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Item-Level RFID in the Retail Supply Chain

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Analyzing the proliferation of item-level RFID, recent studies have identified the cost sharing of the technology as a gating issue. Various qualitative studies have predicted that conflict will arise, in particular in decentralized supply chains, from the fact that the benefits and the costs resulting from item-level RFID are not symmetrically distributed among supply chain partners. To contribute to a better understanding of this situation, we consider a supply chain with one manufacturer and one retailer. Within the context of this retail supply chain, we present analytic models of the benefits of item-level RFID to both supply chain partners. We examine both the case of a dominant manufacturer as well as the case of a dominant retailer, and we analyze the results of an introduction of item-level RFID to such a supply chain depending on these market power characteristics. Under each scenario, we show how the cost of item-level RFID should be allocated among supply chain partners such that supply chain profit is optimized.

Key words: RFID; item-level; retail; supply chain; cost sharing
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1. Introduction

1.1. RFID Technology

Radio-frequency identification (RFID) is a sensor technology that has attracted much attention in the supply chain arena. It is based on so-called smart tags, which are essentially transponders that can be affixed to a variety of surfaces on spare parts, entire products, containers, or any kind of equipment. The tag contains a small computer chip[1] that can hold a certain amount of data. The tag broadcasts the data (a unique serial number, for example) contained in the chip when it is close to a smart tag reader device. This contactless data communication method is known as radio-frequency identification. In contrast to barcode scanning, RFID does not require line of sight between the tag and the reader. For supply chain management, RFID holds much promise because this technology can be used to automatically identify items flowing through the channel. The identification information can then be used to enable complete tracking of an item, thus potentially creating complete visibility of item progress through manufacturing, distribution, storage and inventory, and retail environments. This information, in turn, can be used to streamline supply chain operations.

In this research, we focus on the case of product- or item-level RFID in the retail supply chain. Item-level RFID promises some unique benefits for the retail supply chain; moreover, the retail industry has traditionally played an early-adopter role, for example, when bar code technology was introduced.

1.2. Implementation and Adoption Dilemma

Although a number of major companies (e.g., Wal-Mart, Tesco, Gap Inc., Marks & Spencer, and Metro AG) have implemented pilot projects on item-level RFID, one of the major barriers to universal adoption is the cost of a supply-chain wide RFID implementa-

[1] There are chipless RFID tags as well. These tags make use of certain properties of materials to hold a unique RF signature.

tion. Other challenges exist, e.g., consumer privacy concerns and a lack of global technology standards, but these are outside the scope of this paper. The main cost components are the smart tags, the stationary readers, and the corresponding IT infrastructure. The tag cost is a variable cost, while the installation of the readers and the adaptation of the IT infrastructure are primarily a fixed cost. Thus, for supply chain aspects such as inventory stocking decisions, service level considerations etc., the variable cost of the tags can be considered the factor that most influences the RFID-enabled retail sector (see, for example, the Auto-ID Center white papers by Accenture and IBM Consulting: Kambil and Brooks 2002; Alexander et al. 2002a). Consequently, our model, detailed below, uses tag prices and tagging cost as the main RFID cost factor influencing supply chain decisions.

Manufacturers and retailers typically see very different benefits from RFID (see, e.g., Kambil and Brooks 2002). Manufacturers are generally most interested in tracking cases or pallets of their product via the transportation channel up to the retail outlets, whereas retailers typically are expected to gain most benefit from individual-product tracking on their shelves (Chappell et al. 2002; Kambil and Brooks 2002; Alexander et al. 2002a). However, item-level tags are usually part of the item packaging: They are frequently placed inside the product's carton wrapping, or in the case of apparel, sewn into the product by the manufacturer. In addition, attaching the tag at the retailer location would, in most cases, not make economic sense, since it would require the availability of tag placing and tag encoding equipment at each retailer site. Therefore, in virtually all existing RFID supply chain implementations, the manufacturer places the smart tag on the finished good. Thus, if we consider the supply chain as a whole, the dilemma becomes clear: Item-level tagging seems to hold the most potential for the retailer, but is the costliest solution for the manufacturer who is best positioned to put on the tags.

In a competitive environment, the manufacturer will thus require some kind of contractual incentive to incur the tag cost, and downstream supply chain partners will need to share in the cost of the tag (see also the following Industry Briefs by Forrester Research and The Gartner Group: Crawford 2003; Woods et al. 2003). While much attention has been placed on the RFID technology, these complications have not been sufficiently addressed.

1.3. Research Questions

The main questions that this paper addresses are:

(1) What level of tag prices make item-level RFID economically feasible?

(2) What is the impact of item-level RFID on the decentralized supply chain? How should the tag cost be shared among the supply chain partners? How does the relative market power of the retailer vs. the manufacturer affect our conclusions?

This paper is organized as follows: In the following section, we present an overview of the current state of RFID application, as well as a review of related academic work. Section 3 explains the setting of our model. Section 4 presents the basic centralized-system model and addresses Research question #1. In Section 5, we introduce the decentralized system and explore Research question #2. Finally, Section 6 presents conclusions and directions of our further research.

2. Literature Review

This section gives an overview of the existing RFID applications in industry. In addition, we review the academic literature on RFID and supply chain management that is relevant to our work.

2.1. Industry Initiatives: Trials and Pilots

Radio-frequency identification in non-military applications has been in use for over two decades. Earliest applications focused on very specific areas, for example, in livestock tracking (Beigel 2003). RFID is also used extensively in military applications to allow tracking and identification of containers (see DeLong 2003 for an overview). In October 2003, the U.S. Department of Defense announced that its 43,000 suppliers will be required to use RFID tags at the pallet/case level by 2005 (Green 2003).

Among the first to use RFID in a retail supply chain setting was Gap Inc. in 2001. Gap Inc. ran an extensive three-month pilot project to test the promise of item-level RFID on one of their fashion lines, achieving a 99.9% inventory accuracy rate (Texas Instruments Press Release 2001; Sliwa 2002). Analysts also claimed that Gap saw a 2 to 7% increase in sales by using item-level RFID due to higher availability of products (Abell 2003).

More recently, the most significant advances in the use of RFID (and particularly item-level RFID) have been made in the retail supply chain with players such as Marks & Spencer, Gillette, Tesco, Wal-Mart, and Metro AG in Germany.

Wal-Mart (together with Procter & Gamble) has conducted trials of smart shelves and item-level RFID for cosmetics (Wolfe et al. 2003). Wal-Mart has also required its top 100 suppliers to implement RFID on the case- and pallet-level by 2005 (Romanow and Lundstrom 2003). Gillette and Tesco have been cooperating on item-level RFID in the United Kingdom. Gillette tagged razor blade cartridges and Tesco used a smart shelf system to monitor stock in retail stores.

This system was primarily designed to prevent theft, and it was combined with an extensive camera surveillance system that was triggered by removal of product from the smart shelf. Consumer privacy concerns have prompted the trial to be ended in 2003 (Wolfe et al. 2003).

Metro AG in Germany has launched what is likely the most ambitious real-world trial of item-level RFID to date (Roberti 2003). In their Future Store in Rheinberg/Dusseldorf, item-level tags are used on Gillette razor blades, P&G shampoo, Kraft cream cheese, and DVDs. The item-level RFID data are used to drive both in-store and outside stock replenishment. In addition, several consumer benefits such as shopping carts with automatically updated shopping lists and a self checkout system have been implemented. Metro also uses pallet- and case-level tags on all outgoing dry goods shipments from their Essen distribution center to the Rheinberg store.

German retailer Kaufhof, a subsidiary of Metro AG, runs a pilot program in conjunction with Gerry Weber apparel. In this pilot, clothing items are tagged at the item level. Tagged items flow from the Gerry Weber manufacturing plant, through an RFID-enabled Kaufhof distribution center, into the Kaufhof retail stores (Metro Group Future Store Initiative 2003).

2.2. Existing Research on RFID

The Auto-ID Center and its member institutions have done research on several supply chain aspects of RFID. Within the Auto-ID Center, Jogesh (2000), using the beer game model foundation, offers a simulation approach to the value of information visibility through RFID. Accenture, one of the partners of the Auto-ID Center, has presented several papers offering qualitative insight into the benefits of RFID sensor technology in supply chain management; see Kambil and Brooks (2002). Wong and McFarlane (2003) describe the in-store replenishment policies with and without item-level RFID. IBM, also an Auto-ID Center partner, offers further qualitative work on RFID use in logistics and warehousing. See Alexander et al. (2002a,b).

Researchers at Helsinki University of Technology have done additional qualitative work on wireless product identification and intelligent products. For a good overview, see Karkkainen (2002). In military applications of RFID, Doerr et al. (2003) have presented a cost-benefit and simulation study of ordnance tracking via RFID. More recently, Gaukler et al. (2006) derive a compound inventory control policy that makes use of information on order progress afforded by RFID. Gaukler and Hausman (2006) analyze the cost savings from using RFID in an assembly setting. Finally, Lee and Ozer (2005) have provided an excellent overview of current RFID-related research in operations management.

2.3. Supply Chain Research Foundations

We build upon the structure of the classical Newsvendor model (see Nahmias 2001; Porteus 2002), which is frequently employed to explore "fashion goods" supply chains. Lariviere presents an excellent overview of decentralized supply chain control in Lariviere (1998). Lariviere and Porteus (2001) present further results for contracting under a newsvendor structure. We build on several of their results in this paper.

The qualitative, case-study type of research that has focused on RFID technology and its supply chain applications is quite extensive. However, to our knowledge, there exist no quantitative models based on established inventory control methods that would help supply chain partners to determine the costs and benefits of RFID or the implications of an introduction of RFID to a supply chain. Thus, our research breaks new ground.

3. System Structure

In this section, we review the nature of the benefits from item-level RFID in a retail setting. We then formulate our model and give an overview of the different scenarios to be analyzed.

3.1. Modeling the Benefits of Item-Level RFID

We focus on product availability on the retail shelf in our research, which is—along with theft reduction—the area that retailers overwhelmingly focus their initial item-level RFID efforts on (cf, Agarwal 2001; Alexander et al. 2002a; Alexander et al. 2002b; Kambil and Brooks 2002). There are other potential benefits of item-level RFID in a retail setting, such as automated check-outs at the cash register for example, that we do not model in this paper.

In our research we use the "shelf stock/backroom stock" paradigm to model the stocking decisions at the retail location. The backroom stock in our model is replenished once at the beginning of the selling season through an order that is placed by the retailer to the manufacturer.[2] Products are replenished from the backroom stock location to the shelves. Replenishments from backroom stock to shelf stock typically happen frequently during the selling season, as retail shelf space is limited. For some fast-moving items, this might happen multiple times during a day. The penalty for empty shelves in our model framework is lost sales.

[2] Note that the store backroom in our research is an abstract concept that does not necessarily have to be a location physically separated from the store itself; at Wal-Mart, e.g., the store backroom corresponds to overstock locations on top of the actual retail shelves.

We view the effectiveness of the retailer's in-store shelf replenishment as the main driver of product availability in the store. By enabling smarter inventory management from store backroom to retail shelf and the reduction of non-sale shrinkage (i.e., theft), plus the reduction of shelving errors (a product that is placed on the wrong shelf at the other end of the store is not available to satisfy customer demand), item-level RFID can achieve a higher product availability rate on the retail shelf. In addition, item-level RFID is expected to generate more accurate POS data than conventional manual methods: Raman et al. (2001), e.g., cite frequent cashier barcode scanning errors and other sources of systematic and random data contamination in traditional POS systems.

By increasing product availability, item-level RFID is expected to decrease the number of lost sales and hence increase revenue.

3.2. General Model Framework

Our model has one manufacturer and one retailer. The manufacturer makes a single product, incurring a unit production cost c. He sells this product to the retailer at a wholesale price w. It is assumed that the manufacturer already puts RFID tags on cases/pallets for his own benefit (tracking of outgoing orders; his own inventory is based on cases/pallets, not single items). Thus, the manufacturer's benefits from RFID are already fully realized with pallet/case level tagging. However, he also offers to put individual tags on each item, at a price t per tag. The parameter t includes the cost of the tag as well as the per-unit cost of applying the tag.

The fixed costs of scanners, infrastructure, and IT investments necessary to implement item-level RFID are deliberately not part of our model. Estimates of these costs are relatively well-known, and can be assumed not to vary with the model parameters. Thus, the ultimate decision about using item-level RFID can be made by taking the benefit results from our model, and comparing these to the estimated fixed costs utilizing a net present value or ROI analysis.

The retailer sells the product in retail stores to the end customer at a unit price r, which is exogenous, as are c and t. The retailer is interested in a relatively high service level, because if he runs out of stock of his product, he incurs a lost sale. The retailer cannot directly observe lost sales. His backroom stocking decision is made within a one-period Newsvendor framework, based on his knowledge of the demand distribution.

In order to model the retailer benefits of item-level RFID as outlined in the previous subsection, we define the parameter θ, $0 < \theta \leq 1$, as the conditional probability that, given there is ample backroom stock, a customer will find the retail shelf stocked with the product. Thus, θ is a measure of the responsiveness and effectiveness of the in-store backroom-to-shelf replenishment process. θ also includes the related effects of:

- Theft from the shelf: stolen items reduce shelf availability[3];
- Mis-categorization of products: products that are on the wrong shelf are not available;
- Plus other execution errors that prevent products that have been delivered to the backroom from being stocked on the shelf.

For the sake of brevity, we use θ to denote the shelf replenishment process effectiveness exclusively, but it is understood that the factors discussed above are included in θ as well.

The θ in the no-RFID situation is assumed to be the retailer's highest-possible θ in the sense that the retailer cannot increase θ in a profitable manner unless resorting to item-level RFID. For example, the retailer could always hire more store clerks to continuously scan the shelves for stockouts and thus increase his θ, but this of course also increases staffing cost. Our assumption is that the retailer has set his store operation optimally, and his θ is such that any further increase of θ using non-RFID means (tracking via barcode scans, POS systems, frequent shelf checks etc.) is not economically viable.

Note that modeling the shelf replenishment process using our θ construct avoids having to model in detail the actual shelf replenishment process. The latter may involve a planned rule (e.g., replenish shelf inventory of SKU i when shelf inventory falls to a value R_i, with a quantity Q_i if backroom stock allows) or it may be more informal, e.g., a store manager simply telling the store clerks "when you observe low shelf inventory, replenish product from the backroom." Also, varying levels of training, skills, and attention of store personnel over time will likely cause any specific policy not to be followed precisely at all times. If $\theta = 1$, then the shelf replenishment process, whatever the details and execution, never results in a situation where the backroom has stock but the shelf does not. Values of θ below 1.0 represent the net effect of the various potential causes of the shelf having no stock even though the backroom does have stock.

Customer demand over the selling season is the superposition of individual customer demands and is assumed to follow a normal distribution with mean μ

[3] We point out that theft from the shelf has two effects: (1) reduced shelf availability, and (2) loss of inventory. Our model is limited in the sense that it only accounts for the reduced shelf availability effect of theft. The model thus gives a conservative estimate of the value of RFID.

and standard deviation σ. This assumption is justified by the central limit theorem for a reasonably high demand rate during the selling season. We assume that both retailer and manufacturer know μ and σ, but do not include θ in their decision-making.[4]

The replenishment process responsiveness is highest for $\theta = 1$. It is convenient to normalize θ such that for the item-level RFID case, we can take $\theta = 1$. This can be done without loss of generality: If, e.g., $\theta_R < 1$ is the efficiency under RFID, and the demand under RFID is given by $N(\theta_R\mu_R, \sqrt{\theta_R}\sigma_R)$, this is equivalent to setting $\theta = 1$ and using demand $N(\mu = \theta_R\mu_R, \sigma = \sqrt{\theta_R}\sigma_R)$.

The exogenous parameter θ is the retailer's in-store replenishment responsiveness without item-level RFID, given that the responsiveness under RFID is taken to be 100%. For example, a value of $\theta = 0.9$ means that without RFID, the retailer operates at 90% of the item-level RFID responsiveness. We expect realistic values for θ to be around $\theta = 0.9$.[5] Wong and McFarlane (2003) estimate the efficiency of the retail replenishment process from backroom to shelf at 90 to 93%; surveys by ECR Europe carried out by Roland Berger Strategy Consultants (2003) quote similar numbers and note that products that are on sale tend to score higher out-of-stock rates and decreased replenishment efficiency. Chappell et al. (2003) report that in their surveys around 30% of items unavailable on the shelf were actually available in the retail backroom.

3.3. Model Scenarios

In order to explore this setting, we examine two different scenarios:

(1) The centralized case, with and without item-level tagging. This case establishes the baseline for assessing the quantitative benefits of item-level RFID.

(2) The decentralized wholesale price contract case with item-level tagging. In this case, there is no cooperation between manufacturer and retailer; each optimizes his or her own profit function. This case explores the allocation of item-level RFID costs across the supply chain. There are two sub-cases: Either the manufacturer or the retailer has the major market power.

[4] In reality, μ and σ will be the results of a forecast; we assume that these parameters represent the best possible estimates, and that the retailer and manufacturer agree on these estimates. Thus, their decisions will be based on these estimates.

[5] One way of obtaining the parameter value θ for a particular retail application would be to observe and compare actual sales in parallel using both RFID-tagged and non-RFID-tagged products. In most cases, it will not be feasible to do this, however.

4. Base Model—Centralized System

This section details the base model for the centralized supply chain. The focus will be on the analytic inventory control-based model of costs and benefits, and on exploring the maximum tag prices that still make item-level RFID feasible (Research question #1).

The retailer's demand distribution that he takes into account for his backroom stocking decision is $N(\mu; \sigma)$. Let F be the normal cumulative density function (cdf) of $N(\mu; \sigma)$, and let F^{-1} be its inverse normal cdf. Define ϕ (Φ) to denote the standard normal pdf (cdf). Parameters are the unit retail price r; the unit manufacturing cost c; the tag price t; the unit salvage value s; and θ. We let the symbol z represent the z-value of the standard normal distribution. Thus, z denotes the (backroom) stocking level S at the retailer through the identity $S = \mu + z\sigma$.

Our goal is to compare the expected profits under item-level RFID with the expected profits that are achievable without RFID. Thus, we need to evaluate the optimal stocking decisions in both cases using the respective reference demand distributions. It is important to note that while *true* demand under no-RFID is $N(\mu; \sigma)$, this is not the *effective* demand that the retail shelf can satisfy: Effective demand at the retail shelf under no-RFID will be $N(\theta\mu; \sqrt{\theta}\sigma)$, because the shelf is assumed to be empty $100(1 - \theta)$% of the time because of less effective shelf replenishing, and thus effective demand is 100θ% of true demand. Hence, the effective demand distribution is $N(\theta\mu; \sqrt{\theta}\sigma)$, because the normal distribution is infinitely divisible.[6] The difference between true demand and effective demand is that effective demand reflects those lost sales due to shelf stockouts that could have been avoided (i.e., where backroom stock was present). The difference between effective demand and actual sales reflects those lost sales due to unavailability of the item anywhere in the store, including the backroom.

The general expected profit as a function of θ, t, and z for the centralized system is

$$\prod(\theta, t, z) = (r - s)\theta\mu\Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right) - (r - s)\sqrt{\theta}\sigma\phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right) - (c + t - s)S\Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right) + (r - c - t)S\left(1 - \Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right)\right) \quad (4.1)$$

[6] Another way to arrive at this result is from first principles by assuming an underlying compound Poisson demand, applying Bernoulli trials with thinning probability θ, and finally invoking the central limit theorem for regenerative processes to approximate the effective demand distribution.

For the RFID case (where $\theta = 1$), the preceding equation simplifies to

$$\Pi(t, z) = \mu(r - c - t) - L(z)$$

$$= \mu(r - c - t) - z\sigma(c + t - s) - \sigma(r - s)I_N(z) \quad (4.2)$$

where $L(z)$ is the usual holding and shortage cost function, and $I_N(z)$ is the standard normal loss function, $I_N(z) = \int_{x=z}^{\infty}(x - z)\phi(x)dx$ (cf. Porteus 2002). The profit is explicitly written as a function of the tag price t in order to emphasize that interrelation; for the no-RFID case, $t = 0$.

Since the profit function has the general form of a Newsvendor profit function, it is concave in the stocking level. Therefore, the unique profit-maximizing stocking levels $y_{RF}(t)$ and $y_{No}(t)$ are given by

$$y_{RF}(t) := F^{-1}\left(\frac{r - c - t}{r - s}\right)$$

$$= \mu + z_{RF}(t)\sigma \quad (4.3)$$

where $z_{RF} = \Phi^{-1}((r - c - t)/(r - s))$ for the RFID-enabled system, and by

$$y_{No} := F^{-1}\left(\frac{r - c}{r - s}\right)$$

$$= \mu + z_{No}\sigma \quad (4.4)$$

where $z_{No} = \Phi^{-1}((r - c)/(r - s))$ for the system without RFID. Observe that in direct consequence of the definition, we have that $z_{RF}(t) \leq z_{No}$ for all t, with equality holding for $t = 0$; and indeed $z_{RF}(t)$ is decreasing as t increases. Hence, also $y_{RF}(t) \leq y_{No}$ for all t, with equality holding for $t = 0$. In general, we shall require that the optimal stocking levels be positive, i.e., $y_{No} > 0$ and $y_{RF}(t) > 0$. Notice that even though backroom stocking levels are lower under RFID, the existing stock is replenished more efficiently to the shelves under RFID ($\theta = 1$, versus $\theta < 1$ without RFID). Thus, in essence the backroom stock is utilized better under RFID.

Under no-RFID, there exists the penalty of missing sales due to less effective shelf replenishment. Hence, the maximum expected profit for the centralized system without RFID is given by $\Pi_{No}(\theta) = \Pi(\theta, 0, z_{No})$. For the centralized system with RFID, the maximum expected profit is $\Pi_{RF}(t) = \Pi(1, t, z_{RF}(t))$, since $\theta = 1$ under RFID.

A key performance measure is the expected service level of the system. The expected service level (fill rate) achieved by the centralized system is defined as

$$\beta := \frac{\text{exp. sales}}{\text{exp. demand}}$$

$$= \frac{\mu - I_N(z)\sigma}{\mu}$$

$$= 1 - \frac{\sigma}{\mu} I_N(z) \quad (4.5)$$

(See e.g., Porteus 2002).

Thus, in the item-level RFID case, $\beta_{RF} = 1 - (\sigma/\mu) I_N(z_{RF}(t))$.

Theorem 4.1. *For the centralized system with RFID, the service level β_{RF} is decreasing as t increases.*

Intuitively, service level decreases as tag prices become more expensive because the tag price influences the amount of the retailer's backroom stock. As the tag price increases, the retailer optimally stocks less in his backroom.

In order to evaluate the benefit of an item-level RFID implementation for a specific retailing situation under the parameter vector $(r, c, s, t, \theta, \mu, \sigma)$, we introduce the benefit function $B(t, \theta)$:

$$B(t, \theta) = \Pi_{RF}(t) - \Pi_{No}(\theta)$$

$$= \Pi(1, t, z_{RF}(t)) - \Pi(\theta, 0, z_{No}) \quad (4.6)$$

Theorem 4.2. *For the centralized system, the benefit function $B(t, \theta)$ is strictly convex-decreasing in t.*

Since $B(t, \theta)$ is strictly convex-decreasing in t as long as stocking levels are positive, for every θ there exists a unique tag price t_0 such that there is a positive benefit of item-level RFID for the centralized system for all $t < t_0$. This "break-even point" t_0 satisfies the equation

$$\Pi(1, t_0, z_{RF}(t_0)) - \Pi(\theta, 0, z_{No}) = 0 \quad (4.7)$$

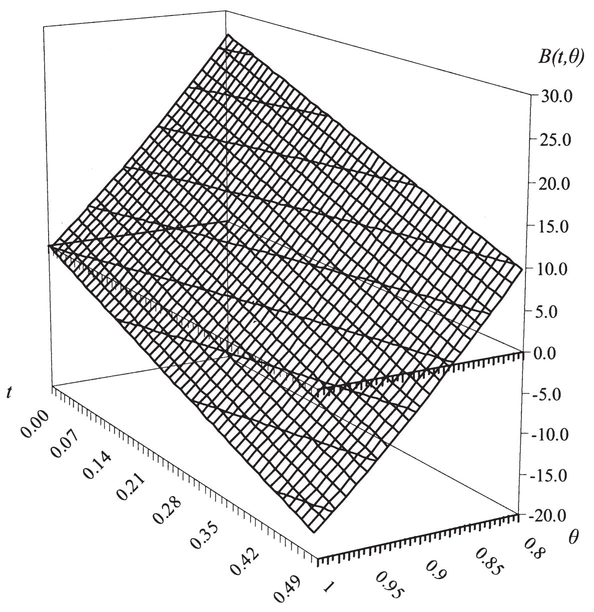
We observe that for $\theta = 1$, obviously $t_0 = 0$, and RFID tags need to be free in this situation. Figure 1 shows the benefit function for a sample data set ($r = 7$, $c = 2.5$, $s = 0$, $\mu = 30$, $\sigma = 15$).

An efficient search method can be employed to solve exactly for t_0 in (4.7) because t_0 is unique as long as the optimal stocking levels are positive according to our requirement. An alternative could be to approximate Φ^{-1} polynomially in order to evaluate the expression directly.

5. The Decentralized System

In this section, we explore the impact of item-level RFID on a decentralized supply chain with a separate manufacturer and a separate retailer. In our analysis of the decentralized system, we shift our focus to a different problem area. While the previous section

Figure 1 Item-level RFID benefits vs. t and θ.



concentrated on the optimal benefits of introducing item-level RFID, we now emphasize the consequences of decentralization and the allocation of the tag price between two supply chain partners.

In the following, we analyze wholesale price contracts, because these are common contracts that easily lend themselves to the retailing context.

5.1. Retailer or Manufacturer as Stackelberg Leaders

In the decentralized case, different scenarios may exist as to which of the supply chain partners takes the initiative in implementing RFID. In the consumer packaged goods industry, e.g., Wal-Mart as the retailer has taken the lead and mandated that its suppliers (e.g., Procter & Gamble) implement RFID as well. In this situation, Wal-Mart is perceived as the clear leader through its market power. However, in other situations, manufacturers may well be the leading party. Consider a large manufacturer like Procter & Gamble, which is (hypothetically) putting item-level tags on its products that are shipped to Wal-Mart. Since tags are placed on the product as part of the packaging operation, it may make economic sense for this manufacturer to put tags on all products, regardless of whether they are shipped to Wal-Mart, or to a smaller retailer. This will be especially true if the vast majority of the manufacturer's products go to Wal-Mart, and only a relatively small fraction go to alternate outlets (convenience stores, etc.). The economic drivers here are (dis)economies of scale (i.e., special non-tagged packaging for a small fraction of products), and the pooling principle: Less overall inventory is required if only one product is stored in manufacturer's warehouses, rather than two distinct products (RFID and non-RFID).

Of course, the manufacturer will still want to recoup his costs of applying the tag from the retailer. Thus, this same manufacturer that is the "follower" in his relationship with Wal-Mart, may play the role of RFID implementation "leader" in its relation with other retail outlets. We will model the leader-follower notion by using the Stackelberg Game framework. We examine both the case where the retailer leads, and the case where the retailer follows.

Regardless of whether the retailer or the manufacturer is the Stackelberg Leader, the retailer's profit function is similar to the profit function of the centralized system in the previous section, with two important changes:

(1) The cost per unit of the product from the retailer's perspective is different: The retailer now pays a wholesale price w to the manufacturer (whose unit cost is still c, as before).

(2) The cost of the RFID tag is now allocated between manufacturer and retailer. Let α be the fraction of the tag cost borne by the retailer, and $(1 - \alpha)$ be the fraction that is paid by the manufacturer, for $0 \le \alpha \le 1$. Here, α may be either exogenous, or it may be a contracting parameter. The extreme case of the manufacturer (retailer) bearing all of the tag cost is attained by setting $\alpha = 0$ ($\alpha = 1$).

The retailer's general expected profit function for the decentralized system is

$$\Pi_R^D(\theta, t, w, z) = (r - s)\theta\mu\Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right) - (r - s)\sqrt{\theta}\sigma\Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right) - (w + \alpha t - s)S\Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right) + (r - w - \alpha t)S\left(1 - \Phi\left(\frac{S - \theta\mu}{\sqrt{\theta}\sigma}\right)\right) \quad (5.1)$$

The unique profit-maximizing stocking level for the retailer under item-level RFID is given by

$$y_{RF}^D(t, w) := F^{-1}\left(\frac{r - w - \alpha t}{r - s}\right) = \mu + z_{RF}^D(t, w)\sigma \quad (5.2)$$

where $z_{RF}^D(t, w) = \Phi^{-1}((r - w - \alpha t)/(r - s))$.

When item-level RFID is not available, the profit-maximizing stocking level for the retailer becomes

$$y_{No}^D(w) := F^{-1}\left(\frac{r - w}{r - s}\right) = \mu + z_{No}^D(w)\sigma \quad (5.3)$$

where $z^D_{No}(w) = \Phi^{-1}((r - w)/(r - s))$. Again, $y^D_{RF}(t, w) \le y^D_{No}(w)$ for all w, t, with equality holding for $t = 0$, and we shall require that the optimal stocking level be positive, i.e., $y^D_{RF}(t, w) > 0$ and $y^D_{No}(w) > 0$.

The maximum expected profit for the retailer in the decentralized system without RFID is given by $\Pi^D_{No}(\theta, w) = \Pi^D(\theta, 0, w, z^D_{No}(w))$; the maximum expected profit for the retailer in the decentralized system with RFID is $\Pi^D_{RF}(t, w) = \Pi^D(1, t, w, z^D_{RF}(t, w))$.

The total supply chain profit is the sum of manufacturer's and retailer's profit, $\Pi^D_T = \Pi^D_M + \Pi^D_R$. The difference between the "Retailer as Stackelberg leader" and the "Manufacturer as Stackelberg Leader" scenarios lies in the way the wholesale price w is determined.

5.2. Wholesale Price When Retailer is Driving Force

In this scenario, the retailer acts as the Stackelberg Leader. This means that the retailer sets the wholesale price, knowing the manufacturer's participation constraint. Thus, under item-level RFID, the retailer offers a wholesale price of $\hat{w} = c + \alpha t + \gamma$, where $0 \le \alpha \le 1$ and $\gamma \ge 0$. The exogenous parameter γ is the price for the manufacturer's marginal capacity that the retailer has to pay. γ will depend on the market structure; if the manufacturer is a monopolist, he will be able to charge a high price for his marginal capacity (i.e., marginal capacity for producing one additional item for the retailer). The capacity premium that the retailer has to pay will tend to decrease as the number of manufacturers that offer the product increases.

The retailer's expected profit is then given by using (5.1) and the transformation $w = \hat{w} - \alpha t$. The manufacturer's expected profit is $\Pi^D_M = (\hat{w} - c - t)y^D = (\gamma - (1 - \alpha)t)y^D$. A necessary (but not sufficient) participation constraint for the manufacturer is $\gamma - (1 - \alpha)t \ge 0$.

5.3. Wholesale Price When Manufacturer is Driving Force

In this scenario, the manufacturer assumes the position of the Stackelberg Leader: the manufacturer takes the initiative and proposes the terms of the contract between the two supply chain partners. Thus, the manufacturer has the wholesale price w as his decision variable.

In the following we shall concentrate on the case where item-level RFID has been enabled. The results that we derive are valid for the no-RFID case as well, with the obvious modification that in this case, $t = 0$, and there is no need for a parameter α.

The manufacturer's expected profit is given by

$$\Pi^D_M(t, w) = y^D(\cdot, w)(w - c - (1 - \alpha)t) \quad (5.4)$$

where $y^D(\cdot, w) = y^D_{RF}(t, w)$ in the item-level RFID case, and $y^D(\cdot, w) = y^D_{No}(w)$ along with $t = 0$ in the no-RFID case.

Note that since the manufacturer is able to anticipate the retailer's optimal behavior, the function y is deterministic for him. The manufacturer's problem then is to choose the wholesale price w that maximizes $\Pi^D_M(t, w)$.

It is advantageous to follow Lariviere (1998), and to express the manufacturer's optimization problem as dependent on y, the amount of the product sold to the retailer.

The transformed expression for manufacturer profit is

$$\Pi^D_M(y) = y[\hat{w}^D(y) - \hat{c}] = y(w^D(y) - c - (1 - \alpha)t) \quad (5.5)$$

where $\hat{w}^D(y) = w^D(y) - s + \alpha t = (1 - F(y))\hat{r}$, and $\hat{c} = c + t - s$, and $\hat{r} = r - s$. By performing this optimization step, the manufacturer effectively controls the amount of stock of the product in the channel, which is simply the amount of the product sold to the retailer, namely, y.

Several well-known price-only contract results from the literature can be invoked directly, as the following Theorem shows.

Theorem 5.1 (Lariviere 1998)

(1) *For the item-level RFID case, the manufacturer's first-order optimality condition for the optimal amount of product to sell to the retailer is* y^* *such that* $\hat{w}(y^*)(1 - g(y^*)) = \hat{c}$, *where* $g(y) = yf(y)/(1 - F(y))$ *is the generalized failure rate of the demand distribution.*

(2) *For the no-RFID case, the manufacturer's first-order optimality condition for the optimal amount of product to sell to the retailer is* y^* *such that* $\hat{w}(y^*)(1 - g(y^*)) = c - s$, *where* $\hat{w}^D(y) = (1 - F(y))\hat{r}$ *and* $g(y) = yf(y)/(1 - F(y))$ *is the generalized failure rate of the demand distribution.*

(3) *For both cases:*

(a) This first-order condition is sufficient, and its solution is a unique global maximum.

(b) Further, y^* *is lower than the minimum* y *for which* $g(y) = 1$.

5.4. General Results in the Decentralized System

This section contains results on profits and benefits from an item-level RFID introduction, in both the "Retailer as Stackelberg Leader" and the "Manufacturer as Stackelberg Leader" scenarios.

Lemma 5.2. *In the decentralized system under a price-only contract, regardless of who is the Stackelberg Leader:*

(1) *The manufacturer's optimal amount of product sold to the retailer,* y^*, *decreases as the unit production cost* c *and the tag cost* t *increase, and is invariant in* θ;

(2) *The manufacturer's optimal wholesale price charged to the retailer, w^*, decreases as the unit production cost c and the tag cost t decrease, and is invariant in θ.*

Lemma 5.3. *In the decentralized system under a price-only contract, regardless of who is Stackelberg Leader:*

(1) *The manufacturer's profit decreases as the tag price t increases;*

(2) *The manufacturer's profit is invariant in θ;*

(3) *The retailer's profit decreases as the tag price t increases;*

(4) *The retailer's profit increases as θ increases;*

(5) *The wholesale price under item-level RFID is always at least as high as the wholesale price without RFID.*

Thus, an increase in θ is beneficial for the retailer, but does not affect the manufacturer directly. As expected, increases in the tag price have negative consequences for retailer and manufacturer, regardless of who takes the initiative.

We can define the benefit from item-level RFID in this environment as $B^D(t, \theta) = \Pi^D_{T,RF}(t) - \Pi^D_{T,No}(\theta)$, where $\Pi^D_{T,RF}(t) = \Pi^D_{M,RF}(t) + \Pi^D_{R,RF}(t)$ and $\Pi^D_{T,No}(\theta) = \Pi^D_{M,No}(\theta) + \Pi^D_{R,No}(\theta)$. The break-even tag price t_0 is then obtained from the solution to $B^D(t_0, \theta) = 0$.

The benefit function is difficult to evaluate analytically for the case where the manufacturer is the Stackelberg Leader, because the wholesale prices in the RFID and no-RFID cases are the results of the manufacturer's separate non-linear profit optimization (see eq. 5.5).

5.5. Influence of Tag Cost Sharing

We now examine the influence of tag cost sharing when either retailer or manufacturer are Stackelberg Leaders.

Theorem 5.4.

(1) *When the manufacturer is the Stackelberg Leader, tag cost sharing does not affect the distribution of profits: The manufacturer's expected profit, Π^D_M, the retailer's expected profit, Π^D_{RF}, and the expected total system profit are independent of the tag cost sharing parameter α.*

(2) *When the retailer is the Stackelberg Leader, there exists a tag cost sharing fraction α_0 such that the highest possible supply chain profit is attained, while ensuring manufacturer participation. If the manufacturer participates at a unit profit margin $0 \leq \gamma_n \leq \gamma$, then $\alpha_0 = [1 - (\gamma - \gamma_n)/t)]^+$. In particular, if $\gamma_n = \gamma$, then $\alpha_0 = 1$, and the retailer bears the cost of the tags alone.*

When the manufacturer leads, his profit is independent of the tag cost sharing because he always sells y^*, and he chooses $w(y^*)$ such that his portion of the tag cost is borne by the retailer through a higher wholesale price. Conversely, the retailer's profit is independent of the tag cost sharing because his unit product cost changes with α such that the retailer always buys an amount y^* of the product. Thus, α can be taken as an exogenous parameter: since α does not impact profits, there is no need for the parties to contract on α in a modified price-only contract. Essentially, the wholesale price implicitly reflects the sharing of the tag cost.

When the retailer leads, the supply chain optimal tag cost sharing policy would be to set $\alpha = 0$, i.e., the manufacturer bears the tag cost alone. However, this policy would violate the manufacturer's participation constraint in the sense that the manufacturer would be worse off under RFID than under no-RFID. Given the manufacturer's reservation unit profit margin γ_n, the maximum fraction of the tag cost the manufacturer is willing to pay for is $1 - \alpha_0$. If the retailer is in a position powerful enough to make the manufacturer give up part of his unit profit margin he enjoyed under no-RFID, then $\alpha_0 < 1$. Otherwise, $\gamma_n = \gamma$ and $\alpha_0 = 1$, and the retailer must bear the cost of the tags in full.

There is an existing stream of literature that examines incentives in two-firm interactions where one firm exerts costly effort to increase customer demand, which results in both parties being better off. Examples of these are a retailer's advertising efforts for a supplier's product, or increasing shelf space at a retailer for a certain product. Cachon (2003) gives a comprehensive overview of such incentive problems and coordination approaches. Our model of item-level RFID benefits differs from this existing body of research in three ways: (1) the costly effort is exerted by the upstream firm, i.e., the manufacturer, (2) the effort results in benefits for the downstream firm (i.e., the retailer) only, and (3) the effort is assumed to be observable (tag prices are known to all parties). Cachon (2003) reports that in general, asymmetric effort problems are difficult to coordinate when contracting on the effort level is not possible. In our case, the effort level (the tag price) is observable, and thus the model presented here is easily coordinated using classical contracts: In the scenario where the manufacturer is the Stackelberg leader, a buy-back contract can be used to coordinate the system; and in the case where the retailer is the Stackelberg leader, a franchising (or lump-sum transfer payment) contract coordinates the channel.

In conclusion, based on our model, supply chain partners should not be concerned about who bears what percentage of the tag cost if the market situation is one where the manufacturer is the driving force. It simply does not matter. This is thus a very benevolent aspect of the introduction of item-level RFID. On the other hand, when the retailer is the driving force, there exists an optimal way to share the tag costs that maximizes retailer and supply chain profit. In this case, the way the tag cost will be shared will depend on the retailer's power to make the manufacturer accept a lower unit profit margin.

6. Conclusions and Further Research

In this paper, we have presented an analytical model of item-level RFID in the retail supply chain. Our model captures the most important benefits of item-level RFID at the retailer and attempts to reflect the real-world cost considerations in the deployment of item-level RFID. In addition, the model describes the dilemma of a supply chain in which costs and benefits of a collaborative technology are distributed in an asymmetric fashion.

Analyzing the base model of a supply chain with centralized decision making, we derive the break-even tag price, i.e., the price at which one is indifferent between RFID and no-RFID, for any given set of model parameters.

We then explore the decentralized scenario, in which the supply chain partners make decisions that optimize their own local profit. We show that the issue of sharing the RFID tag cost between supply chain partners is a non-issue when the manufacturer is the Stackelberg Leader: tag cost-sharing changes neither the overall profit nor the distribution of profits as long as wholesale prices can be freely adjusted. However, when the retailer is the Stackelberg Leader, there is indeed value to tag cost sharing for the supply chain, and we demonstrate how the tag cost allocation can be performed in an optimal fashion.

For our further research on this topic, we have two main directions. First, there are opportunities concerning the game theoretic modeling of the manufacturer-retailer interaction. It would be interesting to extend the model to one with multiple competing manufacturers or retailers. Second, our model currently does not consider consumer substitution decisions. It can be argued that the effects of stock-outs are more pronounced for the manufacturer than for the retailer, because if consumers buy substitute products when the product of choice is not available, the retailer makes a sale in any case, but the manufacturer does not. Allowing for substitution effects could lead to further interesting dynamics between manufacturer and retailer. Substitutable products could easily be incorporated in the general framework of our demand model; an initial focus on a retailer offering two substitutable products from two different manufacturers might prove fruitful.

7. Appendix Proofs

Proof. Theorem 4.1

Differentiating yields: $d\beta_{RF}/dt = -\sigma(c + t)/((r - s)^2\mu\phi(z_{RF}(t))) < 0$. □

Proof. Theorem 4.2

We first ascertain the shape of the profit functions:

$$\frac{d}{dt}\Pi_{RF}(t) = (c + t)\frac{1}{r-s}\sigma\frac{d}{du}\Phi^{-1}(u) - \sigma z_{RF}(t) - \mu - (c + t)\frac{1}{r-s}\sigma\frac{d}{du}\Phi^{-1}(u) = -\sigma z_{RF}(t) - \mu < 0$$

by the requirement of positive optimal stocking levels.

Moreover, $\frac{d^2}{dt^2}\Pi_{RF}(t) = \frac{1}{r-s}\sigma\frac{d}{du}\Phi^{-1}(u) = \frac{\sigma}{r-s}\frac{1}{\phi(z_{RF}(t))} > 0$.

Therefore, the strictly decreasing property in t follows directly because $\frac{\partial B(t,\theta)}{\partial t} = \frac{d\Pi_{RF}(t)}{dt} < 0$.

The second order result follows directly by observing that $\frac{\partial^2 B(t,\theta)}{\partial t^2} = \frac{d^2\Pi_{RF}(t)}{dt^2} > 0$. □

Proof. Theorem 5.1

Parts 1 and 2: The governing demand distribution according to which the manufacturer and retailer make their stocking decisions is $N(\mu, \sigma)$. Then the proof follows directly from Theorem 1 in Lariviere (1998) and the observation that the Normal demand distribution has increasing general failure rate.

The proof of Part 3 is the same as in Lariviere (1998). □

Proof. Lemma 5.2

Part 1, retailer as leader: As t and c increase, w increases as well. Then the result follows directly from the definitions of y^D_{No} and y^D_{RF}. Also from the definitions of y^D_{No} and y^D_{RF} it can be seen that θ does not influence the stocking level.

Part 1, manufacturer as leader: The statements concerning c and t follow after rewriting the manufacturer's first-order condition (see Theorem 5.1, part 1) in the form $(r - s)(1 - F(y))(1 - g(y)) = c + t - s$, noting that F is IGFR and creating the partial differentials. The statement concerning θ follows because by definition, the stocking levels and the wholesale price are independent of θ.

Part 2, retailer as leader: This follows directly from the definition of the wholesale price.

Part 2, manufacturer as leader: Recall that $w(y^*) = (1 - F(y^*))(r - s) + s - \alpha t$. Since $dw(y)/dy = -(r - s)f(y) < 0$, we know that $w(y)$ is strictly decreasing as y increases. Thus, w^* decreases as c decreases. Further, if $\alpha = 0$, then it is clear that w^* decreases as t decreases. In Theorem 5.4, we show that the manufacturer's profit and the optimal number of units sold are invariant with respect to α, for any $t > 0$. Using this fact here, we let $X = \Pi_M(\alpha = 0, t)$, $Y = y^*_{RF}(\alpha = 0, t)$. Then, for any $1 \geq \alpha > 0$, it must hold that $\Pi^D_M(\alpha, t) = X = Y(w - c - \alpha t)$.

Thus, under the positive α, the profit must be the same, but the cost side has risen (compared to $\alpha = 0$).

In order to keep the balance, consequently w must increase (by αt) compared to the case when $\alpha = 0$. Thus w^* increases as t increases for any α. Finally, by definition, w is invariant with respect to θ. □

Proof. Lemma 5.3

(1) When manufacturer leads: Proof by contradiction. Assume that the tuple $(y_1, w(y_1))$ is optimal under some $t_1 > 0$. Let $(y_2, w(y_2))$ be the optimal tuple under $t_2 < t_1$. Claim that $\Pi_M^D(y_1, w(y_1), t = t_1) \geq \Pi_M(y_2, w(y_2), t = t_2)$. However, this yields a contradiction because we can use $(y_1, w(y_1))$ under $t = t_2$ as well, and clearly this yields a higher profit, which contradicts the claim. Therefore, the manufacturer's profit must decrease as t increases. When retailer leads, then as $t \uparrow$, manufacturer's profit margin $\gamma - (1 - \alpha)t \downarrow$, and his sold quantity $y^D \downarrow$.

(2) This follows from the preceding Lemma, in which it was shown that the quantity sold by the manufacturer and the wholesale price are invariant in θ.

(3) Regardless of who leads, we know from Lemma 5.2 that as t increases, w^* increases as well. Thus, we can write $\tilde{c} = w^* + \alpha t$, which increases as t and w^* increase. It is clear that $z_{RF}^D = \Phi^{-1}((r - w - \alpha t)/(r - s)) = \Phi^{-1}((r - \tilde{c})/(r - s))$ decreases as $\tilde{c}$ increases. The retailer's expected profit under item-level RFID can then be written as $\Pi_{RF}^D = \mu(r - \tilde{c}) - z_{RF}^D \sigma(\tilde{c} - s) - \sigma(r - s)I_N(z_{RF}^D)$. This is the classical Newsvendor formulation with $c = \tilde{c}$, and therefore we already know that Π_{RF}^D decreases as $\tilde{c}$ increases.

(4) Retailer's profit increases because wholesale price and quantity ordered are invariant in θ, and the effective demand at the retail shelf increases stochastically as θ increases.

(5) Manufacturer leads: From Lemma 5.2 we know that a higher $\hat{c}$ results in a higher wholesale price. Retailer leads: follows from definition of wholesale price. □

Proof. Theorem 5.4

Part 1: The manufacturer's expected profit is given by $\Pi_M^D = y^*(w(y^*) - c - (1 - \alpha)t)$, which after substituting $w(y^*) = (1 - F(y^*))(r - s) + s - \alpha t$, is equivalent to $\Pi_M^D = y^*((1 - F(y^*))(r - s) + s - c - t)$, which is independent of α. The retailer's expected profit, given the manufacturer has set the wholesale price $w(y^*)$, is $\Pi_{RF}^D = \mu(r - w(y^*) - \alpha t) - z_{RF}^D \sigma(w(y^*) + \alpha t - s) - \sigma(r - s)I_N(z_{RF}^D)$, which after substitution becomes $\Pi_{RF}^D = \mu(r - (1 - F(y^*))(r - s) - s) - z_{RF}^D \sigma((1 - F(y^*))(r - s)) - \sigma(r - s)I_N(z_{RF}^D)$. However, $z_{RF}^D = \Phi^{-1}((r - w(y^*) - \alpha t)/(r - s)) = \Phi^{-1}((r - (1 - F(y^*))(r - s) - s)/(r - s))$, and thus Π_{RF}^D is independent of α as well. Finally, since both manufacturer and retailer profits are independent of α, so is the total system profit.

Part 2: The necessary participation constraint for the manufacturer is $\gamma \geq (1 - \alpha)t$. If this constraint is violated, the manufacturer loses money on every item he sells. If his reservation unit profit margin is γ_n, then his necessary and sufficient participation constraint is $\gamma - (1 - \alpha)t \geq \gamma_n$. Thus, $\alpha_0 = [1 - (\gamma - \gamma_n)/t]^+$. □

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