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Unlocking the Value of RFID

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RFID (Radio-Frequency Identification) technology has shown itself to be a promising technology to track movements of goods in a supply chain. As such, it can give unprecedented visibility to the supply chain. Such visibility can save labor cost, improve supply chain coordination, reduce inventory, and increase product availability. Industry reports and white papers are now filled with estimates and proclamations of the benefits and quantified values of RFID. Early adopters are now rallying more and more followers. However, most such claims are educated guesses at best and are not substantiated, that is, they are not based on detailed, model-based analysis. This paper argues that there is a huge credibility gap of the value of RFID, and that a void exists in showing how the proclaimed values are arrived at, and how those values can be realized. The paper shows that this credibility gap must be filled with solid model analysis, and therefore presents a great opportunity for the Production and Operations Management (POM) research community. The paper reviews some of the ongoing research efforts that attempt to close the credibility gap, and suggests additional directions for further strengthening the POM's contribution to help industry realize the full potentials of RFID.

Key words: supply chain management; value of visibility; inventory management; radio-frequency identification; value of information technology
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1. Introduction

RFID (Radio Frequency Identification) technology has emerged as one of the hottest technologies in supply chain management today. The technology is based on an integrated circuit with an antenna, known as a "tag," attached to a conveyance, which could be a case, pallet, the packaging material of a product, or the product itself. Product information as well as other relevant information can be stored in the tag. Some tags can allow additional information to be written onto them as the tags pass through different parts of the supply chain. Using wireless technologies, readers can be set up to read the information on the tags without contact or a line of sight. Passive tags do not have power themselves and respond to signals emitted by the readers, while active tags have power within themselves and therefore are capable of sending out signals to readers, allowing them to be read at greater distances.

As a new information capture technology, RFID has fascinated the world of supply chain management. The Economist (2003) introduces RFID in an article with the title "The Best Thing Since the Bar-Code." AMR's Lundstrom (2003) proclaims that "RFID Will Be Bigger Than Y2K." With Wal-Mart's request to their top suppliers to start shipping selective cases and pallets equipped with RFID tags to their distribution centers beginning 2005, the "RFID frenzy" began (Kinsella 2003). Retailers like TESCO, Albertson, Target, CVS, and the Department of Defense have also requested or mandated suppliers to start implementing RFID-enabled conveyances. RFID is said to revolutionalize supply chain management, releasing great values (a good discussion of the benefits of RFID on supply chain management can be found in Rutner et al. 2004). Venture Development Corporation estimates that the RFID systems and software market will grow by more than 37% from 2003 to 2005 (Clark, March 16, 2004).

Consultants and technology solution providers have rushed in to develop data integration, planning and monitoring solutions for companies. Many white papers and reports exist today, many of which are written by consultants and systems integration providers, on how RFID can provide values. Many of them have also made statements about the ROI (return on investment) and quantifiable values unleashed by RFID. But so far, very few of the industry white papers or reports describe in detail how the ROIs or dollar values are derived. In addition, although it is common for these reports to claim that the benefits of RFID will come in the form of improved forecasts, reduced inventory, reduced stockouts, and increase revenues, they are not explicit in how these benefits can be arrived at with RFID. We think there exists a credibility gap in all these reports, and in extreme cases, they amount to hypes. Hype gets the attention of senior executives, but they cannot help companies realize the benefits. In the end, frustrated executives may possibly give up and abandon the technology. We think there is a need to close the credibility gap, and operations management research offers a great opportunity to accomplish this. Our research methods can provide the means to help industry with the process and methods through which the benefits can be realized, as well as to help concretely quantify these benefits instead of having to make guesses or rough estimates.

It is instructive for us to look at a similar industry movement in the early nineties, dubbed the ECR (Efficient Consumer Response) (Kurt Salmon Associates 1993). When the industry report first came out with the proclamation that there was a $30 billion potential savings in the US grocery industry, a frenzy arose among senior executives of the grocery industry. The lack of solid explanation and substantiation of how this $30 billion came about, and the difficulties in getting the lessons of how to make supply chain improvements to realize the benefits ultimately led to substantial loss of interest in ECR by some in the grocery industry. In fact, skepticism of the value of RFID has started to emerge (Lacy 2005).

This paper is about what we believe are opportunities for the production and operations management community to produce research that can help industry to use RFID technology for supply chain gains, as well as to solidify the quantification of these benefits. The research efforts should address the potential of RFID as technology advances over time in addition to what RFID can do today. This distinction is important because companies often invest in a new technology, not because of what the technology can do today, but what the technology promises. We think our community is best equipped to close the credibility gap on the values of RFID and its potential. In Section 2, we review the current views on the value of RFID, and point out some of the gaps in Section 3. Some research efforts have already been undertaken, but more are needed. In Sections 4 to 6, we will review some of these ongoing efforts, and highlight directions for additional work in Section 7. This time, we think the POM research community can fill the void left by consultants and solution providers, and turn potentials into realizable actions.

2. Current Views on the Value of RFID

Industry reports and white papers are filled with estimates and best guesses of quantifiable values of RFID. We will first give a quick overview of what values have been cited, and then give a critical review of these reports. Some industry reports have given broad statements of RFID values, such as the AMR Report, which states that the total supply chain cost can go down by 3 to 5%, while revenues can increase by 2 to 7% at early RFID adopters (Abell and Quirk 2002). A more recent Grocery Manufacturers of America (2004) report gives a very comprehensive discussion of the benefits of RFID. It also shows some of the benefits in quantifiable terms, but the data is based on a sample of companies' self-reported estimates.

2.1. Labor Cost Savings

Since RFID tags can be read without having a person to scan the object, such as in the case of traditional bar-codes, there can be significant labor savings. As line of sight is not required, and since multiple tags can be read simultaneously instead of one at a time, the efficiency savings could be huge. Such labor savings occur in the receiving side of stores or warehouses, as well as in inventory audits. At distribution, some reports estimate that the labor cost reduction can be as high as 30% (Pisello 2004), while retail stores can see a labor reduction of 17% (estimates by Kurt Salmon Associates in METRO Group 2004). AT Kearney (2003, 2004) estimates the labor savings at manufacturers to be 9% and at retailer stores and warehouses to be 7.5%. Accenture estimates, as reported in Lacy (2005), that the savings in receipt is 6.5%, while 100% of the labor in physical inventory count could be eliminated. Accenture (Chappell et al. 2002a,b) also reports labor savings in receipt as 5 to 40%, stocking as 22 to 30%, cycle counting as 95%, and checkout as 5 to 45%. McKinsey's estimates (McKinsey Quarterly 2003) are 0.5 to 1.6% in distribution, and 0.9 to 3.4% in the stores. SAP's estimates (SAP 2003) are more aggressive. At retailer warehouses, they estimate a reduction of 20 to 30% in receiving cost, and 40 to 50% in picking cost. At stores, they estimate a reduction of 65% in receiving, 25% in stocking, and 25% in cycle counting. Finally, Booth-Thomas (2003) reports Marks and Spencer obtaining labor saving equivalent to 1% of its revenue in their RFID project.

2.2. Inventory Reduction

Most industry reports claim that the higher visibility offered by RFID technology will reduce forecast error and inventory discrepancy (the difference between actual inventory and inventory records), leading to inventory reduction. Booth-Thomas (2003) cites an Accenture study showing inventory reduction of 10 to 30% in the supply chain. For inventory at the retailers, AT Kearney (2004) estimates a reduction of 5%, while SAP (2003) estimates a reduction of 8 to 12%. Economist (2003) cites IBM's estimates to be at 5 to 25%, while Pisello (2004) estimates a more modest rate of 1 to 2%. Niemeyer et al. (2003) put McKinsey's estimate on inventory reduction through VMI (Vendor-Managed Inventory) enabled by RFID, to be at 20 to 40%.

2.3. Shrinkage and Out-of-Stock Reduction

Inventory shrinkage is a major problem for retailers, and, to a lesser degree, for manufacturers. Inventory shrinkage is caused by theft, damages, fraud, misplacements, and other process errors, and can lead to a big discrepancy between inventory records and actual inventories. Raman et al. (2001a,b) and ECR Europe (2003) are examples of empirical studies that document the severe problems of inventory shrinkage and discrepancies. As a result, stockouts are widespread at retailers (Corsten and Gruen 2003). RFID can help address the problem in two ways. First, by having visibility so that the inventory record corresponds closer to actual inventory, replenishment can be more accurate, leading to fewer stockouts. Second, the ability to accurately monitor inventory can reduce the process failures, prevent misplacements, and avoid frauds,[1] leading to a direct reduction of inventory shrinkage.

IBM's estimate (Alexander et al. 2002) is that shrinkage can reduce by 2/3 of the current 0.22 to 0.73% of sales at manufacturers, and by 47% of the current 1.75% of sales at retailers. Chappell et al. (2002a) estimate that retailer shrinkage could reduce from 1.69% of sales to 0.78%. The METRO Group (2004) estimates that theft will be reduced by 11 to 18% at retailers, while out of shelf rates will be reduced by 9 to 14%. Chappell et al. (2002b) estimate the reduction of inventory mis-picks, which is a source of the process failure, to be at 5%. Based on a survey of 500 respondents, Clark (September 16, 2004) finds that the average shrinkage reduction estimated by the respondents was 12.3%. AT Kearney (2004) estimates the reduction of out-of-stock at retailers to be 0.07% of sales. SAP (2003) estimates (store) theft loss to reduce by 40 to 50%, stock availability to improve by 5 to 10%, and sales to go up by 5 to 10%. Lower stockouts will be translated into increased sales. McKinsey (2003) estimates that the combination of fewer stockouts and less markdown as a result of RFID, will help increase sales by 0.6 to 1.5% at high-end apparel retailers. Booth-Thomas (2003) reports the Accenture estimate of sales increase to be at 1 to 2%. Pisello (2004) has a higher estimate: 2 to 3% increase in revenue.

Most recently, some empirical studies have reported the out of stock reduction as a result of RFID. Based on test store results, METRO reported a reduction of 11% (Johnson 2005). A live test based on 12 RFID-enabled stores and 12 control stores at Wal-Mart showed that the incremental reduction of out of stocks with RFID-tagged cases (from distribution to backroom of stores) averaged about 16% (Hardgrave et al. 2005). These empirical studies provided more concrete values, relative to the previously speculative work. However, these empirical studies may not be readily generalizable to products or retail settings that are very different from those of METRO and Wal-Mart. For example, suppose we consider apparel products with much greater demand variability, higher value, and longer lead time than those of grocery consumer goods, would the out of stock reduction be the same? Analytically-based models are still the best vehicle to develop analysis that can be of more general applicability.

3. A Critical Review of Current Value Estimates

There are three ways to assess the value of a new technology. First, one can ask experts or practitioners to subjectively give their best estimates. Second, we can conduct in-depth case studies of some early pilots, and infer the value from observing the results at these pilots. Third, we can start with understanding how the new technology can influence the fundamental operating characteristics of a system, and then see how the changes in the operating characteristics can give rise to enhanced planning and operational decisions, and then deduce the final performance.

For technological advances that are evolutionary in nature (such as an extension of an existing technology), it is quite reasonable to use the first two approaches to estimate the value of the technology, since presumably the experts and practitioners are quite familiar with the underlying technology. But for revolutionary technological advances such as RFID, it is

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[1] Note that today's RFID technology is such that shoplifting is not easily preventable, but RFID has been found to be effective in reducing shrinkage in the backroom and in the pipeline (see Gozycki, Johnson, and Lee 2004). Over time, as the RFID technology advances, shrinkage due to store front thefts can also be addressed.

very questionable that we can get meaningful results from these two approaches. Consequently, the best approach is to get down to the basics, i.e., to start with the most fundamental operating characteristics, and see how the technology leads to a chain of improvements and therefore values.

If we examine all the industry studies and reports so far, we can say that the value estimates of labor savings are mostly grounded in the second and third approaches. For example, the METRO Group (2004) report is based on detailed time-motion studies by Kurt Salmon Associates on the tasks involved in receiving, put-away, stocking, picking, cycle counting, and verification of inventory. The actual labor hours saved can then be computed fairly accurately, leading to the overall labor savings. Labor savings can be concretely estimated because the studies start with the basic operating characteristics of the receiving and counting operations, and examine which tasks can be significantly shortened by RFID in processing times. Simple pilots can be used to provide accurate estimates of the times to read tags on cases and pallets. This is exactly the approach described by Subirana et al. (2003), which is based on a detailed process mapping and time-motion analysis. Then, the estimates of RFID values in the form of labor savings are solid.

However, as we move from labor costs to inventory savings, shrinkage reduction, out of stock reduction, and sales increases, the estimates are much fuzzier. First, most pilots have not been addressing these factors, and so we have much less experience on which to base conclusions. Second, asking a large sample of participants to give us their best estimates is problematic. These participants have not had the experience, and so they are purely guessing. In addition, the value of RFID comes in the form of increased visibility. But how does a company make use of increased visibility to manage their inventory and replenishment well? Most companies do not know how this can be done. Cognitively, we know that increased visibility will improve forecasting, planning, inventory, and then service. But exactly how and how much? Wild guesses are given as answers, and as a result, they are neither very reliable nor convincing. The consultants and technology providers have not gone through full scale analysis using the third approach, either. Hence, their estimates are also, at best, their best guesses.

To illustrate the deficiency of current studies, take the example of discrepancy between inventory record and actual inventory. RFID is supposed to provide better visibility and therefore eliminate or reduce inventory discrepancy. Now, suppose the inventory discrepancy used to be $x\%$, say, due to all kinds of causes. How would eliminating this discrepancy lead to $y\%$ of inventory reduction and $z\%$ of less stockout? Without performing a detailed model analysis, we contend that even experts would just be making "educated" but wild-guesses.

The third approach requires the use of analytical models that link the underlying operating characteristics to control decisions, and ultimately to performance measures. When such linkages are explicitly modeled, the impact of RFID can be very clearly and concretely inferred. This is the area in which the current business literature on RFID values is lacking, and this is also the area that we think the POM research community can play a significant and important role.

Another important pitfall in assessing the values of RFID is the base case to which the incremental values are derived. For example, if a company is not even aware of inventory discrepancy and does not use statistics of inventory discrepancy in its replenishment decisions, then comparing this base case with the case in which RFID eliminates inventory discrepancy confounds the effects of improved inventory replenishment with RFID's value. We can easily improve the performance of the company by first working on improving the replenishment control policies in the absence of RFID. After that, the added incremental performance improvement will be a more appropriate assessment of the value of RFID. However, most standard industry reports do not make such distinctions. Again, analytical models can help establish the correct base case and thereby quantify the RFID value accordingly. Some of the latest models on the value of RFID, (such as Atali, Lee, and Özer 2004 and others described later) also allow the effectiveness of RFID to be parameterized. For example, one can parameterize the theft reduction effectiveness of RFID to be 0%, 50%, all the way to 100%. Doing so enables one to model the value of RFID as the technology evolves and advances.

In what follows, we provide *examples* of some ongoing research that incorporate information provided by RFID into the underlying operating characteristics, control decisions and the resulting performance measures.[2] Our focus will be more on the modeling aspect of the reviewed papers and less on the analysis. Hence, we will state only the main assumptions, discuss how the models can be (or are) used to quantify the value of RFID and some selective analytical results.

The rest of the paper is organized as follows. In Section 4, we focus on the value of visibility brought forth by RFID within a company. Here, we essentially focus on the role and value of RFID in better managing inventory systems with inventory inaccuracies. In Sec-

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[2] When possible, we will also refer the reader to review papers for a comprehensive review of the existing literature.

tion 5, we provide modeling examples to value RFID information obtained by a downstream firm and shared with an upstream firm. In Section 6, we focus on the role of upstream RFID information shared downstream. In Section 7, we provide some ending thoughts and possible future directions.

4. Value of Visibility Within a Company

Since the early 1980's, availability of cheaper and faster computation enabled companies to automate their inventory management processes and to use inventory management softwares. Automatic replenishment systems track the number of products in stock, often by using point-of-sales data, and place replenishment orders based on the control policies set by the underlying software. The software system often records and controls the stock keeping units on the individual item, case or pallet level based on the specific inventory environment. Regardless, a crucial assumption used by these inventory management systems is that inventory record and actual on-hand inventory are the same measures.

Similarly, the standard literature on inventory models has not differentiated between inventory record and actual inventory. The two have always been considered to be the same. The concern was always on how, having observed demand and the resulting inventory levels, an inventory manager should determine when and how much to replenish. Based on recent empirical observations, this implicit assumption has proven to be wrong. In both retail and distribution environments, unobservable demands occur, as well as other activities that could result in the recorded inventory being quite different from actual inventory.

The recent surveys and empirical work have shown that unaccounted inventory discrepancy—the difference between inventory record and actual inventory—has a daunting effect on the resulting operating costs *and* revenue. Intuitively, if information provided to an automated replenishment system is incorrect, and if the control mechanisms do not account for inventory discrepancy, the system fails to order when it should or it carries more inventory than required. Either outcome results in lost sales and revenue or a high level of unnecessary inventory and operating costs.

Rinehart (1960) reports on a case study of a Federal government supply facility and discusses the extent to which inventory discrepancy impacts performance of the supply chain. He reports that among the randomly selected 6,000 SKUs, approximately 2,000 SKUs had accumulated discrepancy. Iglehart and Morey (1972) report inventory discrepancy from a survey conducted at the Naval Supply Depot in Newport Rhode Island in 1965. A sample of 714 SKUs out of 20,000 SKUs carried in the depot reveals that 25% of the SKUs accumulated discrepancies. The accumulated errors were approximately 4% of the monthly turnovers. In a more recent work, Raman, DeHouraious and Ton (2001) report that out of 370,000 SKUs investigated in apparel retail stores, more than 65% of the inventory records did not match the physical inventory at the store SKU level. Raman and Ton (2004) further investigate and carry out empirical analysis to show that the discrepancy problem still exists today.

Comparison of these case studies reveals two important observations. First, retail environments (that have high inventory turnovers and more contact with customers) accumulate much more discrepancy than distribution centers (that have lower inventory turnovers and less contact with customers). Second, clearly the recent developments in information technology have not yet addressed and eliminated the inventory discrepancy problem.

Presumably with a real-time tracking technology, the manager can have complete visibility of inventory movement within the company at any point in time. Consider the RFID technology. When readers are installed at appropriate locations, the movement of tags on cases or products can be tracked. The tagging can be done on the item, case or pallet level. Theoretically, RFID enables tracking and tracing of items in stock and in the pipeline, thus, creating complete inventory visibility, leading to an accurate account of inventory discrepancy. Of course, we keep in mind that any new technology will be perfected over time. Here, we focus on the value of this visibility for inventory management within a company. Note that in what follows we often use "item" or product to refer to a unit of inventory. This terminology does not suggest that we exclude case or pallet level RFID applications. In inventory control literature, the term "item" is a simple nomenclature that refers to the unit of inventory. For example, a unit of inventory (an "item") could be a shirt, boxes of shirts or a pallet of boxes of shirts.

There is a good parallel of earlier efforts in studying the value of emerging information technologies to the current ones on RFID. In the early nineties, we have seen many studies on the value of Electronic Data Interchange (EDI). Expectations and hopes were high when EDI was introduced as a means to connect trading partners with timely and accurate information. Interestingly, the observations on the values were mixed. Some were encouraging, but most were negative. Carter (1990), Eckerson (1990), and Wallace (1988) all reported that most companies did not achieve significant cost savings or other benefits from EDI. There was a rich literature on empirical studies of the values of EDI, and we will not be able to go through a thorough review here. Ultimately, studies that found positive returns showed that companies must reengineer their business processes in order that new information systems like EDI can benefit trading partners (Clark and Hammond 1998; Riggins and Mukhopadhyay 1994). Others have found that supply partners must learn how to make use of the new technology so that the positive results only show up in longitudinal studies (Mukhopadhyay et al. 1995).

The observations from the EDI literature corroborate with ours. Being able to get more information faster and accurately by itself does not produce business values. It has to be used intelligently. Most of the EDI literature was empirical studies of the impact of EDI, while our interest is how analytical models can be developed to make use of the information. Of course, we should note that RFID offers a much richer scope of possible data accessibility than EDI.

4.1. Transaction Errors Only

Iglehart and Morey (1972) provide the first modeling approach that addresses inventory inaccuracy due *only* to transaction errors, such as scanning error. Note that such errors affect *only* the inventory record and leaves actual inventory unchanged.[3] They consider a single-item, periodic-review inventory system with a *predefined* stationary stocking policy. In other words, they do not consider establishing an optimal replenishment policy. Instead they take the control policy such as (s, S) as given. Their objective is to establish an optimal buffer stock that protects against inventory inaccuracies and to determine an optimal frequency of physical inventory counts to correct the discrepancy between inventory record and actual inventory on hand.

The transaction errors, D_t^τ, are modeled as independent and identically distributed random variables with mean 0 and variance σ^2. The authors do not consider misplacement or theft. The objective is to set a buffer stock such that the probability of the transaction errors *not* depleting this buffer stock between inventory counts is greater than $1 - \alpha$. Let N denote the number of periods between inventory counts.[4] The error buffer stock $B(N)$ is set such that

$$Pr\{\max_{1\le k\le N} S_k \le B(N)\} > 1 - \alpha, \tag{1}$$

where $S_k = \sum_{s=1}^{k} D_s^\tau$. To calculate the above probability, the authors first show that

$$\lim_{N\to\infty} Pr\left\{\max_{1\le k\le N} \frac{S_k}{\sigma\sqrt{N}} \le x\right\} = 2\Phi(x) - 1.$$

Using this relationship, one can approximate the probability in Equation (1) by assuming that the number of periods between successive counts is large. This approximation provides a simple, closed-form formula for the buffer stock.

$$B(N) = \sigma\Phi^{-1}\left(1 - \frac{\alpha}{2}\right)\sqrt{N}.$$

The total expected cost per period is $C(N) = K/N + hB(N)$, where K is the fixed inventory counting cost and h is the holding cost per item per period. The minimizer of this function gives us the optimal (up to the approximation) counting frequency, which is

$$N^* = \left\lfloor \left\{2K\Big/\left[\sigma h\Phi^{-1}\left(1 - \frac{\alpha}{2}\right)\right]\right\}^{2/3} \right\rfloor.$$

Now consider an item having a mean daily demand of 400 units; a holding cost of \$1.50 per unit per day; a standard deviation of the random error term of $\sigma = 0.3$ per demand (approximately plus or minus 18 units of error per day)[5]; and a cost per count of $K = \$150$. If the desired probability of a customer denial occurring between inventory counts due to errors is to be less than $\alpha = 1\%$, the optimal counting frequency is to count the inventory after every 40 days. The resulting optimal average cost is $C(N^*) = \$11.9$.

Suppose RFID enables a 90% reduction in transaction errors (approximately plus or minus 2 units of error per day down from 18 units) to $\sigma = 0.1$. The resulting average error buffer stock cost is then $C(N^*) = \$5.3$, a reduction of 55% in total average cost related to transaction errors. Note that this percentage reduction is not the reduction in the inventory related cost. It is the reduction in transaction error related cost due to counting inventory and carrying a separate buffer stock for transaction errors. For example, suppose that the inventory manager can perfectly match demand without carrying inventory, but carries buffer stock to protect against transaction errors. The reduction in inventory related cost for this manager would be 55%. However, consider a manager who poorly manages his inventory to begin with and is incurring \$100 of holding and penalty cost on average in addition to $C(N^*) = \$11.9$ to manage the transaction error buffer stock. The reduction in the transaction error buffer

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[3] The authors do not refer to the error source as transaction error. However, as we will show in this section that different error sources affect inventory management in a substantially different way. Hence, a characterization of error sources is necessary.

[4] In addition to the fixed interval of counting that we review, Iglehart and Morey also consider an inventory count that is triggered at the beginning of periods in which the cumulative demand since the last count first exceeds x units.

[5] The total error standard deviation is therefore $6 = \sqrt{400 * 0.09}$. Hence, approximately this figure translates into plus or minus 18 units of error.

stock due to RFID reduces this manager's inventory related cost by 5.9% (= (111.9 − 105.3)/(100 + 11.9)). The percentage cost reduction due to RFID is system dependent. It depends on the transaction error distribution as well as on the prior inventory management practice, i.e., before the use of RFID. As we argue later, the true value of RFID for inventory management can be obtained only after the best benchmark is established.

Iglehart and Morey provide a useful and easily implementable formula to hedge against inventory inaccuracies due to transaction errors. However, their approach is an approximation for two reasons. First, it assumes that the resulting optimal number of periods between successive counting periods is large. Second, it takes the underlying inventory control problem for the regular inventory as given and separates this problem from the transaction error management problem. In a way, the system carries two buffer stocks, one to hedge against the random transaction errors and the other one to hedge against the uncertain paying customer demand. So, the system does not gain from "risk pooling."

Recently, Kök and Shang (2004) study an inventory replenishment problem together with a counting (inventory audit) policy to correct transaction errors. As in Iglehart and Morey, they only consider transaction errors as a source for discrepancy and assume that these error terms are identically and independently distributed with zero mean. In particular, they consider a periodic-review, stationary inventory system in which transaction errors accumulate until an inventory count. The manager incurs a linear ordering, holding and penalty cost and a fixed cost K per count. The objective is to decide whether to count or not and how much to order to minimize the total cost of ordering and counting. Essentially, when the inventory is not counted the total transaction error term since the last inventory count, that is $e^{\tau} \equiv \sum_{k=1}^{i} D_k^{\tau}$, where i is the number of periods since the last inventory count, inflates uncertainty together with the random paying customer demand D^p. The trade off is whether to deal with a larger uncertainty $D^p + e^{\tau}$ or to count and incur K, but deal with a smaller uncertainty D^p.

Through a numerical study, the authors show that an *inspection-adjusted* base-stock policy is close to optimal[6] for a finite horizon problem. The policy is such that if the inventory record is below a threshold $\bar{x}$, an inventory counting is requested to correct the errors (that is, to set $e^{\tau} = 0$) and the optimal base stock level is s_0. Otherwise, the optimal base-stock level is $s(i)$. In a numerical study with a planning horizon $T = 4$ periods, they compare the cost of essentially two classical periodic-review inventory control problems for which base-stock policies are optimal. They compare the cost of a periodic review system facing demand uncertainty $D_t = D_t^p + D_t^{\tau}$ at each period to another one that faces only D_t^p. They interpret the first problem as the "never audit" scenario, yet the authors assume that the transaction errors are observed at the end of each period. They interpret the second problem as "no error" system. Comparing the two, they illustrate that the cost can be reduced by around 11% if the manager can eliminate all transaction errors.[7]

4.2. Shrinkage Only

Shrinkage due to theft, spoilage, or damage is more challenging to deal with than transaction errors. While transaction errors can occur independent of available inventory (such as mis-scanning of another product), shrinkage depends on the amount of available inventory.

Kang and Gershwin (2005) consider errors caused only by the *shrinkage* and its impact on inventory management through a simulation study.[8] They illustrate how shrinkage increases lost-sales and results in an indirect cost of losing customers (due to unexpected out of stock) in addition to the direct cost of losing inventory. The objective is to illustrate the effect of shrinkage on lost-sales through simulation. They do not consider transaction errors and misplacement, nor do they consider optimal inventory counting decision. However, they provide some plausible methods to compensate for inventory inaccuracy.

In particular, the authors address a continuous review system with (Q, R). They approximate this continuous review inventory system with a periodic-review system. Next, they simulate the periodic review system under a (Q, R) policy.[9] An alternative approach

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[6] They construct a lower bound to the original dynamic program by replacing the cost-to-go function with a convex cost-to-go function. They show numerically that the optimality gap is on average 0.4%.

[7] This comparison does not differentiate between the cost reduction due to *visibility* and *prevention.* Their comparison only gives us the value of prevention. For example, even without observing the transaction errors the manager can compensate for transaction errors using an *informed* policy. Comparing this informed policy with the above "never audit" scenario yields the true value of visibility. Later, in Section 4.3, we discuss in more detail the value of visibility and prevention.

[8] Kang and Gershwin refer to demand for *shrinkage* as demand for *stock-loss.*

[9] Note that a (Q, R) policy is often used for continuous review systems. The policy allows the manager to replenish inventory by placing a *fixed order* whenever the inventory position falls below a reorder level R. For a periodic review system, a better choice, for example, is an (s, S) policy, which allows the manager to place variable order at *fixed time intervals.* A fixed order quantity in a periodic review system may not be enough to bring the inventory level back to a level greater than the reorder point. Nevertheless, in their numerical study, Kang and Garshwin consider experiments

to Kang and Garshwin's simulation method is to use discrete event system simulation and generate demand for purchase and theft and study the continuous review system.

The sequence of events is as follows. The on-hand inventory record[10] is reviewed and an order z_t is placed if the inventory record x_t^r falls below the reorder point R. The incoming order is received and sales and shrinkage take place during period t. The system evolves as follows.

$$x_{t+1}^r = x_t^r + z_t - a_t$$

$$x_{t+1}^a = x_t^a + z_t - a_t - \min\{D_t^s, x_t^a + z_t - a_t\},$$

where a_t is *sales* in period t and x_t^a is the *actual* inventory on hand. D_t^s is the total shrinkage during period t.

The realization of a_t is different from that of paying customer D_t^p. Total sales depends on the actual inventory available at the store when demand for purchase arrives. The authors estimate the sales as follows

$$a_t = \begin{cases} D_t^p, & \text{if } D_t^p + D_t^s < x_t^a + z_t, \\ (x_t^a + z_t)\dfrac{D_t^p}{D_t^p + D_t^s}, & \text{otherwise.} \end{cases}$$

The above is an approximation because the actual sales depend on the sequence of shrinkage and paying customer arrival.[11]

In such a system, the inventory record can deviate from actual on-hand inventory due to shrinkage, which depletes physical inventory but leaves inventory record unchanged. The discrepancy between x_t^a and x_t^r grows *until* the actual on-hand inventory hits zero ($x_t^a = 0$) and customers consistently leave the store without purchasing ($a_t = 0$) *while* the inventory record is still higher than the reorder level ($x_t^r > R$). This event is referred to as "replenishment freeze" at which point the system stops placing replenishment orders and the inventory discrepancy remains constant. However, lost-sales increase to the maximum possible level equal to D_t^p for all periods after a replenishment freeze.

The authors simulate a daily-review system with $Q = 40$, normally distributed paying customer demand with $\mu_{D_t^p} = 10$, $\sigma_{D_t^p} = 2$, supply lead time $L = 3$, and planning horizon of $T = 365$ days. Through simulation runs, they obtain a reorder level of $R = 41$ that produces approximately a stock-out of 0.5%, that is, lost sales as a percentage of total demand over the planning horizon T. Next, shrinkage distributed with Poisson with mean λ is introduced into the simulation model. When the average shrinkage is at 2.4% (that is, $\lambda = 0.24$), it is shown that more than half of the customer demand is lost due to inventory inaccuracy. The indirect profit loss due to lost-sales as a result of inventory inaccuracy (due to shrinkage), is shown to be ten to twenty times higher than the direct loss of inventory to shrinkage. These results are parameter-sensitive and are based on simulation runs. In particular, they depend on the rate of shrinkage, the order size, demand rate, reorder level, *and* the planning horizon T. Any period after a replenishment freeze may also likely signal an error in the system. Nevertheless, such simulation analysis enables a company to quantify the impact of shrinkage and the resulting lost-sales under various plausible scenarios.

The authors also consider methods to compensate for shrinkage and to reduce their impact on lost-sales. Some of the methods that they consider are (1) counting the inventory, for example, twice in a year, (2) adjust the inventory record by reducing it with the mean of shrinkage at each period, i.e., set $x_{t+1}^r = x_t^r + z_t - a_t - \lambda$, and (3) invest in RFID which is assumed to provide perfect measurement of inventory record, that is $x_t^r = x_t^a$ at all time periods. By simulating the system under these suggested corrective actions, the authors plot the resulting average stockout (lost-sales) against average inventory.

These simulations are used to illustrate that, when the adjustment to inventory record is not taken to avoid inventory inaccuracies due to shrinkage, a small rate of shrinkage can significantly affect the replenishment process and create high level of stockouts. To compensate for such stockouts, the manager needs to carry substantially more inventory when a corrective action is not taken as opposed to a system that works to eliminate discrepancy in inventory record and actual inventory. The numerical study also suggests that even without RFID, the manager can effectively control the inventory inaccuracy problem (as illustrated in Figure 1).

Note that there is a small resemblance of the inventory discrepancy problem due to shrinkage to the conventional inventory models with random yields (see Yano and Lee 1995, for a review). However, random yield model usually have yield loss occurring to incoming replenishments and not to existing inventory and yield loss is revealed immediately, so there is no uncertainty about the shrinkage once a replenish-

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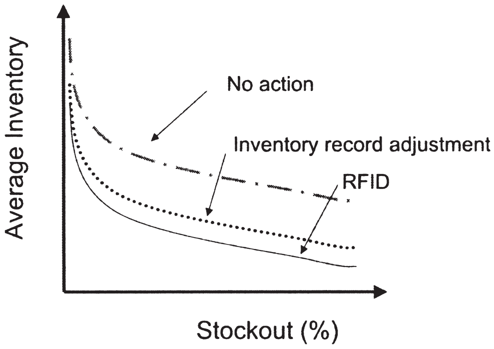
with frequent review periods (i.e., daily reviews) and large order quantity (i.e., $Q = 50$) and small demand (i.e., $\mu_{D_t^p} = 10$ and $\sigma_{D_t^p} = 2$). Hence, it is likely that after ordering, the inventory position in their numerical study is brought to a level larger than R.

[10] Inventory position (on-hand plus the pipeline inventory) record when the system is facing a positive supply lead time.

[11] The authors round the second line in the equation to the nearest integer.

Figure 1 **Impact of RFID on average inventory and stockout.**



ment arrives. In a similar context, Rekik, Sahin, and Dallery (2006) compare newsvendor solutions to provide some insights into the benefit of RFID technology.

4.3. Misplacement, Shrinkage, and Transaction Errors

The scant previous modeling work to assess the impact of shrinkage and transaction errors contributed to our understanding of the potential value of RFID in both the reduction/elimination of the errors and shrinkage, and the visibility of such occurrences. But as we noted earlier, the inventory accuracy problem is rarely a result of only shrinkage or only transaction errors, but both. In fact, there are many sources that lead to discrepancies of inventory record and actual inventory. The previous work did not consider any other major sources—misplacements of inventory, and the joint effect of multiple sources. To fully assess the value of visibility afforded by RFID, one needs to have models that consider the joint effects of these multiple sources.

The first attempt that treats multiple sources of inventory inaccuracies is Fleisch and Tellkamp (2005). Three key sources are explicitly modeled: theft and unsaleables, misplaced items, and incorrect deliveries. Unsaleables are due to damaged goods or products that have exceeded their shelf life, and so they are shrinkage similar to theft. Incorrect deliveries are deliveries from the supplier that are different from the stated delivered quantities. If incorrect deliveries were not identified by the receiver, then the receiver's inventory record and actual inventory will differ. Fleisch and Tellkamp (2005) use a simulation model to evaluate the impact of these multiple sources to stockouts and total operating costs of the system. The value of RFID is assessed by creating a parallel simulation model where, in each period, the quantities of these discrepancies were identified, and the inventory control system can then be based on the actual inventory. The simulation model is based on a three level supply chain, where discrepancies can occur at each level. The multiple simulation runs gave rise to summary observations which can be used for statistical analysis.

The simulation work of Fleisch and Tellkamp (2005), while a good first attempt, has some limitations. First, simulation models do not readily give rise to structural results. Second, the authors do not consider what decision makers can do in the presence of discrepancies. Hence, the benchmark is based on a naive inventory system, as opposed to a "smarter" one that would take account of the potential discrepancies to make better reorder decisions. With the benchmark used, the value of RFID could be over-estimated. To-date, the first analytical model that considers all the three key sources of discrepancies jointly, and which addresses the two limitations of the simulation approach of Fleisch and Tellkamp (2005), is the recent work of Atali, Lee, and Özer (2004, 2006).

Atali, Lee, and Özer (2004, 2006) characterize three different kinds of demand streams that result in inventory discrepancy. Some demand streams result in permanent inventory shrinkage (such as theft and damage). They refer to this stream as *shrinkage.* Some demand streams are temporary and can be recovered by physical inventory audit and returned to inventory (such as misplacement). They refer to this demand stream as *misplacement.* The final group of demand stream (such as scanning error) affects *only* the inventory record and leaves actual inventory unchanged. They refer to this stream as *transaction errors.*

This characterization is necessary for two reasons. First, each of these demand sources affects the inventory management system (and the control problem) differently. Second, RFID can eliminate some of the error sources, but not all. Hence, to accurately assess the magnitude of improvements of such technologies, one needs to have the distinct demand streams explicitly modeled.

To fully capture the impact of inventory discrepancy, the authors explicitly model and incorporate the three demand sources for discrepancy in addition to the paying customer demand to a finite horizon, single-item, periodic-review inventory problem. They show how an optimal inventory control can be designed in the presence of unobserved inventory discrepancies in real time, using only statistical estimates, such as their distributions, of the demand streams. The model is also used to assess the value of having visibility of inventory and the elimination or reduction of some of the causes of inventory discrepancy. This model is a concrete step towards measuring the true values within a company brought forth by RFID as a visibility technology.

Demand streams for paying customer, misplacement, shrinkage, and transaction error affect the system differently.

Paying customer demand affects both the inventory records and actual inventory. This demand stream is the only one where the manager incurs penalty cost for unsatisfied customers. It is also the only one whose realization is tracked by point of sales data. Let $D_t^p \geq 0$ denote the random demand from customers who arrive at the store to purchase the product during period t.

Misplacements are the most challenging among the four demand streams to incorporate in an analytical model because they affect *sales-available* inventory and their realizations are affected by the level of *sales-available* inventory. Note the difference between physical and sales-available inventory. Kang and Gershwin (2005) and others use the term *actual* or physical inventory (instead of sales-available) because they do not consider misplacement. When the system faces errors due to misplacement, part of the "physical" inventory is still not accessible to customer. Hence, the manager must differentiate between physical inventory and *sales-available* inventory when the system faces discrepancy due to misplacement. Misplacement reduces sales-available inventory but leaves physical inventory unchanged. In addition, misplacements are returned back to inventory after an inventory count; hence their presence can increase or decrease the sales-available inventory. The inventory manager continues to incur a holding cost even when the misplaced item is not available for sales. Let $D_t^m \geq 0$ denote the number of misplaced items during period t.

Demand for **shrinkage,** such as theft, unobserved damage, and spoilage affect the physical inventory but leave the inventory record unchanged. Unlike misplacement, they cannot be returned back to inventory. The realization of this demand stream cannot be negative. If shrinkage and misplacement are the only demand source (in addition to the paying customer demand), the inventory record will always be larger than the sales-available on-hand inventory. Let $D_t^s \geq 0$ be the demand for shrinkage during period t.

Technically, **transaction errors,** such as scanning errors, are easier to deal with compared to theft or misplacement because they affect only the inventory *record* but leave the physical inventory unchanged. They can often be modeled as zero mean random disturbances and are independent of the level of physical inventory. Let D_t^τ be the transaction error during period t. The realization of this demand stream could be positive or negative, unlike shrinkage or misplacement.

Misplacement, shrinkage and transaction errors would be unnoticed between consecutive inventory audits without tracking technologies such as RFID. These errors accumulate until a physical inventory count is carried out. They denote by e_t^m, e_t^s, e_t^τ, the accumulated error terms due to misplacements, shrinkage and transaction errors, respectively, since the last inventory audit. Physical counting of inventory is carried out every N periods, when misplaced items are returned to inventory; accumulated error terms are set to zero; and the on-hand inventory record is set equal to actual on-hand inventory. The total error is denoted by $e_t = e_t^m + e_t^s + e_t^\tau$.

The sequence of events is as follows. (1) At the beginning of period t, the inventory manager reviews the state of the system and decides how much to order $z_t \geq 0$ from an outside supplier with ample supply. The replenishment lead time is assumed zero. The cost of ordering is c_t per unit. (2) Sales and inventory errors due to misplacement, theft, and incorrect transaction take place during the period. (3) At the end of the period, the manager incurs a linear holding cost h_t and a linear lost-sales cost p_t based on the end of period physical on-hand inventory. Holding cost is incurred for the misplaced items even though they are not available for sales. No lost-sales cost is incurred for unmet demand from nonpaying customers. (4) If the period is a counting (audit) period, an inventory audit is conducted at the end of that period. The inventory record is reconciled: error is corrected, and all misplaced items are returned to inventory. Otherwise, errors continue to accumulate. The planning horizon is a multiple of counting cycle length, that is, $T \in \{N, 2N, 3N, \ldots\}$. At the end of the planning horizon T, the inventory left over is sold for a linear salvage value of c_{T+1}.

RFID has two values to an inventory manager. First, the visibility provided by this technology allows inventory replenishment to be more precise by eliminating the discrepancy between inventory record and physical inventory. This visibility can eventually scrap the need for regular inventory audits. Second, the magnitude of some of the causes of inventory discrepancy, such as shrinkage, may be reduced. Being able to monitor paying and non-paying customer demand, the manager can act to prevent or discourage, for example, theft. The authors first focus on the value of *visibility.* To do so, they establish an inventory control policy when the manager observes the realization of all demand streams through RFID. The authors also provide a policy that partially compensates for the discrepancy problem in the absence of RFID. Comparison of these two models constitutes the *true* value of visibility due to RFID.

4.3.1. RFID-Enabled Model: Visibility. At the beginning of period t, the manager observes the inventory record x_t^r, the error terms e_t^s, e_t^m and e_t^τ and the number of periods elapsed since last inventory count, i_t. The state space of such a system can be summarized by (x_t, e_t^m, i_t), where

$$x_t = x_t^r - e_t^m - e_t^s - e_t^\tau$$

is the *sales-available* on-hand inventory, and $i_t \in \{0, 1, \ldots, N-1\}$. The state of the system evolves according to the following equations.

$$x_{t+1} = \begin{cases} [y_t - D_t]^+, & \text{if } i_t \neq N-1 \\ [y_t - D_t]^+ + e_t^m + m_t, & \text{if } i_t = N-1 \end{cases} \quad (2)$$

$$e_{t+1}^m = \begin{cases} e_t^m + m_t, & \text{if } i_t \neq N-1 \\ 0, & \text{if } i_t = N-1 \end{cases} \quad (3)$$

$$i_{t+1} = (i_t + 1) \bmod N, \quad (4)$$

where $y_t = x_t + z_t$ and $D_t = D_t^p + D_t^s + D_t^m$ and m_t is the realized misplacement. The single period expected holding and penalty cost charged to period t is based on *sales-available* on-hand inventory and the accumulated misplacement.

$$\tilde{G}_t(y_t, e_t^m) = h_t E_{D_t, m_t}([y_t - D_t]^+ + e_t^m + m_t) + p_t E_{D_t^p, a_t}(D_t^p - a_t), \quad (5)$$

where a_t is realized sales. Transaction errors are random observation disturbances and they have no direct impact on the *sales-available* on-hand inventory x_t.

With perfect visibility, the manager optimizes the stock levels in full awareness of the inventory errors that take place during period t. Let J_t^v be the cost of managing this system for a finite horizon with $T - t$ periods remaining to the termination planning horizon. The optimal replenishment policy would be to select the value of y_t that minimizes the following dynamic programming algorithm.

$$J_t^v(x_t, e_t^m, i_t) = \min_{y_t \geq x_t}\{G_t(y_t, e_t^m) + \alpha E J_{t+1}^v(x_{t+1}, e_{t+1}^m, i_{t+1})\}, \quad (6)$$

where $J_{T+1}^v(x_{T+1}, \ldots) = 0$ and $G_t(y_t, e_t^m) = c_t y_t - \alpha c_{t+1} E x_{t+1} + \tilde{G}_t(y_t, e_t^m)$. The left overs at the end of the planning horizon $T + 1$ are salvaged for a linear price. The revised cost function $G_t(\cdot, \cdot)$ is the outcome of a transformation used to obtain an equivalent DP with zero salvage value (Atali, Lee, and Özer 2004).

To calculate the aforementioned expectations in the dynamic programming algorithm, we need to obtain the distribution of sales a_t and misplacement m_t during any period t. The realization of these variables and their distribution depend on the sales-available on-hand inventory x_t and the order in which misplacement, shrinkage and paying customer demands arrive. This sequence is impossible to know ex ante. Hence, one has to construct bounds for this DP.

To obtain a **lower bound model,** the authors consider a modified model in which the paying customer demand always arrives first, demand for shrinkage arrives next and demand for misplacement arrives last. With this sequence, sales during any period is maximized while the misplacement is minimized. The transaction error can arrive in any order because it does not affect the physical inventory. Given this sequence, the sales and the misplacement during period t are

$$a_t = \min\{D_t^p, y_t\}, \quad (7)$$

$$m_t = \min\{D_t^m, [y_t - D_t^p - D_t^s]^+\}. \quad (8)$$

The state of the system evolves according to the Equations in (2–4), but with m_t replaced by its new definition above. Similarly, the single period cost function is the same as in Equation (5) but with a_t and m_t replaced by their respective definitions. The optimal replenishment policy would be to select the value of y_t that minimizes the following dynamic programming algorithm.

$$R_t^{LB}(x_t, e_t^m, i_t) = \min_{y_t \geq x_t}\{G_t^{LB}(y_t, e_t^m) + \alpha E R_{t+1}^{LB}(x_{t+1}, e_{t+1}^m, i_{t+1})\}, \quad (9)$$

where $R_{T+1}^{LB}(x_{T+1}, ., .) = 0$.

Similarly to obtain an **upper bound model,** the authors consider another arrival sequence, in which the misplacement arrives first, demand for shrinkage arrives next and paying customer demand arrives last. With this sequence, sales during any period is minimized while the misplacement is maximized.

Atali, Lee, and Özer (2004) show that the resulting models with these particular arrival sequences result in two DPs that yield cost lower and upper bounds to the original DP with arbitrary demand arrival sequence.

Theorem 1. *$R_t^{LB}(x_t, e_t^m, i_t) \leq J_t^v(x_t, e_t^m, i_t) \leq R_t^{UB}(x_t, e_t^m, i_t)$ for any given state (x_t, e_t^m, i_t).*

Intuitively, for the lower bound model, the penalty and holding cost is smaller since the manager satisfies more paying customers and incurs less penalty and holding cost than a system with any other arrival sequence. Hence, the cost of an optimal policy, which is a solution to the DP in Equation (6), must lie between the lower bound model and the above upper bound model.

The authors also provide a simple, easy-to-use and close-to-optimal **heuristic.** To do so, they consider error sources misplacement and shrinkage to be independent of actual inventory regardless of the level of sales available-on hand inventory. Under this assumption, the authors obtain the following result.

Theorem 2. *An optimal policy for the DP with the above mentioned assumption is a state-dependent base-stock policy and the base stock level is given by* $S_t(e_t^m, i_t)$, *which depends on the accumulated misplacement and the number of periods since the last inventory audit*.

Now a manager can use these base stock levels as a heuristic policy for the original problem. To obtain the cost of implementing this heuristic policy, the authors simulate the system (with arbitrary demand arrivals) under this heuristic. The resulting cost is an upper bound to J_t^v defined in Equation (6) because it is a *feasible* policy. Atali, Lee, and Özer (2004) show that the cost difference between this upper bound and the lower bound (which constitutes the optimality gap) is quite small.

4.3.2. RFID-Enabled Model: Prevention. In addition to providing visibility to the system, RFID can also reduce costs by eliminating redundant operations. Being able to observe the misplaced items, shrinkage and inventory in real time, the manager can re-shelve misplaced items at the end of each period instead of waiting for a particular counting period, that is $N = 1$. Hence, RFID may reduce the frequency of inventory audits or completely eliminate them. Tracking and tracing inventory may also enable a manager to reduce the sources of inventory discrepancy. Atali, Lee, and Özer (2004) model these cases to quantify the value of prevention for an RFID-enabled system.

When $N = 1$, we have $e_t^m = 0$ for any period t. This new system has a smaller state space. In particular, x_t is the only state variable. At the end of period t, the sales-available inventory on-hand x_{t+1} is updated as

$$x_{t+1} = [y_t - D_t]^+ + m_t. \tag{10}$$

The sequence of paying customer demand and misplacement still affects the performance of the system. Hence, an analysis similar to the one in the previous subsection yields **lower and upper bound models.** These sequences result in the same characterization of sales a_t and misplacement m_t as in Subsection 4.3.1, that is, for the lower bound model sales and misplacement are given by Equations (7) and (8). The difference is in the state space and in the single period cost function.

The authors provide a simple **heuristic policy** for this scenario as well. By comparing the result of this heuristic policy to the one in the previous subsection, the authors reveal one of the values of RFID, that is, elimination of inventory counts. Note that the value of being able to scrap inventory counts could be larger than the value provided by this comparison. Often inventory audits have a fixed cost that can be eliminated when the manager does not need to count inventory.

4.3.3. Without RFID: Lack of Visibility. In a system without RFID, or a system that lacks inventory visibility, the manager is unaware of the accumulated errors status until the inventory is counted physically. He has two ways to manage such a system. The first way is to ignore the discrepancy issue and simply follow an inventory policy established for a system that does not face the discrepancy problem. Empirical and survey analysis show that most of the current inventory management systems ignore these errors. We refer to this policy as an *ignorant* policy. The second way is to develop an *informed* policy that recognizes the existence of discrepancy even though it cannot observe the discrepancy. To obtain the *true* value of visibility created by RFID, we compare the *informed* inventory control policy to the one with RFID-enabled policy of Section 4.3.1. Atali, Lee, and Özer (2004) provide one such informed policy, which we summarize next.

Without RFID, the manager is left with the inventory record information x_t^r and the number of periods since the last inventory count i_t. Atali, Lee, and Özer (2004) define a system whose state at period t is the set of all variables the knowledge of which can be of benefit to the inventory manager when making the replenishment decision at period t. Under a mild assumption, the authors show that the state of such a system is given by x_t^r and i_t. Also the manager this time observes $a_t^r = a_t - D_t^\tau$, record of sales. The state updates are then

$$x_{t+1}^r = \begin{cases} y_t^r - a_t^r, & \text{if } i_t \neq N-1, \\ [y_t^r - e_t - D_t]^+ + e_t^m + m_t, & \text{if } i_t = N-1 \end{cases} \tag{11}$$

$$i_{t+1} = (i_t + 1) \bmod N, \tag{12}$$

where $y_t^r = x_t^r + z_t$. Next, the authors provide a dynamic programming formulation for this inventory problem.

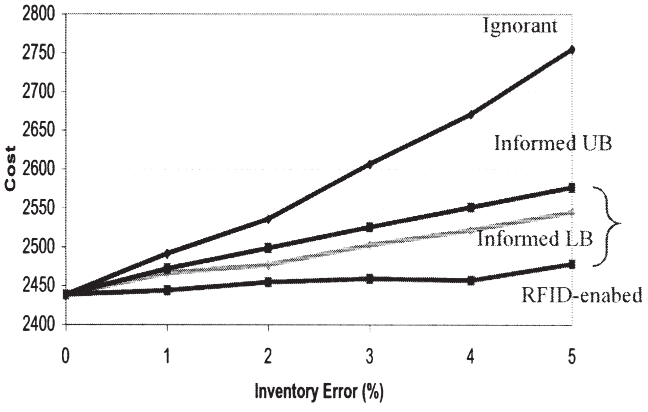
As in the previous subsections, the above state updates, the expectations in the DP formulation depend on the realization of sales a_t and misplacement m_t, which in turn depend on the sequence of paying customer, misplacement and shrinkage arrival. Similar to the RFID-enabled system, **lower** and **upper bound** models can also be obtained. The authors also propose a simple close-to-optimal **heuristic policy,** which is a base stock policy.

4.3.4. Imperfect RFID. In Subsection 4.3.1, RFID was assumed perfect in that it does not cause any transaction errors. However, a developing technology is perfected over time. Atali, Lee, and Özer (2004) also consider the scenario in which RFID is not perfect. In other words, scanning errors, or in this case RFID reading errors introduce discrepancy between actual inventory and inventory records. Errors in reading tags accumulate until a physical inventory audit takes place. The authors formulate a dynamic program in the presence of errors due to RFID readings. The analysis is similar to the case without RFID, however, with different state updates.

4.3.5. Value of RFID. RFID has two distinct values: visibility and prevention. Each of these values can be measured by comparing lower and upper bound models. These comparisons yield a maximum and a minimum value for RFID. Consider, for example, the value of visibility. When the system is not RFID-enabled, the manager can use either the *informed* policy developed in Subsection 4.3.3 or an *ignorant* policy that is obtained without taking into consideration the discrepancy problem. The *true* value of visibility is given by the cost difference between the informed policy and the RFID-enabled policy of Section 4.3.1. The *minimum* value of visibility is given by the comparison between the cost of the lower bound model developed for a system without RFID in Section 4.3.3 and the upper bound model for the RFID-enabled system in Section 4.3.1. The maximum value can similarly be obtained. Comparing the cost of the proposed heuristics under each scenario gives us the value of RFID that can be captured if the manager follows the proposed heuristics.

Figure 2 compares the resulting cost for a problem instance as a function of total error with respect to paying customers. The lowest curve is the cost of following a policy that is an optimal solution to the lower bound model when the system is RFID enabled (i.e., the lowest cost the manager can expect to incur by using RFID). This figure illustrates that by using an informed policy to compensate for the discrepancy problem, the manager can reduce the costs significantly. The value of RFID also increases with the total percentage errors. For an example, consider a system with $h = 1$, $c = 2$, $p = 19$, $T = 10$, $N = 5$. The manager faces the following demand distributions: D^p is Normally distributed with mean 20 and std 4; D^s is Poisson with mean 0.35; and D^m is Poisson with 0.40 per period.[12] When compared to the ignorant policy, the RFID-enabled system reduces cost by 9.1% and increases sales by 1.8% due to visibility. However, when compared to the informed policy, the cost is reduced by 3.1% and the sales is increased by 0.1%. For this system, assuming that RFID also enables one to reduce the shrinkage rate by 50%,[13] the manager can save (the difference between the RFID-enabled systems with different shrinkage rates) an additional 2.6%, and increase sales by 0.1%, both of which can be interpreted as the value of prevention due to RFID. Atali, Lee, and Özer (2004, 2006) provide an extensive numerical study to quantify the value of RFID as a function of audit frequency, individual error sources and the planning horizon.

Figure 2 **Value of RFID as a function of error source.**



4.3.6. Demand Model with Random Disaggregation. Recently, Atali, Lee, and Özer (2006) model demand streams using a random disaggregation model. In particular, let D_t denote the random customer demand during period t. An arriving customer buys the product with probability θ_t^p; misplaces the item with probability θ_t^m; or damages/steals the item with probability θ_t^s such that $\theta_t^p + \theta_t^m + \theta_t^s = 1$ for all t. Both demand modeling approaches have their own appeal. Random disaggregation approach simplifies the previous analysis. In particular, one does not need to construct bounds through demand prioritization. Calibrating the model and fitting data is relatively simpler as well. Note also that paying *and* non-paying customer demands are related through D_t. For example, when a product is sought after by paying customers it will also be attractive for thieves. Yet, the previous approach allows for independent demand streams for paying and non-paying customers. One can also fit different distributions to each demand streams. For example, misplacement could be due to the complex store environment or back-room operations which may have no effect on paying customer demand.

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[12] Roughly speaking, the average shrinkage level is 1.75% of average sales and the average misplaced items is 2% of sales without any transaction errors. Note that without the knowledge of the actual data, the conversions of these average statistics to distributions are very rough estimates. The scenario discussed here is meant as a simple illustration.

[13] The studies by Alexander et al. (2002) and Chappell et al. (2002a) both indicate that the total non-paying demand is reduced by 50% with RFID.

Hence, the previous approach is relatively more "flexible" at the expense of making the analysis complex and relatively less transparent in providing insights.

5. Value of Visibility Across Companies: Downstream Information Shared Upstream

The Wal-Mart initiative of requesting its top suppliers to provide RFID-ready cases and pallets to the Wal-Mart DC is considered to be a major landmark in the advancement of RFID. As mentioned earlier, since then a number of major retailers, such as Albertsons, Target, and Tesco, as well as the US Department of Defense (DoD), have followed suit. While RFID-ready cases and pallets will make it much easier for the retailers and DoD to track and audit their inventory receipts and movements, the benefits to the suppliers (manufacturers) are not so clear-cut. The usual argument was that retailers like Wal-Mart would share the information on when and how much the inventories are used to satisfy demands, which should be of value to suppliers. The idea is that the downstream visibility of inventory movement can help suppliers better predict the demands that will be forthcoming from the downstream sites.

We are not yet aware of explicit RFID-based analytical research that focuses on how suppliers can make use of downstream visibility to coordinate the supply chain, which would of course give rise to the value of RFID in providing downstream visibility. But there is actually a rapidly increasing literature on the value of information sharing from retailers to manufacturers in a supply chain, which mimics the value of downstream visibility provided by RFID technology. Information sharing is usually in the form of sharing the retailer inventory levels with the supplier. If RFID technology enables the supplier to have real-time demand information at the retailers, then effectively, the supplier would know the inventory levels at the retailers. Hence, the production and operations management community has already provided the groundwork for more concrete assessment of RFID values in this regard. Here, we briefly review some representative work in this area.

Gavirneni, Kapuscinski, and Tayur (1999) explore the value of information sharing by a retailer to a supplier that is capacity-constrained when the retailer uses a periodic-review (s, S) inventory control policy. By knowing the retailer inventory position, the supplier can better utilize its limited capacity. In a similar two-level supply chain with non-capacitated supplier, Lee, So, and Tang (2000) show that information sharing can have great values when the demand stream is not IID, but follows an AR(1) model. The value to the supplier is that the supplier can reduce its demand uncertainty through the knowledge of point of sales (POS) at the retailer. Raghunathan (2001), however, shows that the value of sharing POS data diminishes as the supplier uses more complete order history to forecast the retailer's future orders.

In a multiple retailer setting, Cachon and Fisher (2000) consider the use of retailer inventory information by the supplier to better allocate stock to the retailer. All retailers use a (Q, R) inventory control policy. A simple but optimal rule is to prioritize the retailers based on their needs, i.e., in ascending order of their inventory positions. Moinzadeh (2002) considers a similar model, but shows that the supplier can use a simple reorder policy to make even greater improvements. The simple reorder rule is based on the inventory position at the retailer, and the essence is that the supplier should trigger its reorder decision before a retailer's inventory position reaches its reorder point. This way, the supplier can be proactive, and get replenishment early in anticipation of the order coming in from the retailer.

Instead of simply reacting to retailer orders, Cheung and Lee (2002) show that the supplier can improve its performance by being the decision maker to initiate the replenishment orders to the retailers. Of course, to be able to do so, the supplier has to have information on the inventory positions at the retailers. This is a setting similar to the common VMI (Vendor-Managed Inventory) system. In addition to determining when a replenishment order should be initiated, the supplier can also make last minute allocation of the inventory to the retailers when the order finally arrives at the retailer sites. Cheung and Lee (2002) call this stock rebalancing, and it is appropriate only when the retailers are in close geographical proximity to one another.

Retailer inventory information helps the supplier (or the distribution center) to better predict the orders that will be placed by the retailers, leading to improved performance at the supplier. A similar benefit can be achieved if customers place orders in anticipation of future requirements. The retailers can share this information with the supplier. There is a line of research that focuses on the value of using such information, known as ADI (Advance Demand Information). For a centralized system, Özer (2003) establishes inventory control policies for a supplier that replenishes the inventory of multiple retailers who obtain ADI. The author also provides *closed-form* solution to approximate the system wide inventory level. Using such explicit solutions, and the replenishment policies, he quantifies the joint role of risk pooling and ADI for a periodic review distribution system. The author also shows how ADI can be a substitute for replenishment lead times and inventory and how it enhances the outcome of delayed differentiation. Recently, for a decentralized system, Lutze and Özer (2003) show how the supplier can use ADI to segment the market when retailers differ in their service strategy to end customers. They provide a pricing mechanism to share the benefits of ADI between a supplier that supplies multiple products to multiple retailers. They also consider the impact of point of localization, postponement strategies to this mechanism. Gallego and Özer (2001a,b) provide a comprehensive review of this literature that uses current demand information (obtained through POS data as discussed previously) and advance demand information (obtained through, for example, the Internet) to drive inventory replenishment policies in supply chains.

Inventory sales information shared upstream could be delayed due, for example, to order processing, lack of proper information systems or management. Chen (1999) shows that information lead time—defined as the delay between the time an order is placed by a retailer and the time the order request is received by its supplier—plays a very similar role as the transportation lead times in the determination of the optimal replenishment strategies. The author also illustrates that the information lead times are less costly than the supply leadtimes. Recently, Bensoussan, Cakanyildirim, and Sethi (2005) address how to manage a single-item, periodic-review inventory control problem when the state information, e.g., the actual value of net inventory, is observed after a time delay. RFID can possibly reduce such information delays and help managers to obtain timely information regarding the status of an order as well as the state information. These models can be used to quantify the value of "timely" information. The idea would be to solve a DP without delay (or information leadtime) and another one with delay.

Although none of the above models mention RFID, they certainly can be adapted as quantitative models for the assessment of the value of RFID in providing downstream visibility to a supply chain. There are two possible modeling areas related to this literature.

First, RFID may help reduce information asymmetries between firms and share downstream information *credibly* with the upstream. We are unaware of any model-based analysis to quantify the value of RFID in such a setting. Nevertheless, we provide a brief discussion of this literature in Section 5.1 to provide pointers for future research.

Second, RFID can also provide downstream information regarding the potential returns of inventory from customers. Recently, Karaer and Lee (2005) summarize research based on Intel Corporation's DC having to process customer returns. Unlike customer demands, customer returns will add to the inventory pile as opposed to depleting it. In that sense, the returns can be viewed as RFID providing downstream visibility of "negative" demands. We describe some highlights of this model in Section 5.2.

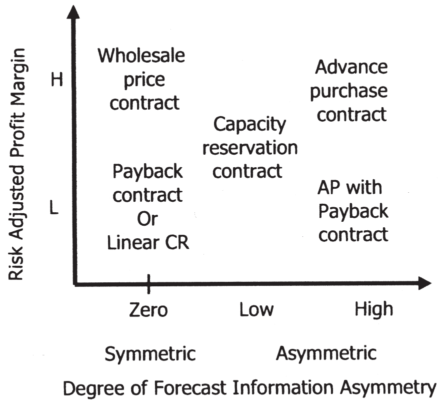
5.1. Asymmetric Information and RFID

RFID can reduce information asymmetries and the incentive problems arising between a downstream and an upstream party. Two main sources of information asymmetry for a supply chain are costs and forecasts. A growing literature focuses on contract design to achieve credible information sharing between parties (for a comprehensive review, see Cachon 2003; Chen 2003).

Wal-Mart's suppliers are often concerned that RFID costs are mainly shouldered by the supplier while the benefits accrue only to the retailers. Notice, however, that being able to track the inventory and sales better at the retail level enables the retailer to improve her forecasts. The retailer shares better forecast information with the supplier. This improved information in turn helps the supplier better plan for capacity. However, the downstream party may have an incentive to provide inflated forecasts. Cohen et al. (2003) provide empirical evidence for the forecast inflation problem and several examples from various industries. This incentive often makes it difficult for the supplier to trust the forecast information provided by the retailer. Using contracts designed for the retailer to offer to the supplier (Cachon and Lariviere 2001); or contracts designed for the supplier to offer to the retailer (Özer and Wei 2006), the supply chain can achieve credible forecast information sharing.

Özer and Wei (2006) develop various contracts and provide explicit formulae to enable credible forecast information sharing. The authors also identify two key drivers of the (supplier's, retailer's, and the supply chain's) expected profits under different contracts. These drivers are the *risk adjusted profit margin* and the *degree of forecast information asymmetry*, which is a measure of how much the retailer (the downstream party) knows about demand as compared to the supplier (the upstream party). One possible measure of degree of forecast information asymmetry is the ratio of the standard deviation of the supplier's and the retailer's forecast errors. The authors show that the supplier and the retailer can choose among structured agreements that enable a mutually beneficial partnership depending on these two factors. The results are summarized in Figure 3. For example, when forecast information between the parties is highly imbalanced, and the risk adjusted profit margin is high, then their analysis shows that the advanced purchase contract

Figure 3 **Mutually beneficial contracts.**



generates higher profits for both parties. Özer (2004) also maps various industries along these two dimensions based on private conversations with executives from several industries as shown in Figure 4. For example, in the semiconductor industry, compared to the manufacturer (the downstream party in this industry), the supplier knows very little about the manufacturer's private forecast. Further empirical and field research is needed to verify Figure 4.

Note, however, that often contractual agreements are difficult to administer and could be complex to describe. Instead, if the supplier is granted permission to observe the movement of inventory and sales, that is, if the supplier has access to RFID data, he may better predict and verify the retailer's forecast. Hence, RFID here can enable the retailer both to improve her forecasts and to reduce forecast information asymmetry.

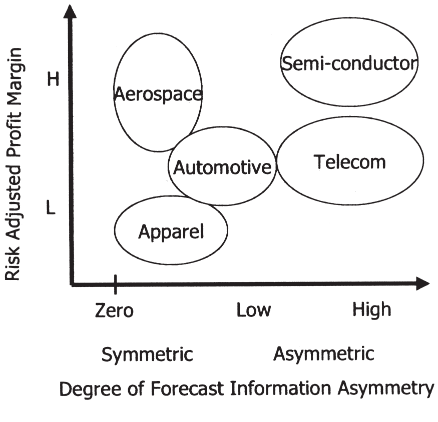
Similarly, RFID may enable verification of the service level provided by the retailer to the end consumers. The supplier often charges a higher price for shorter delivery lead times because a shorter lead time requires him to carry more safety stock, whereas it requires the retailer to carry less back-room inventory. However, this price implicitly depends on the service level provided by the retailer to the consumer. Recently, Lutze and Özer (2004) study promised lead time contracts that explicitly set prices for corresponding lead times. The supplier agrees to ship orders in full after a promised lead time, and the buyer pays the supplier for this privilege. The supplier and retailer each carry inventory, depending on the agreed upon promised lead time and their respective production and processing lead times. A promised lead time shifts responsibility for demand uncertainty from the supplier to the retailer. The authors structure an optimal price lead time pair. They also show that the retailer has every incentive to conceal his service level provided to consumers. If asked for this information, the retailer has an incentive to exaggerate the service level, thereby shortening the promised lead time for the same agreed upon price and reducing his expected inventory cost per period. However, if the retailer is RFID-enabled, and the inventory movement, lost sales, and sales information are shared, over time the supplier may learn the true service level provided by the retailer. Hence, RFID can enable parties to share service information credibly and without explicitly designed contracts.

Hence, the information collected by RFID is also valuable for the supplier. Note that the difference between the resulting cost or benefit of a contractual agreement under symmetric information and asymmetric information can provide the value of RFID in enabling credible information exchange.

5.2. Reverse Channel with RFID

Consider a distribution center (DC) that stocks inventory to meet customer demands. Customers may also return products to the DC. Returned products have to be inspected, verified for customer reimbursement or credit updates, reworked or refurbished if necessary, and then returned to the DC inventory stockpile to satisfy new demands. Clearly, if the rework or refurbishment is significant, the product cannot be sold as new. But often, returns are products that are unused, and the rework or refurbishment consists of simple testing and repackaging. There is a lead time in processing the returned items. Most DCs do not have good visibility of what is in the pipeline of the return channel. As a result, they manage their inventory stockpile either ignoring the return channel inventory, or use some adjustment to account for the possible return channel inventory. One potential use of RFID is that, if the product has an RFID-tag attached to it, then the visibility of the return channel inventory is assured easily. Inventory in the return channel acts like future "negative" demands, and so the visibility of the return channel is similar

Figure 4 **Capacity risk drivers across different industries.**



to having advanced negative demand information. This should help the DC to manage its inventory more efficiently.

A simple model to capture the value of RFID in this case can be developed as follows. Suppose that the DC uses a periodic review inventory control policy to reorder the product from the factory, which is assumed to have ample capacity. Customer demands and returned products follow two independent IID distributions. The replenishment lead time from the factory is L periods. The processing of return items consists of two stages. First, there is an inspection and evaluation stage, which takes L_1 periods. After this stage, a fraction α of the products found to be good as new and can be returned to the DC inventory stockpile immediately. The other returned products would then go through $L_2 - L_1$ periods (where $L_2 > L_1$) of rework and refurbishment, after which the products can be sent to the DC stockpile. We assume that $L_2 > L_1 > L$. Hence, we assume that all products can eventually be returned to the DC inventory stockpile, i.e., no returned products are scrapped. It turns out that, with the assumption that $L_2 > L_1 > L$, the resulting analysis does not depend on L_1, L_2, and α. Karaer and Lee (2005) show how the other lead time cases, as well as relaxing the assumption of no scrap, can be developed. Let p be the shortage cost per unit per period at the DC, and h be the holding cost per unit per period.

Define D as the customer demands over $L + 1$ periods, and μ, σ, and $F(\cdot)$ be its corresponding mean, standard deviation, and cdf respectively. Define also R as the total returns over $L + 1$ periods, and μ_R and σ_R be its corresponding mean and standard deviation, respectively. Define $H(\cdot)$ as the cdf of $D - R$.

We consider three cases. The first case represents a naive approach where the DC does not have visibility of the return channel and ignores its existence. The second case is a "smart" approach where the DC does not have visibility of the return channel, but makes use of its statistical properties to adjust its inventory decision. The third case is the "RFID" approach where the DC has full visibility of the return channel, enabled by the RFID technology. Suppose, in all three cases, the DC uses a base-stock policy to manage its inventory control.

Naive Approach: By ignoring the existence of the return channel, the DC would set its target base stock to be at:

$$\hat{S} = F^{-1}\left(\frac{p}{p+h}\right).$$

The average holding and backorder cost is:

$$C_N = hE[\hat{S} - (D - R)]^+ + pE[(D - R) - \hat{S}]^+ = h[\hat{S} - (L + 1)(\mu - \mu_R)] + (h + p)\Gamma_{D-R}(\hat{S}),$$

where $\Gamma_X(y) = E[X - y]^+$.

Smart Approach: The DC now recognizes that the net demand to the DC is $D - R$, and accordingly, sets the target base stock to be at:

$$S^* = H^{-1}\left(\frac{p}{p+h}\right).$$

The average holding and backorder cost is:

$$C_S = h[S^* - (L + 1)(\mu - \mu_R)] + (h + p)\Gamma_{D-R}(S^*).$$

RFID Approach: With RFID, the DC can always net out the known inventory in the return channel, so that the replenishment order would be adjusted accordingly. The target base stock would again be $\hat{S}$.

The average holding and backorder cost is:

$$C_R = h[\hat{S} - (L + 1)\mu] + (h + p)\Gamma_D(\hat{S}).$$

Since D stochastically dominates $D - R$, it is easy to see that $\hat{S} \geq S^*$.

When D and R are normal, then we can have a simplified way to evaluate the three cost functions to gain insights on the value of RFID. Let $\Phi(\cdot)$ be the cdf of the standard normal distribution. Define: $\sigma' = \sqrt{\sigma^2 + \sigma_R^2}$ and

$$z^* = \Phi^{-1}\left(\frac{p}{p+h}\right),$$

$$z^0 = \frac{(L+1)\mu_R + z^*\sigma\sqrt{L+1}}{\sigma'\sqrt{L+1}},$$

$$I(y) = \int_y^\infty (x - y)\,d\Phi(x).$$

Then, we can derive:

$$C_N = \sigma'\sqrt{L+1}[hz^0 + (h + p)I(z^0)]$$

$$C_S = \sigma'\sqrt{L+1}[hz^* + (h + p)I(z^*)]$$

$$C_R = \sigma\sqrt{L+1}[hz^* + (h + p)I(z^*)].$$

Suppose that the negative tails of the normal demand streams of D and R are negligible, as would be the usual assumption when we use the normal distribution to represent demands, then one can show that $z^* \leq z^0$. Moreover, we can show that $hz^* + (h + p)I(z^*) \leq hz^0 + (h + p)I(z^0)$. Since $\sigma \leq \sigma'$, it is easy to see that $C_N \geq C_S \geq C_R$. The value of using the smart approach is to help the DC with a lower safety factor in the target inventory level, while the incremental value of RFID over the smart approach is in shrinking the demand uncertainty via visibility of the return channel. Depending on whether one wants to use C_N or C_S as the base case, the value of RFID would differ.

6. Value of Visibility Across Companies: Upstream Information Shared Downstream

Traditional inventory models usually assume replenishment lead times either as constants, or as stochastic but independently drawn from a given distribution. With stochastic supply lead times, the most usual assumption is that the orders do not cross over time, i.e., an order placed at a later time will not arrive prior to another order placed earlier. There is a rich literature of stochastic lead time inventory models (e.g., see Chapter 7 of Zipkin 2000).

When lead times are stochastic, the standard inventory models assume that the decision maker does not have prior knowledge of what the actual lead time would be, but instead, has to make replenishment decisions based on the statistical characterization of the lead time, such as its distribution. Often, the statistical characterization boils down to the mean and standard deviation, and safety stocks can be based on these two statistics. With RFID at the supplier site, or at the intermediate points along the replenishment pipeline, the inventory system could have some advanced knowledge about what the actual lead times could be. In the terminology of logistics, these intermediate points are called "choke points," and it is possible to imagine that RFID readers are installed at these points, and if the product conveyances are equipped with RFID tags, then the passing-through of the products can be recorded and transmitted immediately to the receiving inventory system. This is like having some visibility of the replenishment process, leading to a reduction of the supplier uncertainty during the replenishment cycle, which in turn should lead to improved inventory performance.

We have started to see some recent research that is tied to having some form of visibility of the supply process. The research does not point to RFID directly, but the resemblance is there. A noteworthy work is Song and Zipkin (1996), which models the supply process as an evolving Markov Chain. If the inventory manager has visibility of the state that the supply process is in, then he/she can use that information to revise the inventory ordering decision in the period. The state information is useful to the inventory manager to deduce the most current lead time distribution, which is a much better estimate than the general lead time distribution. The result is that a state-dependent ordering policy can be used. Chen and Yu (2005) consider the case in which the inventory manager has no access to the supply process, hence the leadtime information. Unlike in Song and Zipkin, the manager does not know the exact value of the supply leadtime at the beginning of the period. However, she knows that the leadtime is generated by a Markov process. Through a numerical study, the authors quantify the value of leadtime information by comparing the model in which leadtime is unobservable to that of Song and Zipkin's. The authors conclude that the value of leadtime information can be significant. We can imagine RFID as the enabling information technology that allows the inventory manager to find out the state of the supply process, thereby gaining visibility.

A more recent work by Moinzadeh (2004) is based on the inventory manager's knowledge of whether the supplier has inventory in stock or not. The model is based on Poisson demands at the downstream site, and the supply site operates like an M/M/1 queue. The inventory manager uses a two-parameter base-stock policy, depending on whether the supplier inventory is positive or not. If the supplier is out of stock, then the inventory manager would use a higher base stock level, since he/she is inferring that the resupply lead time is going to be longer. Again, there is a weak link to RFID here—RFID can enable us to find out whether the supplier is out of stock or not.

The above examples of research are good beginnings, but RFID technology provides information beyond just the state of the supply process, or whether the supplier is stocked out or not. Much more concrete modeling is needed to capture the value of upstream visibility provided by RFID. There are two possible modeling avenues.

First, as we described earlier, RFID can give us more updated information on the status of the replenishment in the pipeline when readers are set up at appropriate choke points. Without such information, the lead time is indeed simply a random variable. But with the information on the product passing through the choke points, we can actually update the posterior probability distribution of the remaining lead time at those points. This can give rise to much more precise characterization of the lead time distribution, based on which inventory performance can be improved. One such effort is described in Section 6.1.

Second, suppose the uncertainty of lead time could be resolved at the time when the order is placed, but the lack of information access has resulted in the inventory manager still treating that lead time as random. Then, we can view RFID as an enabler for us to find out what the revealed uncertainty is, and the inventory manager can act accordingly. In that case, RFID helps to transmit information revelations of actual lead time immediately to the manager. It turns out that this case fits the potential use of RFID in creating secure trade lanes for container transportation (see Lee and Whang 2005, for details), and we describe such an application in Section 6.2.

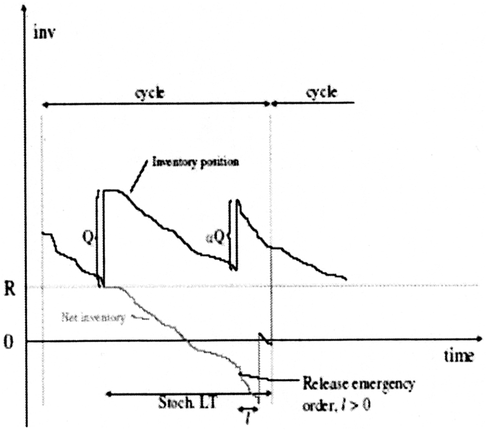
6.1. RFID and Supply Visibility

Gaukler, Özer, and Hausman (2004) quantify the benefit of order progress information, obtained by RFID, for a retailer facing uncertain replenishment lead time and uncertain demand. Inventory is reviewed and replenished continuously, where unsatisfied demand is backlogged. The premise is that when production and replenishment lead times are uncertain, RFID may enable the use of order progress information in deriving replenishment strategies. The authors develop a model to show how a retailer can use this information to efficiently place an emergency order.

The authors model the effects of increased supply visibility through RFID by incorporating order progress information into the replenishment process. To do so, the supply process is divided into $N \geq 1$ stages. The status of the regular order is observed through RFID read points, which are positioned at N distinct stages in the supply process. All outstanding orders enter the system from stage 1. They progress through each stage consecutively until they reach to stage N, which indicates the arrival of the order to the retailer. With this order progress information, the retailer knows whether the regular order has completed a certain supply milestone, plus the updated distribution of the remaining replenishment lead time beyond that milestone. The sojourn time for a regular order to move from one RFID read point to the next is assumed to be exponential with rate λ and independent of the stage number.[14] The overall replenishment lead time is therefore Erlang with parameter N.

The authors propose and evaluate a replenishment policy that uses order progress information for emergency ordering together with the (Q, R) policy. In particular, the (Q, R) policy is used to release *regular* replenishment orders at cost A of size Q when the inventory position y drops to the reorder level R. The retailer also has the option of releasing an emergency order at a cost premium $K(l)$ of size αQ, with $\alpha > 0$, which arrives after a known deterministic lead time $l \geq 0$.

Figure 5 **Replenishment cycle.**



The problem structure does not allow for an exact analysis of an average cost expression. Two assumptions are required to enable tractable analysis. First, at any given point in time, there is never more than a single *regular* order outstanding.[15] This assumption implies that inventory position y is equal to the on-hand inventory at the time reorder point is reached. It also guarantees that inventory position (or on hand inventory) will always be raised above the reorder point when an order arrives. Hence, the time between successive arrivals of regular orders define a renewal cycle. Figure 5 illustrates one such cycle. Second, the authors assume that an emergency order arrives either within the cycle it is placed or the following cycle. Note that the availability of emergency ordering makes it more likely that at most one single regular order will be outstanding at any point in time. Also, an emergency order would be beneficial if its lead time is sufficiently smaller than the regular order's.

Next the authors obtain an optimal emergency ordering policy by evaluating the expected inventory and backorder costs at the *end* of each regular order replenishment cycle. To do so, they compare the cost of emergency ordering to that of not ordering. Let X_b be the remaining lead time of the regular outstanding order with a pdf $g_b(\cdot)$ and cdf of $G_b(\cdot)$, which are Erlang with order $N - b$. The probability that the emergency order, which is released while the regular order is at stage $b \in \{1, 2, \ldots, N - 1\}$, will arrive after the regular order arrives is then given by $p_b(l) := Pr\{X_b < l\}$. Let $D(t)$ denote the random demand in any time interval of length t with a probability density function of $h(x, t)$ and mean γ. Hence, demand within the remaining lead time is $D(X_b)$ and has a pdf of $f(x|b) := \int_0^\infty h(x, t) g_b(t)\, dt$. Given order progress information, the expected cost of emergency ordering at the end of a cycle can be easily calculated.

Let $C_0(y, b)$ denote the end of period expected cost

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[14] The authors also consider the impact of general distribution.

[15] Hadley and Whitin (1963) introduce this assumption and develop the well-known heuristic treatment of (Q, R) policy. Inventory managers often use this heuristic policy for several practical settings.

if the emergency order is not released. If the emergency order is released when the regular order is at stage b (i.e., RFID read point b), then the expected cost at the end of the cycle is

$$C_1(y, b) = K(l) + p_b(l)C_0(y, b) + (1 - p_b(l))C_0(y + \alpha Q, b).$$

The retailer can compare these end of period costs and place an emergency order when $C_1(y, b) \leq C_0(y, b)$. The optimal emergency order policy is, therefore, given by the following thresholds for each RFID read points:

$$\bar{y}_b := \min\{y : C_0(y, b) \leq C_1(y, b)\} \quad \text{for all } b \in \{1, \ldots, N - 1\}.$$

Note that the optimal threshold that triggers emergency ordering depends on factors such as the emergency leadtime l, the stage b and the fixed cost of ordering K.

These thresholds together with a (Q, R) policy defines a *compound* policy that uses order progress information. The threshold level depends on inputs such as on the choke points (that is, read points), emergency replenishment lead time and cost. Under this compound policy, the manager observes the inventory position y at any point in time. If no regular order is outstanding, and if the inventory position is less than R, she places a regular order of size Q. If a regular order is outstanding, the retailer monitors the outstanding regular orders location in the supply system, that is, the last RFID read point b that the regular order is registered. If the inventory position is less than $\bar{y}_b$, the retailer places an emergency order of size αQ.

The calculation of the thresholds $\bar{y}_b$ take (Q, R) levels as given. One plausible way to choose these policy parameters is to follow Hadley and Whitin's classical heuristic treatment and set $Q^{HW} = \sqrt{2\gamma A/h}$ and $G_N(R^{HW}) = 1 - Q^{HW}h/(b\gamma)$, where h is the holding cost per unit per time and b is the backlogging cost per unit. In fact, these parameters would be the best (Q, R) levels without the order progress information (no-RFID case). The availability of an emergency order and other parameters such as the size of the emergency order α should have an impact on the choice of the (Q, R) levels. The authors show that the optimal reorder level with the option of emergency ordering is less than R^{HW}. In other words, the option of emergency ordering is a substitute for safety stock.

The authors conduct a numerical study to demonstrate the potential cost savings resulting from the order progress information (hence, the option of emergency ordering). To do so, they simulate the traditional (Q^{HW}, R^{HW}) policy without the emergency ordering option and the compound policy with the emergency ordering option. They compare the resulting total average cost with and without order progress information. They report overall cost savings ranging from 2.8–5.5% due to supply visibility. They illustrate that the emergency ordering option cut 90% from the average cost incurred due to backlogging customers. To isolate the true value of order progress information, the authors also compare the compound policy to a plausible emergency ordering option in the absence of RFID (and hence without order progress information). In particular, the plausible policy sets another reorder point R_e which is less than R. Whenever the *inventory position* falls below R, the system places a regular order of size Q. If the *net inventory* falls further below R_e, the system places an emergency order of size αQ. Through a simulation based optimization, the authors identify an optimal R_e^* value.[16] Comparing the cost of this policy with that of the compound policy reveals the true value of order progress information. Based on numerical experiments, the authors conclude that 47–65% of the above mentioned cost savings are attributable to the order progress information.

6.2. RFID and Supply Security

Under the threat of terrorist attack via containers arriving at US ports, the US government has stepped up the inspection rate of incoming containers at the ports. Increased inspection would of course lead to added congestion and longer lead times for imported goods to US customers. U.S. Senator Patty Murray of the State of Washington, Chairman of the US Senate Appropriations Committee's Subcommittee on Transportation, announced the formation of the Smart and Secure Tradelane initiative (SST) in 2002. Under this initiative, the world's three largest seaport operators started to collaborate and deploy automated tracking, RFID-based detection and security technology for containers entering US ports (see McHugh and Damas 2002, and Cuneo 2003, for more details). Containers leaving the participating ports can be equipped with RFID-based electronic seals that can be used to track whether the containers have been tampered with during transit. Containers identified can then be sorted out for special inspection. A by-product of such monitoring efforts is theft prevention. Some research has been directed to quantify the value of SST (see Lee and Whang 2005; Wilson and Hafer 2003).

Let p be the inspection rate of containers arriving at a destination port. Hence, we can interpret p as the probability that a container load will be inspected by

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[16] A similar policy, that is (Q_1, R_1, Q_2, R_2)—policy, for deterministic lead time problems is first suggested by Moinzadeh and Nahmias (1988).

Customs. Given the heightened concerns about terrorism, it is generally expected that US Customs will increase p from its current level. The immediate effect of this increase is that the direct cost of inspection will increase, and it is expected that this cost will be passed onto shippers and carriers. Besides the direct inspection cost, additional inspection will lead to potential congestion at the destination ports, since inspection resources are limited. The increase in inspection rate may not lead to a corresponding increase in inspection resources. A simple queueing model can be used to quantify the additional waiting time for the increased inspection.

The overall lead time, given by the sum of the transit (transportation) lead time and the inspection dwell time (which would be zero if a shipment does not have to go through inspection, and is a random variable equal to the total waiting time of the queueing system at the inspection point), will ultimately affect both the pipeline inventory (using Little's Formula) as well as the required safety stock at a distribution center (DC) in the destination country. Suppose that the transit lead time is independent of the inspection dwell time. Let:

x = transit lead time in days, a random variable;
y = inspection dwell time in days, a random variable;
T = total lead time in days.

Then,

$$E(T) = E(x) + pE(y);$$

$$Var(T) = Var(x) + p\ Var(y) + p(1-p)[E(y)]^2.$$

Note that $E(y)$ and $Var(y)$ are given by the queueing model that describes the inspection process. Without any visibility of whether the containers will be picked for inspection, the US customer will have to develop safety stock based on the uncertain lead time as characterized by $E(T)$ and $Var(T)$.

With RFID-based containers, US Customs would not apply the same intensity of inspection. In fact, the idea is that US Customs can make use of such information and focus their efforts on higher risks cargos, and give SST-compliant manufacturers close-to "green lane" treatment. In addition, with a transparent process and early information on the content and transportation needs, and tighter monitoring of the transit process, some of the uncertainties in the transit process can be reduced. This reduction results in a smaller value of $Var(x)$. Finally, collaborative efforts with US Customs can result in RFID-based shippers being given advanced information on whether the shipment will be inspected or not. In other words, part of the uncertainty around the replenishment lead time uncertainty is resolved at the beginning of the lead time.

Let:

μ = mean daily demand of a product;
σ = standard deviation of the daily demand of the product;
R = inter-replenishment time in days for the DC;
k = safety stock factor;
p' = new inspection rate under SST;
$1-\theta$ = percentage reduction of the transit time variance as a result of SST.

Hence, the new transit time variance under SST is given by $\theta\ Var(x)$.

Without SST, i.e., in the current process, the safety stock is given by (see, for example, Silver et al. 1998):

$$S_0 = k\sqrt{\mu^2\ Var(T) + \sigma^2 E(T+R)}.$$

With RFID-based SST, the resulting expected safety stock is:

$$S_1 = k\{p' \times \sqrt{\mu^2[\theta\ Var(x) + Var(y)] + \sigma^2[E(x) + E(y) + R]} + (1-p')\sqrt{\mu^2\theta\ Var(x) + \sigma^2[E(x) + R]}\}.$$

It is easy to verify that $S_1 \le S_0$. To see this, let:

$$H_1 = \mu^2 Var(y) + \sigma^2 E(y) + H_2, \quad \text{and}$$

$$H_2 = \mu^2\theta\ Var(x) + \sigma^2[E(x) + R].$$

Then, we can express $S_0 \ge k\sqrt{pH_1 + (1-p)H_2}$, and $S_1 = k\{p'\sqrt{H_1} + (1-p')\sqrt{H_2}\}$. Note that, for any non-negative random variable Z, $\sqrt{E(Z)} \ge E(\sqrt{Z})$, based on Jensen's inequality. Hence, we have:

$$S_0 \ge k\sqrt{pH_1 + (1-p)H_2} \ge k\{p\sqrt{H_1} + (1-p)\sqrt{H_2}\} \ge k\{p'\sqrt{H_1} + (1-p')\sqrt{H_2}\} = S_1.$$

The last inequality above follows from the fact that $p \ge p'$, and $H_1 \ge H_2$.

One of the values of SST is to have the potential of giving advanced lead time information to the manufacturer. Such advanced information, in general, is very powerful. It is more valuable than simply reducing the variance of lead time. We demonstrate this with a simple analysis below. Let t be the random variable denoting the exposure time, and μ and σ be the mean and standard deviation of demand per unit time. With advanced knowledge of t, it is possible that the manufacturer can dynamically adjust the safety stock at each replenishment instance. Without advanced lead time knowledge, the safety stock requirement is $k\sqrt{\mu^2\ Var(t) + \sigma^2 E(t)}$, where k is the safety factor. With advanced lead time knowledge, the average safety stock requirement is $k\sigma E(\sqrt{t})$. We can express the safety stock requirement without advanced lead time knowledge as:

$$k\sqrt{\mu^2 Var(t) + \sigma^2 E(t)}$$
$$= k\sqrt{\mu^2\ Var(t) + \sigma^2[Var(\sqrt{t}) + (E\sqrt{t})^2]} \geq k\sigma E(\sqrt{t}).$$

The difference between the two safety stock requirements is greater with higher values of $Var(t)$ and $Var(\sqrt{t})$. With advanced lead time knowledge, we can reduce the safety stock not only from the $\mu^2\ Var(t)$ term, but also from the $\sigma^2\ Var(\sqrt{t})$ term.

Lee and Whang (2005) report the application of this model to a hypothetical US electronic manufacture shipping products from Malaysia to Seattle. With RFID-based SST, the manufacturer can reduce inventory while improving service at the same time, as seen from Figure 6.

7. Ending Thoughts and Future Directions

Based on our review of the ongoing research efforts so far, we think that the POM community definitely has a lot to offer in the advancement of RFID in supply chain management. In Figure 7, we classify some of the research discussed in this paper to help identify and position new research work. Recall that the general models discussed in the paper were developed not specifically about the RFID technology; but the models could be easily adapted so that the RFID-benefits can be inferred. Focused models were developed based on how the RFID technology could bring forth visibility and how this visibility can be used effectively to manage supply chains.

There are several themes that summarize our views, including directions for continual research efforts by our community.

1. When we conduct research on assessing the value of RFID, it is important to establish the right benchmark. One benchmark is how the system performs in a naive manner, where the management control is based largely on ignorance. Another benchmark is how the system can be "optimally" controlled, given that we do not have the complete visibility and monitoring capabilities of RFID. The performance of the system with RFID can then be compared to the benchmark to assess the value of RFID. The performance under the naive benchmark is easy to obtain, and is probably what most standard industry consultants and systems integrators used in their studies. We think this is not sufficient. Instead, research should also be directed to developing models to optimally manage the system in the absence of RFID. Hence, for example, even without the visibility of inventory shrinkage, misplacement and transaction errors, one can still use better inventory replenishment policies to improve performance, compared with the naive one that ignores the existence of the sources of such inventory discrepancies. The reasons for pursuing this line of research as a new benchmark are two-fold. First, this benchmark enables us to get to the real incremental value of RFID, and not confound it with "smarter" systems management. Second, there are still many systems that will not have RFID for a long time, and we, as POM professionals, should strive at improving the operations performance of such systems. Hence, research is needed on managing operations both in the absence and in the presence of RFID.

Figure 6 **Improving service and inventory.**

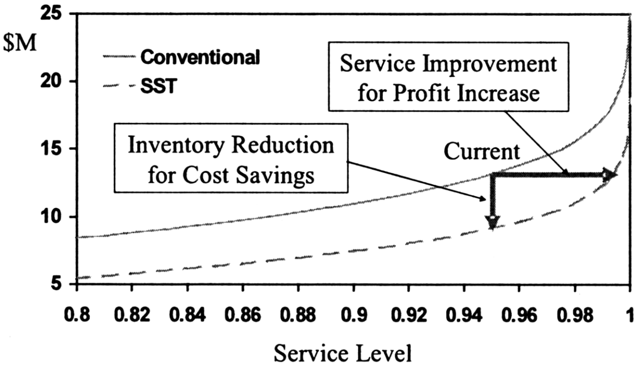

Figure 7 **Representative OM-based models of RFID benefits.**

	General Models (RFID-Inferrable)	Focused Models (RFID-Specific)
Within Company Visibility	Iglehart & Morey (1972): Kok & Shang (2004); Fleisch & Tellkemp (2005) Atali et al (2006)	Atali et al. (2004,2006); Kang & Gershwin (2005); Rekik et al. (2006)
Downstream Visibility	Lee et al. (2000); Cachon & Fisher (2000); Gavirneni et al (2000); Lutze & Özer (2004) Moinzadeh (2002); Özer (2003)	Karaer & Lee (2005)
Upstream Visibility	Song and Zipkin (1996); Moinzadeh (2004); Chen and Yu (2005)	Gaukler et al. (2004) Lee & Whang (2005)

2. As a new technology, RFID is not going to be perfect on day one. Hence, there could be misreads and missing reads. We need to model the impact of an RFID-enabled system that is not 100% reliable. Moreover, we may only be able to have RFID readers installed at intermittent points in the supply chain, so that visibility is partial, not total. Again, this calls for developing models with partial-RFID systems.

3. Our current review shows that most of the RFID work has focused on logistics and inventory management applications. But the potential of RFID in other areas of operations, such as manufacturing, after-sales

service support, and total product life cycle management, is also huge. RFID can help to improve assembly operations, both in terms of efficiency improvement, or error reduction. In after-sales service support, a product equipped with an RFID tag that records details of the product in its manufacturing and consumption stages can help to speed up the diagnosis of failure causes and service treatments. It could also support preventive maintenance activities. Finally, an RFID tag with full product information can help product disposal at the end-of-life stage. The detailed information can help determine the parts of the product that can be recycled, re-used, re-manufactured, or disposed. It can also help support the satisfaction of recently enacted laws and regulations on product recycling and hazardous materials disposal.

4. We believe that the bottom-up approach, i.e., starting with the operating characteristics of the processes, is a sound way to assess the value of RFID. This is also the approach of the research tradition of the POM community. Hence, the POM community has a great deal to offer. We hope to see more of the use of this approach in future RFID research. In parallel, the POM community should pursue field-based, or case-based research on RFID pilots. Such studies could help us to ascertain the assumptions used in how RFID could affect the operating characteristics of the system. They could also help in understanding the limitations or imperfections of RFID today, enabling us to conduct research on modeling imperfect RFID systems.

5. Given the value that POM community can offer, we believe that the community should be more proactive in disseminating and communicating our research results that bridge the existing credibility gap of RFID value in industry. The industry reports that are in existence, as we critically reviewed, have not been based on sound analysis grounded on the basic operating characteristics of the system. One direction for the POM community is to have our version of industry analyses, which could either challenge or confirm the existing observations from industry reports. In this way, the value of the POM research community to industry and practice can be made more recognizable. Furthermore, since our research is based on operational management and control, it has the potential of being usable in application software for RFID deployment. This would be another avenue for our community to contribute to industry practice.

6. We should recognize that there are other research areas that the current paper has not addressed. Some of them have received research interest, and initial results are emerging. For example, we have not addressed the important incentive and coordination problem with RFID. The benefits of RFID may not be commensurate with the investments put in by manufacturers and retailers (Gaukler, Seifert, and Hausman 2003). Incentive incompatibility could either slow down the adoption of RFID, or lead to sub-optimal decisions, i.e., independent decisions by both parties that are not optimal from the total system point of view. Recent line of research also started to analyze the impact of different sources of inventory inaccuracy, such as misplacement, and the impact of RFID on decentralized supply chains (Camdereli and Swaminathan 2005; Heese 2005). Second, we have not considered the potential of having each RFID tag equipped with local information, being able to have decentralized control and decision-making capabilities. The tag can store information, but it can also contain logics and control rules for some limited decisions and actions. In this way, each tag can be viewed as an agent that can utilize its local information to take local actions. The management of such highly decentralized systems with multiple agents is another area of research. Third, we have not considered the value of RFID in counterfeit prevention, facilitation of product recall, and support of product traceability, which are important concerns in food and drug industries. Finally, we have also not addressed the social implications of RFID, such as how it affects law enforcement, privacy concerns, and macro-economic issues.

RFID is a disruptive technology that has great potential. The POM community can play a central role in the advancement and development of this technology. We are pleased to see that emerging research in our community has already been directed towards this objective. But more is needed. In the end, a new technology should not be one that makes our past research obsolete, but instead, enables us to apply our foundational knowledge, build new research models, and make a difference.

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