ANALYSIS OF IMPERFECT RFID VISIBILITY IN A MULTI-ECHELON SUPPLY CHAIN

NEBIL BUYURGAN[1], Ph.D.

Department of Industrial Engineering

University of Arkansas

4207 Bell Engineering Center

Fayetteville, AR 72701

nebilb@uark.edu

Phone: +1 (479) 575 7423

Fax: +1 (479) 575 8431

MANUEL D. ROSSETTI, Ph.D., P.E.

Department of Industrial Engineering

University of Arkansas

4207 Bell Engineering Center

Fayetteville, AR 72701

rossetti@uark.edu

RONALD T. WALKER

Resource Optimization and Innovation (ROi)

Sisters of Mercy Health System

14528 S. Outer Forty, Suite 200

St. Louis, MO 63017

Ronald.Walker@Mercy.Net

[1] Corresponding Author

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Abstract

This study investigates how imperfect inventory information provided by Radio Frequency Identification (RFID) technology can be used in inventory management. A simulation-based approach is utilized to understand the potential uses and impacts of imperfect RFID data in multi-echelon retail supply chains. Research efforts in this study are focused on observing how a retail supply chain is affected by allowing RFID inventory systems with imperfect visibility make all replenishment decisions. Furthermore, the use of RFID as a supporting technology to an existing inventory replenishment system is also examined. Simulation results reveal that when used as the primary decision making tool, RFID could be a valuable technology even without perfect visibility. However, unforeseen trends and system behaviours are observed on the level of inventory record inaccuracy. When RFID is used to monitor the inventory as a supporting technology, the information provided can be used to trigger inventory correction activities.

Keywords: Inventory management, Radio frequency identification, Supply chain management

[2] This material is based upon work supported by the U.S. Air Force Office of Sponsored Research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Air Force.

Biographical Notes

Nebil Buyurgan, Ph.D., is an assistant professor in the Industrial Engineering Department and the director of the AT&T Material Handling Laboratory at the University of Arkansas. He received his doctorate in engineering management, from the University of Missouri-Rolla. As the author or co-author of over 40 technical papers, his research interests include radio frequency identification technologies and their supply chain management applications, humanitarian and healthcare logistics, and modelling and analysis of discrete event systems. He has received research funding from, among others, the National Science Foundation, Air Force Research Lab, and Wal-Mart Stores.

Manuel D. Rossetti, Ph.D., P.E., is an associate professor in the Industrial Engineering Department at the University of Arkansas. He has published over 70 journal and conference articles in the areas of transportation, manufacturing, health care, and simulation, and he has obtained over $3.1 million in extramural research funding. His research interests include the design, analysis, and optimization of manufacturing, health care, and transportation systems. He served as co-editor for the 2004 and 2009 Proceedings of the Winter Simulation Conference and is the author of the textbook, Simulation Modeling and Arena published by John Wiley & Sons.

Ronald Walker is a consultant for Resource Optimization and Innovation (ROi), the supply chain division for Sisters of Mercy Health System. He received is Masters of Science in Industrial Engineering from the University of Arkansas the spring of 2008. He has conducted research for the Center for Engineering Logistics and Distribution (CELDi), and the Center for Innovation in Healthcare Logistics (CIHL). His interests include modelling and analysis of inventory management systems, transportation and logistics, AutoID technologies, and healthcare engineering.

1. Introduction

Radio Frequency Identification (RFID) is an automated technology primarily used for identification and tracking purposes. RFID has been in use since World War II; however, recently the technology has become cheaper and has been increasingly applied within information systems. This trend has lead organizations (e.g., Wal-Mart, the Department of Defense (DOD), and the U.S. Food and Drug Administration (FDA) etc.) to actively research ways to implement RFID in their systems. In addition, a number of deployment projects have been seen in numerous industrial sectors to improve the quality and reduce costs.

Despite its advantages and potentials, RFID is currently not a perfect technology and often does not reach the maximum performance of a 100% read accuracy (Buyurgan *et al.*, 2007, Kang, 2004). This causes imperfect visibility and state information for supply chains thus; the supply chain becomes more vulnerable (Glickman and White, 2006). A supply chain with imperfect visibility results in businesses having errors in vital inventory records (Viau *et al., 2009*). These errors may further lead to inventory discrepancies between on-hand quantity and actual physical count.

In reality, inventory record inaccuracy is one of the main reasons that many businesses (especially retailers) implement RFID technology as support systems for their inventory control and replenishment systems (White *et al.*, 2008). Companies anticipate having better inventory and supply chain visibility, better store sales and shelf inventory tracking, and out of stock reduction by implementing RFID in their supply chains (Vijayaraman and Osyk, 2006). These same implementers are currently assessing RFID's performance in different processes with specific requirements. For example, retailers are racing to put RFID systems at the dock doors of their warehouses and stores and still use their existing replenishment systems fed by manual inventory records.

On the other hand, there are potential uses and anticipated benefits of RFID technology even with its immaturity. Companies integrating RFID into their enterprise systems expect to see more from it than those adopting a “slap and ship” approach (White *et al., 2008*). It may be the primary system that is used for automated replenishment or it may be a secondary system that supports a current replenishment system. In any case, RFID systems provide a set of inventory data, which may be used to realize and correct inventory discrepancy. The main question that needs to be answered is “how would one use this (potentially imperfect) information provided by RFID technology to improve a business by using it in inventory management.”

This study investigates how imperfect information from RFID technology can be used in inventory management in multi-echelon supply chains and how inventory information provided by RFID systems can affect inventory control decisions. A simulation-based approach is used to understand the potential uses and impacts of imperfect RFID data in supply chains. Specifically, this study focuses on two objectives. The first objective is to observe how the supply chain is affected by allowing RFID inventory systems with imperfect visibility to make all of the replenishment decisions. Since RFID technology is not 100% accurate all of the time, an analysis is conducted to see how inventory record accuracy is affected by allowing RFID to do all of the replenishment work. Furthermore, this study also examines using RFID as a part of an inventory record correction mechanism. In this case, RFID is used as a supporting technology to an existing inventory replenishment system, which monitors the inventory of items and initiates item level inventory counts. Thus, the second objective is to investigate how RFID technology can be used as a triggering mechanism for item level inventory counts. By inspecting the use of

RFID with its current weaknesses, this study outlines research applications that make RFID more valuable for organizations, mainly within inventory management.

The rest of the paper is organized as follows. A literature review on the use of RFID in supply chain management and inventory management is presented in Section 2. In Section 3, a simulation model for the analysis of RFID in inventory management and triggering inventory counting is given; Conducted experiments are detailed in Section 4. The results of the experimentation are analyzed and discussed in Section 5. Finally, conclusions and discussion are presented in Section 6.

2. Literature Review

Radio Frequency Identification (RFID) technology is a generic term for one of the fastest growing automatic data collection technologies that utilizes a wireless radio communication to uniquely identify objects, animals, or people by using radio frequency signals (Lee and Ozer, 2007). RFID technology implementation in supply chain management (SCM) increased at an accelerated pace in the last decade. Sabbaghi and Vaidyanathan (2008) examine the appropriate business processes affected by the RFID technology, the required planning and examination for successful implementation, and many potential impacts on effectiveness and efficiency of SCM. They consider eight key processes in investigating the effectiveness and efficiency of RFID implementations, namely customer relations, customer service, demand management, order fulfilment, manufacturing flow, supplier relationship, product development and commercialization, and returns. After assessing these processes, they conclude that as companies develop their RFID strategies, they should look for the true business value of the technology.

Holmqvist and Stefansson (2006) investigate how RFID can be utilized in more innovative ways and by that create new opportunities in a complex content SCM in Volvo. An innovative mobile RFID solution is evaluated with the perspective of operational flexibility, usability, and productivity in order to explore the business value in new RFID setups in the supply chain. Lee *et al.* (2004) investigate the impact of RFID on supply chain dynamics. They use simulation models to analyze the effects of RFID on inventory replenishment decisions and shrinkage; the model included one supplier, one distribution centre (DC), one store, and one stock-keeping unit (SKU). The research primarily investigates benefits of RFID for reduced inventory levels and service level improvement and concluded that RFID improved the performance of the supply chain, by reducing inventory levels and sustaining adequate service levels.

In parallel with SCM implementations, the use of RFID technology in inventory management and control is increasing. Hardgrave *et al.* (2005) conduct a study to determine the effects of an RFID tracking system on out-of-stock items (one of the primary performance metrics in inventory management) in retail stores. The study is conducted on 24 retail stores; 12 with RFID and 12 without RFID. The results show that stock-outs are reduced by 26% just by tracking items with RFID. As an extension to that study, Hardgrave *et al.* (2006) conduct experiments to test the effect of RFID on out-of-stock items by their sales velocity. The results indicate that items with a velocity of 0.1 to 15 units per day reduced their out of stock figures by 30%.

Heese (2007) analyze how inventory record uncertainty affects optimal stocking decisions in an integrated supply chain. Then the optimal wholesale price is determined along with stocking decisions in the decentralized supply chain. Assuming RFID can reduce the problem of inventory record accuracy, the author models the dynamic of a decentralized supply chain and determines the cost thresholds at which RFID adoption becomes profitable. Fleisch and Tellkamp (2003) examine the effects of inventory inaccuracy on the supply chain via simulation. Considerations for inventory inaccuracy include theft and unsaleable items (e.g., those that are out of date, discontinued, promotional, or seasonal). The authors suggest the implementation of RFID on high cost items because of the high costs of RFID tags. Similarly, Joshi (2000) investigates the impact of information visibility on a supply chain and models one item through the entire supply chain. Joshi finds that the inventory costs are reduced by 40%-70% percent by increased information visibility. With the implementation of RFID, the real time visibility for a product reduces cost even more.

Floerkemeier (2007) develops a probabilistic model to handle RFID's uncertainty of reading a tag. He considers two types of errors associated with whether an RFID reader reads a tag or not namely false negative (i.e., a tag is not read at a location although the tagged item is in that location) and false positive (i.e., a tagged object is outside the desired area, but the reader recognizes the object and thinks it is in a region). An example of the second type of error can be inventory in a warehouse; an item might be in receiving, for instance, but since it is close to the shipping staging area, the system may pick up the signal and believe the item is being shipped.

Even though some of the abovementioned research tries to capture the dynamics of RFID and its effects on inventory management, most of them have common shortcomings. Some of them do not consider the imperfect visibility that RFID provides, while some focus on one store and do not consider the entire supply chain. Studies that analyze multi-echelon supply chain models typically consider one inventory management strategy (e.g., all inventory holding points use the (r,Q) inventory model). Moreover, many researchers concentrate only on one SKU and never take different demand rates (thus different error rates) for items into account. In this research, a multi-echelon supply chain with different inventory control policies is modelled using simulation. Products with different demand rates pass though RFID read points as they enter and exit inventory holding points (e.g. warehouse, retailer) so that on-hand inventory is calculated. The use and the effects of imperfect RFID are investigated in two scenarios. First, RFID is used as the primary inventory management system for an optimized supply chain. Reorder points and quantities for inventory holding points are optimized to provide a desired level of customer satisfaction. Then, replenishment decisions are made based on RFID readings in that optimized system. Second, RFID is used as a supporting technology to a manual inventory management system, which is a common case within the retail industry. Replenishment decisions are made based on the existing system. The RFID readings are used to trigger item level counting and record correction.

3. Multi-Echelon Supply Chain Model

Simulation modelling is used in this research to analyze the potential uses and impacts of imperfect RFID technology in the multi-echelon supply chain and inventory management due to the stochastic nature of demand arrivals and the complexity inventory replenishment decisions based on triggered inventory counting. Also, simulation models allow for the more realistic representation of real-life scenarios. The model consists of a supplier, a DC, and two retail stores. Retail stores are considered in two parts namely the backroom and the sales floor. A supplier with no capacity constrains supplies products to the DC; then the products are transported to retail stores.

3.1 System Overview

The modelled supply chain covers a two echelon supply chain, which includes SKU's coming from the supplier to the DC to the retail stores. Here locations that may hold inventory (e.g. the DC) are referred to as inventory holding points (*IHP*'s). The inventory policy used for the DC is a continuous review (s,S) model with backordering permitted. A continuous review mechanism checks the inventory position (*IP*) every time inventory state changes. When *IP* (i.e., On-hand Inventory + Inventory On-order – Backorder Quantity) falls below a reorder point (*s*), the mechanism orders enough items to reach the maximum inventory level (*S*), therefore the order quantity is *S* - *IP*.

There are two retail stores being supplied by the DC. Each retail store is divided into two different sections: a backroom and a sales floor. The inventory systems between the backroom and sales floor are completely independent of each other. The backroom uses an (r,Q) model, but partial fulfilment is allowed for the backroom orders. The (r,Q) model is also a continuous review inventory system with backordering. Whenever *IP* falls below the reorder point (*r*), the system orders the reorder quantity (*Q*). Partial fulfilment is defined as partially filling the demands (of the sales floor) and backordering the rest of the demand. The inventory policy that the sales floor uses is a periodic review (*R*,*S*) model where R is the review period and *S* is the order up to level. The inventory on the shelves is checked periodically on the sales floor (i.e., once a day in our model) and if there is more capacity on the shelves, the products are ordered from the backroom. The reason the retail store is split into two sections is due to the RFID read points. In a retail store, a common implementation for RFID is to have an RFID system between the backroom and the sales floor to monitor the inventory. A read point is defined as the point when an item is read by an RFID reader, the read points for this model are shown in Figure 1.

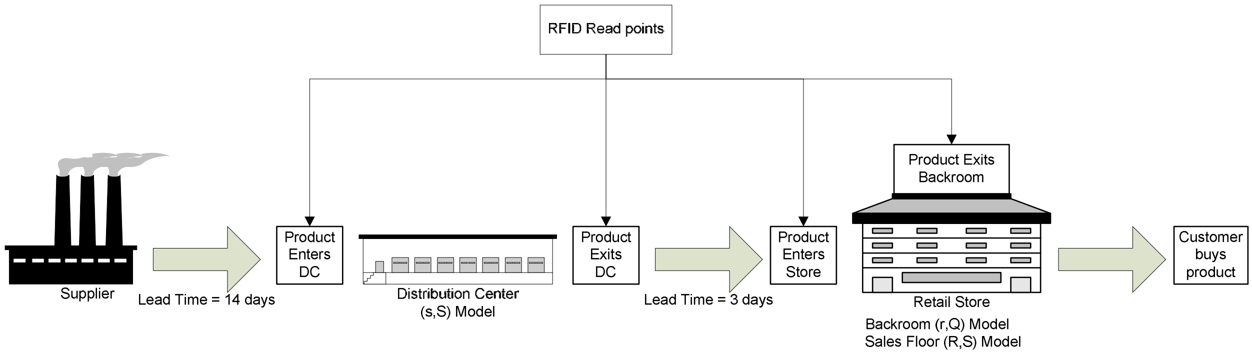

Figure 1: Inventory Flow and RFID Read Points in the Supply Chain

There are three demand rates; high, medium, and low. All of the demand rates are modelled as a Poisson arrival process. High, Medium, and low demand rates have mean arrival rates of 100, 10, and 1 customers per day, respectively. When a customer arrives, the on-hand inventory is checked. If there is enough on-hand inventory to fill the customer's demand, then the demand is reduced by the inventory. If the customer's demand cannot be filled, then loss sales are incremented. The inventory is checked at the sales floor every day. Since the sales floor uses a (R,S) model, the amount ordered is the difference between *IP* and the shelf capacity (i.e., maximum inventory capacity). When the backroom receives an order from the sales floor, the demand is checked with its on-hand inventory. The backroom either fulfils the demand or partial fills and backorders the rest. When *IP* is below the reorder point, an order is placed at the DC. *IP* is checked every time a transaction occurs. When an order is made to the DC from the backroom, the on-hand inventory at DC is checked to see if the demand can be met. If so, the inventory is sent to the backroom; the lead time for this transaction is considered to be three days. If the demand cannot be met, the backorder inventory is increased. If *IP* at the DC is below the reorder point, then the inventory is ordered from the supplier. It is assumed that the supplier can always fill the DC's order and the DC's on-hand inventory is increased after a lead time of 14 days.

When an item is received at the DC, backroom, or sales floor, the on-hand inventory is increased. Figure 1 shows a diagram of this process.

3.2 Modelling Errors

The two types of errors modelled in the system are stock loss errors (also known as shrinkage) and transaction errors. Stock loss errors transpire when the on-hand inventory level decreases due to unforeseen events. Four common types of stock loss errors are process errors, external theft, internal theft, and supplier fraud (Alexander *et al*., 2002). Stock loss errors occur at the DC level, backroom level, and sales floor level. Transaction error is another type of error modelled. Transaction errors happen when inventory is lost during transportation. In the modelled system, the transaction errors occur when inventory is sent from the supplier to the DC or from the DC to the backroom. These errors can affect inventory replenishment decisions such as determining reorder points, reorder quantities, and trucking schedules.

Stock loss error is modelled as a renewal process that occurs between time intervals. The time intervals are based on an exponential distribution with a mean time between stock loss events (TBSLE). The frequency of stock loss occurrence is the reciprocal of TBSLE. In Rossetti *et al*. (2009), a large retailer's discrepancy data was examined and indicated that the expected value for the mean stock loss quantity can be estimated as 2.05. Based on those results, this model uses two for the stock loss quantity when a stock loss error occurred. During experimentation, the TBSLE is changed to determine the effects of more or less stock loss in the system. In the model when a stock loss error event occurs, the amount of actual on-hand inventory is checked and if it is greater than or equal to two, then the actual on-hand value is decremented by two. The actual on-hand inventory is set to zero, if it is less than two.

Transaction error is modelled through a series of probabilistic processes. It is assumed that there is a probability that a transaction error occurs during a transaction. The probability of an error occurring for products shipped from the supplier to the DC is 0.04, and for products shipped from the DC to the backroom is 0.08. In their research Rossetti *et al*. (2009) determined the expected value of the quantity lost or gained is two based on a retailer’s past discrepancy data; the same parameters are used in this model. If an error does not occur, nothing happens to the on-hand inventory. If an error does occur, then the direction of the error (i.e., positive vs. negative error) is generated, with a 50% chance. Once the error direction is determined, the amount is calculated based on quantity received and on-hand inventory. There are two other conditions that must be considered with transaction error. First, the transaction error amount cannot be greater than the quantity being received. Second, if the transaction error is negative, then the error amount cannot be greater than the current recorded on-hand inventory. For further explanation, let Z be the amount of inventory lost or gained (note that E[Z] = 2), W the transaction error amount, Q the transaction quantity, and $I^r(t)$ the recorded on-hand inventory for SKU *I* at time *t*. Then the transaction error amount becomes:

$$W = \begin{cases} Z, & \text{Positive error} \\ \max(-I^r(t), \min(Q, Z)), & \text{Negative error} \\ 0, & \text{No error} \end{cases} \tag{1}$$

3.3 Modelling RFID in the Supply Chain

As previously mentioned, every *IHP* considered in this study (i.e., DC, backroom, and sales floor) has RFID read points at the receiving and shipping areas, where RFID antennas and readers are located to monitor inventory movements. Note that the retail stores are split into two sections: backroom and sales floor. The only place where RFID read points are not considered in this model is the shipping area of two sales floors (i.e., point of sales). It is assumed that only barcodes (or similar technologies) are used at the point of sales and that the technology provides 100% visibility.

When RFID is used as the primary inventory management system, replenishment decisions are made based on RFID readings. Specifically, IP, calculated using RFID records, triggers replenishments. In those scenarios *IP* is calculated as follows:

$$IP = RFID\ Onhand\ Inventory + Inventory\ On\ Order - Backorder\ Quantity \quad (2)$$

When items leave an *IHP*, RFID on-hand inventory is checked. If the transaction amount is more than or equal to RFID on-hand inventory, then RFID on-hand inventory is set to zero. If the transaction amount is not more than RFID on-hand inventory, then RFID on-hand inventory is reduced by the transaction amount times a read percent error.

In other scenarios where RFID is used as a supporting technology to a manual inventory management system, replenishment decisions are made based on the existing system. In those scenarios *IP* is calculated as follows:

$$IP = Recorded\ Onhand\ Inventory + Inventory\ On\ Order - Backorder\ Quantity \quad (3)$$

RFID transaction error is modelled as read percent error. For example, if RFID is reading 97% of the products on a pallet and a pallet of 100 items come in, then only 97 products would be incremented to the RFID inventory on-hand. However, RFID read error rates are not a constant percentage. In order to help the model become more realistic, a triangular distribution is assumed in order to determine each transactions error percentage. The parameters for the triangular distribution are a minimum (*min*.), a maximum (*max*.), and a most likely value (MLV). For MLV's for RFID read rates of 40% - 90% *min.* and *max.* values are assumed to be plus and minus 10% of MLV. For example, if MLV of the read rate is 40%, then *min*. is 30% and *max*. is 50%. In order to investigate the effects of better RFID visibility (i.e., more than 90% read rate), RFID systems are modelled with more precision. For those cases, *min.* and *max.* values for the triangular distribution are assumed to be plus and minus 1% MLV. For example, if MLV of the read rate is 96%, then *min.* is 95% and *max.* is 97%. When the MLV is 100% of the read rate there is no *min.* or *max.* value. The model also assumes that only false negative RFID errors occur in the system.

3.4 Modelling Item Counting and Record Correction

Item level inventory counting is a tool often used to improve the inventory accuracy of a facility; in the supply chain it is modelled with RFID to determine how each of these tools affects each other. The main assumption this model considers with inventory counting is the time it takes to count the items. Inventory counting is instantaneous in this model. Therefore, when a count event occurs, recorded on-hand inventory and RFID on-hand inventory values are reset to the actual on-hand inventory values immediately.

Two scenarios are considered that involve RFID and inventory counting. The first scenario implements scheduled inventory counting (scheduled cycle counting) and RFID makes all the replenishment decisions in the supply chain. Therefore, the inventory record is based solely on the RFID on-hand inventory value. Because RFID readings are not perfect, cycle counting needs to be used to keep the inventory accuracy as high as possible.

The second scenario uses RFID to determine when inventory counting (triggered cycle counting) should be triggered. This scenario has both RFID on-hand inventory and the recorded on-hand inventory. The idea is to trigger cycle counting when the difference between the RFID on-hand inventory and the recorded on-hand inventory reaches a certain value. Therefore, the *IHP* knows the inventory is not correct and a cycle count needs to be done in order to correct inventory records. The triggering value for the cycle counting uses a percent difference instead of a discrepancy value. The percent difference is used because the on-hand quantities do not affect the decision based on demand. High demand items have more inventories compared to low demand items. When an item's on-hand inventory changes due to shipping or receiving items, the RFID on-hand and recorded on-hand inventories are tested. If the percent difference is greater than the trigger percent, then the item is cycle counted. If the percent difference is less than the trigger percent, then nothing happens in the model.

Whenever a cycle count occurs in the model, the inventory position is checked to determine if the item needs to be replenished or not. This is done in order to reduce the number of stock outs that occur in the model. If the actual on-hand inventory is well below the inventory record, then the chances of a stock out increase and inventory needs to be ordered. If the actual on-hand inventory is greater than the recorded/RFID inventory then the result will not hurt the fill rate but the *IHP* will have a higher inventory cost due to the increased inventory at that facility.

4. Experimentation

Two phases of experiments were conducted. In the first phase, a base model was developed to understand the dynamics of the supply chain system and the behaviour of different inventory management policies for *IHP*'s. Optimized values for system parameters are determined in order to develop a base model. There is no RFID system implementation modelled in *Phase I*.

Phase II uses the base model from the first phase with its optimized system parameters and analyzes the use of RFID. Experimentation in this phase involves analysis of the use of RFID, where RFID drives replenishment decisions and where it is used as a backup system. Analyses in this phase include the effect of RFID in the supply chain where there is no stock loss and transaction error in the system, the effect of RFID where there are errors in the system, the effect of RFID where there are scheduled cycle counts for system inventory, and the effects of RFID where there are triggered cycle counts in the system. The number of replications for each experiment was 30.

4.1 Phase I-Base Model Optimization

The base supply chain model developed in the first phase of the experimentation does not include any of the abovementioned errors. Thus, there is no error involved in purchase and replenishment activities. In addition, there is no RFID system in the supply chain. The model functions as an ideal inventory system, all of the inventory values are perfect (i.e., recorded on-hand inventory = actual on-hand inventory). Once the base model is developed with *IHP*'s with their specific inventory management strategies, replenishment decision variables (i.e., reorder points or levels and quantities) are optimized. The variables are optimized in order to minimize actual on-hand inventory in the system while achieving minimum 0.90 fill rate for every *IHP*. OptQuest® for Java® is used to solve this optimization. OptQuest heuristic model ran for over 10,000 iterations before a solution was found. The optimized results are given in Table 1.

Table 1: Optimized Results

System Variable	**Optimized Value (Items)**
High Demand Item DC Reorder Point (*s*)	1,684
High Demand Item DC Maximum Level (*S*)	2,878
Medium Demand Item DC Reorder Point (*s*)	454
Medium Demand Item DC Maximum Level (*S*)	480
Low Demand Item DC Reorder Point (*s*)	281
Low Demand Item DC Maximum Level (*S*)	286
High Demand Item Backroom* Reorder Point (*r*)	339
High Demand Item Backroom Reorder Quantity (*Q*)	1,424
Medium Demand Item Backroom Reorder Point (*r*)	212
Medium Demand Item Backroom Reorder Quantity (*Q*)	162
Low Demand Item Backroom Reorder Point (*r*)	1
Low Demand Item Backroom Reorder Quantity (*Q*)	109
High Demand Item Sales Floor* Maximum Level (*S*)	229
Medium Demand Item Sales Floor Maximum Level (*S*)	271

Low Demand Item Sales Floor Maximum Level (*S*)	111

*Average values for two backrooms and sales floors.

4.2 Phase II-RFID Implementation

In the first experiments, where RFID is the primary inventory management system and makes replenishment decisions, the technology is added to the base model with no stock loss or transaction error. Analysis of this experimentation provides a better understanding of RFID data and its effects on an optimized system. Since there are no errors involved in the supply chain, excessive positive or negative discrepancy (i.e., SKU’s being overstocked or under stocked) in the system is a result of imperfect RFID data and the decisions made based on that data. Next analysis was done on the same system considering stock loss and transaction errors. This analysis helps to illustrate the system dynamics when errors are involved. The interaction between different levels of RFID system accuracy and stock loss error provide insightful information. The supply chain system has imperfect records due to the errors in the system; however, replenishment decisions are still made by RFID data.

The third set of experiments was carried out by implementing a scheduled cycle counting inventory correction process. The effects of correcting on-hand inventory records regularly and using RFID system are analyzed with given predefined errors. High demand SKU’s have more frequent stock loss errors (i.e., TBSLE = 0.2 days) than other SKU’s (i.e., TBSLE = 2 days for medium demand SKU’s and TBSLE = 20 days for low demand SKU’s). Stock loss error rates are taken from the Rossetti *et al*. (2009) study. Transaction error is calculated as explained in the previous sections. The fourth set of experiments, involves an RFID system with triggered cycle counts. In that case, both recorded on-hand inventory and RFID on-hand inventory values are used to determine the timing of the cycle counts.

Consider a manager at a retail store, who is in charge of replenishment. The manager has two (potentially incorrect) on-hand inventory numbers at any time; one is derived from the records and the other is reported by the RFID systems. If these two numbers are relatively close to each other (within a certain tolerance), the manager would trust one of the numbers and would not count the items at the store due to the cost of counting. However, if these two numbers are very different, then it may be worth counting. From this standpoint, if the difference reaches a certain percent of recorded on-hand inventory, the system triggers a cycle count. Since the replenishment decisions are based on the recorded inventory, it is considered as the main metric of concern. Every time a cycle count occurs, all on-hand inventory records are set to the actual on-hand value. It is assumed that cycle counts occur instantaneously.

5. Results

In this section the results of the experimentation are discussed. The major performance metric of the analysis is the amount of discrepancy at the *IHP*'s.

5.1 Supply Chain Behaviour Analysis with RFID

Initial experiments in *Phase II* investigate the effect of implementing RFID technology into the supply chain with no other error present in the system. RFID systems are added to each *IHP* and analyzed on an individual basis. First, RFID systems are considered for only inbound shipments (i.e., RFID systems are located only at the receiving docks of *IHP*'s). Then the same exercise is repeated for only outbound shipments (i.e., RFID systems are located only at the shipping docks of *IHP*'s). Finally, an RFID implementation for both inbound and outbound shipments is analyzed. As discussed in the previous sections, RFID error is implemented using a triangular distribution with a minimum (*min.*), a most likely (MLV), and a maximum (*max.*) value. Average annual discrepancies (i.e., actual on-hand – RFID on-hand) for different *IHP*'s, different demand rates, and different MLV's for RFID read rates of inbound shipments are given in Table 2.

Table 2: Average Annual Discrepancy for Inbound Shipments

		RFID MLV					
		40%	**50%**	**60%**	**70%**	**80%**	**90%**
		x-bar (*s*)	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**
Distribution Center	**High Demand**	3468 (1039)	1927 (617)	2400 (730)	1958 (392)	1462 (278)	1111 (228)
	Meduim Demand	4478 (99)	3371 (159)	2390 (153)	1531 (128)	661 (149)	140 (41)
	Low Demand	1296 (144)	892 (73)	625 (59)	398 (41)	245 (31)	101 (17)
Backroom	**High Demand**	34362 (4784)	25506 (3856)	16636 (2548)	13476 (1889)	8150 (2235)	2358 (1238)
	Meduim Demand	7348 (140)	4969 (108)	3309 (80)	2130 (43)	1244 (47)	546 (26)
	Low Demand	604 (46)	426 (35)	298 (29)	195 (22)	113 (14)	49 (13)
Sales floor	**High Demand**	28084 (4832)	23316 (4120)	18236 (2814)	13714 (2639)	9887 (1594)	2383 (1325)
	Meduim Demand	7490 (99)	5017 (70)	3357 (51)	2154 (32)	1254 (19)	562 (16)
	Low Demand	815 (25)	499 (23)	252 (15)	190 (17)	56 (6)	4 (2)

As seen in the figure, the worst discrepancy is observed at the backrooms with the highest demand; the better the RFID read rate, the lower the discrepancy. In addition, it is also observed that the lower the demand, the lower the discrepancy because there is less items passing by the RFID readers that result in less error. Another important observation is that the discrepancies at all *IHP*'s are positive (i.e., actual on-hand > RFID on-hand). Logically, this makes sense because RFID systems always read fewer items that actually arrive; therefore, the actual on-hand inventory is larger than the RFID on-hand inventory. The results for MLV's for RFID read rates between 90% and 100% show similar characteristics.

Average annual discrepancies when implementing RFID systems in outbound shipments for different *IHP*'s, different demand rates, and different MLV's for RFID read rates are given in Table 3.

Table 3: Average Annual Discrepancy for Outbound Shipments

		RFID MLV					
		40% **x-bar (*s*)**	**50%** **x-bar (*s*)**	**60%** **x-bar (*s*)**	**70%** **x-bar (*s*)**	**80%** **x-bar (*s*)**	**90%** **x-bar (*s*)**
	High Demand	-4871 (459)	-4732 (576)	-4723 (271)	-4367 (354)	-4053 (398)	-3708 (284)
Distribution Center	**Meduim Demand**	-1483 (59)	-1482 (64)	-1442 (57)	-1370 (43)	-1149 (44)	-741 (45)
	Low Demand	-427 (33)	-376 (20)	-335 (17)	-272 (14)	-199 (17)	-99 (15)
	High Demand	-1072 (16)	-897 (18)	-1600 (451)	-1316 (216)	-973 (117)	-855 (101)
Backroom	**Meduim Demand**	-906 (7)	-861 (13)	-849 (14)	-845 (23)	-795 (8)	-493 (13)
	Low Demand	-108 (3)	-75 (4)	-42 (3)	-36 (3)	-39 (5)	-4 (2)
	High Demand	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Sales floor	**Meduim Demand**	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Low Demand	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

As seen in the table, the discrepancies for *IHP*'s are negative (i.e., actual on-hand < RFID on-hand). Since only the items shipped go through RFID systems, inventory management system records fewer items than actual shipment. The worst discrepancy in this case belongs to the items with high demand level at the DC level. The same system behaviour is observed in this as well, namely the better the RFID read rate or the lower the demand, the lower the discrepancy. One exception can be seen at the backrooms level. 50% MLV for RFID read rate gives lower discrepancies than 60%, 70%, and 80% MLV's for RFID read rates. However, the standard deviations for those values are very high, thus the results at these levels may be inconclusive. Note that there is no discrepancy at the sales floors level; because the simulation model was developed such that there is no error at the point of sales. System behaviour for MLV's for RFID read rates between 90% and 100% are similar.

The difference in average discrepancy for inbound and outbound shipments at different *IHP*'s can be explained by different inventory policies and the nature of the errors. For inbound shipments, the RFID on-hand inventory is always smaller than the actual on-hand inventory. Due to this fact, there are more frequent item orders to the supplier to replenish the inventory by the RFID system. However, in reality the system is overstocking. The discrepancy is a lot higher due to the volume of products passing through the receiving area. On the opposite side, errors associated with the outbound shipments enable the RFID system to order fewer products because it thinks the system is carrying enough inventory. However, in reality, the system is under stocked.

The next analysis discusses the implementation of RFID errors at both the inbound and outbound shipment areas. Average annual discrepancies when implementing RFID systems in both inbound and outbound shipments for different *IHP*'s, different demand rates, and different MLV's for RFID read rates are given in Table 4.

Table 4: Average Annual Discrepancy for Inbound and Outbound Shipments I

		RFID MLV					
		40% x-bar (*s*)	**50% x-bar (*s*)**	**60% x-bar (*s*)**	**70% x-bar (*s*)**	**80% x-bar (*s*)**	**90% x-bar (*s*)**
Distribution Center	**High Demand**	-755 (806)	-490 (1053)	-325 (1059)	-338 (1064)	-319 (765)	-173 (452)
	Meduim Demand	-181 (77)	-145 (75)	-102 (90)	-43 (136)	-23 (60)	-21 (55)
	Low Demand	-19 (28)	-19 (26)	-5 (19)	1 (19)	6 (24)	5 (19)
Backroom	**High Demand**	-1072 (16)	-897 (18)	-642 (270)	-356 (387)	-184 (341)	-78 (228)
	Meduim Demand	-138 (74)	-89 (47)	-39 (46)	-38 (39)	-15 (38)	-7 (24)
	Low Demand	-108 (3)	-75 (4)	-42 (3)	-36 (3)	54 (22)	48 (12)
Sales floor	**High Demand**	28084 (4832)	23316 (4120)	18236 (2814)	13714 (2639)	9887 (1594)	2383 (1325)
	Meduim Demand	7490 (99)	5017 (70)	3357 (51)	2154 (32)	1254 (19)	562 (16)
	Low Demand	815 (25)	499 (23)	252 (15)	190 (17)	56 (6)	4 (2)

The interesting phenomenon occurring in this experiment is the level of inaccuracy. The discrepancy between the actual on-hand and RFID on-hand inventories is relatively small, the inbound and outbound error seem to be cancelling each other out and results in a small discrepancy. This concept makes sense because not all of the items are being read when they enter *IHP*'s and not all the items are being read when they exit. The system is making better decisions due to this offset in discrepancy. This is interesting because this may mean that RFID visibility does not have to be perfect in order to reduce the discrepancy of the inventory. The same improvement pattern is present with this scenario as with the other two experiments: the better the RFID system read accuracy, the smaller the discrepancy. The DC and the backroom are under stocked for the high and medium demand items while the sales floor has an overstock of inventory.

Average annual discrepancies MLV's for RFID read rates between 90% and 100 % are given in Table 5.

Table 5: Average Annual Discrepancy for Inbound and Outbound Shipments II

		RFID MLV									
		90%	**91%**	**92%**	**93%**	**94%**	**95%**	**96%**	**97%**	**98%**	**99%**
		x-bar (*s*)	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**	**x-bar (*s*)**
Distribution Center	**High Demand**	-85 (62)	-54 (101)	-86 (55)	-62 (70)	-60 (51)	-56 (62)	-34 (66)	-39 (60)	-33 (70)	-25 (51)
	Meduim Demand	-17 (6)	-16 (10)	-18 (7)	-11 (8)	-11 (8)	-12 (6)	-8 (9)	-1 (8)	-5 (8)	-4 (5)
	Low Demand	4 (4)	1 (3)	2 (3)	1 (3)	0 (2)	1 (2)	1 (2)	1 (2)	0 (3)	0 (3)
Backroom	**High Demand**	-67 (38)	-69 (41)	-54 (29)	-40 (24)	-36 (33)	-43 (30)	-20 (34)	-30 (29)	-12 (32)	-12 (25)
	Meduim Demand	-16 (9)	-35 (7)	-56 (7)	-64 (8)	-46 (12)	11 (7)	93 (8)	132 (6)	101 (4)	50 (4)
	Low Demand	50 (3)	46 (2)	40 (3)	34 (2)	30 (2)	25 (1)	19 (2)	14 (2)	10 (1)	4 (1)
Sales floor	**High Demand**	2447 (1284)	1732 (1057)	1719 (980)	1491 (937)	1173 (718)	844 (395)	608 (421)	649 (424)	341 (231)	149 (119)
	Meduim Demand	549 (7)	511 (5)	478 (6)	444 (6)	383 (11)	271 (13)	122 (9)	20 (4)	0 (1)	0 (0)
	Low Demand	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

The same pattern is noticed in Table 5: the better the read rate the smaller the discrepancy. The amount of discrepancy gained from getting the system from 90% to 99% accuracy is minimal. In addition the standard deviations are very high.

5.2 Supply Chain Behaviour Analysis with RFID and Stock Loss Error

In order to analyze the effect of RFID technology with imperfect visibility on inventory management more realistically, the next step is to introduce stock loss error into the supply chain. Figures 2, 3, and 4 show the surface curves of the average annual discrepancy based on different MLV's of RFID errors and TBSLE's for high, medium, and low demand items respectively at DC level (s,S policy). As discussed earlier, the stock loss amount is fixed at two and the interval between errors is varied in this analysis. The time between error (TBSLE) ranges from 0.1 days to 51.2 days.

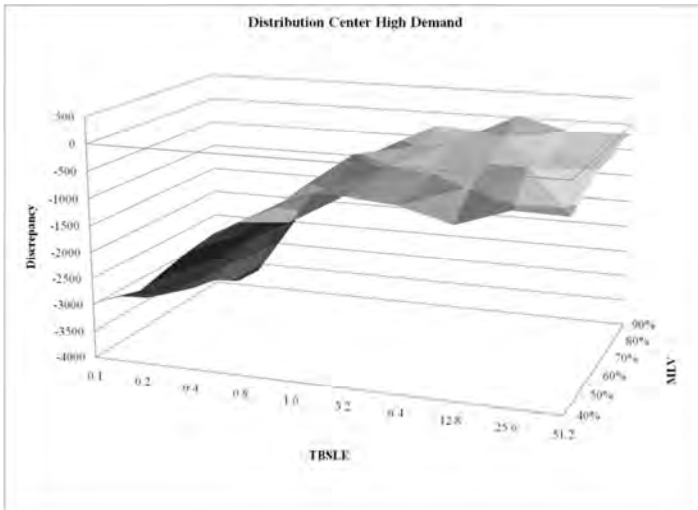

Figure 2: Average Annual Discrepancy at DC for High Demand Rate

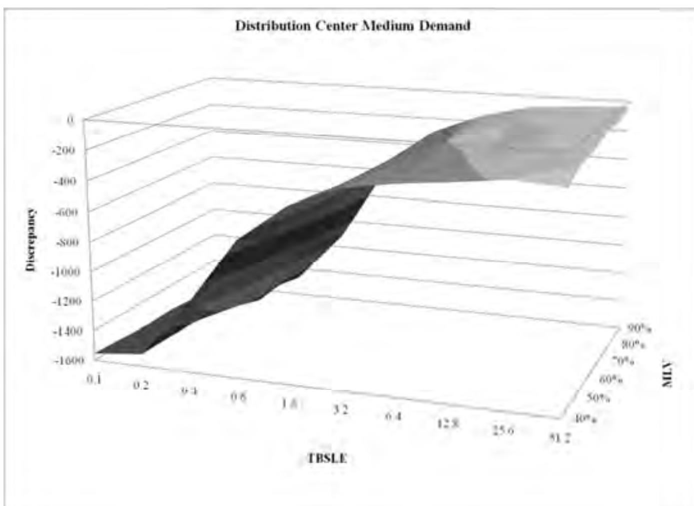

Figure 3: Average Annual Discrepancy at DC for Medium Demand Rate

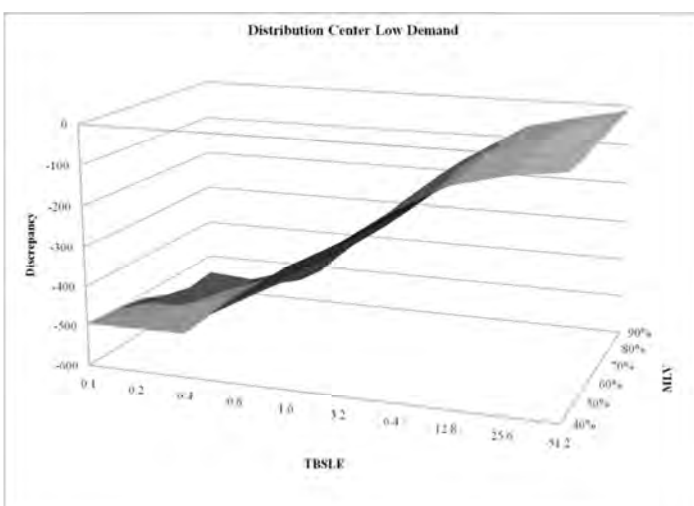

Figure 4: Average Annual Discrepancy at DC for Low Demand Rate

As can be seen in the figures, the supply chain systems show similar behaviours for all demand rates at the DC level; however, discrepancy ranges change. MLV's for RFID read rates do not seem to have significant impacts on the discrepancy values at different TBSLE's. There is a slight improvement with the increased RFID read rate. The main factor contributing to the discrepancy is the time between errors (i.e., TBSLE's). As discussed earlier, the discrepancy for the inbound/outbound at the DC is negative, so there are less orders being placed to the supplier. When stock loss occurs, the actual on-hand inventory is less than the RFID on-hand inventory and results in even less orders being placed to the supplier. The RFID error also helps mask the discrepancy caused by stock loss error.

The backroom results are very different from the distribution centre's discrepancy results. Figures 5, 6, and 7 show the surface curves of the average annual discrepancy based on different MLV's of RFID errors and TBSLE's for high, medium, and low demand items respectively at backroom level (r,Q policy).

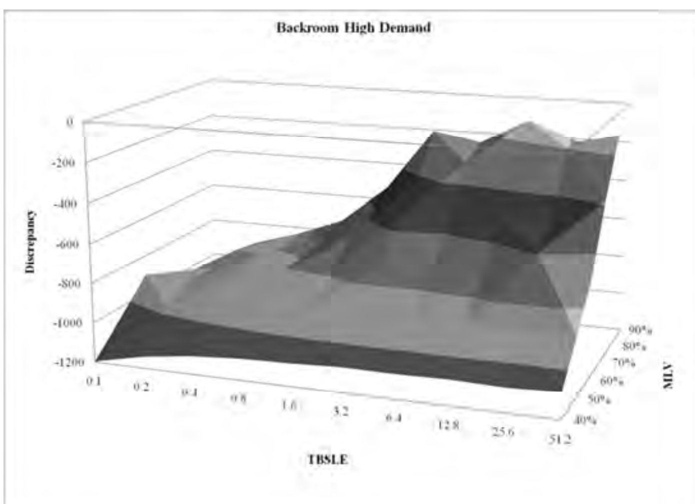

Figure 5: Average Annual Discrepancy at Backrooms for High Demand Rate

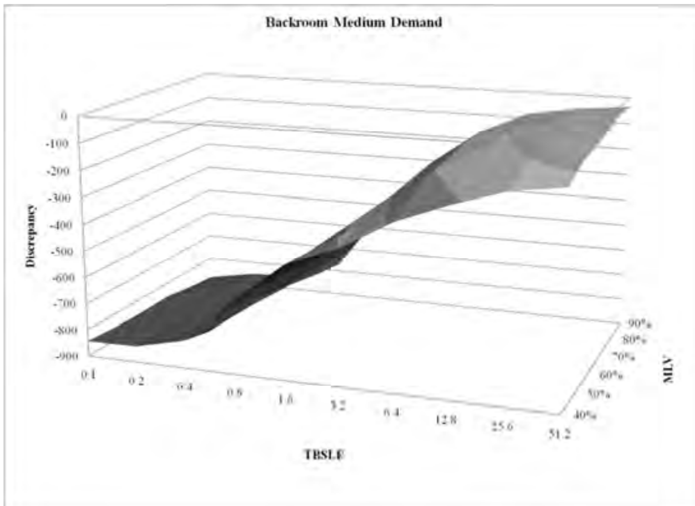

Figure 6: Average Annual Discrepancy at Backrooms for Medium Demand Rate

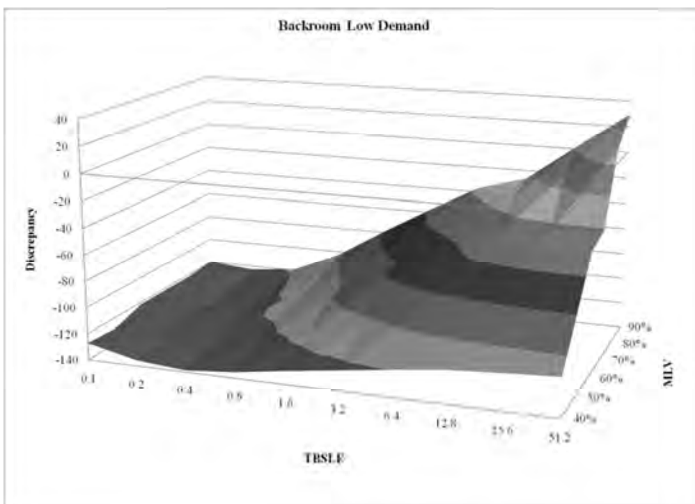

Figure 7: Average Annual Discrepancy at Backrooms for Low Demand Rate

For high and low demand, the RFID read rate has more of an affect than TBSLE. When there are a lot of stock loss errors occurring (i.e., shorter TBSLE's), the RFID read rate does not have a huge impact on the discrepancy. However, when TBSLE is greater than 1.6 days, the improved read rates improves the discrepancy. The main difference between the backroom and distribution centre is the inventory policy, the backroom has a fixed reorder quantity and distribution centre has a dynamic reorder quantity and this is why the difference in the surface curves are noticed. For the low demand item, the time between stock loss errors seems to have a higher improvement of discrepancy as the time between events increases. The high demand has the same pattern, but less of an affect. The medium demand item has the same curve as all demands of the distribution centre; TBSLE greatly affects the discrepancy amount. The surface curves for the 90%-99% RFID read rates are similar to the 40%-90% RFID read rate surface curves with a less noticeable pattern. This is the result of changing the read rates by small amounts.

The sales floor discrepancy results are different from both the backroom and distribution centre. The discrepancy surface curves for the high, medium, and low demand items are shown in Figures 8, 9, and 10 respectively. The RFID read rates have a bigger impact on the discrepancy than TBSLE for all demands. The higher RFID read results in lower discrepancies and TBSLE has less of an impact on the total inventory discrepancy. The reason RFID affects the discrepancy is due to the nature of the point of sales in this model.

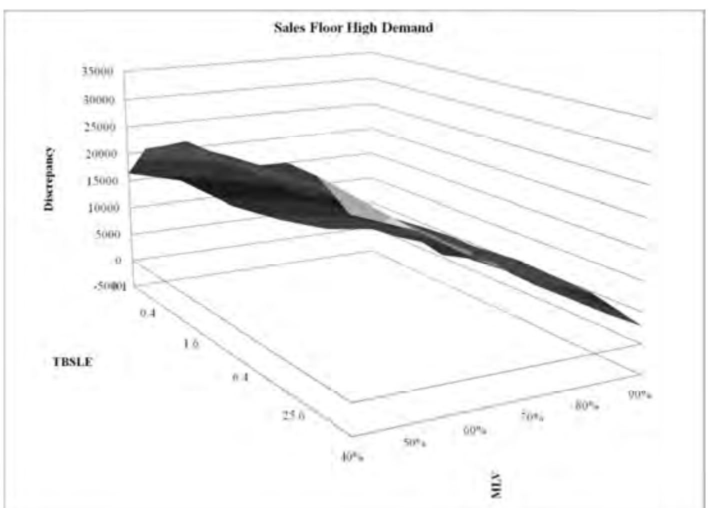

Figure 8: Average Annual Discrepancy at Sales Floors for High Demand Rate

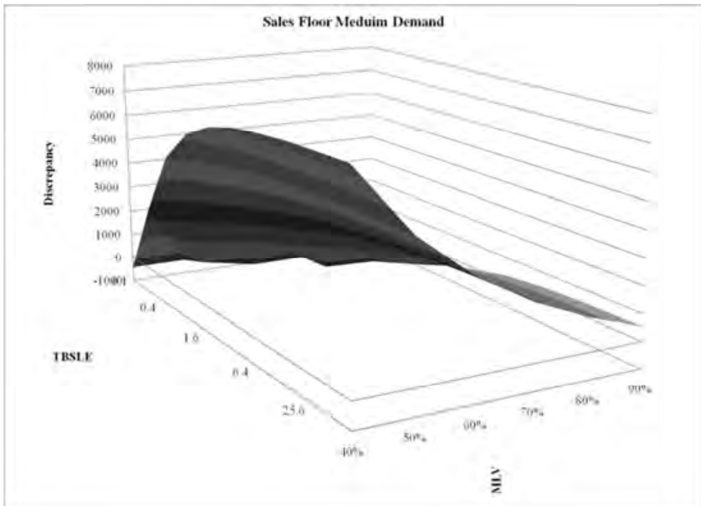

Figure 9: Average Annual Discrepancy at Sales Floors for Medium Demand Rate

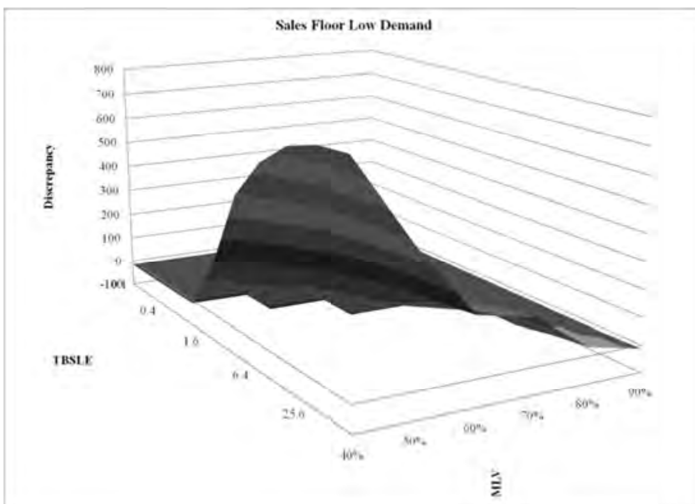

Figure 10: Average Annual Discrepancy at Sales Floors for Low Demand Rate

Stock loss error with RFID error results an interesting trend based on which IHP the errors are applied. Discrepancy at the distribution centre is affected by stock loss more than the MLV for RFID read rates. Discrepancy at the backroom is affected by both RFID error and stock loss error. High stock loss error has more of an impact than RFID error, but low stock loss error and low RFID error results in lower discrepancy. At the sales floor, RFID error has more of an impact on discrepancy than stock loss error.

5.3 Supply Chain Behaviour Analysis with RFID and Scheduled Cycle Counting

In this analysis, cycle counting is implemented into the supply chain system. Since the inventory accuracy is not perfect due to errors with RFID and stock loss, scheduled cycle counting is implemented in the model. Experiments in this section include both stock loss and transaction errors. The time between cycle counts (TBCC's) and MLV's for RFID read rates are varied to determine their effect on discrepancy. TBCC is varied between seven days (i.e., weekly cycle count) and 336 days (i.e., yearly cycle count) in increments of seven days. Once more, MLV's for RFID read rates ranged from 40%-90% in increments of 10%, and then from 90%-99% in increments of 1% with a triangular distribution. The surface curves for high demand items at the DC, backroom, and sales floor are shown in Figures 11, 12, and 13 respectively.

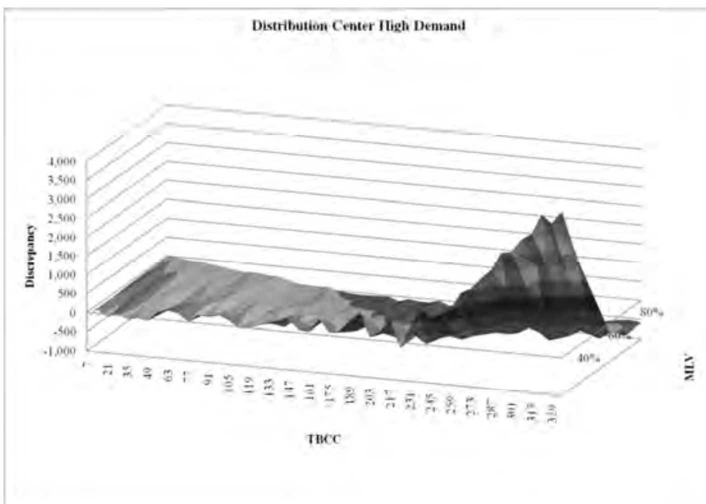

Figure 11: Average Annual Discrepancy at Distribution Centre for High Demand Rate

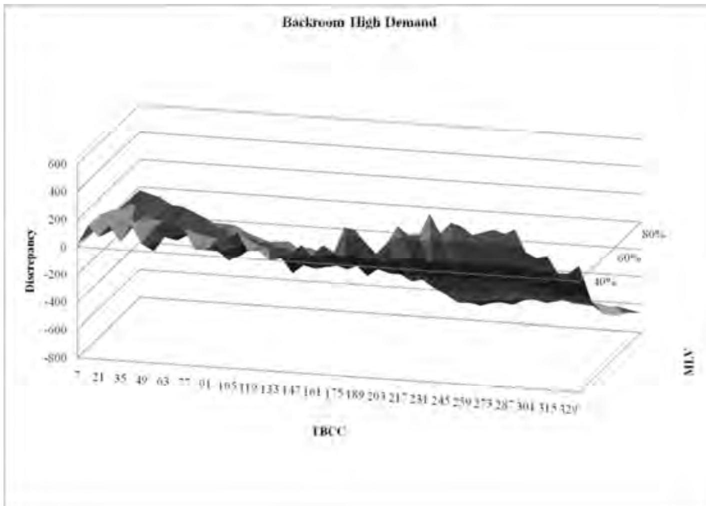

Figure 12: Average Annual Discrepancy at Backrooms for High Demand Rate

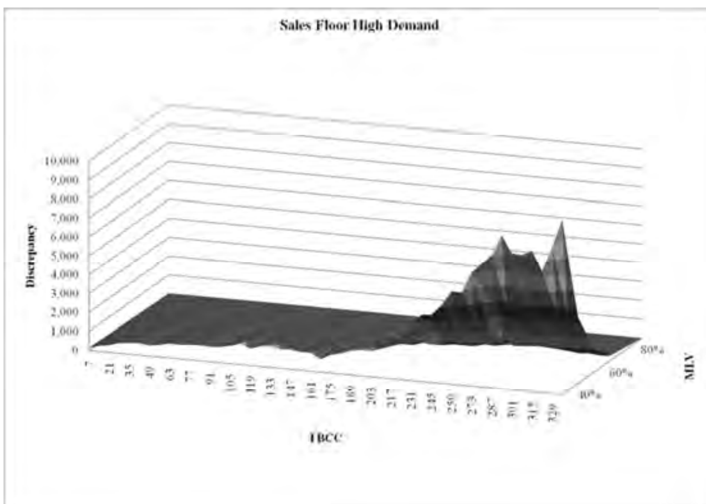

Figure 13: Average Annual Discrepancy at Sales Floors for High Demand Rate

The DC's surface curve shows a very interesting result. The discrepancy is relatively stable when the cycle counts range from 7 days to 231 days for all RFID read rates. However, when the inventory is counted every 231 days or more, the discrepancy increases dramatically as TBCC increases and MLV's for RFID read rates deceases. For fixed TBCC values, higher RFID accuracy results in lower discrepancies. At 315 days between cycle counts and 70% RFID read rates, the discrepancy is close to zero. However, for the more accurate RFID read rate, the discrepancy becomes more negative. DC shows the same behaviour for medium and low demand items. The surface curve for backrooms (Figure 12) is very similar to the curve for the DC. At around 175 days of TBCC, the discrepancy becomes worse and more variable due to the RFID read rate. The variation is not as noticeable as for the DC. The higher percentages result in worse discrepancy. This pattern is also noticed in the previous section. The patterns of medium and low demand curves for the backroom are similar to the high demand curve. For the sales floor, the discrepancy increases for lower RFID read rates at approximately 200 days TBCC. The higher the read rate, the closer the discrepancy is to zero for the larger TBCC periods. The surface curves for the low and medium demand item have similar curves as the high demand item. Overall, the surface curves for all the demand and all *IHP*'s have similar patterns. The discrepancy is very small and stable for all RFID values until a certain time interval for cycle counts occurs. Once the time interval is large enough, the RFID read rates drive the level of discrepancy.

5.4 Supply Chain Behaviour Analysis with RFID and Triggered Cycle Counting

This section investigates the use of RFID to trigger cycle counts. Experiments in this section include both stock loss and transaction errors. Replenishment decisions are made based on inventory records. RFID is used as an inventory accuracy tool and does not have an impact on the decisions. There are two types of discrepancies in this model, recorded (i.e., actual on-hand inventory – recorded on-hand inventory) and RFID (actual on-hand inventory – RFID on-hand inventory). The recorded discrepancy is the main metric of concern since the recorded inventory makes the replenishment decisions. The triggering mechanism uses both the recorded inventory and the RFID inventory. When the percent difference reaches a certain amount, a cycle count is triggered and recorded on-hand and RFID on-hand inventories are changed to actual on-hand inventory. The surface curve of annual average recorded discrepancy for medium demand at the distribution centre is shown in Figure 14; the RFID discrepancy is shown in Figure 15.

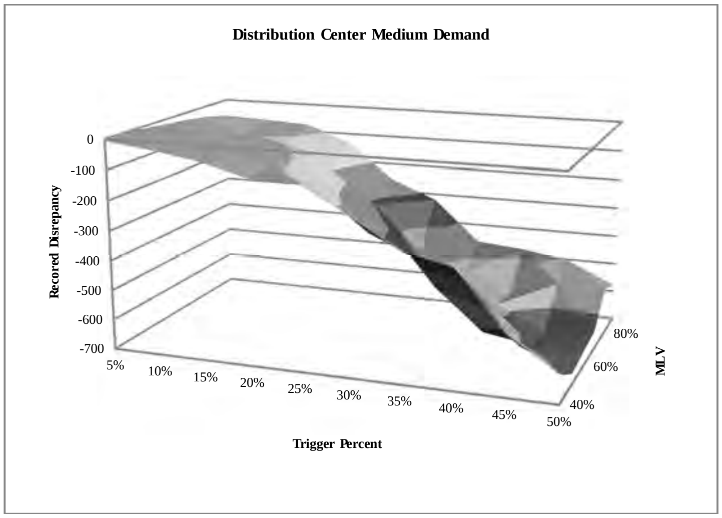

Figure 14: Average Annual Recorded Discrepancy at Distribution Centre for Medium Demand Rate

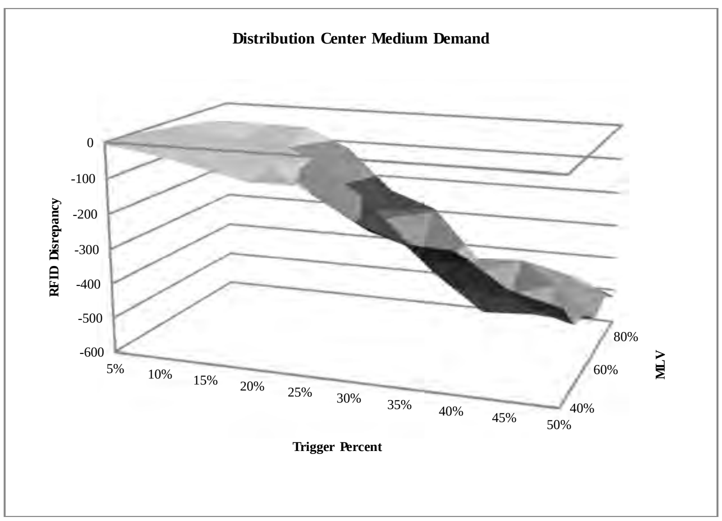

Figure 15: Average Annual RFID Discrepancy at Distribution Centre for Medium Demand Rate

As shown in Figures 14 and 15, the higher the trigger percent, the higher the discrepancy. Using a 5% cycle count trigger with the higher RFID accuracy, the discrepancy increases because the cycle counts are not being triggered because there is more visibility in the RFID system. This means that the inventory record and the RFID records are close together and the discrepancy is being caused by the stock loss error. The higher trigger percent results in higher discrepancy values for any given RFID read rate. RFID discrepancy is less than recorded discrepancy and this is thought to be another instance of the stock loss masking affect. The backroom surface curves are shown in Figures 16 and 17 for recorded discrepancy and RFID discrepancy, respectively. The graphs have a similar pattern as distribution centres' surface curves.

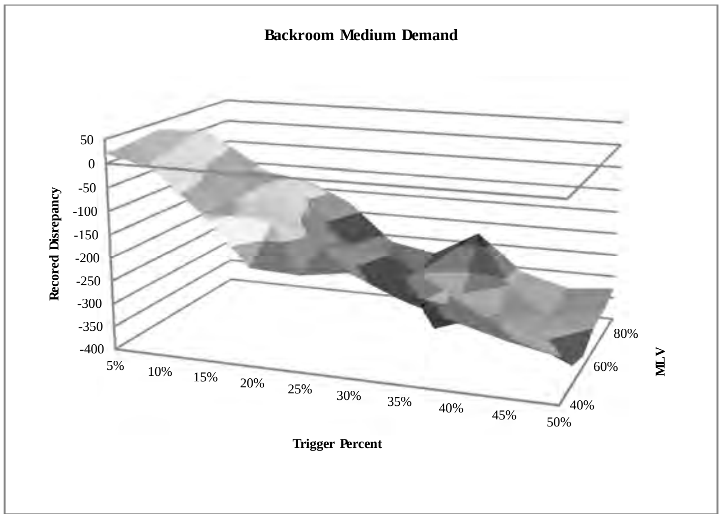

Figure 16: Average Annual Recorded Discrepancy at Backroom for Medium Demand Rate

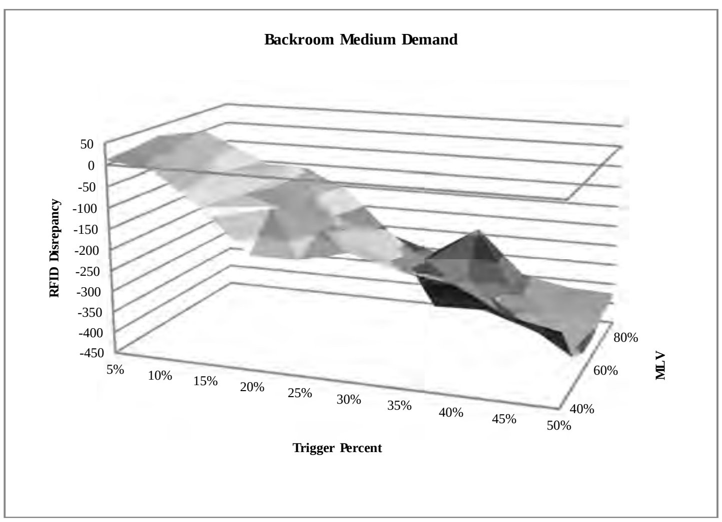

Figure 17: Average Annual RFID Discrepancy at Backroom for Medium Demand Rate

The surface curves for the sales floor medium demand item items are shown in Figures 18 and 19 for recorded discrepancy and RFID discrepancy, respectively. The surface curves do not have the same pattern as the distribution centre and backroom. The RFID read rate has a big impact on the discrepancy because there is only RFID error at inbound shipments and no error associated with transactions due to the nature of the relationship between the backroom and the sales floor. Therefore, the recorded inventory is always closer to the actual inventory because stock loss is the only error. As the RFID read rate decreases, the recorded discrepancy becomes worse due to improved visibility in the RFID system with higher trigger percentage.

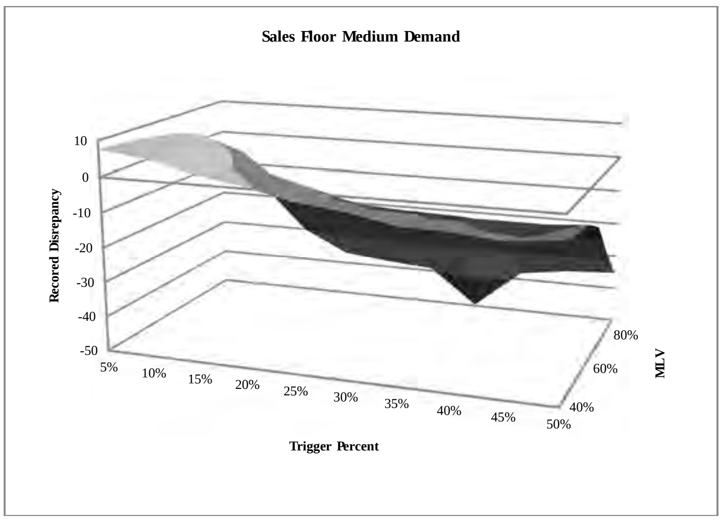

Figure 17: Average Annual Recorded Discrepancy at Sales Floor for Medium Demand Rate

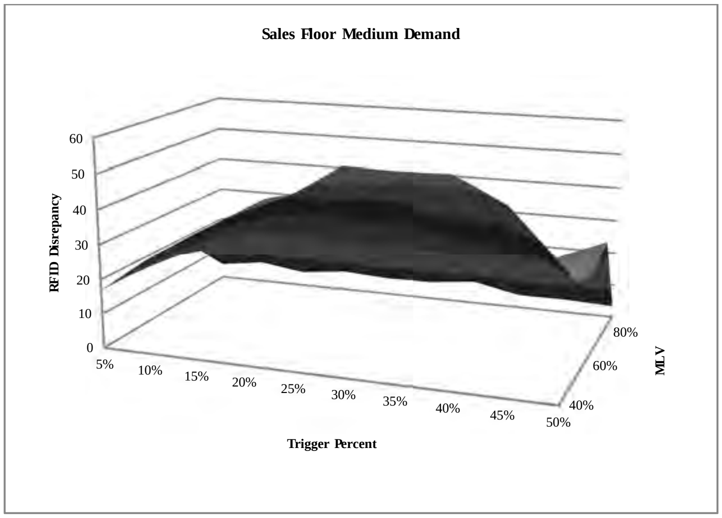

Figure 18: Average Annual RFID Discrepancy at Sales Floor for Medium Demand Rate

A cycle counting strategy using the RFID trigger mechanism is a very useful tool to help reduce the amount of annual discrepancy in the system. The scenario of using RFID readers at both inbound and outbound shipments results in smaller discrepancies for smaller trigger percents. As the trigger percent increases, so does the discrepancy. When RFID readers are used only for inbound shipments, the discrepancies become worse with increased RFID accuracy and increased trigger percentages.

6. Conclusions and Discussions

This study investigates the impact of inventory decisions in the supply chain based on imperfect data generated by RFID systems. A simulation model was developed to represent a two-echelon supply chain, where every echelon has a different inventory policy. The two types of errors associated with inventory are stock loss errors and transaction errors. The RFID system is implemented at the receiving and shipping areas of each *IHP*; the sales floor only had RFID at the receiving area. Experiments were carried out for the supply chain and data was collected to determine the effects of RFID systems with limited visibility.

If RFID is implemented only at the receiving or shipping area, the discrepancy is large due to one sided visibility. However, if RFID is implemented at both the receiving and shipping areas, the discrepancy is small. This reduction in discrepancy is an artificial reduction because the inbound and outbound errors mask each other. That means due to the low visibility for received and shipped items, the system misses not only the items received, but also the items lost and shipped. Thus the discrepancy is relatively small. From SCM point of view this is a vital issue because even thought the inventory management system reports small discrepancy, more numbers of items flow thorough the IHP, which would result in bigger losses. The better the RFID system visibility, the more improved discrepancy in the supply chain; therefore, it is better to have RFID at the inbound and outbound areas of a facility due to the improved accuracy and better replenishment decisions. Typically for the distribution centre and backroom, the discrepancy is negative which results in under stocking of items and lower fill rates. The sales floor is overstocked.

System level stock loss errors were added with RFID error to the supply chain and a discrepancy analysis was conducted. Items having a lot of stock loss errors can sometimes have better discrepancy values with worse RFID accuracy. RFID error helps mask some of the stock loss error and results in better replenishment decisions. Inventory management systems do not track the lost items since they are not captured when they are received by the IHP. However, if the facility can reduce the number of stock loss errors; the higher RFID accuracy results in better discrepancy values. Since RFID is positioned at the entrance and exit of an IHP, the system cannot capture stock loss data accurately. Higher RFID accuracy values result in improved inventory decisions as long as stock loss errors can be controlled or eliminated.

Since deployment of RFID systems in the supply chain does not result in perfect inventory accuracy, two cycle counting strategies were implemented into the supply chain to reduce the discrepancy. The time between implemented scheduled cycle counts on a weekly basis. Typically the RFID accuracy had no affect on discrepancy when implemented scheduled cycle counts. However, there is a certain time between cycle counts (usually around 200 days for this model) where the accuracy of the RFID system has a bigger impact on discrepancy. From a managerial standpoint, with the addition of an RFID system, the number of cycle counts can be reduced due to the improved visibility. For certain levels of stock loss errors, even the most inaccurate RFID system could help maintaining low discrepancy.

At the current state of the technology, RFID has not been responsible for making the inventory decisions for supply chains in industry. Therefore, RFID was tested as a warning tool for out of control inventories. RFID was used as a cycle counting triggering mechanism in conjunction with the inventory record. When the difference between the inventory record and RFID value reached a certain point, a cycle count was initiated and the two records were reset to the actual on-hand inventory. The results of the study show that there is a trade-off between the RFID accuracy and trigger value. Lower RFID accuracy and larger trigger values result in less cycle counts and higher discrepancy. Lower RFID accuracy and smaller trigger values results in a lot of cycle counts and lower discrepancy. Decision makers need to look at their current RFID system parameters and determine what level of inventory accuracy is needed based on the cost of the cycle counts.

Acknowledgement

Authors wish to thank the reviewers for their constructive and helpful comments on the paper.

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