v(1-\eta)(1-\phi) + r = 0$$

$$\Rightarrow (h+g+\omega t)\tau_2\int_0^{\tau_2 Q_{RF}} f(x)dx = (g+\omega t)\tau_2 - v(1-\eta)(1-\phi) - r$$

$$\Rightarrow \tau_2 Q_{RF} = F^{-1}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right]$$

$$\Rightarrow Q^*_{RF} = \frac{1}{\tau_2}F^{-1}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right] \tag{5}$$

A.4. Derivations of Eq. (6)

At Q^*_{RF} the optimal cost with RFID is given by

$$C_{RF}(Q^*_{RF}) = h\int_0^{\tau_2 Q^*_{RF}} (\tau_2 Q^*_{RF}-x)f(x)dx + (g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} (x-\tau_2 Q^*_{RF})f(x)dx + v(1-\eta)(1-\phi)Q^*_{RF} + Q^*_{RF}r + \mathrm{K}$$

$$= h\tau_2 Q^*_{RF}\int_0^{\tau_2 Q^*_{RF}} f(x)dx - h\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + (g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} xf(x)dx - (g+\omega t)\tau_2 Q^*_{RF}\int_{\tau_2 Q^*_{RF}}^{\infty} f(x)dx + v(1-\eta)(1-\phi)Q^*_{RF} + Q^*_{RF}r + \mathrm{K}$$

$$= h\tau_2 Q^*_{RF}F(\tau_2 Q^*_{RF}) - h\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + (g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} xf(x)dx - (g+\omega t)\tau_2 Q^*_{RF}(1-F(\tau_2 Q^*_{RF})) + v(1-\eta)(1-\phi)Q^*_{RF} + Q^*_{RF}r + \mathrm{K}$$

$$= \tau_2(g+\omega t+h)Q^*_{RF}F(\tau_2 Q^*_{RF}) - h\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + (g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} xf(x)dx - (g+\omega t)\tau_2 Q^*_{RF} + v(1-\eta)(1-\phi)Q^*_{RF} + Q^*_{RF}r + \mathrm{K}$$

$$= \tau_2(g+\omega t+h)Q^*_{RF}\left[\frac{g+\omega t}{g+\omega t+h} - \frac{v(1-\eta)(1-\phi)+r}{\tau_2(g+\omega t+h)}\right] - h\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + (g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} xf(x)dx - (g+\omega t)\tau_2 Q^*_{RF} + v(1-\eta)(1-\phi)Q^*_{RF} + Q^*_{RF}r + \mathrm{K}$$

$$= -h\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + \left((g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} xf(x)dx + (g+\omega t)\int_0^{\tau_2 Q^*_{RF}} xf(x)dx\right) - (g+\omega t)\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + \mathrm{K}$$

$$= -h\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + \left((g+\omega t)\int_{\tau_2 Q^*_{RF}}^{\infty} xf(x)dx + (g+\omega t)\int_0^{\tau_2 Q^*_{RF}} xf(x)dx\right) - (g+\omega t)\int_0^{\tau_2 Q^*_{RF}} xf(x)dx + \mathrm{K}$$

$$\Rightarrow C_{RF}(Q_{RF}^{*}) = K + (g + \omega t)\mu - (g + \omega t + h)\int_{0}^{\tau_2 Q_{RF}^{*}} xf(x)dx \tag{6}$$

A.5. Proof of Theorem 1

(1) The difference of $Q_{RF}^{*} - Q^{*}$ is decreasing in ϕ and when $Q_{RF}^{*} = Q^{*}$, we get the threshold value of the shrinkage recovery rate as

$$\phi_c = \frac{\tau_1^2(v + g + \omega t) + \sqrt{\tau_1^4(v + g + \omega t)^2 - 4\tau_1^2(v + r)[(g + \omega t)\tau_1 - h(1-\theta) - v(1-\eta)}}{2(1-\eta)[(g + \omega t)\tau_1 - h(1-\theta) - v(1-\eta)]} - \frac{\eta}{1-\eta}$$

(2) When $Q_{RF}^{*} = Q^{*}$, we can calculate the threshold value of RFID tag price

$$(r_c = (g + \omega t)\tau_2 - \frac{\tau_2^2}{\tau_1^2}[(g + \omega t)\tau_1 - h(1-\theta) - v(1-\eta)] - v(1-\eta)(1-\phi)$$

A.6. Proof of Theorem 2

(1) When $C_{RF}(Q_{RF}^{*}) = C(Q^{*})$,from Eqs. (9) and (10), we can get the threshold value of shrinkage recovery rate,

$$\overline{\phi}_c = \frac{(v + r)}{z(g + \omega t + h)(1-\eta)}\left[\sqrt{\left(\frac{g + \omega t + v}{g + \omega t + h}\right)^2 + z} - \frac{g + \omega t + v}{g + \omega t + h}\right] - \frac{\eta}{1-\eta}, \text{ where}$$

$$z = \left[\frac{g + \omega t}{g + \omega t + h} - \frac{h(1-\theta) + v(1-\eta)}{\tau_1(g + \omega t + h)}\right]^2 + \frac{2k}{\gamma(g + \omega t + h)} - \left(\frac{g + \omega t + v}{g + \omega t + h}\right)^2$$

(2) a. When $C_{RF}(Q_{RF}^{*}) = C(Q^{*})$, we get a threshold value of RFID tag price $\overline{r}_c$ as

$$\overline{r}_c = (g + \omega t)\tau_2 - v(1-\eta)(1-\phi) - \tau_2(g + \omega t + h)\sqrt{\frac{2k}{\gamma(g + \omega t + h)} + \left[\frac{g + \omega t}{g + \omega t + h} - \frac{h(1-\theta) + v(1-\eta)}{\tau_1(g + \omega t + h)}\right]^2}$$

b. By equating $C_{RF}(Q_{RF}^{*})$ and $C(Q^{*})$, we get the threshold value of RFID fixed cost $\overline{K}$ as

$$\overline{K} = \frac{(g + \omega t + h)\gamma}{2}\left[\frac{g + \omega t}{g + \omega t + h} - \frac{v(1-\eta)(1-\phi) + r}{\tau_2(g + \omega t + h)}\right]^2 - \frac{(g + \omega t + h)\gamma}{2}\left[\frac{g + \omega t}{g + \omega t + h} - \frac{h(1-\theta) + v(1-\eta)}{\tau_1(g + \omega t + h)}\right]^2$$

Appendix B

(See Figs. B1–B4).

Fig. B1. Warehouse for Sugar.

Fig. B2. Dedicated Warehouse for Rice.

Fig. B3. Stacking of Sugar in Warehouse.

Fig. B4. Interaction during warehouse visit.

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