Radio Frequency Identification Enabled Business Applications in Supply Chain Management

Diego Klabjan (klabjan@uiuc.edu), Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL

Introduction

Even though the roots of radio frequency identification (RFID) date back to the Second World War, the widespread adoption occurred only in recent years. Just before the turn of the millennium, the Auto-ID Center at the Massachusetts Institute of Technology was established with the backing of several large corporations. The original focus was in supply chain management and the ability to track goods through a supply chain. The center experimented with applying small microchips or tags (called also transponders) to units of goods. The serial number would be stored on the transponder and other pertinent information could be stored in a large database and linked to the serial number. Readers or interrogators mounted in fixed locations would read the serial number from a transponder by means of radio waves as soon as the transponder moves within the read range of an interrogator. These principles form the basis of modern RFID. Later the potential usage of RFID was expanded beyond supply chain management to other areas such as health care.

After very promising initial experiments and business cases, the true breakthrough occurred in 2003 when Wal-Mart, the largest U.S. retailer, and the U.S. Department of Defense made at that time stunning announcements that in a few years their largest suppliers must ship their merchandise with RFID transponders. Under the mandate, the top one hundred suppliers to Wal-Mart have to tag every pallet shipped to a retailer's distribution center. Most of their suppliers immediately rolled up their sleeves and started studying this relatively new technology. A few month later first case studies appeared and the technology had just entered its first level of maturity, Fig. 1.

To comply with the mandates, most of the suppliers rushed with the easiest possible approach of applying transponders just before leaving a distribution center or warehouse. As a result, the RFID technology entered its second level of maturity, known also as slap-and-ship. Clearly in such a business practice the suppliers incur only the cost of tagging with no added value. The sole beneficiary in this case is the retailer by gaining visibility and improving several business processes. The best known and documented benefit is the reduction of out-of-stocks by a stunning 16%, Hardgrave et al. (2005).

With no return on investment for suppliers by using slap-and-ship, it was time to refocus and push the tagging process further upstream in the supply chain. Suppliers gained additional experience either by establishing internal RFID labs or hiring external consultants for further testing and experimenting. Attaching transponders further upstream in the supply chain could yield new untapped benefits such as visibility and traceability. The first step in this direction is to integrate existing enterprise applications with the RFID infrastructure. Many start-up companies offering middleware between interrogators and business applications have come to the market. The technology has entered its third level of application systems integration, which is by now a fairly mature market, Fig. 1.

The next milestone towards the widespread RFID adoption and pronounced return on investment is to change, improve, and align business processes in order to take advantage of the new data streams coming from transponders. We are currently in the early stages of this level. Wal-Mart aligned its store replenishment processes to take advantage of RFID reads of cases entering a store backroom and sales floor, and then the box crusher. The consumer packaged goods firm Proctor & Gamble improved its sales promotions by using real time data from RFID tagged promotion displays and then changing the underlying business processes to track promotion effectiveness.

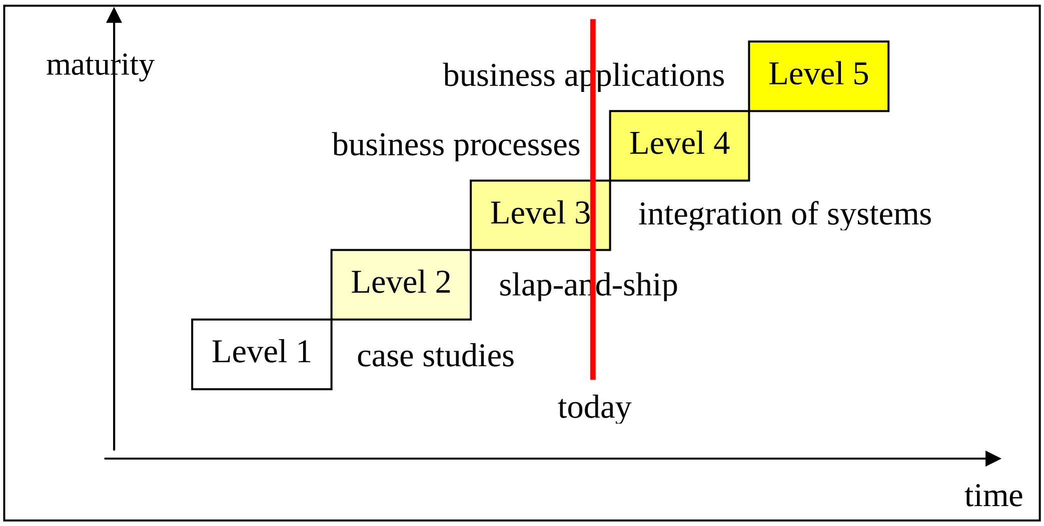

Fig. 1: RFID maturity levels (adopted from Blossom (2005))

The true return on investment and added value of using RFID is in the next level of new business applications that will rely on and exploit the RFID technology. A typical question faced by many suppliers to Wal-Mart is: “We are getting all these data from RetailLink[1], we have a complete visibility of our shipments to Wal-Mart, but how do we use these data for better decision making?” RFID will generate a tremendous amount of new data, especially as the tagging granularity increases from pallets to cases and potentially to item-level tagging. Most companies are currently aligning their processes to account for this new technology. The

---

[1] RetailLink (https://retaillink.wal-mart.com/home) is the online service provided by Mal-Wart to its suppliers. Through RetailLink suppliers can see the status of their shipment, point-of-sale data, etc.

next big step, and the one that will provide significant return on investment, is in developing business applications and analytics that can exploit these data. Especially item-level tagging, which is currently in its infancy, provides numerous opportunities for business applications. Tagging at this scale yields additional benefits and a much larger variety of possible business applications.

In this document we discuss selected future business applications and analytic tools relying on RFID generated data. We also lay ground to some modeling principles resulting from this technology. The analysis of such models is yet to be performed except for a few special cases. In the following two sections we first discuss potential new real-time decision support systems. Reads from interrogators provide real-time information and they enable visibility. As a result, RFID data is mostly about real-time execution and operations. Real-time benefits of RFID go beyond supply chain management into the areas such as preventive maintenance and sensors, Heinrich (2005). In the second section we focus on selected business applications and the underlying models. In particular, we consider marketing and promotions, inventory control, and warehousing.

Analytics and Real-time Decision Support Systems

Traditional supply chains rely heavily on forecasts and as a result are mostly based on planning. Companies usually plan their production, distribution, promotions, etc., and these are well understood and studied areas. While recent efforts such as collaborative forecasting, replenishment, and planning help mitigate effects such as the bullwhip effect and risk, they cannot be complete enablers of a true global demand driven supply chain. It is recognized that superior supply chains are agile and adaptable, Lee (2004), however, this is easier said than done. In agile and demand driven supply chains is all about being able to adapt and respond to events. The focus shifts from planning to the actual execution. The supply chains must become event driven and not heavily relying on forecasts. In recent years many firms transitioned their supply chains into a mixture of the push-pull concept. Upstream in a supply chain the goods are pushed, while downstream the chain needs to be demand driven and thus agile, which requires employing the pull strategy, Simchi-Levi et al. (2003). When goods are pushed, traditional concepts and strategies are well understood. After all, this is the practice used until recently. The pull strategy is relatively new and it is all about execution and operations. While pulling can be achieved without RFID, this technology definitely facilitates responsiveness and agility and it can therefore be a major player in future demand driven supply chains. It allows real time visibility, tracking, and traceability and it is thus a major enabler for responsive supply chains.

RFID is not about planning, it is about real-time operations and execution. This paradigm shift from planning to execution must be present also in analytical tools and decision support systems. Only recently has this shift started to materialize. Future software must be able to processes RFID reads on the fly as the goods transition, quickly analyze the latest information, perform a decision if necessary, and visualize the outcome or, for example, raise an alert in case of an abnormal flow. The traditional model of querying a “static” database, performing an analysis, and then displaying the outcome is going to be gradually phased out.

Promotions Execution

This shift can already be observed in several available products of middleware vendors, i.e., software that links interrogators with back-end enterprise systems.

Early experiments with promotions tracking have been very encouraging, Osofsky and Davis (2006), OATSytems (2005). In a sales promotion, a consumer packaged goods company sends promotion displays to stores. On a given day these displays should be put on the sales floor. Many times the displays are not moved on the sales floor on the specified day or even worse, they have not been received by the store. As a result, such a behavior can greatly reduce the efficiency and profitability of the promotion. With real-time visibility provided by an RFID system these inefficiencies can be substantially trimmed. Consider promotion displays tagged with transponders and interrogators installed at receiving doors of stores and at a point between the backroom and the sales floor. By analyzing the RFID reads, it is possible to deduce if a display has been received by the store and moved to the sales floor in a timely fashion. If it has not been received, say a week before the promotion date, then the company could consult the involved store. In addition, if on the promotion date, a store has not moved the display on the sales floor but it remained in the backroom, a company representative might warn the store to remedy the situation. The underlying software package should process accordingly such alerts and possibly suggest recovery steps.

Proctor & Gamble has just finished a very successful pilot by using a promotions management application, Cantwell (2006). Gillette, a division of Proctor & Gamble, found out that 38% of the stores did not execute the promotion correctly. By monitoring the promotion of a stock-keeping-unit (SKU) and taking proactive correction steps, the company observed a 20% sales lift of this item.

There are additional opportunities for RFID enabled decision support systems besides monitoring a promotion. For example, based on the real time inventory availability within the store during a promotion, shipment quantities can be dynamically adjusted in real time. Traditionally these dynamic adjustments are based on the point-of-sales data, which does not guarantee shelf or backroom availability of the promoted SKU.

Sales Floor Applications

In a retail environment, several other decision support systems could emerge. By continuously monitoring and tracking items as they are moved to the sales floor and when cases are eventually crushed additional added value can be obtained. Some obvious candidates such as performing the on-shelf availability quickly have already been discussed in various publications.

A more advanced application on the horizon could be in handling a product rotation, in particular for produce and other perishable products in a grocery store. Many products, and especially produce, require a carefully managed rotation due to spoilage. Merchandise close to their expiry date is often markdown due to the reduced visual appeal, customer service, or possible regulatory issues. If an RFID system is operational, then it is possible to have an accurate picture of all the items in the backroom and sales floor. With every item an expiry date is associated, which can be read by an interrogator at any point in time and location. A business application should, in real time, display the current age of all the available products, including those on the sales floor, and next analyze these numbers to spot anomalies, provide statistical information on age, and give the item locations. A decision support system could also suggest which product to put next on the sales floor, and suggest a markdown price on a soon to become spoiled product.

Another area calling for an improvement over the current state of the art is in-store replenishments. In most of today's stores, an employee walks up and down the store aisles and creates a picklist, possibly with a wireless handheld device. In many cases the device is not even connected with the information system tracking backroom availability. Such a process is prone to errors and inefficiencies, from erroneously estimating the required quantities, to incorrect availability in the backroom. Clearly a significant amount of time is spent on creating the list. Let us now assume that tagged cases of products are received and interrogators are installed on the receiving docks and between the backroom and the sales floor. First, the backroom inventory count can easily be captured at any point in time by the corresponding information system. By using the information from the number of received items, the number of items moved from the backroom to the sales floor, and the point of sale data, a picklist can be created. From these data the number of items on the sales floor can be calculated and, for example, a simple threshold policy can be easily employed. Apparently such a proactive picklist creation process is already in place at selected Wal-Mart stores. An RFID enabled application should gather all these information and automatically create the picklist and the corresponding reorder quantities. These can clearly be dynamically adjusted to account for the differences in demand patterns. Even more, the application could monitor on-shelf and backroom availability and alert if a stock-out is to happen. It can also recommend backroom and shelf replenishments concurrently before a critical inventory level occurs.

An alternative to the presented strategy for shelf inventory monitoring would be to employ smart shelves. In such a situation, item-level tagging is required and each shelf has its own interrogator that at any point in time keeps track of the corresponding shelf inventory. Such a deployment is much more costly and at present, due to the relatively high cost of transponders, unacceptable for many items. The sole exceptions are high value items such as DVDs and CDs. However, additional benefits beyond replenishments are possible. By monitoring what consumers pick from shelves and then return on the shelf or buy, valuable marketing research data would be available.

Business Applications

While traditional planning based models are abundant and their adoption in business applications is widespread, stepping down to the execution level requires different models, tools, and approaches. It also creates new challenges such as robustness, the need for rule engines, and tractability of the underlying models and methodologies. We next elaborate on several applications, where real-time decision support systems driven by RFID data can have a major impact.

One-to-one Marketing

In one-to-one marketing, marketing material is targeted and customized for a particular consumer and it therefore takes into account his or her particular individual needs. As such, it focuses on economies of scope rather than scale. While selected forms, e.g., mail-in catalogs, of one-to-one marketing date back many years, it is in the past few years that it gained much traction due to advances in information technology. Consumer tailored email marketing, see e.g., Byron (2005), and cross selling through customized web sites, (Amazon.com is considered a pioneer in this area) are now established marketing practices.

In its infancy are one-to-one marketing opportunities exploring the near field communication (NFC) protocol, which enables secure short range communication among devices such as cellular phones and terminals. So called contactless smart cards (e.g., payments are made by simply waving the card) are slowly penetrating the market. In particular, cellular phones are well suited for performing one-to-one marketing tasks. Consider, for example, a payment made by using an NFC enabled cellular phone. During the payment communication, the vendor’s NFC enabled terminal can easily pass along a web site link with promotional material. Trials have also been performed on establishing communication between a billboard and a passing by consumer carrying a cellular phone. Other applications are listed in O’Connor (2006).

Another, well established and more traditional form of one-to-one marketing, used by high-low pricing retailers are coupons. We do not mean manufacturer coupons (e.g., peel-off or in box coupons, or coupons distributed by newspapers or magazines), but coupons distributed by the retailers. Using scan or point of sales data, retailers can target coupons to individual consumers. A big limitation of such a strategy is the fact that the coupons are distributed to a consumer either before the actual shopping experience (mail-in coupons), or after the shopping trip, i.e., during the checkout process. So far one-to-one marketing during the actual shopping experience has been elusive. The potential revenue increase can be substantial since approximately 60% of the purchasing decisions by consumers in grocery stores are made in the store.

RFID enables coupon distribution during a shopping trip. Consider a store employing item-level tagging together with smart shelves. Such a prototype store has already been built in Rheinberg, Germany, www.future-store.org, by Metro, a German retailer. Interrogators mounted on shelves can query the items already purchased by a consumer that are in the shopping cart. An interrogator reads the already purchased items of the consumer by interrogating the tags attached to these items in the shopping card. Based on these information, a different device with a display, attached in the vicinity of the shelf in question, can then issue coupons to the consumer and shows her a good route in order to redeem the coupons. Let us assume that the consumer has already purchased cheese. If the store has selected wine brands on promotions, the display might issue to the consumer the associated coupons and show him or her where in the store to find the promoted brands. (We assume that purchases of cheese and wine are highly correlated.) If based on the current basket of the consumer, other related brands in various categories are on promotions, several coupons can be given and the corresponding route showing the consumer how to navigate through the store can be displayed. Clearly, in a potential implementation of this strategy, only selected locations (frequently visited and sufficiently far from the store entrance) in the store should have the coupon issuing capability.

We next outline the underlying modeling framework (details and further extensions are given in Klabjan and Io (2006)). Consider a consumer *k* at time or shopping trip *t*. Most of the modern stores have loyalty programs and we consider that the consumer is part of the loyalty program. As a result, past purchases of consumer *k* are available. Let us assume that she is standing in front of a coupon issuing display. Her current items in the shopping cart are read by the interrogator and let S_{tk} be the set of all categories purchased so far, i.e., those categories that are in the shopping cart. We want to estimate the probability $prob_{tki}(S_{tk})$ of an impulse purchase from category *i* given S_{tk}. By using the multivariate logit model adopted from Russell and Petersen (2000) and Boztug and Hildebrandt (2005) to suit our purpose we have

$$\begin{aligned} prob_{tki}(S_{tk}) &= 1 \big/ \left(1+e^{Z_{tki}(S_{tk})}\right), \\ Z_{tki}(S_{tk}) &= \beta_i + Mix_{tki} + HH_{tki} + \sum_{j \in S_{tk},\, j \neq i} Q_{tkj}, \end{aligned} \tag{1}$$

where β_i is the category dummy variable, Mix_{tki} denotes the market mix variables (e.g., price), HH_{tki} is the consumer specific contribution (e.g., loyalty, time since the last purchase), and Q_{tkj} is the cross category parameter. If the consumer is not enrolled in the loyalty program, then attributes such HH_{tki} are not considered and the consumer index is dropped in (1).

Russell and Petersen (2000) suggest using

$$\begin{aligned} Mix_{tki} &= \gamma_i \ln(price_{tki}), \\ HH_{tki} &= \delta_1 \ln(time_{tki}+1) + \delta_2 \ln\left(\frac{n_{ik}+0.5}{n_k+1}\right), \\ Q_{tkj} &= \delta_{ij} + \gamma size_k . \end{aligned} \tag{2}$$

Here $price_{tki}$ is the average price of the products in category *i* purchased over a period of time, $time_{tki}$ is the time since the last purchase, n_k is the number of purchases made so far by consumer *k*, n_{ik} is the number of purchases from category *i*, and $size_k$ is the average basket size of consumer *k*. All of the parameters such as $\beta_i, \gamma_i, \delta_1$ are computed by using standard multinomial logit maximum likelihood estimation.

In order to find which coupons to display and to compute the suggested route, we maximize the total expected profit subject to not stretching the shopping time too much. Let $\overline{price_{ti}}$ be the average price of products on promotion in category *i* during the trip at time *t*, and let s_{ij} be the estimated travel time from category *i* to category *j*. Note that these times can be easily computed from the store layout. The proposed model is to find a subset $U \subseteq C$ such that

$$\begin{gathered}\max \sum_{i\in U} prob_{tki}(S_{tk}) \cdot \overline{price_i} \\ \sum_{i\in U,\, j\in U} s_{ij} \le \alpha_{tk}.\end{gathered} \tag{3}$$

The set of all categories with a promotion is denoted by *C* and α_{tk} is the parameter controlling the added shopping time. Optimization problem (3) is a well studied problem, known also as the orienteering problem, and several efficient heuristics and exact algorithms have been proposed in the past, Fischetti et al. (1998), Feillet et al. (2001).

A business application based on these concepts would compute the necessary parameters required in (1) and (2) in predetermined intervals, e.g., overnight. During a shopping trip of a consumer, when a stop is made before a display, either the main server or an embedded device could solve (3) by a fast heuristic and issue accordingly the coupons to the consumer and recommend the computed route.

As we have already eluded, coupons should not be given too often since it would have a negative annoying impact on consumers. A few selected locations need to be considered. This location selection process can be facilitated if the shopping cards are RFID enabled as well. In such a case, a transponder is embedded in a shopping card and the interrogators (either on the shelves or implanted in the floor) can also compute the route of the consumer before reaching the current shelf. Tracking shopping cards with RFID has already been experimented with, Sorensen (2003), Larson et al. (2005).

Inventory Control

Complete visibility upstream and downstream in the supply chain leads to interesting new inventory models and potential resulting business applications. Inventory inaccuracy is a well documented problem for many firms. It can result from human errors, shrinkage, misplacements, etc. Many of these reasons can be elevated by using RFID to keep track of the goods. As a result, with a more accurate inventory count, adjusted or new replenishment policies are possible.

Upstream Visibility

One of the first benefits of RFID tagging for Wal-Mart was the visibility of shipments within their own supply chain. The pallets are for the first time read as they enter the distribution center and then they are tracked until they are crashed at a box crusher in a store. There are clear low hanging benefits of such a visibility, from chargeback settlements to streamlining warehousing operations. However, a potentially greater benefit could be in using the RFID data to streamline replenishment policies. The current replenishment policies would be replaced with much more robust and dynamic policies. Consider placing a replenishment order by considering a quoted or estimated lead time. A few days after, through RFID data reads, we know the precise location of the order within the supply chain. Suppose that the order due to unexpected disruptions is further upstream than we have anticipated. Then we can be proactive in several possible ways. We can

- expedite the order in the supply chain, or
- we can place an emergency order, or
- we can place a new regular order sooner than we would have otherwise.

On the other hand, if the order is to arrive earlier than anticipated, we can potentially postpone the next replenishment order.

The work by Song and Zipkin (1996) provides a modeling framework for such options. The presented model is adopted to fit our RFID setting. Let us focus on a single product by a firm who is using a single supplier and faces exogenous stochastic demand. We assume a periodic review setting and backlogging.

Whenever the firm places an order, the order enters the supply chain. As time progresses, the order moves in the supply chain, which has a given finite number of intermediate stages, e.g., major production processes, distribution centers, ports, etc. The stages can be arranged in a linear sequence so that an order always moves from a stage to any downstream stage. Clearly the order can stay put at a stage. In order to model the stochastic lead time, an order moves from one stage to another downstream stage, which is selected randomly based on a given distribution. In our RFID world, the supplier affixes transponders to an order and the stages represent locations of readers and the corresponding read events. Through the reads, the firm knows at any point in time in which stage the order is located.

To formalize this concept, let us assume there are n stages labeled from 1 through n. We also assume that placing the actual order corresponds to being at stage 0, i.e., stage 0 represents that the order enters the supply chain. Similarly, we add stage n+1 corresponding to the event of the order arrival to the final destination.

In order to model this as a dynamic program, we define

$R_t =$ inventory on hand at time t,

$\hat{R}_{tk} =$ amount of the outstanding orders at time t and stage k,

$\mathrm{X}_{\mathrm{t}} =$ the procurement quantity.

The first two quantities above describe the state space and the last one corresponds to the decision of placing an order. Fig. 2 shows the main concept. For ease of notation we define $\hat{R}_t = \left(\hat{R}_{tk}\right)_{k=0}^{n+1}$.

In order to model stochastic transitions, we introduce a random variable W_t. For each realization w_t of W_t there is a transition matrix $M(w_t)$ that specifies where outstanding orders at a stage transition next. This matrix has n+2 rows and columns and it encodes the transitions. In Fig. 2 we show two such possible transitions. Self loops correspond to the events that the outstanding order stays put at the stage. For example, under the top realization we have (4) and under the bottom realization we obtain (5).

$$\hat{R}_{t+1,n+1} = \hat{R}_{t3} + \hat{R}_{tn} \tag{4}$$

$$\hat{R}_{t+1,3} = \hat{R}_{t1} + \hat{R}_{t2} \tag{5}$$

In order to set up the well known optimality equation for dynamic programs, we introduce the value or cost-to-go function V_t. The value $V_t(R_t, \hat{R}_t)$ corresponds to the minimum expected cost from time period t onwards given that at time period t the current inventory on hand is equal to R_t and the outstanding orders correspond to vector $\hat{R}_t$. Let D_t be the stochastic demand at time period t and we assume linear holding and backlogging cost. In addition, the procurement cost has a fixed cost component, which is stationary in time, and there is also variable procurement cost. Let $E^{(D_t,W_t)}$ denote the expectation with respect to the two random variables.

The optimality equation reads

$$V_t(R_t, \hat{R}_t) = \min_{X_t \geq 0} \left\{ c_t(X_t) + E^{(D_t,W_t)} \left[h_t\left(R_t + \left(M(W_t)\hat{R}_t \right)_{n+1} - D_t \right) + V_{t+1}(R_{t+1}, \hat{R}_{t+1}) \right] \right\}, \tag{6}$$

where the procurement and holding cost components are defined as

$$c_t(X_t) = \begin{cases} 0 & X_t = 0 \\ K + \bar{c}_t X_t & X_t > 0, \end{cases}$$

$$h_t(\bar{X}_t) = \bar{h}_t \left(\bar{X}_t\right)^+ + \bar{p}_t \left(-\bar{X}_t\right)^+,$$

and the systems dynamics as

$$R_{t+1} = R_t + \left(M(W_t)\hat{R}_t \right)_{n+1} - D_t,$$

$$\hat{R}_{t+1} = M(W_t)\left(\hat{R}_t + X_t e_0 \right).$$

Here e_0 denotes an n+1 dimensional vector with all zeros except a 1 as the first coordinate and the subscript n+1 denotes the n+1’th coordinate of the underlying vector.

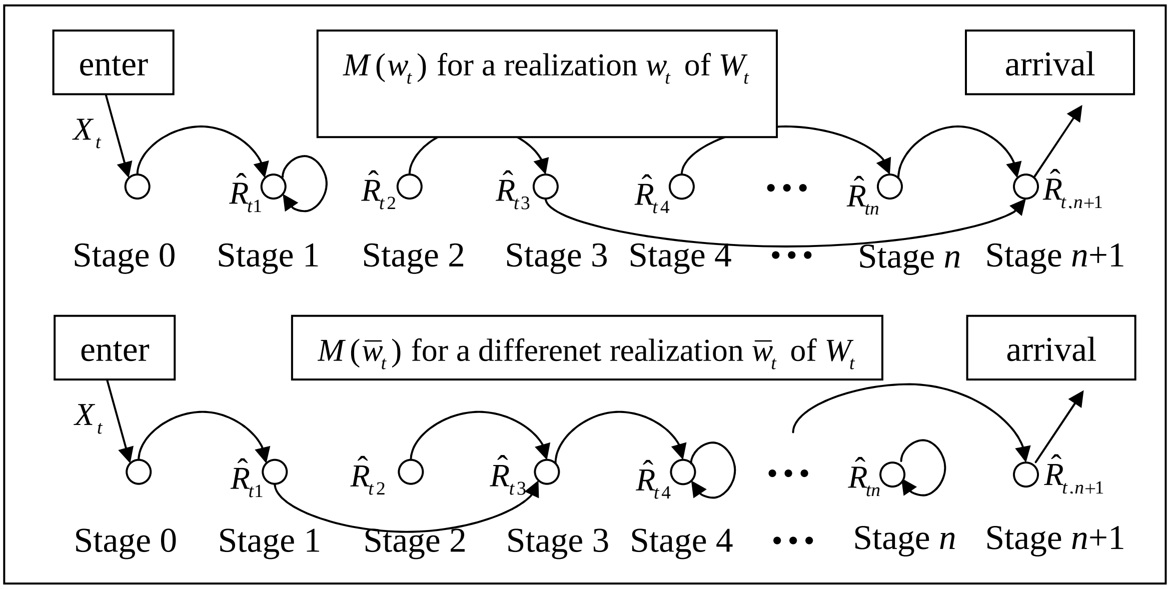

Fig. 2: Two possible outstanding order transitions

By analyzing (6), Song and Zipkin (1996) were able to show after some mild assumptions (the most important is the non crossing order property, which imposes that the outstanding order transition matrices *M* inflict that the orders do not cross in time) that the optimal ordering policy satisfies the (*s*,*S*) property with respect to the inventory position. Formally, let the inventory position be defined as $\bar{R}_t = R_t + \sum_{k=0}^{n+1} \hat{R}_{tk}$. Then in every time period there are two numbers s_t and S_t, $s_t \le S_t$, such that if $\bar{R}_t > s_t$, then we do not place an order and otherwise we order $S_t - \bar{R}_t$.

A future business application can exploit the presented model on a rolling horizon basis. We first compute V_t over a certain horizon by estimating the unknown distributions. Next, from the RFID data, we obtain the inventory position and the application recommends a replenishment quantity. Periodically, again based on the RFID data, which give us the exact knowledge of the past flow of goods and the time spent at each stage, we update the transitions matrices of outstanding orders and recompute the value function.

Visibility of Distribution Channels

While in the previous section we discuss a model and business applications as they relate to retailers or manufacturer, here we focus on the other side of the chain, i.e., suppliers who tag their products and therefore gain complete visibility into their distribution chain. Much too often stories have been written about slap-and-ship. A supplier to a retailer who had imposed an RFID mandate, in order to comply with the requirement, applies transponders to pallets or cases just before they leave the distribution facility and bound to the retailer. Clearly, there is no added value to the supplier under such strategy unless the supplier takes advantage of the visibility in the distribution channel. The return on investment for the supplier is possible in two ways.

- The supplier can apply transponders earlier in its own supply chain. Potentially the tagging process can be pushed all the way back to production. But even pushing it back within the distribution facility can yield benefits. These benefits include improved putaway and picking, shipping accuracy, automated advance shipping notification, simplified settling of chargebacks, and many more (see, e.g., the report by Symbol Technologies (2004)).
- Based on the visibility of shipments, better decision making can be made and thus benefits can be gained even by slap-and-ship. Consider a shipment that is expected to arrive at a store backroom in five days, but it is stalled in a distribution center of the retailer for several days and therefore it is anticipated not to arrive within the predicted five days. The supplier can then accelerate the next shipment, even though originally it was planned to occur a few days from now. Many retailers already provide systems to exchange RFID data, e.g., Wal-Mart's RetailLink and Target's Partners Online[2] are two such services.

Cleary an optimal strategy is the best of the two worlds. While many firms have realized the benefits of the former, the latter is yet relatively untapped. Consider the following case of Ballantine Produce Co. that sells produce to Wal-Mart and even though not falling under the mandate, it tags its shipments. As a result the company is able to see the status of every single container through RetailLink. However, the company is yet to determine how to use these data, Douglas (2005).

We next show how a business application can use these data. Consider a supplier who ships its product to a retailer. As before, it is assumed that every shipment goes through several stages (each stage corresponding to a transshipment point or a distribution center, a backroom, a sales floor, etc.). RFID interrogators are installed at these points and therefore at any point in time the supplier knows the location of every single shipment. The retailer's demand is stochastic as are the movements among the different stages. We assume that the orders can be shipped only once a day, i.e., a periodic review setting with a finite number of time periods.

We again model the problem as a dynamic program where the decision to be made is how much to ship and to procure on a given day. The latter can easily be neglected if so required. For simplicity we assume that there is no lead time on the procurement side. We assume that stage 0 denotes the entering point of the distribution chain and stage $n+1$ the point-of-sale event. Thus there are n intermediate physical locations where the reads happen, Fig. 3.

The holding cost is accrued only at the supplier, i.e., the firm in question, and a backlogging penalty applies as well. In order to capture the state of the system, we need the following three state variables:

---

[2] See https://retaillink.wal-mart.com/home for RetailLink and http://www.partnersonline.com for Partners Online.

$R_t =$ inventory on hand at time t,

$\hat{R}_{tk} =$ shippment amount at time t and stage k,

$\tilde{R}_t =$ the available amount at the last stage, i.e., at the point-of-sale location.

The third variable is required in order to capture the penalty cost. There are two decision types: how much to ship and how much to procure. We denote them as

$X_t =$ the amount to ship at time t,

$Y_t =$ the amount to procure at time t.

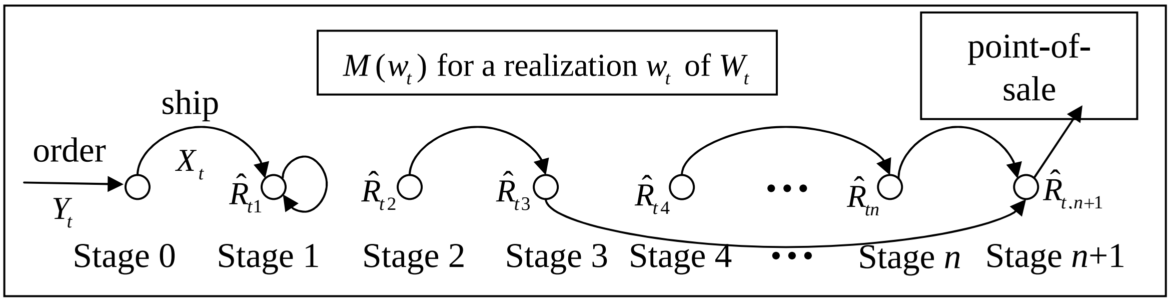

Fig. 3: The flow of shipments

As before we denote $\hat{R}_t = \left(\hat{R}_{tk}\right)_{k=0}^{n+1}$. The transitions of shipments are governed by a random variable W_t. Each realization w_t of W_t imposes a transition matrix $M(w_t)$, which specifies the next location of outstanding shipments.

If V_t is the value function, then the optimality equation reads

$$V_t(R_t,\hat{R}_t,\tilde{R}_t) = \min_{\substack{X_t \ge 0, Y_t \ge 0 \\ X_t \le R_t + Y_t}} \left\{ \begin{aligned} & c_t(Y_t) + s_t(X_t) \\ & + E^{(D_t,W_t)}\left[\overline{h}_t R_{t+1} + \overline{p}_t \left(-\tilde{R}_{t+1}\right)^+ + V_{t+1}(R_{t+1},\hat{R}_{t+1},\tilde{R}_{t+1}) \right] \end{aligned} \right\}. \tag{7}$$

The procurement cost function is denoted by c_t and the shipping cost function by s_t. As before $\overline{h}_t$ and $\overline{p}_t$ denote the per unit holding and penalty cost, respectively. The system dynamics are

$$\begin{aligned} R_{t+1} &= R_t + Y_t - X_t, \\ \hat{R}_{t+1} &= M(W_t)\left(\hat{R}_t + X_t e_0\right), \\ \tilde{R}_{t+1} &= \tilde{R}_t + \left(M(W_t)\hat{R}_t\right)_{n+1} - D_t. \end{aligned}$$

Note that $R_{t+1} \ge 0$.

Based on (7) an optimal policy could be computed. To the contrary to the model presented in the previous section, this model has not yet been analyzed and therefore the structure of the optimal policy is not known.

In a business application, this model can be used in a similar way. A business application based on this model could significantly contribute to the bottom line of many suppliers to retailers. It would give a valuable analytical and decision making tool to Ballantine Produce Co., the company mentioned earlier.

Inventory Accuracy

It is a known fact that inventory inaccuracy poses a serious challenge. The discrepancy between the actually physical inventory count and the amount shown by information systems can be as high as 65%, Raman et al. (2001a), Raman et al. (2001b). There are three driving forces behind this discrepancy. Items can be misplaced in the warehouse or backroom. The more handling is required, the more likely misplaced items occur. Shrinkage in the form of theft, damage, fraud, etc. is another major source of inaccuracy. Then there are transaction errors made by humans.

One of the most important consequences of this discrepancy are out-of-stocks. Many out-of-stocks do not occur due to pure planning, but mostly due to inferior execution. It is common that an out-of-stock happens even though there are items in the backroom, but they are not shown by the inventory system or the items are not found in the right place. RFID can clearly have a big impact in reducing the sources of discrepancy. Even though to locate misplaced items within the facility a more costly real time location system must be put in place, RFID data can confirm that items have been misplaced without locating them (items might be out of the reading range of every interrogator in the facility). Shrinkage can also be reduced by tagging products since records are kept about the last location and time of the goods. Finally, receiving can be fully automated, which should reduce transaction errors. The reduction of inventory inaccuracy due to RFID can boost sales from 1-2%, which can be a significant profitability increase. We point out that RFID will not completely remove inventory inaccuracy, but it will significantly reduce it.

Today's business applications take a snapshot of the current state and then suggest a replenishment quantity. By doing so they completely rely on the information system and the inventory count recorded by the system. RFID will clearly by default improve the replenishment policy by simply providing a more accurate inventory count. However, if a proactive decision is to be made by considering potential future events, then more advanced modeling techniques must be employed.

Lee and Özer (2005) provide such a framework based on periodic replenishments. They assume a single item and a single stock keeping facility. In their work they assume stochastic misplacements that are modeled by random variable D_t^m at time period t. In addition, similarly, shrinkage is represented by random variable D_t^s. Transactions errors do not influence the underlying model and therefore, for simplicity, we leave them out.

Paying customers arrive stochastically based on random variable D_t^p, which is observed from the point-of-sales data. When considering misplacements, a differentiation is required between the physical inventory and the inventory available for sale, called sales-available inventory. Misplacements count toward the former, but they do not count towards the latter. In view of this, the main difference between misplacements and shrinkage is the fact that misplacements return back to the system after a physical inventory count is performed. Thus, they affect the sales-available inventory. Let us also assume that the inventory count is performed every N time periods.

Lee and Özer proposed a dynamic programming model. The system is completely defined by the sales-available on-hand inventory, the number of misplaced units, and the elapsed time since the last inventory count. Thus we have

$R_t =$ sales-available inventory on hand at time t,

$\bar{R}_t =$ the number of misplaced units at time t since the last inventory cout,

$i_t =$ the number of time periods since the last inventory count.

We also need to differentiate between paying customers and the number of sales W_t^s in time period t. Total sales depend on the number of available inventory on the sales floor when the actual paying demand occurs. Similarly, the number of actual misplacements W_t^m clearly depends on the available inventory. Both of these two quantities depend on the arrival process of customers, i.e., the interaction between misplacements and order arrivals.

The decision is about the procurement quantity X_t in time period t. The sales-available inventory is equal to the inventory record subtracted by the number of misplaced and shrinkage items, and transaction errors. Let $D_t = D_t^p + D_t^s + D_t^m$. If V_t is the value function, then the optimality equations read

$$V_t(R_t, \bar{R}_t, i_t) = \min_{X_t \geq 0} \left\{ \begin{aligned} & c_t(X_t) + \bar{h}_t E^{(D_t, W_t^m)} \left[\left(R_t + X_t - D_t \right)^+ + \bar{R}_t + W_t^m \right] \\ & + \bar{p}_t E^{(D_t^p, W_t^s)} \left[D_t^p - W_t^s \right] + E^{(D_t, D_t^p, W_t^m, W_t^s)} \left[V_{t+1}\left(R_{t+1}, \bar{R}_{t+1}, i_{t+1} \right) \right] \end{aligned} \right\}.$$

As before, the procurement cost function is denoted by c_t and $\bar{h}_t$ and $\bar{p}_t$ denote the per unit holding and penalty cost, respectively. We point out that W_t^s and W_t^m depend on the underlying action and state.

The system dynamics are specified by the following equations. Since the inventory count is performed every N time periods, we have

$$i_{t+1} = \left(i_t + 1 \right) \bmod N.$$

The misplaced inventory obeys

$$\bar{R}_{t+1} = \begin{cases} \bar{R}_t + W_t^m & i_t \neq N-1, \\ 0 & i_t = N-1. \end{cases}$$

Observe that the number of misplaced items is set to zero after the physical inventory count. Finally, the sales-available inventory satisfies

$$R_{t+1} = \begin{cases} \left(R_t + X_t - D_t \right)^+ & i_t \neq N-1, \\ \left(R_t + X_t - D_t \right)^+ + \bar{R}_t + W_t^m & i_t = N-1. \end{cases}$$

Unfortunately this dynamic program is hard to compute and analyze. For these reasons the authors propose two approximations, both of them based on assumptions with respect to W_t^s and W_t^m.

In the first approximation it is assumed that the paying customers arrive first, then the demand for shrinkage occurs, and at the end the demand for misplacements happens. Under this assumption we have

$$W_t^m = \min\left\{D_t^m, \left(R_t + X_t - D_t^p - D_t^s\right)^+\right\},$$
$$W_t^s = \min\left\{D_t^p, R_t + X_t\right\}. \tag{8}$$

Let us denote by V_t^{LB} the value function corresponding to (8).

In the second case the other extreme is assumed, i.e., the misplacements happen first, next shrinkage occurs, and at the end the paying customers arrive. Now we have

$$W_t^s = \min\left\{D_t^p, \left(R_t + X_t - D_t^m - D_t^s\right)^+\right\},$$
$$W_t^m = \min\left\{D_t^m, R_t + X_t\right\}. \tag{9}$$

Let V_t^{UB} be the value function based on (9).

The authors show that $V_t^{LB} \le V_t \le V_t^{UB}$. They also argue that computing these two bounds is computationally more efficient than to compute the original value function.

Warehousing

One of the largest immediate impacts of RFID is in the domain of the warehousing and distribution center operations. This is a domain where many prototype large-scale tests have already been completed and a few production implementations are already in place. For example, Proctor and Gamble[3] in one of their plants in Spain decided to start loading pallets directly to outbound trucks instead of first storing them for a later pickup. To prevent errors such as loading a pallet to a wrong truck going directly to a customer, the company decided to use RFID. They mounted interrogators on forklifts and tagged pallets. A similar strategy was employed by International Paper[4]. In order to track rolls of paper in their warehouse, the company mounted interrogators to forklifts and transponders to paper rolls. Note that using interrogators on forklifts is cheaper than mounting them all over the warehouse. In addition to standard benefits such as detecting misplaced or diverted pallets or cases and advanced shipping notification there are additional opportunities leading to potentially even larger savings. We next identify two such opportunities with potentials for being part of a future business application.

Reducing Storage Capacity

Consider the standard putaway process in a warehouse or a distribution center. The current practice of using dedicate storage is to store items based on the SKU num-

---

[3] RFID Speeds P&G Plant Throughput, *RFID Journal*, March 2003. Available at https://www.rfidjournal.com/article/articleview/291/1/4/

[4] J. Masseli, IP Taps Matrics for RFID Tags, *RFID Journal*, December 2003. Available at http://www.rfidjournal.com/article/articleview/694/1/1/

bers. Such an arrangement requires grouping them by SKU and a specific storage location is dedicated to an individual SKU. Most modern warehouse management systems (WMS) adjust the locations and occasionally reassign SKUs to different locations. In such a setting, whenever a new item arrives, it is assigned by the WMS to a location.

Consider pallet operations. Pallets are typically stored on the floor and zoning is based on lanes. If a lane holds a pallet, then the entire lane is assigned to a single SKU. If several SKUs are assigned to a single lane, then by using bar codes it is very difficult to find a specific pallet for pickup. Since bar codes require line of sight, an employee would have to manually scan the pallets. There is also a second drawback of assigning several SKUs to the same lane. It is related to the fact that sometimes double-handling would occur during retrieval. The need for double-handling is due to the pallets being stacked on top of each other or because the depth of a lane is more than one.

On the other hand, if RFID transponders are attached to pallets and a real time location system put in place, each individual pallet can easily be located within the putaway area, in particular within a lane. As a result, there is no longer a technological obstacle requiring a single SKU to be assigned to a lane. If more flexibility is allowed in the putaway arrangement, then the storage capacity can be used more efficiently. In a longer time span it means smaller warehouses and thus less capital tied to warehouse facilities. While lanes would still be needed to allow for easy access, the mapping of SKUs to lanes would no longer be required.

Before such a strategy, which we call the virtual lane strategy, becomes part of a business application, several trade-offs need to be accessed and studied. The benefits of the virtual lane strategy are as follows.

- Reduced storage requirements: If dedicated lanes are used, then it is clear that each lane holds only as many pallets as we have in the warehouse of a specific SKU. At any point in time there could be several lanes holding only a fraction of its storage capacity, which is known as honeycombing. Under the virtual lane strategy, the pallets can be mixed within the lanes and therefore, at least in theory, every lane would be filled up to its capacity or empty, with an exception of a single lane that would be neither of the two cases. Clearly this strategy requires lower space requirement. During periods with many empty lanes, the empty storage area could be reassigned for other activities. Future warehouses could be built under the virtual lane strategy and therefore they would be smaller.
- The pallets of the same SKU would be dispersed throughout the lanes and thus picking could be more efficient. It is known that random storage strategies are better suited for picking than dedicated storage areas. In the dedicated lane assignment, all pallets of the same SKU are in the same lane and therefore they are not dispersed. This can significantly increase the picking time. On the other hand, under the virtual lane strategy, the pallets would be scattered, which would reduce the picking time.

There is also a clear drawback of the virtual lane strategy. In order to pickup a pallet not on the top of the stack or facing the lane, the picker would need to first reposition other pallets before getting to the desired one.

Before a business application is built on top of the virtual lane strategy, a study is required assessing these trade-offs and establishing the best practices among possible variants of the strategy. For example, do we want the flexibility of every SKU being assigned to every lane or do we want a group of the SKUs assigned to a single lane? If the latter, how many SKUs and which ones?

Cross-Docking Operations

Cross-docking is a business practice enabling a quick transfer of specific items within a warehouse. In a true cross-docking facility, goods are unloaded from inbound trucks, quickly sorted, and loaded to outbound trucks. The total time an item spends in the facility is typically only a few hours. As a result, it is an extremely time sensitive operation. The advantages of cross-docking are mainly associated with savings for not holding inventory within the facility, and, more importantly, in transportation. Mostly expensive less-than-truckload (LTL) shipping is used on the inbound said. The goods are then consolidated within the cross-docking facility and quickly loaded into full truckloads, which is a much cheaper mode of transportation. Among the U.S. retailers, Wal-Mart, Costco, and Home Depot all excel in cross-docking.

In such time sensitive operations, visibility is a driving force and therefore again RFID is an enabling technology to even more efficient operations. By receiving already tagged shipments and installing interrogators at selected important locations in the facility, a complete visibility of goods can be achieved. For example, interrogators can be mounted on receiving and shipping docks, and along conveyer belts. Interrogators can then feed the location of goods to a central computer system.

Sophisticated decision support systems and business applications can be designed based on the RFID data. Typical decision making in a cross-docking facility revolves around the following tasks.

1. As incoming and outgoing trailers are coming in, they first need to be parked in designated areas. Accordingly they need to be queued as well and at a later time assigned to a specific dock.
2. At any point in time, labor needs to be assigned to individual tasks and locations. For example, as a trailer is pulled at the receiving door, labor needs to be assigned to this door. Likewise, labor needs to be assigned to each outbound trailer.
3. Cross-docking operations use sophisticated materials handling equipment. As with labor, the equipment needs to be assigned to individual tasks.
4. A more strategic decision is in matching the inbound goods with the outbound goods. The sorting equipment needs to be set up appropriately. Reas-

signments must be handled dynamically during operations on a per needed basis.

In many cross-docking facilities most of these tasks are performed manually by experienced employees. An automated, computer based system can dramatically improve efficiency of cross-docking operations. In addition, the last three tasks can use RFID data to even further cut the bottom line. Consider an outbound trailer waiting to be loaded. Suppose that it has already been almost loaded with several items. Some of the items were late on the inbound side due to some unscheduled events and are currently within the four walls of the facility. The main decision to be made is if the outbound trailer should wait for the missing items or depart and arrive at the store on time. By using RFID data, the system can find out the current location of the items within the facility and estimate the remaining time to load the entire trailer. Based on this estimate a decision to send the trailer or not can be made. Likewise, with any unexpected event, if it happens outside of the facility to the corresponding conveyance or within the facility, labor and material handling equipment need to be reassigned on a timely basis. These reassignments can exploit the information about the current status of the items, in particular, those that are involved with the disruption. All of these recovery procedures can be performed more efficiently by using real time RFID data.

Summary

In the past few years RFID has evolved from the initial hype to a technology with potential return on investment. A few companies are already observing return on investment and prototype implementation are mushrooming. All of the current benefits are hidden in streamlining the underlying business processes. While automatically sending advance shipping notices and alerts if a wrong pallet is put on a truck are important improvements over the existing practice, more pronounced benefits are possible by building and using business applications capable of exploring the massive amount of RFID data.

Visibility into the supply chain is one of the most important factors in a sucessive supply chain. Running an efficient supply chain is a competitive advantage for many companies. RFID plays a crucial role towards the goal of a complete visibility. Visibility is all about execution and real time operations. Companies have mastered optimization based planning tools, Simchi-Levi at al. (2003), Shapiro (2000), however optimization in execution is very limited. With all the data coming from RFID reads, there is a great opportunity to close this gap in the following years. We keep stressing that RFID is not about planning, but it is all about execution. By analyzing RFID data we can improve forecasting and thus the planning models become more reliable, however, this is only a tiny benefit. The true bottom of the line benefits of RFID are in day to day operations. Consider the discussed cross-docking application. We can plan cross-docking operations very efficiently without any RFID reads. The situation changes in execution optimization. Real time data are required for execution optimization and RFID is an enabling technology.

Beyond cutting cost in the supply chain, RFID together with NFC can also improve customer service and experience. We have discussed one such potential application. We can go even a step further. Interrogators linked to servers can also engage in dynamic pricing with a consumer. Consider an interrogator mounted on a shelf, which reads the transponder affixed on a product that the consumer is considering buying. Based on the potential historical buying patterns of this consumer and her loyalty to the store or brand, the interrogator might engage in a virtual dialogue with the consumer with respect to the price of the product. The interrogator can determine that it might be profitable to propose a reduced price to this loyal consumer. Dynamic pricing based on added value also benefits from RFID and it can yield interesting new business application.

Bibliography

Blossom, P. (2005). Levels of RFID Maturity. *RFID Journal*, January.

Boztug, Y., and Hildebrandt, L. (2005). *A Market Basket Analysis Based on the Multivariate MNL Model*. In 34th EMAC Proceedings - Rejuvenating marketing: contamination, innovation, integration, Milan, Italy. Available at http://opus.zbw-kiel.de/volltexte/2004/1633/.

Byron, E. (2005). Subject: Email ads grow up. *The Wall Street Journal*, November, 23.

Cantwell, D. (2006). *RFID R&D Opportunities and the Supply Chain*. Presentation given at the first RFID Academic Convocation, Massachusetts Institute of Technology, Cambridge, MA.

Douglas, M. (2005). RFID Bears Fruit. *Inbound Logistics*, June.

Feillet, D., Dejax, P., Gendreau M. (2001). *Traveling Salesman Problems with Profits: An Overview*. Technical report. Available at http://citeseer.ist.psu.edu/feillet01traveling.html.

Fischetti, M., Gonzalez, S., and Toth, P. (1998). Solving the Orienteering Problem through Branch-and-Cut. *INFORMS Journal on Computing* 10, 133-148.

Hardgrave, B. C., Waller, M., and Miller, R. (2005). *Does RFID Reduce Out of Stocks? A Preliminary Analysis*. Technical report, Information Technology Research Institute, University of Arkansas, Fayetteville, AR. Available at http://itri.uark.edu.

Heinrich, C. (2005). *RFID and Beyond: Growing your Business through Real World Awareness*, John Wiley & Sons.

Klabjan, D., and Io, F. (2006). In-store One-to-one Marketing. Technical Report, University of Illinois at Urbana-Champaign, Urbana, IL. Available at http://netfiles.uiuc.edu/klabjan/www.

Larson, J., Bradlow, E., and Fader, P. (2005). An Exploratory Look at Supermarket Shopping Paths. *International Journal of Research in Marketing* 22, 395-414.

Lee, H.L. (2004). The Triple-A Supply Chain. *Harvard Business Review*, October issue, 102-112.

Lee, H.L., and Özer, Ö. (2005). *Unlocking the Value of RFID*. Technical report. Stanford University.

OATSytems. (2005). *Real-time Promotion Execution*, Technical report. Available at http://www.rfidjournal.com/whitepapers/download/125.

O'Connor, M.C. (2006). RFID gets personal. *RFID Journal*. Available at http://www.rfidjournal.com/article/view/2233/1/3/.

Osofsky, M., and Davis, L. (2006). *Real-Time Promotion Execution: Improving Promotions Performance With RFID*, Technical report. Available at http://www.rfidsolutionsonline.com/content/news/article.asp?docid=3bb79856-48e1-41cd-9e31-a4b46e193e20.

Raman, A., DeHoratius, N., and Ton., Z. (2001a). The Achilles Heel of Supply Chain Management. *Harvard Business Review*, May, 136-152.

Raman, A., DeHoratius, N., and Ton., Z. (2001b). Execution: The Missing Link in Retail Operations. California Management Review 43.

Russell, G.J., and Petersen, A. (2000). Analysis of Cross Category Dependence in Market Basket Selection. *Journal of Retailing* 76, 367–392.

Shapiro, J. (2000). *Modeling the Supply Chain*. Duxbury Press.

Simchi-Levi, D., Kaminsky, P., and Simchi-Levi, E. (2003). *Designing and Managing the Supply Chain*. Mc-Graw Hill.

Song., S., and Zipkin, P. (1996). Inventory Control with Information about Supply Conditions. *Management Science* 42, 1409-1419.

Sorensen, H. (2003). The Science of Shopping. *Marketing Research* 15, 30– 35.

Symbol Technologies. (2004). *Business Benefits from Radio Frequency Identification (RFID)*. Technical report. Available at http://www.symbol.com/assets/files/RFIDBenefits.pdf