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## A Quantitative View on How RFID Will Improve a Supply Chain

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# A Quantitative View on How RFID will Improve a Supply Chain

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## ABSTRACT

Radio-frequency identification (RFID) as an emerging technology has generated enormous amount of interest in the supply chain arena. There are a number of theoretical advantages of RFID technology. Inventory can be tracked more accurately in real time, resulting in reduced processing time and labor. More significantly, the complete visibility of accurate inventory data throughout the entire supply chain, from manufacturer's shop floor to warehouses to retail stores, brings opportunities for improvement and transformation in various processes of the supply chain. In this study we investigate how these advantages can contribute to the performance of a supply chain and hence to business value. We identify existing supply chain results, most of which were developed for purposes other than RFID but are applicable to RFID, and model the impact of RFID in a manufacturer-retailer supply chain environment using computer simulation when we cannot find relevant existing results. Our study provides a comprehensive view on how to demonstrate the potential benefits of RFID in terms of inventory reduction and service level improvement.

*Keywords*: Radio Frequency Identification;  Supply Chain; Inventory Management; Simulation

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# 1   INTRODUCTION AND OBJECTIVE

Radio Frequency Identification (RFID) technology has been gaining a lot of attention in industry and academia in the recent few years. (The military has long used RFID technology, but as such is limited to niche applications.) A main reason is that the cost of RFID tags has begun to decrease to a point where large scale applications in both the enterprise and consumer space are possible today or within reach in the near future. As of 2004, a passive RFID tag costs in the range of US$0.25. Ongoing efforts by vendors are aiming to reduce this cost to US$0.05. In the consumer space, the current cost is still too expensive for many household goods but is more than reasonable for major appliances, personal computer equipment, or sophisticated consumer electronics. At the same time, the physical size and form of RFID tags is now very practical for many potential applications. International standards on the physical characteristics of RFID (such as frequency and coding schemes) are well under way (including ISO 18000 by the International Standards Organization, EPC by EPCglobal Inc.) Such technology push, together with a few high profile and successful commercial applications (such as the EZPass highway toll collection system and the Mobil Speedpass payment system), have prompted many businesses to investigate potential applications of RFID in their own industries. Responding to such extensive interests, a number of publications and web sites dedicated to this subject have been launched, including the RFID Journal (www.RFIDjournal.com), RFID Gazette (www.RFIDgazette.org), RFID News (www.RFIDnews.org) among others.

The supply chain has been widely identified as one key business application of RFID technology. RFID initiatives by such influential organizations as Wal-Mart, Target, Tesco, Metro Stores, and the US Department of Defense in non-weaponry supplies have accelerated the pace of adopting the technology in industry. For example, Wal-Mart mandated their top 100 suppliers

to deliver products with RFID tags at the case and pallet level by the first quarter of 2005. While companies are trying to follow Wal-Mart's request to become RFID compliant, there is a need to understand the potential long-term benefits of the technology to different players in the supply chain. To this end, many return-on-investment (ROI) studies have been conducted. Most of them focused on the direct benefits provided by RFID, which typically include reduced labor costs (since bar code scanning will be eliminated and physical inventory activities will be significantly reduced), reduced inventory shrinkage (since shrinkage points can now be identified and appropriate preventive actions taken), and other directly observable benefits. While these benefits may be quite significant for some enterprises, it may not be so for other businesses, especially those that are already highly automated (for example, using automatic material handling equipment and automatic bar code readers). In such cases, is RFID not useful? Or can it bring other advantages beyond these direct benefits? The objective of this paper is to explore this subject in a comprehensive way, combining existing knowledge in traditional supply chain management literature (i.e., literature not directed towards RFID) and complement such results using lessons learned from our own simulation model of a typical manufacturer-retailer supply chain.

The rest of the paper is organized as follows. Section 2 contains a description of our contribution. Section 3 uses a case study approach to explore a list of key benefits of RFID in a supply chain. For each benefit we give an intuitive description, point out where existing supply chain literature can be found to analyze a similar effect, and illustrate the effects through a numerical example based on our simulation model. Section 4 contains a formal simulation experiment to validate the results of the case studies in Section 3. Conclusions are given in Section 5.

## 2 CONTRIBUTION OF THIS PAPER

Studying the benefits of RFID is certainly not new. However, among the large number of papers and reports published in RFID benefits, almost all of them are qualitative studies providing business cases for RFID deployments. For example, IBM Business Consulting Services have published a series of papers (Alexander et al. 2003a, b, c, d) on discussing the impact of RFID technology on supply chain performance with a focus on consumer goods and retail value chains. Topics of this white paper series range from analyzing the benefits of RFID in terms of improving product availability at the retailer's shelf, reducing losses associated with product obsolescence, product shrinkage, and inventory inaccuracy, to articulating how RFID would affect the replenishment policies at the store and distribution center (DC) to achieve better customer services and reduce inventory cost. Other reports of a similar nature include Agarwal (2001) and Kambil and Brooks (2002).

To help organize our thinking on the benefits of RFID, we classify the benefits as follows.

1. Direct benefits. Intuitively, we can think of the direct benefits as those given by the automation aspect of RFID. Just like any automation device, it attempts to reduce total costs by reducing labor and error.

2. Indirect benefits. There are two sources of indirect benefits.

    a. The first kind of indirect benefits are those resulting from dynamic effects of small changes brought about by RFID in one area of the supply chain. Because a supply chain is a complex set of activities connected with each other and connected in time, small changes in one area may lead to unpredictable and/or significant consequences elsewhere in the supply chain or later in time. The well known "bullwhip effect", first studied by Forrester (1958) and later by Lee et al.

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(1997) and many others, is an example of small changes propagated and amplified through the dynamic behavior of a supply chain. In our study of RFID, for example, the direct loss due to inventory shrinkage is just the value of the unaccounted inventory itself. The indirect loss of inventory shrinkage may include losses from stock-outs as the result of poor replenishment due to inventory inaccuracy (caused by the unaccounted shrinkage).

b. A second source of indirect benefits that might be overlooked by a traditional ROI analysis is the need for a business process transformation to take advantage of the information now available from the RFID tags. A simple example is the commonly used, periodic inventory replenishment process – most retailers replenish their stores once a week based on a predetermined decision-making cycle for each product. To take full advantage of the potential real-time inventory information provided by RFID, this periodic replenishment process needs to be redesigned – perhaps as simple as reducing the cycle to a day rather than a week, if other considerations (such as the workload of the planners) allow. Such a change, simple it may seem, may have significant impact on the performance of the enterprise. (In this case we know from inventory theory that the average inventory will be decreased rather significantly.)

In this paper we focus on the quantification of RFID benefits through modeling and explore all three types of potential benefits provided by RFID – automation oriented, dynamic consequences, and those resulting from business process transformations enabled by RFID. In general we find that research on the impact of RFID on supply chains using analytical approaches is still at an early stage. We hope to help set a research agenda for the RFID community by surveying

the existing landscape and providing a glimpse of the future landscape. Specifically, our contributions are as follow.

1. We identify key benefits of RFID in a typical manufacturer-retailer supply chain, using the above framework as a reference. We recognize that some types of benefits have been studied in other contexts and published in the non-RFID supply chain literature. For these benefits we provide leads to the existing literature so that quantitative insights on these advantages can be obtained using existing models as much as possible.

2. Other benefits are specific to the inherent technical advantages of RFID and have not been studied before. For these we use a simulation model to explore their relative contribution to supply chain performance. In particular, we study effects of frequency of shelf replenishment in a retail store from the backroom, visibility of inventory information and time delays in information under realistic but theoretically non-optimal conditions, and replenishment ordering using information that is not synchronized with inventory information.

## 3  BENEFITS OF RFID IN A SUPPLY CHAIN

In this and the following sections we discuss the impacts of RFID in a typical manufacturer-retailer supply chain. Key insights are presented in this section using a case study approach, while a more formal exploration using experimental design is discussed in Section 4. The results of the formal experiment serve to validate the observations made in the case studies.

In this work, we used a simulation model of a simple manufacturer-retailer supply chain in the Consumer Product (CP) business. We developed a three echelon supply chain simulation model (Figure 1), which consists of a manufacturer, a distribution center (DC, that belongs to the manu-

facturer) and a retail store. The application of RFID technology is modeled in each of echelon in the supply chain. In the manufacturer, we modeled RFID tag reading at the points of production completion and shipping. In the DC, we modeled tag reading at the receiving and shipping docks. In the retailer, we modeled tag reading at receiving, the backroom and the shelf in the store. Various simplifications and assumptions are made to capture the essence of the supply chain behavior without making the model unnecessarily complicated.

For the retail store, we modeled four products which are sold to customers with equal probability. Customers arrive with an inter-arrival time characterized by a log-normal distribution, and their purchase quantity on each purchase occasion is assumed to be uniformly distributed between 1 and 3. The store replenishment is based on an (s, S) policy: re-order point, s, and target inventory, S. Shelf replenishment is also based on an (s, S) policy.

For the manufacturer, we assumed that the daily production quantity for each product is decided based on a certain policy, and is shipped to the DC once a day. Several different production policies are simulated. The lead time for shipment from manufacturer to DC is one day. For the DC, the products are pulled from the retailer based on the retailer's replenishment policy and decision frequency. The lead time for shipment from the DC to the retailer is one day.

## 3.1 Automation

The most obvious use of RFID is as an automatic version of bar code scanning. If bar codes are manually scanned at different points in a supply chain (e.g., the shipping and receiving docks of warehouses and stores) at present, the application of RFID will provide a *direct benefit* of eliminating those labor costs. Computation of such labor savings is relatively straightforward – the average time spent in each relevant manual operation can be collected and the average num-

ber of such operations can be estimated from the movement volume of the supply chain and the procedures used in handling the physical goods. We give a list of common, manual operations that can potentially be saved (at least partially) by using RFID as an automation device, as follows:

1. Production reporting at the end of production lines

2. Shipping and receiving of pallets, cases, or items

3. Handling of inventory flow-through or cross-docking

4. Physical or cycle counting

5. Inventory auditing

6. Printing and handling of pallet license plates and case labels

7. Inventory reconciliation of damaged products

8. Reconciliation and handling of shipment errors and subsequent claims

In addition to labor savings, another important advantage of an automation device is data accuracy. Today's bar codes have extremely good read accuracy in a laboratory environment and very good accuracy in normal use. The only key advantages of RFID over bar codes in read accuracy is that bar codes can get dirty or damaged relatively easily and that bar code reading needs a clear line of sight (and some minor orientation requirements). If an enterprise faces significant issues because of these reasons, RFID will be one (but not the only) potential solution. The *direct benefit* due to a reduction in inventory read errors is the inventory value, the inventory carrying and handling costs to cover extra stock in the supply chain because of such errors. (A fraction of the inventory is in fact not usable because their record is incorrect, so the supply chain in time will carry extra inventory in order to satisfy customer service level requirements.)

Another advantage of RFID as an automation device is the ability to detect the presence or absence of the tags very frequently at almost no marginal cost. The direct consequence is that we can now detect where and when (up to a certain resolution in space and time) material losses are incurred. We can then investigate the sources of such losses and devise action plans to remedy them. In this way, RFID can prevent shrinkages, even though they themselves do not prevent breakages or thefts. The *direct benefit* is similar to the inventory read accuracy discussed above.

Typically the direct losses in inventory related costs due to data accuracy is relatively small, in the order of 1% of total inventory. (While this may still amount to significant monetary value in high-volume supply chains, there are usually opportunities of higher orders of magnitude.) However, as we shall see in subsequent sections, the important impacts of RFID lie in the indirect consequences of the improved inventory accuracy. The dynamic effects of such small changes tend to have far more significant impact than the direct savings. This is what we shall explore next.

## 3.2   Inventory Shrinkage

Nowadays a retailer's replenishment decisions are based on inventory information kept in a computer system (system inventory), which is often assumed to be accurate. However, system inventory and actual inventory count (physical inventory) are seldom synchronized due to causes such as shrinkage or stock loss, transaction error, inaccessible inventory, and incorrect product identification. The error between the system inventory and physical inventory accumulates over time and is never corrected until a physical inventory counting takes place, which happens infrequently (typically few times a year) due to its labor-intensive nature. In fact inventory inaccu-

racy has been identified as a leading cause for operational inefficiency in the retail industry. A recent study (DeHoratius and Raman, 2004) shows that the value of the inventory reflected by these inaccurate records amounted to 28% of the total value of the on-hand inventory for a leading retailer in US. Wayman (1995) indicates that inventory which is not tightly controlled is a liability for any company, and discussed that inventory accuracy in a warehouse can be improved by deploying bar coding.

Under the multi-period setting with inventory replenishment, Iglehart and Morey (1972) provided perhaps the first modeling study on the impact of the inventory inaccuracy on inventory management. In particular, they indicated that the inaccuracy would cause lost sales due to insufficient inventory to meet the demand. We can improve the inventory counting process by conducting more frequent inventory counting at a higher cost. An optimization problem can be formulated to address the tradeoff between the reduction of lost sales and the additional cost due to more frequent inventory counting. Furthermore, additional safety stock can be introduced to further reduce the lost sales by taking into account the variability due to the residual inventory counting error.

Although not done with RFID in mind, Brown et al. (2001) used simulation models to investigate the general effect of inventory inaccuracy, with respect to frequency, location and magnitude of error, on materials requirements planning inventory and delivery performance. The study found that increasing frequency of error has a consistent and dominant effect on problems associated with customer service levels and inventory carrying costs, and location and magnitude of error have additional effects on due dates and inventory costs under different replenishment policies. The effect of inventory inaccuracy, among other factors, in a manufacturing environment on the inventory and customer service was also studied using a simulation model, called MASS

(Manufacturing Simulation System), by Krajewski et al. (1987). The conclusion there indicated that inventory inaccuracy affects supply chain performance.

Kang and Koh (2002) simulated a single inventory replenishment point with the reorder point/maximum inventory (s, S) policy and inventory shrinkage. They analyzed the stock-out rate as a function of the shrinkage rate, concluding that indirect losses (such as stock-out) due to inventory shrinkage is up to 30 times larger than the direct loss (i.e., the value of the inventory lost). As a follow-on study, Kang and Gershwin (2004) derived an approximate, analytical solution to calculate the stock-out quantity in a single node (Q, R) (reorder point R and constant order quantity Q) inventory replenishment system with inaccurate inventory records. Using a simulation model, they also investigated various methods, including the use of RFID, to compensate for inventory inaccuracy. Our modeling study (described below) can be viewed as an extension of Kang and Koh (2002) in terms of scope and system complexity, to show the possible impact of RFID in a realistic representation of a typical manufacturer-retailer supply chain with many factors present simultaneously.

In the same spirit as Kang and Gershwin (2004), Kök and Shang (2004) developed a method to resolve the inventory inaccuracy problem in replenishment. They propose using inspection in an effective way to form an inspection-adjusted base stock policy for replenishment.

Bensoussan et al. (2005) study a multi-period stochastic inventory problem with backorders where inventories are only partially observed because of information delays and record inaccuracy due to various reasons. They develop the concept of a *reference inventory position,* and show that this position along with the value of the latest delay observation and the age of this observation are sufficient statistics for finding the optimal order quantities. Furthermore, they prove

that the optimal ordering policy is of base stock type with respect to the reference inventory position (or (*s; S*)-type if there is a fixed ordering cost).

Fleisch and Tellkamp (2005) analyzes the impact of different causes of inventory descrepancy between physical and information system inventory on the performance of a retail supply chain. Similar to our study here they also use a simulation model. Their focus, however, is on the direct benefits, such as the cost of physical activities related to inventory inaccuracy, and one indirect benefit of out-of-stock arising dynamically from inventory inaccuracy. Our study can be viewed as a next step to that of Fleisch and Tellkamp (2005) where we emphasize the indirect benefits of dynamic consequence as well as those of business process transformation enabled by RFID.

We focus on a particular reason for inventory inaccuracy: inventory inaccuracy that arises due to product shrinkage (i.e., damaged or lost goods). Further, we observe that RFID will not prevent damages and may not be effective against theft, so we are interested not in the effect of reduced shrinkage itself but its visibility, which can be obtained with RFID deployment. We simulated the effect of visibility of inventory shrinkage at the retail store as well as the distribution center, and show that the economic consequence of inventory shrinkage is potentially far beyond the loss in monetary value of the shrinkage. As we will see below, the discrepancy in inventory records due to shrinkage distorts the replenishment process, causing either inventory overstock or out of stock.

In this case study, we studied the impact of inaccuracy of inventory data as a result of shrinkage at the retailer, which occurs at a rate of 1.6%. This shrinkage rate was used since it seems representative of what a typical U.S. retailer faces (Kang and Koh, 2002). We simulated a case where RFID technology is not deployed, and two cases where RFID technology is deployed. Without

RFID, the inventory reduction due to shrinkage is not known, and the retailer's replenishment deci-

sion is made based on the inaccurate inventory information. With RFID, shrinkage occurs as be-

fore but the replenishment decision is expected to improve due to the more accurate inventory in-

formation to reflect what is physically in stock.

### 3.2.1   Without RFID, Replenishment Policy:(s=36, S=48)

We first simulated the quality of replenishment decisions due to shrinkage at the retail store

where RFID technology is not deployed. In this setting, physical inventory tracking is done only

once every 3 months at the store (using cycle counting), and the inaccuracy of inventory in the re-

tailer's information system accumulates over time until a physical inventory is carried out, at

which time system inventory is synchronized with physical inventory.   The retail store's replen-

ishment policy we used is a continuous review (s, S) policy, with the reorder point (s) of 36 and the

target inventory (S) of 48, based on the system inventory, not on the physical inventory. As shown

in Figure 2, the average physical inventory of one (P1) of the four products for the first 200 days of

simulation gradually decreases until the physical inventory checking is done. (Without shrinkage

the average physical inventory should be stationary as the demand distribution and the replenish-

ment policy are all stationary.) Towards the end of the 3 month period, product shortages start to

appear, shown as lines below zero in the Figure 2.   In this case study, we used a back order model

in handling the shortage. The deviation of physical inventory from the system inventory for a

product, P1, is shown in Figure 3. For this case, the total back order quantity is 2,086, and the av-

erage retailer inventory is 22.58.

### 3.2.2   With RFID, replenishment policy:(s=36, S=48)

With RFID deployment, inventory is tracked more accurately and in real-time, and better re-
plenishment decisions can be made.  To clearly illustrate this effect, we assumed that the accu-
racy of RFID is 100% and the system inventory is same as the physical inventory.  (The read ac-
curacy of 100% is clearly optimistic, especially at the time when entire industry is learning about
the technology.  Our point here is that if the impact is not significant even with the assumption of
100% accuracy, there is no need to investigate further.)  With the same replenishment policy as
the case in Section 3.1 (a case without RFID), the inventory profile of the physical inventory is
more stable as shown in Figure 4.  In this case, the total back order quantity for the four products
was decreased to 17 (99% reduction).  However, since the fluctuation of inventory profile is
much smaller and stable than the case of Section 3.1, the overall inventory on average is 27.11,
which is higher than the case in Section 3.1.  This presents an opportunity to decrease the inven-
tory by modifying the replenishment policy; e.g. lowering the re-order point (s), and target in-
ventory (S), without sacrificing customer service; e.g., back order quantity, from the case in Sec-
tion 3.1.  This case of modified replenishment policy was simulated and reported in the
following section (3.2.3).  As seen in this example, an opportunity to reduce inventory by chang-
ing replenishment policy surfaces with RFID deployment.

### 3.2.3   With RFID, replenishment policy (S=38, s=26)

In this scenario, we lowered re-order point (s) to 26 from 36, and lowered the target inven-
tory to 38 from 48.  The simulation results, as shown in the Figure 5, indicate that the back order
quantity for all four products is 1627 (22% reduction from the case in 3.1) and the average inven-

tory is 17.24 (16% reduction). By shifting the replenishment policy (s, S), various combinations of customer service (back order quantity) and inventory improvement were evaluated.

In summary, better replenishment decisions can be made when RFID technology is deployed since accurate inventory data are readily available then. The improvement in the quality of the decision brings an opportunity of reducing store inventory and improving customer service. The simulation results from three scenarios in this section are summarized in Table 1. Case 3.2.1 is the baseline case of no RFID technology; case 3.2.2 is identical except with RFID's ability to identify shrinkage and correctly reflect the physical inventory amount; case 3.2.3 is a representative scenario of how one might change the inventory policy parameters to account for this new ability of identifying shrinkage. In the end we were able to significantly reduce average inventory while keeping the customer service level (as measured by the backorder quantity) close to the baseline value. Note that this summary is based on all four products simulated, and the percentage improvements in case 3.2.2 and 3.2.3 are with respect to case 3.2.1.

We have also conducted a simulation study on the effect of visibility of shrinkage error for DC inventory, and we observed a similar benefits of reduced back order quantity and inventory. This serves as a good example of what we mean by the dynamic effects of RFID. Even though the direct loss in material value is small and RFID did not directly reduce the shrinkage, its ability to identify the shrinkage losses contributes to potential improvements in inventory levels and/or customer service levels which have a far greater effect than the savings in direct materials.

## 3.3   Inventory Replenishment

Shelf inventory management is critical to a retail business. Quite often, items are out of stock on the store shelf while there is still plenty of inventory available in the backroom of the store.

This is because there is no automatic process for detecting the stockout and restocking the shelf once it becomes empty. It has been reported that "8.3% of items are out-of-stock at any one time around the world" and "25% percent of out-of-stocks are caused by poor shelf management" (GMA, Food Marketing Institute and CIES, 2002). Since inventories in backroom and on the shelf are usually not tracked separately in a typical retailer's inventory management system, a stockout situation is only detected when a customer reports it or when a sales associate sees it. (One reason for not tracking inventory on the shelf and in the backroom separately is the subsequent need to manually enter any goods transfer from backroom to the shelf when they occur. With RFID this manual operation would be eliminated.) It should be realized visual inspection for possible out-of-stock items is not a trivial task considering the huge number of items and is therefore done usually at most once a day. Many other factors, such as checking for expiration dates for medicines and perishable products, can further complicate this task. With RFID technology, shelf inventory can be tracked automatically in real-time. For example, a customer selects the last of a particular item on the store shelf; a restock notice instantly appears on the department supervisor's system console, or even a sales associate's handheld computing device if so equipped.

It is easy to see that more frequent reviews and replenishments should lead to lower costs when the fixed costs associated with review and replenishments are negligible. This is true for the marginal inventory review costs when RFID is deployed. For shelf replenishment inside a store, the cost is driven by labor and the total cost per year follows a step function. When the capacity of the current store crew is exceeded (by replenishment and other store duties), one more person will be hired. Because there are many products to be replenished (typically in the thousands or tens of thousands in a store), as long as the replenishment is done reasonably efficiently (e.g., not making

replenishment trips with very few items), the total cost will not increase substantially when the replenishment frequency is increased.

In the vast inventory literature, there have been numerous studies on how to find optimal or optimal inventory replenishment frequencies. In the case of deterministic demand, this is equivalent to finding the reorder quantity, usually known as the economic lot sizing problem. Chapters 1 and 2 in Graves et al. (1993) contain a summary of single location and multiple location models. In the retail environment, demand is highly stochastic and so we focus on the literature on stochastic demand. In this case, there are relatively few studies treating the replenishment frequency as a decision variable.

Cachon (2001) analyzed three different shelf replenishment policies in a retailer that sells multiple products. Two of the policies are of periodic review type and one policy is of continuous review type. The three policies are structurally comparable and would be reasonable candidates for a retailer to choose from. It was found that the continuous review policy has lower cost than the periodic review ones. However, the conclusions are specific to the system in question and is not clear how general they might be.

Rao (2003) studied the behavior of an inventory system with respect to the replenishment interval in the context of a single inventory location with full backordering and a periodic review, order up-to replenishment policy. It was demonstrated that if we use the optimized reorder quantity $R$ for a given replenishment interval $T$, the total cost function (including a fixed replenishment cost, inventory holding cost, and backorder cost) is convex in $T$. Furthermore, bounds on the cost difference to that at the optimum are obtained when the choice of $T$ is not optimal, but $R$ is the optimal reorder quantity given $T$. We study the case where both the choice of $T$ and $R$ may not be optimal, but based on commonly used heuristics in practice. Rao (2003) also showed that the

continuous review version of the (*R*, *T*) replenishment policy (i.e. when *T*=0) will always provide a lower cost than the periodic review policy when both cases are at their optima.

Eynan and Kropp (1998) developed algorithms to find an approximation of the optimal replenishment interval for the single and multiple product periodic review, order up-to inventory system. The total cost function used is an approximation to the exact one. For this approximate objective, the authors also developed bounds of the total cost when the replenishment interval is not at the optimum.

In our case study, we investigated how the shelf replenishment process affects shelf inventory, backroom inventory, and lost sales at the retail store. Wong and McFarlane (2003) also suggested using RFID to automate and/or change the shelf replenishment process, but did not perform a quantitative analysis. For this case we used a lost sales model in handling the shortage at the store. Without RFID technology, shelf inventory is checked only periodically in person; therefore, it is difficult to replenish shelf continuously. On the other hand, with RFID technology deployed in store (e.g., using "smart shelves"), the shelf inventory can be continuously tracked (or tracked periodically with a very short time interval) and is much easier to decide when to replenish the shelf and how much to replenish. As soon as the shelf inventory reaches a critically low point (i.e., the reorder point for the shelf), more product can be pulled out from the backroom to replenish the shelf.

### 3.3.1   Once a Day Shelf Replenishment (s=12, S=24)

We first simulated a retail store environment where RFID technology is not deployed. In this case the shelf inventory is checked once a day by a store clerk. At that time, if the shelf inventory is below the re-order point for the shelf (s), then the shelf is replenished from the backroom. The

shelf replenishment here is based on an (s, S) policy with s=12 and S=24.  Figure 6 shows the in-ventory profiles of the shelf and backroom for a product, and Figure 7 shows the lost sales quantity encountered at the shelf with four products.  In this simulation scenario, the total lost sales quantity is 480.  The average shelf inventory is 13.24, backroom inventory is 13.99, and store inventory is 27.73.

### 3.3.2   Continuous Shelf Replenishment (s=12, S=24)

In this scenario, we assume that RFID technology is deployed in the retail store, and shelf in-ventory is checked continuously in real time.  Whenever the shelf inventory reaches the re-order point (s), the information system automatically calls for shelf replenishment, and the shelf is re-plenished to the target inventory level (S) by pulling products from the backroom.  The shelf re-plenishment policy was set to be the same as the baseline case without RFID in Section 3.3.1.  The simulation results are shown in Figure 8.  In this scenario, the total lost sales quantity went down substantially to only 7 from 480 (baseline case).  The shelf inventory fluctuated much less, staying mostly within a much narrower range between 12 and 24.  The average shelf inventory is higher at 17.13, and the backroom inventory is lower at 9.80.  The overall store inventory is about the same as the baseline case in Section 3.3.1, because the store replenishment policy stayed unchanged.

### 3.3.3   Continuous Shelf Replenishment (s=6, S=18)

The simulation results in the previous case indicate that the shelf replenishment policy can be changed substantially to reduce the shelf inventory level because the shelf inventory profile stays in a narrow range.  In this simulation scenario, we lowered the shelf re-order point (s) to 6 from

12, and lowered shelf target inventory (S) to 18 from 24. As shown in Figure 9, the simulation results indicate that the shelf lost sales quantity still stayed low at 7, but the shelf inventory went down to 11.75, which is 11.3% reduction from the case in Section 3.3.2. Since the shelf inventory level is lower but the store inventory is kept about the same, the backroom inventory in this case is higher than that of the previous case. Therefore, this simulation scenario brings out an opportunity to reduce the backroom inventory, thus lowering the overall store inventory.

### 3.3.4 Continuous Shelf Replenishment (s=6, S=18) with Lower Store Inventory Target

In this scenario, we investigated the opportunity to decrease the overall store inventory level by reducing inventory on the shelf and in the backroom as a result of continuous shelf replenishment. In the previous scenario in Section 3.3.3, we noticed that the backroom inventory is unnecessarily high. Therefore, in this scenario we reduced the store inventory target. The results are shown in Figure 10 and Figure 11. Comparing with the case in Section 3.3.1, which represents a situation without RFID technology, the lost sales dropped to 79 from 480. The average inventories on the shelf, in the backroom, and in the retail store overall went down to 79, 11.17, and 21.49 respectively, representing reductions of 15.6%, 29.7%, and 22.5% respectively.

In summary, with RFID technology deployed in the retail store, it is much easier to replenish the shelf more often and at the right time, which will reduce inventory on the shelf, in the backroom, as well as the store as a whole. Customer service can also be substantially improved by reducing lost sales encountered at the shelf. The simulation results from the four scenarios in this section are summarized in Table 2. Note again that the percentage improvements in case 3.3.2, 3.3.3, and 3.3.4 are with respect to case 3.3.1. This case serves as an example of process transformations enabled by RFID technology, which are not easily captured by a traditional,

spreadsheet based ROI analysis. It goes one step further than automating an existing process, and is possible because of the application of RFID technology.

We make the following interesting observation which has not been studied in the supply chain literature as far as we know. Consider the retail store consisting of the store shelf replenished from the backroom using a (s, S) policy implemented at the store shelf. The entire store is replenished using an another (s, S) policy on the total inventory of the store (shelf + backroom). By changing only the internal dynamics of store (i.e. replenishment of the shelf from the backroom), we are able to change the behavior of the entire store in the dynamics of the manufacturer – retailer supply chain. Such dynamics propagation could have important managerial implications. For example, store shelf replenishment decisions are usually made by a store manager. Perhaps unexpected by the store manager, this affects the replenishment dynamics of the entire store which may then change the performance of the entire supply chain. The customer service level of other stores may be affected if they are supplied by the same distribution center or plant.

## 3.4    Visibility of Inventory Across the Supply Chain

A high-resolution visibility of inventory and product movement can drive inefficiency and waste out of the supply chain. As an example, out-of-stocks cost consumer product suppliers 6-8% of revenues, according to a study by the University of Colorado. For a large supplier, out-of-stocks cost hundreds of millions of dollars annually. Other areas of waste include charge backs resulting from disputed shipment contents, diversions, shrinkage, and counterfeit. These problems are primarily caused by inaccurate inventory counts, the lack of a real-time replenishment signal, and the inability to track individual products through the supply chain. The advantage of RFID is its ability to provide a high visibility of inventory throughout the entire supply chain, where individual

products are tracked automatically in real-time, providing accurate and timely information in order to ensure delivery of the right product, to the right location, at the right time. This ability enables the participants of a supply chain to optimize manufacturing and distribution operations. It enables businesses to know where inventory is kept at any point in time (which would verify the authenticity of branded goods, improve order receipt accuracy and maintain accurate inventory levels). More importantly, suppliers and retailers can use such inventory information and information about the velocity of product movement to adjust to rapidly changing consumer demands and preferences. Commercial inventory management systems using RFID are already available; some of them are designed to be easily integrated into existing ERP systems, thereby leveraging prior investment in enterprise applications.

Visibility of inventory information is a central aspect in the subject of the value of information in a supply chain. A closely related subject is that of centralized vs. decentralized supply chains. (A centralized supply chain offers more theoretical advantages than just information visibility, a top one being centralized control.) The effects of information sharing on supply chain performance have been studied extensively in the supply chain literature. Li, et al. (2001) indicate that information sharing, particularly sharing the inventory data, improves supply chain performance of overall inventory cost and fill rate. Lee et al. (2000) analyze the value of sharing demand information and concludes that the sharing of information can be beneficial especially when demands are correlated over time. Cachon and Fisher (2000) state that in a traditional supply chain inventory management, orders are the only information that firms exchange, but information technology now allows firms to share demand and inventory data quickly and inexpensively. They study the value of sharing these data in a model with one supplier and $N$ identical retailers. Lee and Whang (2000) also discuss how lack of information sharing among the mem-

bers of the supply chain results in bullwhip effect. Although most of the related work in this area is not specifically linked to RFID, clearly information sharing will be greatly enhanced by the use of RFID as an enabling technology. An analysis which is directly related to RFID is provided by Joshi (2000), where a simulation approach is developed to evaluate the value of information visibility through RFID.

Gaukler et al. (2004) developed an analytical model to study and compare the scenarios of a centralized and a decentralized supply chain under a possible range of store operating efficiencies (with the most efficient case being the one using item-level RFID tagging). Some of the conclusions derived from the model are summarized in Gaukler (2004). That model assumes that RFID will contribute to a change in the demand (actually sales) distribution as seen by the retailer, due to say less out-of-stock situations. It models the effect of RFID at an abstract level that is suitable for the theoretical analysis of the behavior of the manufacturer-retailer system in terms of inventory, quantity sold, and selling price. Our study here explores specific ways through which RFID can make that change in the demand distribution and whether that change is indeed significant.

In this case study, we investigated how complete visibility of inventory data across the entire supply chain (manufacturer, DC, and retail store) affects the manufacturer's decision on production quantity. A key difference between this study and most other works cited above is that we investigate the effect of inventory visibility under non-optimal but practical conditions. Most theoretical works in this area (as discussed above) assumed that the supply chain had been optimized under a single objective in separate scenarios (such as those with centralized and decentralized information) and then compared the two scenarios under optimal conditions. While it is a reasonable way for theoretical development and is a fair comparison regarded by most people, it also presents a

gap between those results and reality. In practice, supply chains are rarely optimized using a single objective function due to many reasons, including the inadequacy of a single objective and difficulties in accurately estimating many of the data elements. In our study, we assume a scenario that is typical in practice and investigate how inventory visibility can affect its performance. Finding a better solution from a feasible solution is a usual practice in engineering.

In the supply chain in this study, we investigate how the visibility of inventory information can be used by the manufacturer. A key decision by the manufacturer is the production quantity and the quality of that decision is manifested in the inventory profile in the manufacturer's distribution center. How does this decision change when inventory information is available? We start from the most simplistic scenario with no information, which is not realistic in today's environment but provides a base line for comparison. We then move onto a more realistic scenario of knowing some information and finally investigate a scenario where RFID is deployed.

### 3.4.1 Without RFID, Manufacturing Quantity = Average Daily Sales Quantity at Retailer

In this most basic setting, we assume that RFID technology has not been deployed in the supply chain, and a manufacturer does not have access to inventory data at the DC or the retail store. (This is perhaps an overly pessimistic case to assume that the manufacturer does not have access to the status of its own DC. We made this assumption to emphasize the difference in performance with latter cases. A more realistic scenario would be the case 3.4.2.) The manufacturer, though, has information on the average daily sales quantity of products, on which the daily manufacturing quantity is based. The simulation results for a product, P2, are shown in Figure 12. A fixed quantity of products are pushed into DC once a day; but varying quantities of the products are pulled by the retail store based on its inventory position. The balance between the

inflow to and the outflow from the DC results in the fluctuation of inventory in the DC as shown in Figure 12. The range of inventory in this case is between -10 and 140, and the average inventory quantity is 54.14 for all four products. The total back order quantity is 44.

### 3.4.2  With RFID, Manufacturing Quantity = (Target Inv. – Current Inv.) at DC

In this setting, we assume that the manufacturer has limited access of inventory data in supply chain. Here, we assumed that the manufacturer has access (due to RFID) to real time inventory data at the DC, but not inventory at the retailer, and the manufacturing quantity is calculated as the target DC inventory minus the current DC inventory position. The simulation results for a product are shown in Figure 13. Since the manufacturing quantity is adjusted based on the inventory level at the DC, the fluctuation of inventory at the DC is much smaller; the range of inventory for all four products is between 6 and 90. The average inventory is 40.18, which is a 26% reduction from the previous case in Section 5.1. The DC back order quantity disappeared completely.

### 3.4.3  With RFID, Manufacturing Quantity = (Target Inv. - Current Inv.) at (Manufacturer + DC + Retailer)

In this setting, we assume that the manufacturer has a full access of inventory in the entire supply chain. Here we assume that the manufacturer has real time inventory information not only at the DC but also at the retail store. The manufacturing quantity is calculated as the total target inventory of the manufacturer, DC, and retailer minus the current inventory of manufacturer, DC, and retailer. The simulation results for a product, P2, are shown in Figure 13. Here, the fluctuation of DC inventory is even smaller than the previous case in Section 5.2; the range of inventory is between 19 and 84 for all four products. The average DC inventory is 41.80, which is a 23% reduc-

tion from the case in Section 5.1. There is no back order in this case either. Since the range of inventory is very small and the average DC inventory is relatively high, this presents an opportunity to reduce the DC inventory by lowering the target inventory at DC, which is discussed in the next section.

### 3.4.4 With RFID, Manufacturing Quantity = (Target Inv. – Current Inv.) at (Manufacturer + DC + Retailer) with Lower Inventory Target at DC

As explained in the previous section, there is unnecessarily high level of inventory at the DC in the scenario in Section 3.4.3. As seen in this example, an opportunity to reduce inventory by changing inventory target surfaces with RFID deployment. Therefore, in this scenario we lowered the target inventory of the DC while keeping other simulation parameters constant as that in Section 3.4.3. The simulation results are shown in Figure 14. The range of the DC inventory for all four products is similar to the case in 3.4.3, but the average inventory is 28.52, much smaller than the previous case. Back order still did not occur. Comparing the simulation results with the case in Section 3.4.1 (without RFID), this case (with RFID) identified an opportunity for a 47% reduction of DC inventory, while eliminating the back order completely. The simulation results for case study 3.4 are summarized in Table 3. This case serves as an example of process transformation taking advantage of new data offered by RFID technology.

### 3.5    Time Delay of Inventory Data

Another potential benefit of RFID is reduction or elimination of time delay in recording and processing the inventory data at various points in the supply chain. With RFID the inventory data is not only more accurate but also in real time, and the resulting supply chain decision qual-

ity can improve various supply chain performance. In this section, we study the effect of delay of inventory data at the retailer receiving dock and at the replenishment decision point.

### 3.5.1  Delay of Receiving Dock Scanning, Without RFID

When products delivered from the DC arrive at the receiving dock of the retailer, the products are put away (in the backroom or on the shelves) and recorded as retailer inventory. Without RFID, however, the received product has to be manually scanned in by store worker, usually after a certain time delay. But with RFID readers deployed at the receiving dock, products would be automatically and instantly recorded as store inventory.

From an inventory replenishment point of view, receiving dock delays cause the following two effects. If the inventory analyst or buyer is aware of the delay at the receiving dock, the replenishment lead time is then lengthened to take the delay into account. This will directly increase the safety stock level, as can be seen easily from commonly used safety stock formulae (see, e.g., Graves et al. 1993, Chapter 1). More often than not, the analyst or buyer is not aware of the delay, or at least not sure of the length of the delay. This results in an error in the replenishment lead time parameters, such as an underestimation of the mean and the variance. In this case, the realized lead times have a slightly different distribution than those specified in the computation of the replenishment policy. At this time, we are not aware of any study on the effect of errors in the lead time mean and/or variance on the performance of the inventory system. The closest set of literature found is on the robustness of the assumption that the replenishment lead time follows the normal distribution (e.g., Lau and Lau 2003, Tyworth and O'Neill 1997). They study the case where the actual lead times are not normal but that assumption is made in the inventory model. (Results seem to be inconclusive in that the effect is significant is some cases

while in other situations the effect is not significant.) They do not explicitly study the case where the actual lead times are indeed normal but the mean and/or variance are not the same as that estimated.

We modeled a situation where RFID is not deployed and product delivery is scanned in by a store worker. The delay of scanning is modeled as a uniform distribution with the minimum of 0 hour and the maximum of 12 hours. In this setting we assume that the store shelf replenishment is continuous with a continuous review (s, S) policy with the recorder point (s) of 12 and the target inventory (S) of 24. (Note that because the reorder point remains the same in the case of delay, we can investigate the effect of the delay when it is ignored in calculating the inventory policy.) The simulation results are shown in Figure 16 (inventory profile in backroom and shelf) and in Figure 17 (lost sales quantity at retailer). The lost sales quantity here is 48, and the average shelf inventory is 16.67 and the average backroom inventory is 7.48.

### 3.5.2  No Delay of Receiving Dock Scanning, With RFID

In the second scenario, we assume that RFID is deployed at the retailer, including RFID readers at the receiving dock, and delay of delivery scanning no longer exists. The inventory profile from the simulation is shown in Figure 8 (described in Section 3.3). The lost sales quantity drops to 7 (85% reduction) from 48. The average shelf inventory is a little higher at 17.13, and the average backroom inventory is also a little higher at 9.80. However, the shelf inventory profile here is more stable than the first scenario (Figure 16), and it can be easily reduced by adjusting the shelf replenishment policy (s, S). Again, an inventory reduction opportunity surfaces with RFID. This reduction of data delay is somewhat equivalent to the lead time reduction, which is well known for its associated benefits in reducing safety stock inventory.

### 3.5.3  Delay of Inventory Data for Replenishment Order, Without RFID

When a replenishment order decision is made, the availability of accurate inventory data dictates the quality of the replenishment decision. RFID enables the availability of accurate, real time inventory data. In this scenario, we studied the effect of delayed inventory data for replenishment decision in the supply chain. We modeled a situation where a store worker records a inventory of product at a specific time during a day. Another worker is in charge of deciding the replenishment quantity and placing an order, and does so at another specific time of the day. However, they are not well coordinated such that the replenishment decision is made a few hours after the inventory status is recorded. Note that this is not equivalent to enlarging the replenishment period. The replenishment period is the same as the data collection period (say one day). The data used in the replenishment decision is also correct, except that they are not the latest data available. In other words, the replenishment cycle is out of synchronization with the data collection cycle. This is actually quite common as data collection is usually of the batch, periodic type and replenishment decisions are usually not completely automatic so that by the time the human gets to a particular product decision, the data is not the most up-to-date any more. At this time we are not aware of any other work in the literature on this issue.

The first scenario we simulated is one with such a non-synchronized replenishment. We assumed that there is an 8-hour delay between when the sales data were collected and when the replenishment decision was made. The simulated inventory profile (shelf and backroom) at the retailer is shown in Figure 18, and the lost sales quantity is shown in Figure 19. The lost sales quantity here is 528. The average shelf inventory is 13.71, the average backroom inventory is 2.92 and the average store inventory is 16.91.

### 3.5.4   No Delay of Inventory Data for Replenishment Order, With RFID

With RFID, however, it is easier to have the accurate and real time inventory data available so that a much better replenishment decision can be made. In this scenario, we assume that the delay of inventory data no longer exists. The inventory profile from the simulation is shown in Figure 8 (described in Section 3.3). The lost sales quantity drops to 7 (99% reduction) from 528. The average shelf inventory is higher at 17.13, and the average backroom inventory is also higher at 9.80. The overall store inventory is higher too at 27.41. However, the shelf inventory profile here is more stable than the first scenario (Figure 19), and it can be reduced by adjusting the shelf replenishment policy (s, S) and target inventory of the retailer. Again, supply chain improvement opportunity surfaces with RFID, and a certain combination of customer service improvement (reduction in lost sales quantity) and inventory reduction can be achieved.

## 4   EXPERIMENTAL DESIGN AND SENSITIVITY ANALYSIS

In order to validate the observations made in Section 3, we employed an experimental design to study whether the RFID related simulation parameters (factors) have statistically significant effects on the key supply chain performance measures. Each experiment was replicated from 5 to 20 times, and confidence intervals were computed for each performance measure to test whether the factors have statistical significance. (95% confidence intervals for all the responses were less than (+/-) 10% of mean responses.)

We designed a 2-level ($2^{k-p}$) fractional factorial design, $2^{5-1}_V$ (see, e.g., Chapter 12 in Box, Hunter, and Hunter, 1978) in order to study the effect of various simulation parameters (factors) on the performance of supply chain. The performance measures (responses) that we are focusing on are: average DC Inventory, average store lost sales quantity, average shelf inventory and average store inventory. We used 5 factors (the independent variables): visibility of shrinkage error, shelf replenishment frequency, inventory visibility of DC and Retailer for the Manufacturer, retailer receiving dock scanning delay and data delay for replenishment order decisions. Table 4 shows the high and low levels for each factor. In the simulation model we used for this experimental design work, we assumed DC inventory can be backlogged, and insufficient shelf inventory at the store results in lost sales (similar to Section 3). All the experiments had a simulation duration of 200 days with the warm-up period of 20 days. The simulation results from the warm-up period was removed before any analysis was performed.

The main purpose for including a formal design of experiment study here is to show that the simulation results obtained in the case studies shown earlier (Sections 3.2-3.5) are indeed statistically significant in a number of different settings. The setting of the 16 experiments in our design and the corresponding simulation results are shown in Table 5. The results of the analysis for the five independent variables (factors) and the five responses are presented in Table 6. The Pareto charts for the standard effects on response variables are plotted in Figures 20-24.

Table 6 shows a statistically significant (negative) effect of factor C (inventory visibility) on the Average DC Backlog, which means that the improved inventory visibility due to the use of RFID will help reduce the backlog at the DC, as indicated in Section 3.4. Factor C may also increase the inventory at the DC, which is necessary for reducing the backlog. Factor B (shelf replenishment frequency) also shows a weak, but statistically significant effect on the DC backlog,

and even a weaker effect on DC inventory. This is because the shelf replenishment frequency (factor B) affects the store inventory, which in turn affects the store replenishment decision. And store replenishment decision affects the DC inventory and backlog.

On the other hand, factor A (visibility of shrinkage error), factors B (shelf replenishment frequency) and E (data delay for replenishment order) are all shown to have statistically significant effects on the three responses at the store level: store inventory, store lost sales and shelf inventory, as indicated in the case studies in section 3.2, 3.3 and 3.4 respectively. Particularly, they all help reduce the lost sales in the store.

We also notice that the results from the experiment are fairly consistent. We can see that factors E and A have significant effects on the store level response variables but no significant effect on the responses at the DC level. Similarly, factor C has no effect on the responses at the store level but shows a strong effect at the DC level. Only factor B (shelf replenishment frequency) has a significant effect at both DC and store levels, which is also reasonable and intuitive.

In this experiment, factor D does not show up as statistically significant in any of the response variables, although it is very close to be statistically significant for shelf inventory as shown in the Pareto Chart in Figure 23. One explanation is that the change of factor D is relatively minor (randomly between 0 and 12 hours in our setting). To confirm this we perform a sensitivity analysis using a separate experiment. We found that factor D showed up as a statistically significant factor when it is set to a longer delay at the high factor level, e.g., 0-24 hours. Also it is easy to see that factor D has little impact when the actual time interval between store replenishments is long (which can be the case even with factor B set at the low level).

We should emphasize that the actual results shown here are only meaningful to the specific dataset that we used in the analysis. We cannot generalize the interpretation to imply that the same relative magnitudes would be true for a different data set. Such analysis should be performed based on the actual data for a particular business case. With the present experiment we show explicitly where RFID can make a difference in a supply chain and how the benefits can be realized. In most cases, simply installing RFID equipment and doing everything else the same way as before may not produce the desirable results.

## 5   CONCLUSIONS

Through this study, we demonstrated that there are opportunities for RFID technology to provide significant benefits in a supply chain, well beyond the automation oriented advantages such as labor savings. We have chosen to analyze simple scenarios that might be extreme and might not be completely realistic, so our numerical results should not be used directly. However, our results do show the potential of RFID in a supply chain that is not widely known in the literature or commonly explored in business practice. Such potential should increase the chance of RFID being deployed as a standard instrument in manufacturer-retailer supply chains. With RFID deployment inventory data become more accurate and it is easier to share the inventory data among supply chain players such as manufacturer, distributor and retailer. As a result, the quality of supply chain decisions, such as replenishment and manufacturing planning, can improve substantially. As shown in this study, opportunities to improve supply chain performance, such as inventory reduction and customer service improvement, surface with RFID deployment. A key managerial implication is that significant work, such as process redesign and transformation, needs to be done with RFID deployment in order to reap the benefits.

It is true that some of the scenarios we studied are possible without RFID. For example, individual scenarios can be achieved by integrating different sources of data available today in a real-time environment. RFID represents one of a number of possible solutions to obtain the required data. It is therefore important to do a cost-benefit analysis to evaluate each alternative solution. The approach discussed in this article is useful for the benefit estimation of such an analysis. We should also note that approaches using existing data sources are not inexpensive, and RFID does seem to be quite attractive if one were to implement all or many of these scenarios. It would be an illuminating exercise to compare the implementation of multiple scenarios using more traditional approaches (but possibly a combination of different technologies) to that using the single technology of RFID.

Other interesting issues to investigate include more complex scenarios that are closer to practice. Examples are: an RFID read accuracy of less than 100%, other supply chain configurations such as the addition of retailer-owned distribution centers. It would be worthwhile to find out whether complexity in the supply chain configuration would amplify or diminish the effect of the RFID benefits explored here.

**REFERNCES**

Agarwal, V. 2001. Assessing the Benefits of Auto-ID Technology in the Consumer Goods Industry, White paper. Auto-ID Center, MIT.

Alexander, K., T. Gilliam, K. Gramling, M. Kindy, D. Moogimane, M. Schultz, M. Woods. 2003a. Focus on the Supply Chain: Applying Auto-ID within the Distribution Center, White paper, Auto-ID Center, MIT.

Alexander, K., T. Gilliam, K. Gramling, C. Grubelic, H. Kleinberger, S. Leng, D. Moogimane, C. Sheedy. 2003b. Applying Auto-ID to Reduce Losses Associated with Product Obsolescence, White paper, Auto-ID Center, MIT.

Alexander, K., G. Birkhofer, K. Gramling, H. Kleinberger, S. Leng, D. Moogimane, M. Woods. 2003c. Focus on Retail: Applying Auto-ID to Improve Product Availability at the Retail Shelf. White paper, Auto-ID Center, MIT.

Alexander, K., T. Gilliam, K. Gramling, C. Grubelic, H. Kleinberger, S. Leng, D. Moogimane, C. Sheedy. 2003d. Applying Auto-ID to Reduce Losses Associated with Shrink. White paper, Auto-ID Center, MIT.

Bensoussan, A., M. Cakanyildirim, S.P. Sethi. (2005). Optimal Ordering Policies for Inventory Problems with Dynamic Information Delays, Working paper, School of Management, University of Texas at Dallas, TX.

Box, G.E.P., W.G. Hunter, J.S. Hunter. 1978. *Statistics for Experiments: An Introduction to Design, Data Analysis, and Model Building*, John Wiley, New York.

Brown, K.L., A. Inman, J.A. Calloway. 2001. Measuring the Effect of Inventory Inaccuracy in MRP Inventory and Delivery Performance, *Production Planning and Control*, 12 (1), 46-57.

Cachon, G. 2001. Managing a Retailer's Shelf Space, Inventory, and Transportation. *Manufacturing & Service Operations Mangement* 3(3), 211–229.

Cachon, G.P., M. Fisher. 2000. Supply Chain Inventory Management and the value of Shared Information, *Management Science*, Vol. 46, 1032-1048.

DeHoratius, N., A. Raman. 2004. Inventory Record Inaccuracy: An Empirical Analysis. Working paper. University of Chicago.

Eynan, A., D.H. Kropp 1998. Periodic Review and Joint Replenishment in Stochastic Demand Environments, *IIE Transactions* 30, 1025-1033.

Fleisch, E., C. Tellkamp. 2005. Inventory inaccuracy and supply chain performance: a simulation study of a retail supply chain, *International Journal of Production Economics*. 95(3). 373.

Forrester, J.W. 1958. Industrial Dynamics – A Major Breakthrough for Decision Makers, *Harvard Business Review* 36(4), 37-66, July-August 1958.

Gaukler, G. 2004. RFID in the Retail Supply Chain: Benefits, Roll-out Strategies, and Cost Sharing Agreements, *The Supply Chain Connection*, Newsletter of the Stanford Global Supply Chain Management Forum, 10(2), 6-7.

Gaukler, G., R.W. Seifert, W.H. Hausman. 2004. Item-Level RFID in the Retail Supply Chain, submitted for publication.

Graves, S.C., A.H.G. Rinnooy Kan, P.H. Zipkin (Eds.) 1993. *Logistics of Production and Inventory*, Handbooks in Operations Research and Management Science, Volume 4, North Holland.

Iglehart, D. L., R. C. Morey. 1972. Inventory systems with imperfect asset information. *Management Science* 8, 18, B388-B394.

Joshi, Y. 2000. Information Visibility and its Effect on Supply Chain Dynamics, Master degree thesis, MIT.

Kambil, A., J.D. Brooks. 2002. Auto-ID Across the Value Chain: From Dramatic Potential to Greater Efficiency & Profit, White paper, Auto-ID Center, MIT.

Kang, Y., S. Gershwin. 2004. Information Inaccuracy in Inventory Systems Stock Loss and Stockout. Joint MIT/INFORMS Symposium.

Kang, Y., R. Koh. 2002. Applications Research, Research Report, Auto-ID Center, MIT.

Kök, A.G., K.H. Shang. 2004. Replenishment and Inspection Policies for Systems with Inventory Record Inaccuracy. Working paper, Duke University.

Lau, H.S., A.H.L. Lau, 2003. Non-Robustness of the Normal Approximation of Lead-Time Demand in a (Q,R) System, Naval Research Logistics 50(2), 149-166.

Law, A., D. Kelton. 2000. *Simulation Modeling and Analysis*, Third Edition, McGraw-Hill.

Lee, H.L., V. Padmanabhan, S. Whang. 1997. The Bullwhip Effect in Supply Chains, *Sloan Management Review* 38(3), 93-102.

Lee, H. L., K.C. So, C.S. Tang. 2000, The Value of Information Sharing in a Two-Level Supply Chain, *Management Science*, 46, 626-643.

Lee, H. L., S. Whang. (2000), Information sharing in a supply chain, *International Journal of Technology Management (IJTM),* 20(3/4).

Li, J., M. Shaw, R. Sikora. 2001. The Effects of Information Sharing Strategies on Supply Chain Performance, Working paper, University of Illinois at Urban-Champaign.

Krajewski, L.J., B.E. King, L.P. Ritzman, D.S. Wong. 1987. Kanban, MRP, And Shaping The Manufacturing Environment, *Management Science*, 33(1), 39-57.

Rao, U., 2003. Properties of the Periodic Review (*R,T*) Inventory Control Policy for Stationary, Stochastic Demand, *Manufacturing & Service Operations Management*, 5(1), pp.37-53.

*RFID Journal*, published by RFID Journal, Inc., in print and on the web at www.rfidjournal.com.

Tyworth, J.E., L. O'Neill, 1997. Robustness of the normal approximation of lead-time demand in a distribution setting, Naval Research Logistics 44(2), 165 – 186.

Wayman, W. A. 1995. Inventory Accuracy Through Warehouse Control, *Production and Inventory Management Journal*, 36(2), 17.

Wong, C.Y., D. McFarlane. 2003. The Impact of Auto-ID on Retail Shelf Replenishment Policies, White paper, Auto-ID Center, MIT.
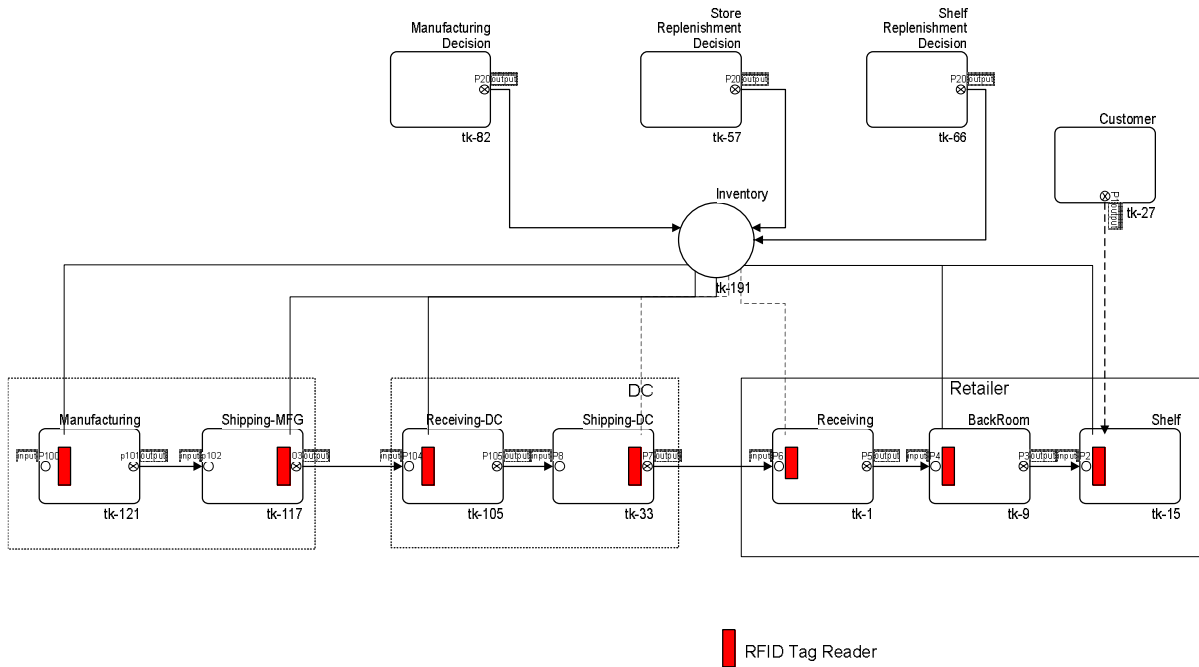
Figure 1   Three Echelon Supply Chain Model for CP Retail Business
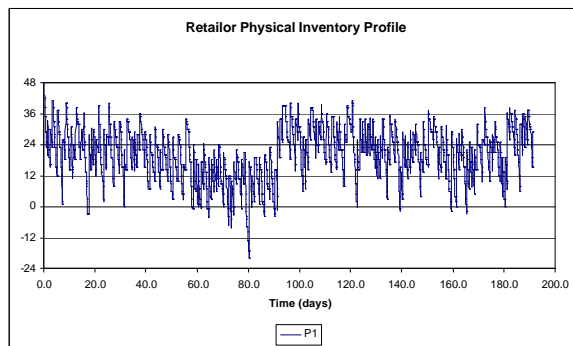


Figure 2
Physical Inventory Without RFID Deployment
ment
(s=36, S=48)
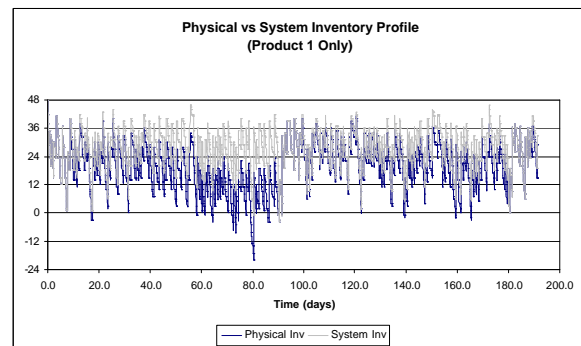


Figure 3
Discrepancy between Physical Inventory
and System Inventory
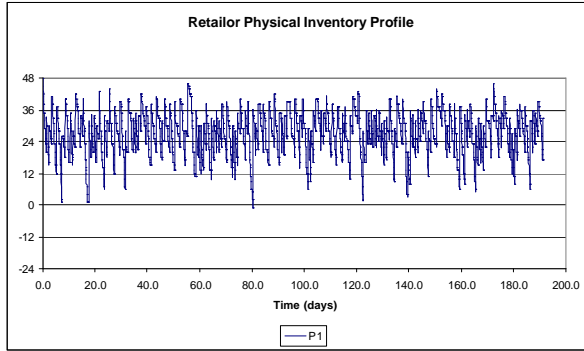
Figure 4
Physical Inventory with RFID Deployment
(S=48, s=36)
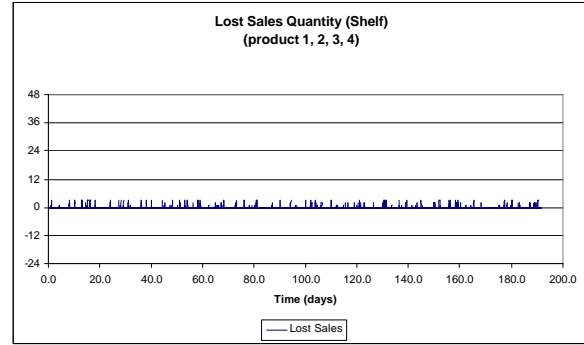


Figure 7
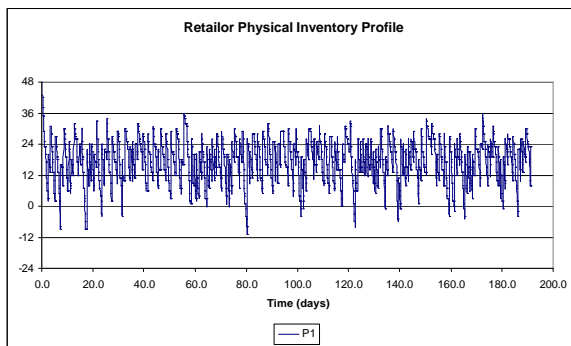Lost Sales with Once-a-Day Shelf Replen-
ishment (s=12, S=24)



Figure 5
Physical Inventory with RFID Deployment
(S=38, s=26)
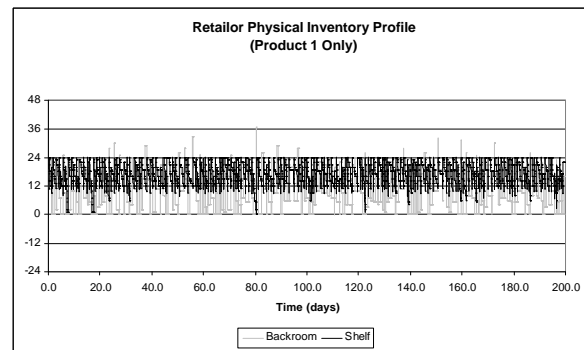


Figure 8
Shelf and Backroom Inventory with Con-
tinuous Shelf Replenishment (s=12, S=24)
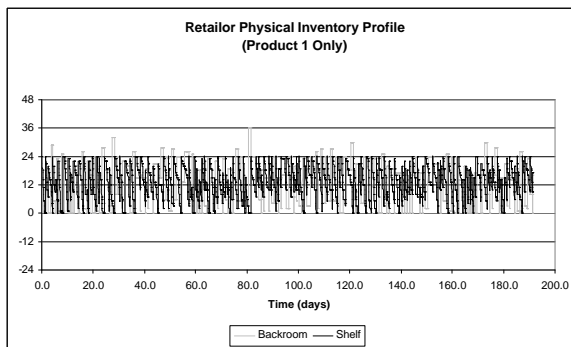


Figure 6
Shelf and Backroom Inventory with Once-a-
Day Shelf Replenishment (s=12, S=24)
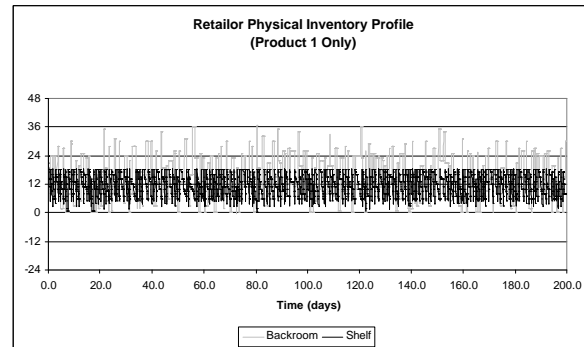


Figure 9
Shelf and Backroom Inventory with Con-
tinuous Shelf Replenishment (s=6, S=18)
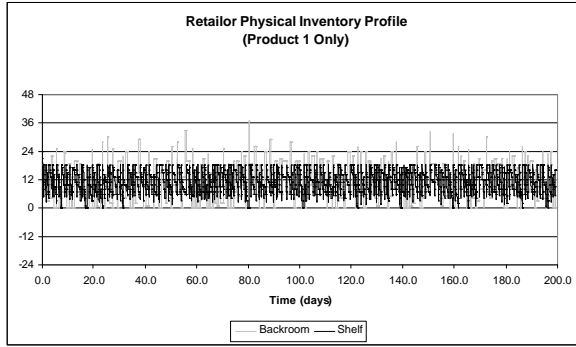
Figure 10
Shelf and Backroom Inventory with Continuous Shelf Replenishment (s=6, S=18) and Lower Store Inventory Target



Figure 11
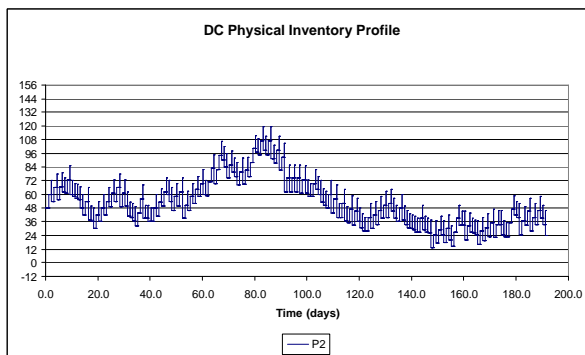Lost Sales with Continuous Shelf Replenishment (s=6, S=18) and Lower Store Inventory Target



Figure 12
DC Inventory Profile with No Inventory Visibility(Daily Manufacturing Quantity is Fixed)
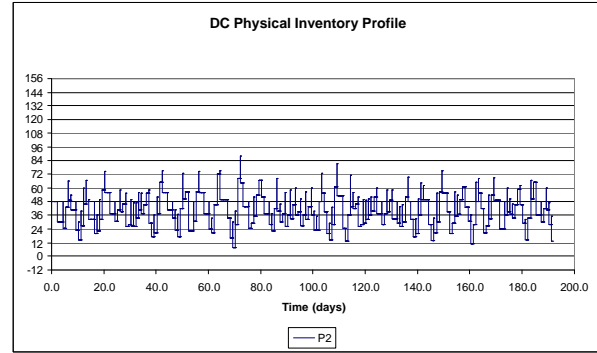


Figure 13
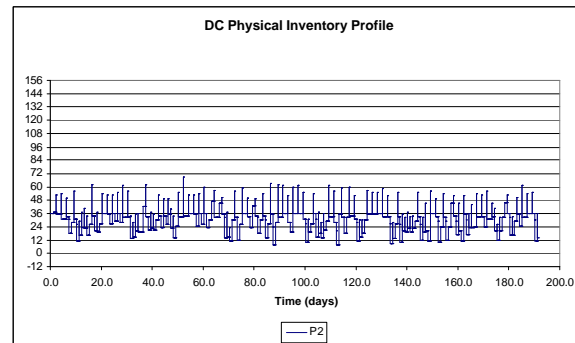DC Inventory Profile with a limited Inventory Visibility (Daily Manufacturing Quantity is Based on DC Inventory)
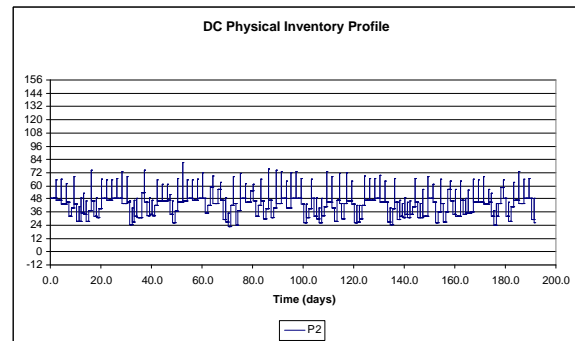


Figure 14
DC Inventory Profile with a full Inventory Visibility(Daily Manufacturing Quantity is Based on Inventory in Manufacturer, DC, and Retailer)



Figure 15
DC Inventory Profile with a full Inventory Visibility and with a Lower DC Inventory Target (Daily Manufacturing Quantity is Based on Inventory in Manufacturer, DC, and Retailer)
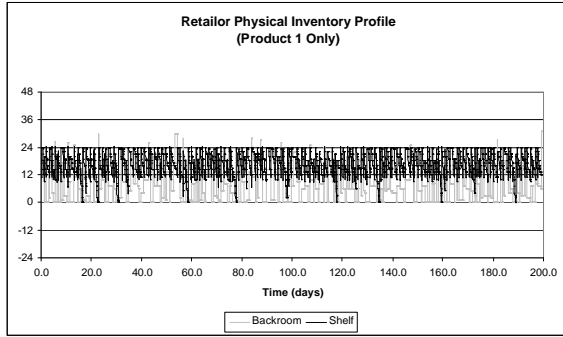
Figure 16
Shelf and Backroom Inventory with a
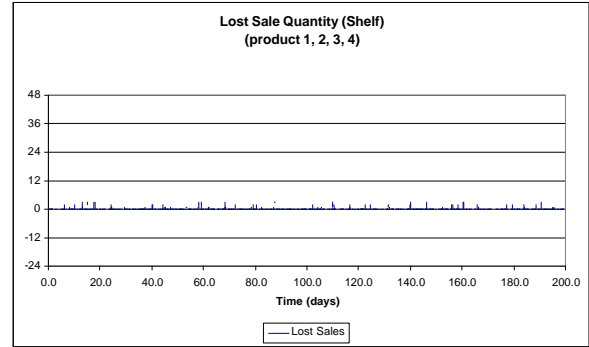Retailer Receiving Dock Scanning Delay,
Uniform [0, 12] hours



Figure 17
Lost Sales Quantity with a Retailer Receiv-
ing Dock Scanning Delay, Uniform [0, 12]
hours



Figure 18
Shelf and Backroom Inventory with a
Delayed Data for Replenishment Order,
(Delay = 8  hours)



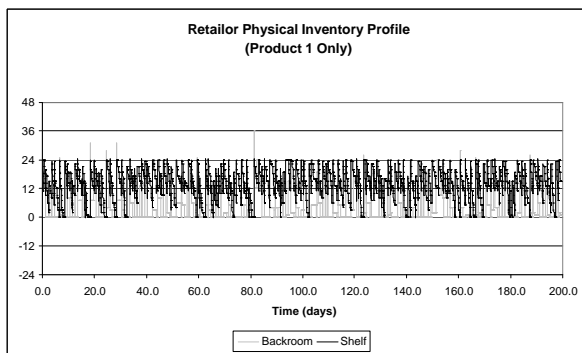Figure 19
Los Sales Quantity with a No Delayed Data
for Replenishment Order (Delay = 0  hours)
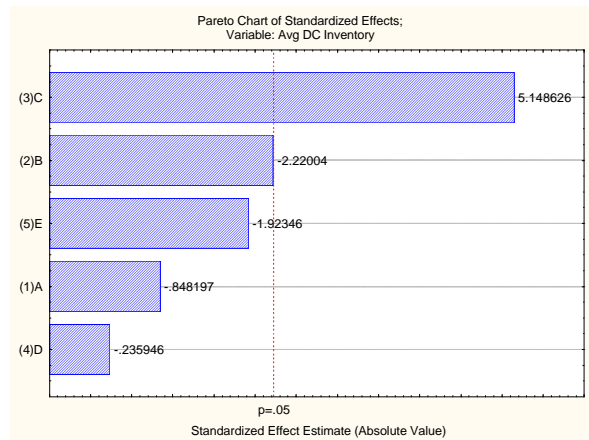


Figure 20
Pareto Chart of Standardized Effects on
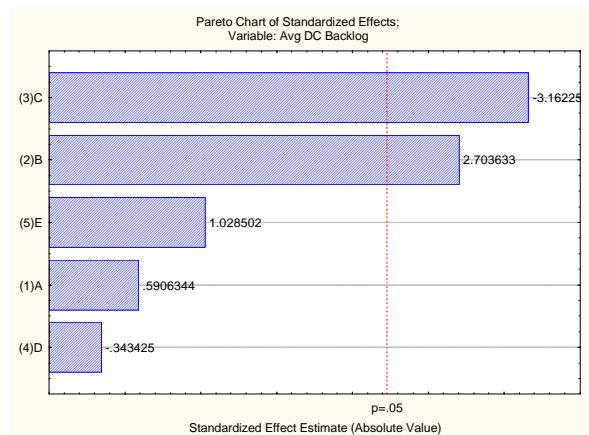Average DC Inventory



Figure 21
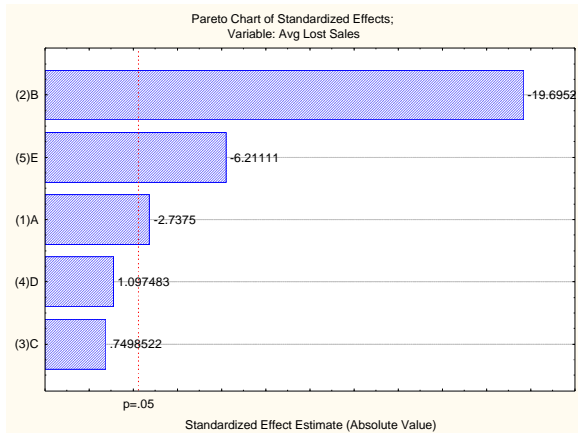Pareto Chart of Standardized Effects on
Average DC Backlog

Figure 22
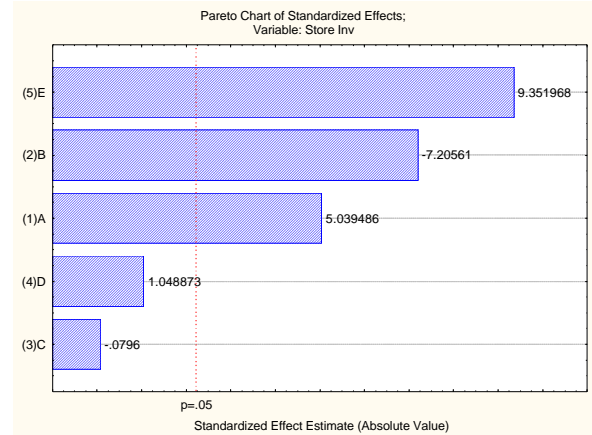Pareto Chart of Standardized Effects on Average Store Lost Sales



Figure 24
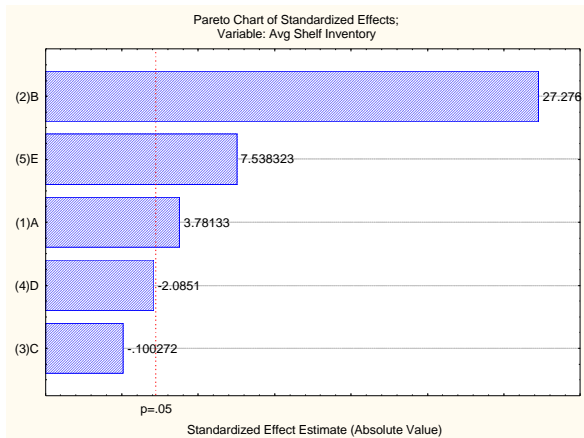Pareto Chart of Standardized Effects on Average Store Inventory



Figure 23
Pareto Chart of Standardized Effects on Average Shelf Inventory

**Tables**

Table 1: Simulation Case Study 1: Summary of Benefits

|  | Without RFID (case 3.2.1) | With RFID (case 3.2.2) | With RFID (case 3.2.3) |
|---|---|---|---|
| Replenishment Policy(s, S) | s=36, S=48 | s=36, S=48 | s=26, S=38 |
| Retailer Back Order Quantity | 2,086 | 17 (99% own) | 1,627 (22% down) |
| Retailer Avg. Inventory | 22.58 | 27.11 | 17.24 (16% down) |

Table 2: Simulation Case Study 2: Summary of Benefits

|  | Without RFID (case 3.3.1) | With RFID (case 3.3.2) | With RFID (case 3.3.3) | With RFID (case 3.3.4) |
|---|---|---|---|---|
| Replenishment Policy (s, S) | s=12, S=24 | s=12, S=24 | s=6, S=18 | s=6, S=18 |
| Shelf Lost Sales Quantity | 480 | 7 (99% down) | 7 (99% down) | 79 (84% down) |
| Shelf Avg. Inventory | 13.24 | 17.13 | 11.75 (11% down) | 11.17 (16% down) |
| Backroom Avg. Inventory | 13.99 | 9.80 | 15.20 | 9.83 (30% down) |
| Retailer Avg. In-ventory | 27.73 | 27.41 | 27.40 | 21.49 (23% down) |

Table 3. Simulation Case Study 3: Summary of Benefits

|  | Without RFID (case 3.4.1) | With RFID (case 3.4.2) | With RFID (case 3.4.3) | With RFID (case 3.4.4) |
|---|---|---|---|---|
| Manufacturing Quantity | Avg. Daily Sales Qty at Retailer | (Target Inv-Inv) at DC | (Target Inv-Inv) at (Mfg+DC+Retailer) | Same as case 5.3, and with Lower DC Inv Target |
| DC Inventory Range | -10 to 140 | 6 to 90 | 18 to 84 | 5 to 72 |
| DC Avg. Inventory | 54.14 | 40.18 (26% down) | 41.80 (23% down) | 28.52 (47% down) |
| DC Back Order Quantity | 44 | 0 (100% down) | 0 (100% down) | 0 (100% down) |

Table 4. Factor Levels

| Factor (Independent variables) | Low (-) | High (+) |
|---|---|---|
| A. Visibility of Shrinkage Error (DC & Store) | Not visible (w/o RFID) | Visible (with RFID) |
| B. Shelf Replenishment Frequency | 1/day (w/o RFID) | Up to 24/day (with RFID) |
| C. Inventory Visibility of DC and Retailer for Manufacturer | Not visible (w/o RFID) | Visible (with RFID) |
| D. Receiving Dock Scanning Delay | None (with RFID) | Delay: [0-12] hours (w/o RFID) |
| E. Delay of Data for Replenishment Order | None (with RFID) | Delay: 8 hours (w/o RFID) |

Table 5. Experiments and Simulation Results*

| | A | B | C | D | E | Avg. DC Inventory | Avg. DC Backlog | Avg. Store Lost Sales Qty | Avg. Shelf Inventory | Avg. Store Inventory |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | - | - | - | + | 51.23 | 0.65 | 5.61 | 11.28 | 23.95 |
| 2 | + | - | - | - | - | 10.34 | 29.31 | 3.56 | 12.48 | 27.57 |
| 3 | - | + | - | - | - | 2.62 | 170.48 | 0.58 | 15.86 | 23.05 |
| 4 | + | + | - | - | + | 3.95 | 139.31 | 0.56 | 15.77 | 22.77 |
| 5 | - | - | + | - | - | 41.34 | 0.00 | 3.88 | 12.35 | 26.76 |
| 6 | + | - | + | - | + | 44.69 | 0.00 | 5.27 | 11.50 | 24.66 |
| 7 | - | + | + | - | + | 46.41 | 0.00 | 1.36 | 14.96 | 20.47 |
| 8 | + | + | + | - | - | 39.13 | 0.00 | 0.19 | 16.64 | 26.21 |
| 9 | - | - | - | + | - | 15.64 | 12.88 | 3.91 | 12.31 | 26.73 |
| 10 | + | - | - | + | + | 32.36 | 1.61 | 4.69 | 11.58 | 24.68 |
| 11 | - | + | - | + | + | 7.47 | 65.22 | 1.86 | 14.39 | 21.46 |
| 12 | + | + | - | + | - | 1.92 | 193.49 | 0.50 | 16.13 | 26.66 |
| 13 | - | - | + | + | + | 45.62 | 0.00 | 5.56 | 11.27 | 23.97 |
| 14 | + | - | + | + | - | 40.57 | 0.00 | 3.64 | 12.62 | 27.50 |
| 15 | - | + | + | + | - | 42.36 | 0.00 | 1.04 | 15.33 | 24.04 |
| 16 | + | + | + | + | + | 43.76 | 0.00 | 1.42 | 15.03 | 23.04 |

* 95% confidence interval is less than (+/-) 10% of the mean response.

Table 6. Responses with Statistically Significant factors

| | Avg. DC Inventory | Avg. DC Backlog | Avg. Store Lost Sales | Avg. Shelf Inventory | Avg. Store Inventory |
|---|---|---|---|---|---|
| Computed Effects (statistically significant, alpha: 0.05) | C B | C B | B E A | B E A | E B A |