Optimal Radio Frequency Identification Deployment in a Supply Chain Network

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Abstract

In recent years, the use of radio frequency identification (RFID) within supply chain management has received considerable attention. A significant upfront investment together with uncertain return on investment, however, remain impediments to deployments of RFID systems. This paper proposes a novel approach to analyze the potential benefits of RFID systems. We suggest deployment strategies that determine an optimal location of RFID within a supply chain network. The resulting models can be used to evaluate the value of information with respect to item losses. In addition, we discuss methods for solving the resulting large-scale optimization problems, and analyze how various system characteristics impact optimal deployment strategies as well as the overall RFID benefits.

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1 Introduction

Over the last few years, radio frequency identification (RFID) has emerged as an important new technology to track the movement of goods in a supply chain. An RFID system consists of three principal components. The first component is a tag with an electronic product code (EPC) to identify pallets, cases, or individual product items. In addition, an RFID system also requires readers that can initialize and receive information from the tags. The communication between the two is by radio waves. The final component is an information system with a data warehouse, which is used to store and manage the data captured from the readers. To operate an RFID system, readers send radio-wave signals over certain pre-specified frequencies. These signals are received by tags in the vicinity of the readers. The tags then transmit stored data (such as the EPC number) back to the reader. The reader, in turn, decodes and transfers this information to the data warehouse together with the time and location stamp.

As a result, RFID has several important advantages over traditional bar coding: items can be read from a distance without optical line of sight, multiple tags can be read simultaneously, and item specific data can be written on a tag, Gale et al. [2005]. The RFID technology yields several important benefits within supply chains. Among others, automated data tracking without human intervention offers faster processing, more accurate inventory records, and advanced shipping notices. Thus, product shrinkage, transaction errors, chargebacks, misplaced products, and incorrect product identification can all be reduced, Kang and Gershwin [2005], Özelkan et al. [2006]. Moreover, unprecedented visibility of the product flows (see Delen et al. [2007] for examples of the detailed level of information that RFID can provide) provides consumers with the right amount of product at the right time while reducing safety stock and the risk of stockouts.

As such, the use of RFID has enormous potential to increase supply chain efficiency. While companies in the U.S. invested $1 trillion on upgrading and improving supply chains in year 2000 alone, Gale et al. [2005], inefficiencies remain high. According to the National Retail Security Survey, for example, the product shrinkage cost for U.S. retailers was over $31 billion in 2001; a similar number, $27.5 billion, has also been reported as the cost of shrinkage in Western Europe, Bamfield [2004]. In addition to this direct financial impact, however, this lack of visibility also has broader impact on supply chain performance, leading to excess inventory and/or lost sales. DeHoratius and Raman [2008] and Kang and Gershwin [2005] present empirical studies, which show that inventory record inaccuracies are substantial and widespread. As a result, companies may fail to order when needed or place orders that are unnecessary. Thus, it is perhaps not surprising that investments in RFID technology have been growing rapidly, spurred - in part - by mandates from industry giants such as Wal-Mart and the U.S. Department of Defense. According to the market research group IDTechEx, IDTechEx [2008], the global RFID market will reach $5.3 billion by 2008, with a five fold increase expected by 2018.

Nevertheless, the introduction of RFID systems poses a number of important issues. Impediments to deployment, for example, arise due to the absence of international standards, security and privacy concerns, and lower read accuracy in environments with liquids or metals. In particular, the high costs of implementation often restrict the adoption of RFID systems in supply chain management, especially in light of the uncertain return on investment. Only about 30% of Wal-Mart's top 100 suppliers, for one, have introduced full-scale RFID deployments and 95% of them did not expect return on investment within two years, Gale et al. [2005], Chuang and Shaw [2005].

As a result, the justification of RFID investments remains a major challenge. Given that it is difficult to measure supply chain benefits that result from visibility improvements, practitioners often resort to rough estimates and superficial analysis (see Lee and Özer [2007] for an excellent discussion). Generally speaking, assessments of RFID's return on investment proceed by comparing a "no-visibility" scenario, corresponding to the current situation, with a "full-visibility" scenario that is based on a complete deployment of RFID. These, however, can be viewed as extremes within a broad spectrum of "partial-visibility" options available to a company when deciding upon the extent and scope of their RFID investments. The main objective of our work, therefore, is to analyze how different RFID deployment levels can benefit the supply chain. In doing so, our goal is to provide new insights on how visibility impacts supply chain performance, which may prove useful when companies contemplate RFID investments.

To address these issues, we evaluate the placement of RFID deployments, i.e., the locations of RFID deployments in the supply chain network. A deployment presents a significant cost, which is typically estimated at up to several hundred thousand dollars at a single location, Simchi-Levi et al. [2007]. While the cost of a reader itself is in the thousands of US dollars, the majority of this amount results from software and integration needs. Decision makers have to consider deployment strategies that balance the benefits of RFID with their deployment costs at an aggregate network level. While recent research considers the performance improvements that may result from RFID installations at a single location, Özelkan et al. [2006], Sounderpandian et al. [2006], we believe that considerations of these macro-level trade-offs have not been addressed before.

We study approaches to evaluate such aggregate benefits of RFID in a supply chain. Specifically, we propose models to determine the optimal locations of RFID systems in the network by trading off their potential benefits with RFID installation costs. To evaluate the potential benefits of an installation strategy, we consider its impact on the effective lead times in the system, which take into account the time spent to recover and/or reship items that are lost. Here, the effective lead times represent not only the time needed to receive a direct order from the supplier, but the order-to-delivery time that includes all of the steps between hitting the reorder point and placing a replenishment order as well as the time to receive goods. Lead times are an important factor in determining supply chain performance, given their impact on pipeline inventory levels, safety stock, transportation costs, etc. We believe that the cost benefits resulting from RFID-induced lead time reductions provide an attractive and novel way of measuring the benefits of increased visibility.

As such, our study concentrates on the marginal benefits that arise from an early detection of supply and shipment disruptions. Within this framework, we consider a variety of model alternatives to address different system characteristics and recovery strategies, each resulting in a complex non-linear location problem. To solve these problems, we propose a novel solution methodology that applies dynamic programming techniques within a branch-and-price framework, together with a heuristic transformation technique to obtain integral solutions. The contributions of our paper are therefore twofold. To the best of our knowledge, our work is the first one to evaluate the aggregate supply chain benefits of an RFID deployment at the system level. In addition, we also propose novel methodologies to solve the models that arise from our approach.

Our models and solution methodologies do not explicitly use any particular features of RFID. Any technology that improves visibility through an ability to track goods can be deployed based on the models provided. RFID is well suited for such a task due to the underlying technological advances and a steadily decreasing deployment cost.

This paper is organized as follows. We start in Section 2 with a brief review of related work. In Section 3, we introduce our approach and outline modeling alternatives by considering RFID deployments in a serial network with a single commodity flow. Section 4 considers the general case with an arbitrary network and multiple commodity flows, and discusses solution methodologies for the resulting optimization problem. We present a computational study in Section 5, where we analyze how systems' characteristics impact RFID benefits and installation strategies. The paper concludes with a summary and discussion in Section 6.

2 Literature Review

The growing adoption of RFID technology has led to an interest in studying the value of increased visibility. Lee and Özer [2007] and Dutta et al. [2007] review the possible benefits of RFID in supply chain management, including labor cost savings, reduced inventory holding costs and stock-outs. A model to capture both inventory inaccuracy and demand distortion is proposed by Bai et al. [2009]. The role of RFID is in reducing inventory inaccuracy. Rekik et al. [2007] consider a newsvendor setting with a single supplier and retailer where inventory inaccuracy results from execution errors. They analytically compare the scenario when errors are observed and absorbed vs. the scenario with RFID that eliminates most of the problems. In Rekik et al. [2008] the authors consider a newsvendor setting of a single retail store where a random fraction of the inventory is misplaced. Similar scenarios are considered with an addition of the case where the retailer is unaware of the errors. A vendor managed inventory setting between a single manufacturer and retailer is addressed by Szmerekovsky and Zhang [2008a] where decentralized, centralized, RFID, and non-RFID cases are considered. Supply chain contracts in a newsvendor setting with or without RFID are addressed in Szmerekovsky and Zhang [2008b]. A different setting of vendor managed inventory is studied by Szmerekovsky et al. [2009]. They assume that one supplier is using RFID while the other one is not with the main goal of setting the selling prices and shelf space availability. Most of the remaining research that considers RFID within the context of supply chain management relies on simulation studies, Lee et al. [2004], Fleisch and Tellkamp [2005], Kang and Gershwin [2005], Amini et al. [2007].

There is, however, limited work providing analytical estimates of the value of increased visibility in supply chain networks (beyond the two echelon setting of a supplier and retailer). Song and Zipkin [1996] provide a modeling framework for inventory control problems with supply information. While this study predates modern RFID systems, it requires data that is available only with today's RFID deployments. Gaukler et al. [2006] quantify the benefits of RFID in the supply system of a retailer who faces uncertain demand and the option of emergency orders. They develop an order progress information model to study the optimal policies for both regular and emergency orders. Under the assumption of a single outstanding order, Atali et al. [2006] analytically study inventory inaccuracy, which is a joint effect of transaction errors, shrinkage and misplacements. This allows for an analysis of more accurate inventory records and easier audits that result from the deployment of RFID. We note, however, that these models are all concerned with tactical decision models that incorporate the additional information provided by RFID, whereas our problem considers aggregate benefits that may result from strategic positioning of RFID installations.

In addition, there has also been interest in new processes that are enabled by RFID. One such process is expediting on the supply side. Kim et al. [2006] address expediting strategies based on RFID data. While expediting strategies will also yield lead time reductions, the focus of this research is also quite different from ours, again focusing on tactical decision-making. Pricing strategies based on added value on goods are discussed in Schneider [2007], where RFID is used as a technology to allow dynamic pricing. Karaer and Lee [2007] show that RFID can also be beneficial in the management of product returns, using new processes that can benefit from an increased visibility into the reverse channel. Another area where RFID can yield process improvement is asset tracking since early detection of lost items may allow appropriate responses. The newsletter contribution, Futuretech Newsletter [2007], introduces and compares technologies for asset tracking. Moore et al. [2006] show an example of an RFID system deployment for asset tracking in military, while Cheek [2006] discusses applications in the food industry. Recently, various technologies, such as 3D bar codes, GPS, sensor networks, RuBee, etc., have been used in conjunction with RFID for asset tracking according to specific application objectives. McKelvin et al. [2005] suggest an integration between RFID and wireless sensor networks to reduce the cost of wiring in harsh environments, while Patil et al. [2005] discuss the combination of RFID and Wi-Fi to continuously track the location of items. We note that our analysis does not account for potential process improvements; nevertheless, it is worthwhile to point out that our general framework might also prove useful to assess RFID benefits in asset tracking applications, considering how visibility may reduce asset cycle times.

Because the deployment costs of an RFID system can be significant, the development of systematic cost-benefit analyses has also received considerable attention. Erick et al. [2007], Özelkan et al. [2006] and Sounderpandian et al. [2006] suggest how to estimate the installation cost for RFID systems by incorporating tag, reader, software and deployment costs. The installation costs are compared with respect to the benefits from RFID systems using simulation and case studies. Cox [2005] introduces the deployment of an RFID system in an airport and discusses its costs, while Roberti [2007] provides an explanation of cost factors that need to be considered when deploying RFID systems. Langer et al. [2007] assess the benefits of an RFID deployment at the return centers of a third-party logistics provider, highlighting its benefits over barcode technology. The abovementioned analyses typically rely on case studies that are specific to the companies under consideration; in contrast, our objective is to develop a more general analytical framework to analyze the supply chain benefits of improved visibility.

Finally, we note that the location of RFID deployments is a critical decision in our models. As such, our overall modeling approach has flavors of the facility location problems, which have been studied extensively. For an in-depth review of facility location problems we refer to Daskin [1995], who discusses various issues related to facility location problems and presents a paradigm for the resulting planning processes. It is important to point out that our model setup does not fit the mold of traditional facility location models, and is further complicated by the non-linearity of the visibility benefits. Closer to our work is perhaps the problem of determining the optimal location of inspection stations in a manufacturing system. Lindsay and Bishop [1964] and Eppen and Hurst Jr. [1974] propose dynamic programming models to optimize the location of inspection stations, while Viswanadham et al. [1996] use simulated annealing procedures and genetic algorithms, and compare the results obtained by these methods. Saxena et al. [1990] provide four heuristic algorithms related to the processing time or the defective rate of stations and identify the significant parameters, while Kang et al. [1990] approach the problem using a rule-base methodology. However, the focus of these models is substantially different from ours since they concentrate on manufacturing related costs (i.e., inspection, processing, scrap) and penalty costs incurred when accepting non-conforming units.

3 RFID Placement in Serial Networks

In this section, we introduce our overall modeling approach by considering RFID deployment locations when items are routed along a single path. We discuss our basic model assumptions, and describe our approach to measuring supply chain performance within this context. In addition, we present a dynamic program for the optimal deployment of RFID on the network consisting of a single path, and we show that the resulting problems can be solved efficiently. We note that the models presented here provide the building blocks for the general network case that is discussed in the next section. We also refer to the Appendix for a summary of the notation and parameters used in our modeling approach.

Let us assume a given path P along which the items are routed. The path P has a source node s (the items' origin), a sink node t, as well as n intermediate nodes D_i ($1 \leq i \leq n$) that represent distribution centers (DCs), warehouses, etc. For ease of notation, we also denote $D_0 = s$ and $D_{n+1} = t$. Let $d_{i,j}$ represent the transportation time between locations i and j, which is viewed as the lead time.

At each location on the path, items can be *lost*. This may happen due to theft, damage, misplacement, transaction errors, or for other reasons. We assume a given loss probability of p at each of the intermediate nodes D_i, which reduces to p_0 ($p_0 \leq p$) when RFID is deployed at a location due to the improved real-time visibility at the node. We define the corresponding survival probabilities as $q = 1 - p$ and $q_0 = 1 - p_0$. The source and sink nodes have special characteristics, and we assume each has a loss probability of $\hat{p_0}$ ($\hat{q_0} = 1 - \hat{p_0}$). For ease of exposition, we have assumed that the loss probabilities are identical at each location. It may very well be the case, however, that the loss probabilities are location specific (i.e., due to the mix and volume of the items processed), but, we note that our modeling approach can easily be extended to incorporate this situation.

A critical aspect of our model is the recourse taken when items are lost. This depends on the system's characteristics and processes, and we introduce a number of novel model alternatives to capture possible behaviors. To represent situations where lost items cannot be recovered, we assume they are reshipped from the origin. It may be the case, however, that a reshipment is also lost, and several shipments are needed before the demand at the destination is met. Alternatively, we might have a situation where lost items can always be recovered. Once an item loss is detected, it is searched for and recovered without exception. Both of these scenarios represent extreme cases, and we also consider situations with partial item recovery. Once a loss occurs, we start searching for the item. If successful, the item continues along the path; otherwise, the item is reshipped from the source node. In this case, we use r to represent the probability that an item can be recovered at a location (given that it is lost), which increases to r_0 when RFID is deployed at the location.

As such, our approach concentrates on the *effective lead time* benefits that may result from an RFID deployment, by taking into account the potential reduction in the time needed to recover and/or reship lost items. It is important to note that installing RFID may reduce the lead time in several ways. Clearly, a reduced loss probability and increased recovery probability will both have a positive effect on the overall lead time. More importantly, RFID increases visibility by reducing the time needed to *discover* that an item has been lost. If, for example, RFID is deployed at location D_i, any item lost prior to location D_i is discovered within time $d_{s,i}$. Without RFID, this discovery time would increase to $d_{s,t}$. Thus, the placement of RFID presents a fundamental trade-off: *deploying RFID early in the chain allows us to discover losses earlier, while placing RFID later in the chain allows us to capture more of the potential losses.* We note, however, that our approach does not explicitly account for the reduction in lead time variability that may result from RFID deployment. While certainly relevant, this generates an additional set of issues that are beyond the scope of our current work.

To investigate this trade-off, we first determine detailed lead time expressions given a set of locations where RFID is deployed. Subsequently, we discuss the optimal placement of RFID deployments when the lead time reduction is traded off with the installation cost of RFID.

3.1 Lead Time Expressions

To determine the lead time expressions, we distinguish between the three model alternatives outlined above. We refer to these alternatives as the *No-Recovery*, the *Full-Recovery*, and the *Partial-Recovery* model. The *No-Recovery* model refers to situations where items that are lost will never be be recovered. This model applies to business settings where products have short life cycles or low price, and recovery may not be viable. The *Full-Recovery* model assumes that lost items will always be recovered, and is better suited to situations where products have a high unit price. Finally, the *Partial-Recovery* model combines these two extremes and yields our most general framework.

To illustrate our approach, let us first consider the overall progression of an item request as depicted in Figure 1. After an item is shipped, it will proceed on the path until, at some location, the item is lost. We refer to the time that passes between the item shipment and item loss as the *loss time*. It might, however, take some time for the loss to be discovered. We use the *discovery time* to represent the time that elapses between the loss of an item, and the discovery of its loss. The discovery event may instigate a search for the missing item, which requires a corresponding *search time*. If the search is successful and the item is recovered, the item will continue along its path (from the location where it was lost); otherwise, the item is reshipped from the source location. This process may repeat several times, until finally the item arrives at the destination.

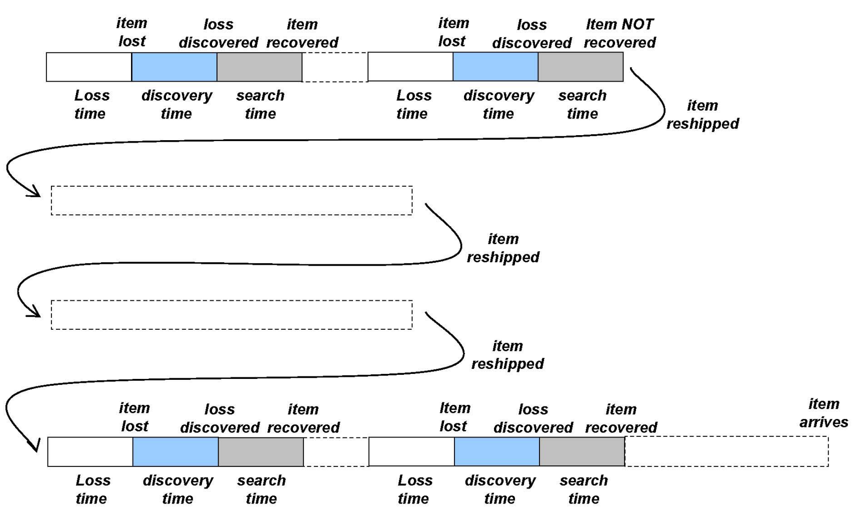

Figure 1: Item Progression

Now, let us consider the *effective lead time* of such a process. First, we observe that several reshipments from the origin may be needed before the requested item arrives at its final destination. That is, the *expected number of shipments* that are needed to fulfill a request equals the expected number of times a shipment is lost and cannot be recovered plus one additional shipment (corresponding to the final shipment that will arrive at the final destination). Next, we observe that each of these individual shipments will add a certain amount to the overall effective lead time of the request. We refer to this amount as the *lead time contribution* of an individual shipment. Thus, the expected effective lead time of a request can be expressed as

Expected number of shipments needed to fulfill a request ×
Expected lead time contribution of an individual shipment.

Note that the lead time contributions themselves can be subdivided into three components: loss time, discovery time, and search time, as illustrated in Figure 1.

3.1.1 No Recovery

As stated before, the no-recovery model applies in situations where theft, spoilage, and damage prevent the lost items from being recovered. As a result, this model assumes lost items are reshipped from the origin node s.

To illustrate the general framework outlined above, we first consider the expected effective lead time $L(\emptyset)$ of a request when no RFID system is installed at any of the intermediate nodes D_i. Following the general lead time expression, we need to determine both the expected number of shipments needed to fulfill the request and the expected lead time contribution of an individual shipment. Let us first consider the expected number of times an item needs to be shipped from the source node. Since the overall probability that an item is not lost along the path equals $q^n \hat{q}_0$, the expected number of items that need to be shipped before the request is satisfied equals

$$\frac{1}{q^n \hat{q}_0}.$$

Without an RFID deployment, the expected lead time contribution simply equals $d_{s,t}$. No matter where the item is lost, we always discover the item loss at time $d_{s,t}$. Note that we assume that no time is spent searching for the lost item within this model, since we know a-priori that the item will not be recovered. Therefore the effective lead time is expressed as

$$L(\emptyset) = \frac{1}{q^n \hat{q}_0} \times d_{s,t}. \tag{1}$$

Now, suppose that RFID is installed at a single location D_k on the path, as illustrated in Figure 2. The probability that an item arrives without being lost equals $q^{n-1} q_0 \hat{q}_0$, and therefore expected number of shipments equals

$$\frac{1}{q^{n-1} q_0 \hat{q}_0}.$$

To determine the expected lead time contribution of a single shipment, we distinguish between two cases: (1) the item is lost before or at location D_k, in which case the contribution equals $d_{s,k}$,

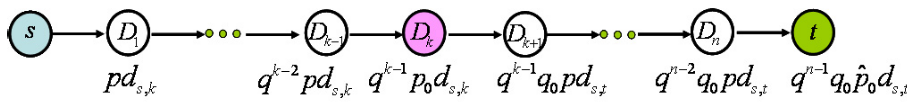

Figure 2: RFID installed at location D_k in the no-recovery model.

and (2) the item is lost after reaching location D_k, and the contribution equals $d_{s,t}$. The probability that an item is lost before or at location D_k equals

$$\sum_{j=1}^{k-1} q^{j-1}p + q^{k-1}p_0 = 1 - q^{k-1}q_0,$$

while the probability that an item is lost after reaching location D_k or arriving at the source node equals to $1-(1-q^{k-1}q_0) = q^{k-1}q_0$. Thus, the overall effective lead time equals

$$L(\{D_k\}) = \frac{1}{q^{n-1}q_0\hat{q_0}} \times \Big((1-q^{k-1}q_0)d_{s,k} + q^{k-1}q_0 d_{s,t}\Big).$$

Finally, let us consider a request's expected effective lead time $L(S)$ when RFID is installed at locations in an arbitrary set $S = \{D_{k_1}, \ldots, D_{k_m}\}$, where we let $k_0 = 0$ and $k_{m+1} = n+1$. Now, the expected number of shipments equals

$$\frac{1}{q^{n-m}q_0^m\hat{q_0}}.$$

In this case, an individual shipment's expected lead time contribution equals d_{s,k_i} if the item is lost before or at location D_{k_i}, but after reaching location $D_{k_{i-1}}$, and $d_{s,t}$ if the item arrives or is lost after reaching location D_{k_m}. The probability that an item is lost before or at D_{k_i} and after reaching $D_{k_{i-1}}$ equals

$$\sum_{j=k_{i-1}+1}^{k_i} q^{j-i}q_0^{i-1}p_0 = (1-q^{k_i-i}q_0^i) - (1-q^{k_{i-1}-(i-1)}q_0^{i-1}) = q^{k_{i-1}-(i-1)}q_0^{i-1} - q^{k_i-i}q_0^i,$$

while the probability that the item arrives or is lost after reaching location D_{k_m} equals

$$\sum_{j=k_m+1}^{n} q^{j-i}q_0^m p_0 + q^{n-m}q_0^m = q^{k_m-m}q_0^m.$$

Thus, an item's expected contribution to the lead time is

$$\sum_{i=1}^{m}(q^{k_{i-1}-(i-1)}q_0^{i-1} - q^{k_i-i}q_0^i)d_{s,k_i} + q^{k_m-m}q_0^m d_{s,t} = \sum_{i=1}^{m+1}\big(d_{s,k_i} - d_{s,k_{i-1}}\big)q^{k_{i-1}-(i-1)}q_0^{i-1}.$$

To conclude, the expected effective lead time of a single item reads

$$L(S) = \frac{1}{q^{n-m}q_0^m\hat{q_0}} \times \sum_{i=1}^{m+1}\big(d_{s,k_i} - d_{s,k_{i-1}}\big)q^{k_{i-1}-(i-1)}q_0^{i-1}.$$

3.1.2 Full Recovery

The full-recovery model can be used in situations where items can always be recovered. This may occur, for example, when item losses are due to misplacement or transaction errors.

In contrast to the previous alternative, the discovery of a loss instigates a search for the missing item. The time needed to locate an item, however, may vary according to the processes that have been implemented to handle such exceptions. We consider two approaches to incorporate these different system characteristics. In the first one, we assume that the search time equals a constant T. This could be interpreted as a simultaneous search in all potential locations of the item and T is the time to search a single location. In addition, we also consider an approach in which the search time depends on the number of locations where the item loss may have occurred. Specifically, we assume that the search process starts by backtracking from the location where the item loss was discovered. Thus, the time to locate an item is proportional to the number of locations between the location of the loss and the first upstream location deployed with RFID on the path.

We also note that in the full-recovery model, an item will never be reshipped. Following our general framework, the expected effective lead time of a request therefore equals the expected lead time contribution of a single shipment.

Constant Search Time

We first consider the effective lead time when no RFID is present. To determine this lead time, we consider the contribution of an arc $(j-1) \to j$. After passing location $j-1$, the segment's contribution towards the lead time is

$$d_{j-1,j} + \begin{cases} p(T + d_{j,t}) & 1 \le j \le n, \\ \hat{p_0} T & j = n+1 = t. \end{cases}$$

In this expression $T + d_{j,t}$ or T are the corresponding discovery times, which are weighted by the loss probability. Thus, the effective lead time equals

$$L(\emptyset) = \sum_{j=1}^{n} (d_{j-1,j} + pT + pd_{j,t}) + (d_{n,t} + \hat{p_0} T) = d_{s,t} + p \sum_{j=1}^{n} (T + d_{j,t}) + \hat{p_0} T. \qquad (2)$$

Suppose now RFID readers have been installed at locations in an arbitrary set $S = \{D_{k_1}, \ldots, D_{k_m}\}$, where again we let $k_0 = 0$ and $k_{m+1} = n+1$. We consider the contribution of an arc $(j-1) \to j$. After passing location $j-1$, the segment's contribution towards the lead time is

$$d_{j-1,j} + \begin{cases} p(T + d_{j,k_i}) & k_{i-1} \le j \le k_i,\ D_j \notin S, \\ p_0 T & 1 \le j \le n,\ D_j \in S, \\ \hat{p_0} T & j = n+1 = t. \end{cases}$$

As a result, the expected effective lead time equals

$$L(S) = d_{s,t} + p \sum_{i=1}^{m+1} \sum_{j=k_{i-1}+1}^{k_i - 1} (T + d_{j,k_i}) + p_0 m T + \hat{p_0} T.$$

Proportional Search Time

Under this setup, the time to locate an item is proportional to the number of locations between the location of the loss and the first upstream RFID deployment. As stated before, this can be interpreted as a backtrack search: when an item is lost at D_i and the loss is discovered at D_k, a search will first be conducted at location D_k. If the item is found, the shipment will resume. Otherwise, we continue the search in D_{k-1} and so forth.

The derivation of the lead time expressions follows the same approach as before, by considering the contribution of individual segments. Suppose again that RFID is not deployed. Then, the contribution of segment $(j-1) \to j$ towards the lead time is

$$d_{j-1,j} + \begin{cases} p\big((n-j+2)T + d_{j,t}\big) & 1 \leq j \leq n, \\ \hat{p_0}T & j = n+1 = t. \end{cases}$$

Therefore, the effective lead time in this case is

$$L(\emptyset) = d_{s,t} + p\sum_{j=1}^{n}\big((n-j+2)T + d_{j,t}\big) + \hat{p_0}T.$$

If RFID is installed at locations in an arbitrary set $S = \{D_{k_1}, \ldots, D_{k_m}\}$, the lead time of the segment reads

$$d_{j-1,j} + \begin{cases} p\big((n-j+2)T + d_{j,k_i}\big) & k_{i-1} < j \leq k_i,\ j \notin S, \\ p_0T & j \in S, \\ \hat{p_0}T & j = n+1 = t. \end{cases}$$

Thus, the expected effective lead time of a request equals

$$L(S) = d_{s,t} + p\sum_{i=1}^{m+1}\sum_{j=k_{i-1}+1}^{k_i-1}((k_i-j+2)T + d_{j,k_i}) + p_0mT + \hat{p_0}T.$$

3.1.3 Partial Recovery

The partial-recovery model is our most general model, which combines and generalizes both the no- and full-recovery models. Upon discovery of an item loss, a search is started for the lost item. If successful, the item continues along the path as in the full-recovery model. Otherwise, however, the item is reshipped from the origin as in the no-recovery model. As stated before, we use a given probability r as the probability that an item is recovered *given that* the item is lost when no RFID is present. This probability is increased to r_0 when RFID is deployed, and equals $\hat{r}_0$ at the destination node.

Constant Search Time

We start by considering a request's expected effective lead time $L(\emptyset)$ without RFID. Following our general framework, we begin with the expected number of shipments to completely satisfy the demand at the destination. To determine this quantity we first define $\bar{p} := p(1-r)$ and $\bar{q} := 1 - \bar{p}$. Value $\bar{p}$ represents the probability that an item is lost and cannot be recovered at a location without RFID, while $\bar{q}$ represents the probability that an item "survives" and proceeds on the path. Similarly, we also define $\bar{p_0} := p_0(1-r_0)$, $\bar{q_0} := 1 - \bar{p_0}$, and let $\tilde{p_0} := \hat{p_0}(1-\hat{r_0})$, $\tilde{q_0} := 1 - \tilde{p_0}$.

Now the overall probability that an item is not lost along the path equals $\bar{q}^n\tilde{q}_0$, and therefore the expected number of shipments needed to fulfill the request equals

$$\frac{1}{\bar{q}^n\tilde{q}_0}.$$

To determine the lead time of a single item, we again consider the individual segments $(j-1) \to j$. If the item survives location $j-1$, the lead time of the segment is

$$d_{j-1,j} + \begin{cases} p(T + d_{j,t}) & 1 \leq j \leq n, \\ \hat{p}_0 T & j = n+1 = t. \end{cases}$$

Therefore, the lead time contribution of an individual shipment equals

$$\sum_{j=1}^{n} \bar{q}^{j-1}(d_{j-1,j} + pT + pd_{j,t}) + \bar{q}^n(d_{n,t} + \hat{p}_0 T),$$

and the effective lead time reads

$$L(\emptyset) = \frac{1}{\bar{q}^n\tilde{q}_0} \times \big(\sum_{j=1}^{n} \bar{q}^{j-1}(d_{j-1,j} + pT + pd_{j,t}) + \bar{q}^n(d_{n,t} + \hat{p}_0 T)\big). \tag{3}$$

It is clear that (3) reduces to (2) when all items are recovered, as $r = 1$ implies that $\bar{q} = 1$. When items remain lost ($r = 0$), $\bar{q}$ reduces to q. In this case, the lead time equals

$$\sum_{j=1}^{n+1} q^{j-1} d_{j-1,j} + \sum_{j=1}^{n} q^{j-1} p d_{j,t} + \sum_{j=1}^{n} q^{j-1} pT + q^n \hat{p}_0 T,$$

or

$$\sum_{j=1}^{n+1} q^{j-1} d_{j-1,j} + \sum_{j=1}^{n+1} (1 - q^{j-1}) d_{j,j+1} + (1 - q^n)T + q^n \hat{p}_0 T = d_{s,t} + (1 - q^n)T + q^n \hat{p}_0 T,$$

which is equivalent to (1) in the no-recovery model, aside from the terms that express the recovery time.

The derivation proceeds in an analogous fashion when RFID readers have been installed at locations in an arbitrary set $S = \{D_{k_1}, \ldots, D_{k_m}\}$. The resulting expression for the effective lead time equals

$$\begin{aligned} L(S) = \quad & \frac{1}{\bar{q}^{n-m}\bar{q_0}^m\tilde{q}_0} \times \\ & \big(\sum_{i=1}^{m+1} \sum_{j=k_{i-1}+1}^{k_i - 1} \bar{q}^{j-i}\bar{q_0}^{i-1}(d_{j-1,j} + pT + pd_{j,k_i}) + \\ & \sum_{i=1}^{m} \bar{q}^{k_i - i}\bar{q}_0^{i-1}(d_{k_i-1,k_i} + p_0 T) + \bar{q}^{n-m}\bar{q_0}^m(d_{n,t} + \hat{p}_0 T)\big). \end{aligned}$$

Proportional Search Time

Following the same approach, we obtain the following expressions for the effective lead time when search time is proportional to the number of locations between the location of the loss and the next RFID deployment on the path,

$$L(\emptyset) = \frac{1}{\bar{q}^n \tilde{q_0}} \times \big(\sum_{j=1}^{n} \bar{q}^{j-1}(d_{j-1,j} + p(n-j+2)T + pd_{j,t}) + \bar{q}^n(d_{n,t} + \hat{p_0}T)\big).$$

A request's effective lead time given RFID deployments at the set of locations $S = \{D_{k_1}, \ldots, D_{k_m}\}$ equals

$$\begin{aligned} L(S) = \quad & \frac{1}{\bar{q}^{n-m}\bar{q_0}^m \tilde{q_0}} \times \\ & \big(\sum_{i=1}^{m+1} \sum_{j=k_{i-1}+1}^{k_i-1} \bar{q}^{j-i}\bar{q_0}^{i-1}(d_{j-1,j} + p(k_i - j + 2)T + pd_{j,k_i}) + \\ & \sum_{i=1}^{m} \bar{q}^{k_i-i}\bar{q}_0^{i-1}(d_{k_i-1,k_i} + p_0T) + \bar{q}^{n-m}\bar{q_0}^m(d_{n,t} + \hat{p_0}T)\big). \end{aligned}$$

3.2 Optimal Placement

The lead time expressions illustrate the potential benefits of increased visibility, and show how the expected effective lead times are reduced for a given set of locations in which RFID has been installed. In this section, we introduce an approach to determine the optimal placement of RFID systems in a serial supply chain network, by trading off the benefits of reducing the effective lead time with the cost of installing RFID.

Our framework assumes a given cost c_i for installing RFID at location D_i $(1 \leq i \leq n)$, which should be interpreted as the per period amortized cost of installing and maintaining RFID at location D_i. The installation costs for a location depend on its size, layout, volume, function, etc. Simchi-Levi et al. [2007], for example, mention that installation cost at a retail location differ substantially from the cost at a distribution center. In addition, we assume that the RFID reward $R(S)$ for installing RFID at the locations in set S is proportional to both the reduction in lead time and the requests processed, i.e.

$$R(S) = \rho\mathcal{D}\big(L(\emptyset) - L(S)\big).$$

Here, ρ represents the monetary value of a per unit reduction in the lead time in a single period; this captures the reduction in pipeline inventory, safety stock, transportation costs, etc. Quantity $\mathcal{D}$ equals the requested volume (demand) per period. Consequently, the resulting optimization problem is expressed as

$$\alpha = \max_{S \subseteq \{1,\cdots,n\}} \Big\{R(S) - \sum_{i \in S} c_i\Big\},$$

which reduces to

$$\alpha = \rho\mathcal{D}L(\emptyset) - \min_{S \subseteq \{1,\cdots,n\}} \Big\{\rho\mathcal{D}L(S) + \sum_{i \in S} c_i\Big\}.$$

We stress that the objective value represents the supply chain profits that result from installing RFID.

This optimization problem can be solved by dynamic programming, using a sequence of shortest path problems that each determine an optimal solution for a given cardinality $m \geq 1$ of the set S. We define the recursive relation as

$$C_k(j;m) = \min_{i:1\leq i<j} \big\{C_{k-1}(i;m) + c_{i,j}(k-1;m)\big\}, \tag{4}$$

where $C_k(j;m)$ represents the minimum cost if the k^{th} RFID location is D_j for $1 \leq k \leq m$ and $k \leq j \leq n-(m-k)$. We also define $C_0(j;0) = \rho\mathcal{D}L(\emptyset)$ for $0 \leq j \leq n$ and $C_0(j;m) = 0$ for $1 \leq m \leq n, 0 \leq j \leq n-m$. Using the lead time expressions, the cost contribution $c_{i,j}(k-1;m)$ for $1 \leq i < j \leq n, 1 \leq k \leq m$ is easily determined for each of our model alternatives.

For the no-recovery model we have

$$c_{i,j}(k-1;m) = c_j + \rho\mathcal{D}\frac{(d_{s,j}-d_{s,i})q^{i-k+1}q_0^{k-1}}{q^{n-m}q_0^m\hat{q}_0},$$

and

$$\alpha = \rho\mathcal{D}L(\emptyset) - \min_{m:0\leq m\leq n}\ \min_{j:m\leq j\leq n} C_m(j;m),$$

where each of the terms $C_m(j;m)$ is obtained by using recursion (4) for $1 \leq m$ or definition for $m=0$.

For the full recovery model with constant search time, we set

$$c_{i,j}(k-1;m) = c_j + \rho\mathcal{D}p\sum_{v=i+1}^{j-1}(T+d_{vj}),$$

while with the proportional search time we obtain

$$c_{i,j}(k-1;m) = c_j + \rho\mathcal{D}p\sum_{v=i+1}^{j-1}((j-v+2)T+d_{vj}).$$

The final value is obtained from

$$\alpha = \rho\mathcal{D}L(\emptyset) - \min_{m:0\leq m\leq n}\ \min_{j:m\leq j\leq n}\{C_m(j;m) + p_0mT + \hat{p}_0T + d_{st}\}.$$

In the partial recovery model with constant search time we have

$$c_{i,j}(k-1;m) = c_j + \rho\mathcal{D}\frac{1}{\bar{q}^{n-m}\bar{q}_0^m\tilde{q}_0}\left(\sum_{v=i+1}^{j-1}\left(\bar{q}^{v-(k-1)}\bar{q}_0^{k-1}(d_{v-1,v}+pT+pd_{vj})\right)\right.$$
$$\left.+\bar{q}^{j-(k-1)}\bar{q}_0^{k-1}(d_{j-1,j}+p_0T)\right),$$

end in the presence of the proportional search time we derive

$$c_{i,j}(k-1;m) = c_j + \rho\mathcal{D}\frac{1}{\bar{q}^{n-m}\bar{q}_0^m\tilde{q}_0}\left(\sum_{v=i+1}^{j-1}\left(\bar{q}^{v-(k-1)}\bar{q}_0^{k-1}(d_{v-1,v}+p(j-v+2)T+pd_{vj})\right)\right.$$
$$\left.+\bar{q}^{j-(k-1)}\bar{q}_0^{k-1}(d_{j-1,j}+p_0T)\right).$$

The optimal value is derived from

$$\alpha = \rho \mathcal{D} L(\emptyset) - \frac{d_{nt} + \hat{p}_0 T}{\tilde{q}_0} - \min_{m:0\leq m\leq n} \min_{j:m\leq j\leq n} C_m(j;m).$$

4 RFID Placement in General Networks

In this section, we generalize our model alternatives by considering optimal placements of RFID in arbitrary supply chain networks.

Let us assume we are given a general transportation network $G = (N, A)$, which is a directed acyclic graph with source s and sink t. Within our framework, multiple commodities are routed through this network. We use K to denote the set of all commodities. Let $P(k)$ for $k \in K$ represent the route commodity k follows within the network. As before, we determine an optimal placement by trading off the lead time benefits that result from RFID installations with the installation cost. We assume that commodity k's RFID reward $R_k(S)$ for deploying RFID at locations $S \subseteq P(k)$ equals

$$R_k(S) = \rho_k \mathcal{D}_k \big(L_k(\emptyset) - L_k(S)\big).$$

As before, ρ_k represents the monetary value of a per unit reduction in the lead time of commodity k in a single period. Quantity $\mathcal{D}_k$ equals the request volume (demand) per period for commodity k.

To formulate the resulting placement problem, we first define the following decision variables:

$$y_i = \begin{cases} 1 & \text{if RFID is deployed at node } D_i \in N/\{s,t\}, \\ 0 & \text{otherwise,} \end{cases}$$

$$x_k(S) = \begin{cases} 1 & \text{if RFID is deployed at nodes } S \subseteq P(k), \\ 0 & \text{otherwise.} \end{cases}$$

With these variables, the formulation reads:

$$\max \sum_{k\in K, S\subseteq P(k):|S|\geq 1} R_k(S) x_k(S) - \sum_{i \in N/\{s,t\}} c_i y_i$$

$$\sum_{S\subseteq P(k):|S|\geq 1} x_k(S) \leq 1 \qquad \text{for all } k \in K \tag{5}$$

$$\sum_{S\subseteq P(k):i\in S} x_k(S) \leq y_i \qquad \text{for all } k \in K, i \in P(k) \tag{6}$$

$$x_k(S), y_i \in \{0,1\}.$$

Again, the objective function captures the overall supply chain profits from installing RFID. Constraints (5) impose that for each commodity at most one set S is selected, while (6) impose that if at a given node i RFID is deployed, the deployment cost is captured correctly.

Given the large number of decision variables (one for each subset of locations within a path) in this formulation, we employ *delayed column generation* (see, e.g., Barnhart [1998]) to solve the LP relaxation, which is often used to solve large-scale linear programs.

Within our context the pricing problem corresponds to determining an optimal RFID placement in a serial network. As such, negative reduced cost columns can efficiently be identified using the dynamic programming approach. Consider the dual problem of our placement model,

$$\begin{aligned}
\min \sum_{k\in K} \lambda_k & \\
\lambda_k + \sum_{i\in S} \mu_{i,k} \geq R_k(S) & \qquad \text{for all } k, S \\
\sum_{k\in K; i\in P(k)} \mu_{i,k} \leq c_i & \qquad \text{for all } i \in N \\
\lambda, \mu \geq 0, &
\end{aligned}$$

where λ_k correspond to (5) and $\mu_{i,k}$ to (6). Column $x_k(S)$ has negative reduced cost if and only if $\lambda_k + \sum_{i\in S} \mu_{i,k} < R_k(S)$ for given dual values. We can find a violated subset S for each commodity $k \in K$ by checking if

$$\max_{S:S\subseteq P(k)} \left\{ R_k(S) - \sum_{i\in S} \mu_{i,k} \right\} > \lambda_k,$$

which can be carried out by the dynamic programming approach outlined in Section 3.2.

The column generation procedure yields an optimal solution to the LP relaxation, and therefore may terminate with a fractional solution. To ensure integer solutions, the column generation procedure can be integrated within a branch-and-bound algorithm. This results in a *branch-and-price* procedure, where the LP relaxations at every node are solved by delayed column generation (see Barnhart [1998] for an excellent survey on branch-and-price methods). We have not implemented a complete branch-and-price procedure. Instead, we used the diving heuristic by fixing y variables and iteratively applying column generation.

Algorithm 1 describes the strategy to fix one or two fractional y variables. Vector $\mathbf{y}^*$ is the current solution obtained from the LP relaxation. After each fixing step, the delayed column generation is employed. At the end of this procedure all y variables are integral. If the LP becomes infeasible, we backtrack along the visited nodes in the depth-first manner.

If all y variables are integral, then an optimal x can be obtained by defining $S_k = \{i \in P(k) : y_i^* = 1\}$ and setting $x_k(S_k) = 1$ and 0 for all other subsets, and for every $k \in K$.

5 Computational Study

In this section, we investigate how system characteristics impact RFID benefits and deployment strategies in each of our model alternatives. We systematically vary selected parameters within our models and analyze their impact on various performance indicators, such as the lead time reductions and the number of RFID deployments.

The determination of appropriate values for our model parameters is a critical aspect of our model which, in practice, requires careful analysis. While these parameters may vary substantially from case to case, we nevertheless believe that reasonable estimates can be obtained using a combination of historical data, pilot studies, and financial analysis. The loss probabilities p and recovery probabilities r, for example, can be approximated using historical data. Suppose, for instance, that a commodity has a historical shrinkage rate of 2% (a figure not uncommon in

Require: Let $\mathbf{y}^*$ be an incumbent solution vector; $\mathbf{y}^* = [y_1^*, \ldots, y_n^*]$.
while $y_i^* \notin \{0,1\}$ for $i = 1, \cdots, n$ **do**
$u = \arg\min_{i, y_i^* > 0} y_i^*$, $v = \arg\max_{i, y_i^* < 1} y_i^*$
if $y_v^* < 0.5$ **then**
$y_u^* = 0$, $y_v^* = 0$
else if $y_u^* \geq 0.5$ **then**
$y_u^* = 1$, $y_v^* = 1$
else $\{y_u^* < 0.5$ and $y_v^* \geq 0.5\}$
$y_u^* = 0$ and $y_v^* = 1$
end if
Resolve the new linear program by column generation
end while

Algorithm 1: A heuristic method to fix y variables

industry[1]), and that its route includes 10 intermediate locations (accounting for warehouses, fulfillment and distribution centers, ports of embarkation and debarkation, etc.). Then, a simple approximation of the loss probability at each location (assuming no recovery) can be obtained by letting $p = 1 - (1 - 0.02)^{1/10} \approx 0.2\%$. Clearly, however, such estimates can be refined by considering additional information about shipment histories. Similarly, we envision that the loss and recovery probabilities when RFID is present (p_0 and r_0) can be identified using pilot studies, or using results from similar implementations elsewhere. The cost of installing RFID at a location can be determined by a financial analysis that accounts for the costs of hardware, software, and integration, considering depreciation and maintenance costs. An accurate estimate of ρ_k, the monetary value of a per unit reduction in the effective lead time, will generally be the most difficult one to obtain. We do believe, however, that a detailed investigation of the cost reductions that result from a decrease in the lead time can yield effective approximations of this reward parameter. For illustration, suppose, for example, that commodities are tagged at the pallet level, and that each pallet holds (on average) 200 units with each valued at \$50. Assuming an annual inventory carrying cost rate of 25%, a one-week reduction in lead time will reduce the in-transit inventory costs by approximately \$50 $\times$ 200 $\times$ 25% / 50 weeks = \$50, where we assume 50 weeks in a year. Thus, with an annual demand of 100 pallets, the overall in-transit inventory cost would be reduced by approximately \$5,000. Again, judicious analysis that incorporates potential safety stock and transportation cost reductions could further refine these estimates. We point out that there can be substantial variations in the magnitude of this reward relative to the RFID installation cost, based on the commodity's value and demand, the complexity (or ease) of installing RFID, etc.

5.1 Experimental Setup

Our computational study consists of four separate experiments. The first two experiments evaluate the impact of loss probabilities p and p_0 and the (conditional) recovery probabilities r and r_0. These experiments shed light on overall RFID system performance and benefits. The third experiment considers the impact of the installation costs c_i. We analyze how these costs impact the distribution and the number of the locations where RFID is installed. In the fourth experiment, we evaluate how

[1] According to the 2007 report from the Food Marketing Institute titled Supermarket Security and Loss Prevention, in 2004 the average shrinkage in US supermarkets was 2%.

the overlap between different commodity paths impacts performance. To this end, we introduce a parameter $p_{overlap}$ that allows us to control the level of overlap among commodity routes.

To perform our experiments, we randomly generated a collection of problem instances. The network configuration in each instance consists of several layers: an input layer with the source nodes, up to eight middle layers, and an output layer with the sink nodes. (Formally, each layer is a set of nodes with equal distance from the source nodes.) The number of locations in each layer is chosen randomly between 10 and 15, and we randomly assign lead times between locations in successive layers. In addition, we assume there are 20 commodities, each one with a different route. We generate the routes for each commodity by randomly selecting a location at each layer. In addition, however, we also allow a direct route to be chosen at each layer: this implies that the subsequent layers are bypassed with a direct delivery to the final destination. In our experiments, we fixed the probability that a direct route is selected at 0.3 for each layer. Overlap parameter $p_{overlap}$ controls the overlap among commodity paths, and is incorporated as follows. First, we randomly generate a path for the first commodity and register the chosen locations in a pool for each layer. For the next path, we first make a decision whether this new path is disjoint with all previous paths or not. The probability of an overlap equals $p_{overlap}$. If the new path is to be overlapped, we next randomly generate k, the number of locations to overlap. Finally, we choose k locations from our current pool of DCs, and randomly select locations at the remaining layers. This process is repeated until all paths are generated.

In all experiments, we average the performance over 100 randomly generated problem instances. The network configuration, i.e., the number of layers and locations in each layer, is generated once and fixed afterwards. The remaining parameters, however, can be fixed or varied in each instance according to the specific experiment. For all fixed parameters, we use $p = 0.0005$, $p_0 = 0.00025$, $\hat{p}_0 = 0.00025$, $r = 0.6$, $r_0 = 0.8$, $\hat{r}_0 = 0.8$, $p_{overlap} = 0.5$, $\rho_k = 1$, $\mathcal{D}_k = 100$, and $T = 4$ as our base case. A summary of our experimental setting is shown in Table 1.

Experiment	Path	Transportation Time	Network	Notes
p and p_0	Varied	Fixed	Fixed	Varying p and p_0
r and r_0	Varied	Fixed	Fixed	Varying r and r_0
p/p_0 and r/r_0	Varied	Fixed	Fixed	Varying p/p_0 and r/r_0
c_i	Fixed	Varied	Fixed	Varying $c_i \in [c_l, c_h]$
$p_{overlap}$	Varied	Fixed	Fixed	Varying $p_{overlap}$
ρ_k	Fixed	Fixed	Fixed	Varying ρ_k

Table 1: The configuration of each experiment

We note that he solution procedure proposed in Algorithm 1 yields high-quality solutions that are nearly optimal. Inspections of the integrality gaps show that our heuristic consistently yields solutions that are within one percent of the optimal solution. This data is not shown here, as the computational aspects are not our primary concern.

5.2 Impact of Loss Probability

Our first experiment evaluates the impact of loss probabilities on RFID performance. We vary both the loss probability p when RFID is not deployed and the loss probability after the introduction of RFID.

Table 2 shows the parameter settings considered. As already discussed, our performance measures are averaged over 100 trials. In each trial we randomly generate the commodity paths, but keep the network configuration unchanged.

	$p_0(1)$	$p_0(2)$	$p_0(3)$	$p_0(4)$	$p_0(5)$
$p = 0.00025$	0.0	0.00005	0.0001	0.00015	0.0002
$p = 0.0005$	0.0	0.0001	0.0002	0.0003	0.0004
$p = 0.001$	0.0	0.0002	0.0004	0.0006	0.0008
$p = 0.0015$	0.0	0.0003	0.0006	0.0009	0.0012

Table 2: Parameter values of p and p_0

Figure 3 illustrates how the loss probabilities impact system performance, both in absolute and relative terms. The relative objective value change is measured as $\frac{V - V_0}{V_0} \times 100$, where V is the underlying objective value and V_0 the minimum objective value of the same model across all considered values of p_0. Both graphs in Figure 3 show how the optimal solution value changes when the loss probability p_0 (with RFID) is varied for $p = 0.001$ (the loss probability without RFID). In other words, the graph illustrates how the loss probability reduction that results from RFID deployment impacts the benefits of deploying RFID.

The leftmost graph in Figure 3 displays the benefits of RFID deployment in absolute terms. Not surprisingly, these benefits are larger when product losses and misplacements contribute more to the effective lead time. For example, the use of RFID produces more benefits in models with proportional search time than in models with constant search time, because of the additional time spent searching for items that have been lost.

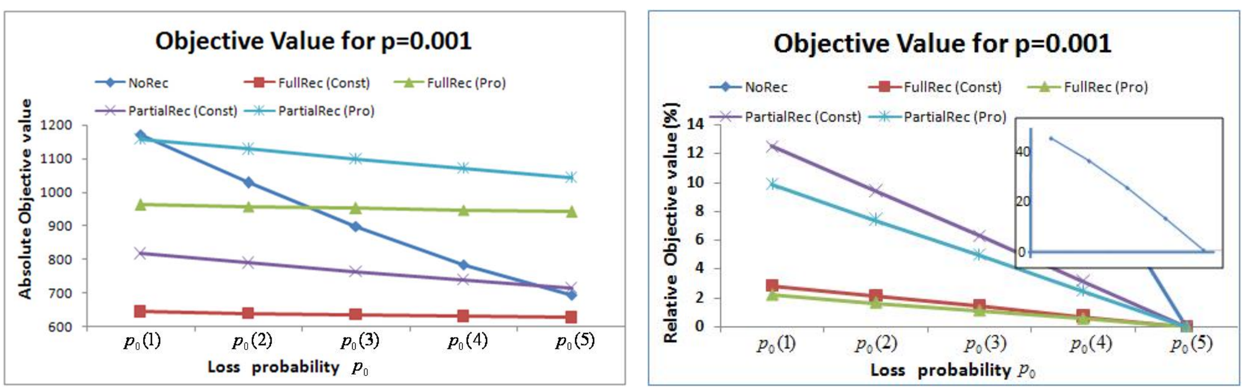

Figure 3: Objective values with varying p_0 when $p = 0.001$

This is also in line with the results shown in the rightmost graph in Figure 3, which shows that the RFID benefits increase faster when the likelihood that reshipments are needed is larger. While expected, it is nevertheless interesting to see the extent to which product losses can impact supply chain performance beyond the product cost associated with the lost items.

It is surprising to see, however, that the deployment of RFID can yield benefits *even if the RFID installations do not substantially reduce the probability that items are lost* (i.e., $p \approx p_0$, corresponding to $p_0(5)$). For the partial-recovery models, this can partly be explained by the fact that the base case implies that RFID increases the probability that items are recovered. Given however that these benefits also occur for the other models, we believe this indicates that the early detection of losses enabled by RFID, together with an increased ability to pinpoint where items have been lost, in and of themselves can already improve supply chain performance.

Figure 4 further shows the optimal solution values (in relative terms) and the number of locations where RFID is deployed for the partial-recovery model with proportional search time when p_0 is varied for the loss probabilities p given in Table 2. The other models yield similar results, and are not shown here. As expected, the leftmost graphs shows that RFID benefits increase more rapidly when the loss probabilities p (and reductions thereof due to RFID) are larger.

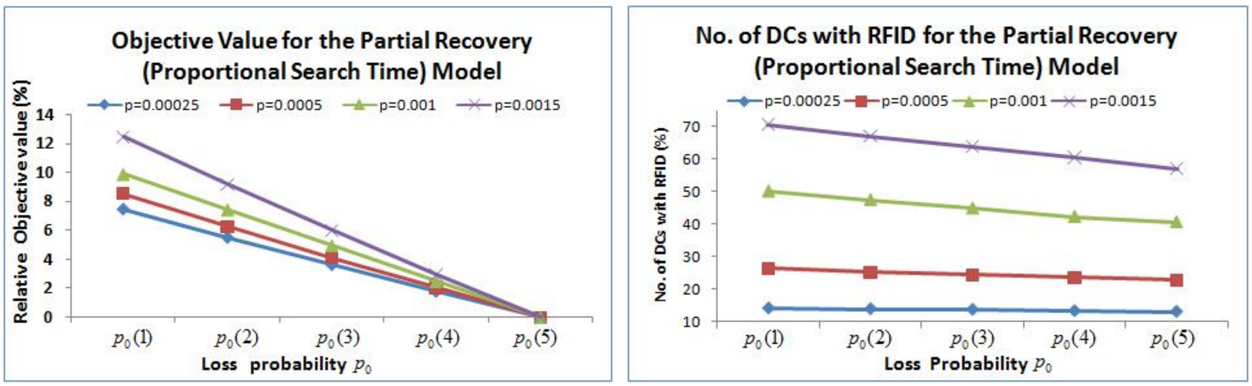

Figure 4: Number of RFID deployments with varying p and p_0

It is interesting to observe, however, that reductions in the loss probabilities p_0 have a diminishing impact on the number of locations where RFID is deployed; on the other hand, the initial loss probability p when RFID is not installed has a substantial impact on the number of RFID deployments. In other words, the optimal RFID configuration is largely driven by the system's loss probabilities *prior to the installation of RFID*, as opposed to the reduction in losses that can be achieved with RFID. While this increased accuracy can have a substantial impact on the actual *benefits*, it appears they have little influence over the optimal *configuration*. We believe that the optimal RFID configuration is principally driven by the ability to detect losses early and by the increased ability to pinpoint where losses may have occurred.

This provides an important insight for the management of RFID systems: initially, it will be critical to focus on the RFID infrastructure in order to detect losses early, whereas subsequent efforts should focus on increasing accuracy at each RFID location to achieve additional benefits.

5.3 Impact of Recovery Probability

The second experiment evaluates sensitivity with respect to the recovery probabilities r and r_0. The recovery probabilities represent the likelihood that an item is recovered after it has been lost, and therefore only affect the partial-recovery models. As in the previous experiment, we vary both the recovery probability r when no RFID is installed and the difference between r and r_0, the increase in the recovery probability after the introduction of RFID. Table 3 shows the parameter settings we considered.

Figure 5 shows how changes in r_0 affect the objective values for given values of r in the partial-recovery model with constant search time. The use of proportional search times yields similar

	$r_0(1)$	$r_0(2)$	$r_0(3)$	$r_0(4)$	$r_0(5)$
$r = 0.3$	1.0	0.85	0.7	0.55	0.4
$r = 0.5$	1.0	0.9	0.8	0.7	0.6
$r = 0.7$	1.0	0.94	0.88	0.82	0.76
$r = 0.9$	1.0	0.98	0.96	0.94	0.92

Table 3: The values of r and r_0

results, and is omitted here. As before, the RFID benefits are more pronounced when product misplacement contributes more to the effective lead time (i.e., when the recovery probabilities are lower). Again, however, we see that the use of RFID yields benefits even when r is close to r_0, i.e., the use of RFID does not substantially increase the likelihood that shipments are recovered. Note, however, that the base case already assumes a decrease in the loss probability p due to RFID.

To better understand how the likelihood of losses and recovery impacts performance, we also evaluate the RFID benefits when both the loss and the recovery probabilities are varied simultaneously. This is shown in Figure 6, which depicts the objective values when both r_0 and p_0 are varied for the partial-recovery models with proportional and constant search time. As expected, RFID benefits are higher in the proportional search time setting, because of the additional time spent searching for items that have been lost. The critical factor that determines these benefits is the probability $\bar{p}_0 = p_0(1 - r_0)$ that shipments are lost and cannot be recovered. For example, when $r_0 = 1$ the model reduces to a full-recovery model and different loss probabilities have little impact. Similarly, when $p_0 = 0$ there are no losses at an RFID enabled site and therefore different recovery probabilities would become irrelevant. Finally, we point out that the use of RFID is beneficial even when p is close to p_0 and r is close to r_0. This confirms our earlier observation that the early detection of losses enabled by RFID by itself can already improve supply chain performance.

5.4 Impact of Installation Cost

Within our framework, the installation costs are an important factor when evaluating installation strategies. The trade-offs they induce are particularly relevant when these costs are large relative to the benefits of reducing the lead time. In such cases, specific placement patterns could become increasingly important. In our third experiment, we therefore analyze how these costs impact the RFID benefits and placement patterns. We systematically increase the installation costs by randomly choosing location installation costs from an increasing range, while keeping the lead time rewards ρ_k constant. The cost ranges are increased from $[0, 5]$ until the objective value equals 0, which implies that the installation costs are prohibitively high and RFID is not used.

Figure 7 shows the impact of these installation costs, considering both the objective value and the number of locations with RFID deployments for each of our model alternatives. As the installation costs increase, both the RFID benefits and the number of RFID locations decrease rapidly. This illustrates that the installation cost can play a critical role in the assessment and justification of RFID implementation efforts. Given, moreover, that in practice there can be substantial differences in these costs relative to the lead time reward, we believe that Figure 7 further confirms that the deployment decisions are an important component in RFID investments. Moreover, the results in Figure 7 also indicate the value of considering "partial visibility" scenarios: aside from cases where the installation cost is very low, the optimal deployment strategies employ RFID at

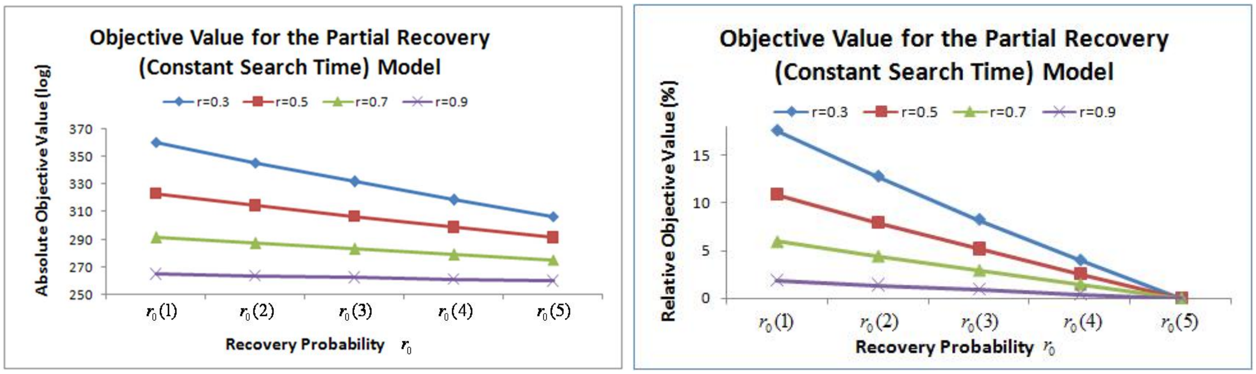

Figure 5: The objective values when r and r_0 vary

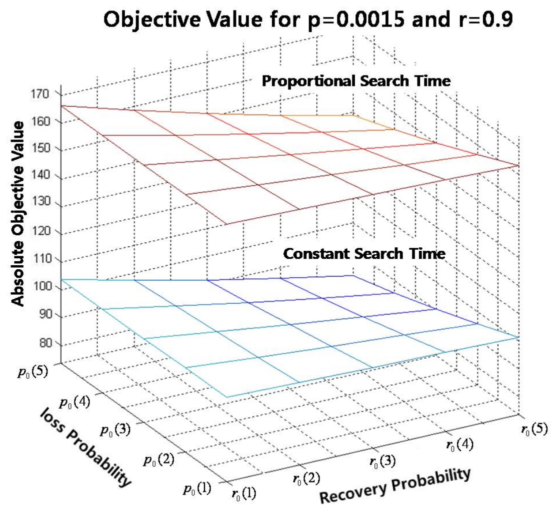

Figure 6: The objective values when r_0 and p_0 simultaneously vary

less than 30% of the locations.

In addition, we also analyzed how installation costs affect the placement of RFID, i.e., where RFID installations are located in the network. Figure 8 shows, for each layer, what percentage of its locations have RFID. When the installation costs are low, locations are evenly spread among the layers. This is perhaps not surprising, given the large number of locations that will have RFID installations. As the cost increases, however, the locations are increasingly concentrated in layer 3. Thus, when costs are prohibitive and limit the total number of RFID installations, the early detection of losses becomes an increasingly important factor in reducing the effective lead times (as opposed to waiting longer to capture more of the losses that may occur).

We also observed that the level of overlap has a significant impact on the placement patterns. In our experiments, we observed that locations along which a single commodity is routed have RFID with a probability of approximately 3.0%, while locations that are part of four commodity paths are selected approximately 33.6% of the time. Note, however, that this also implies that such

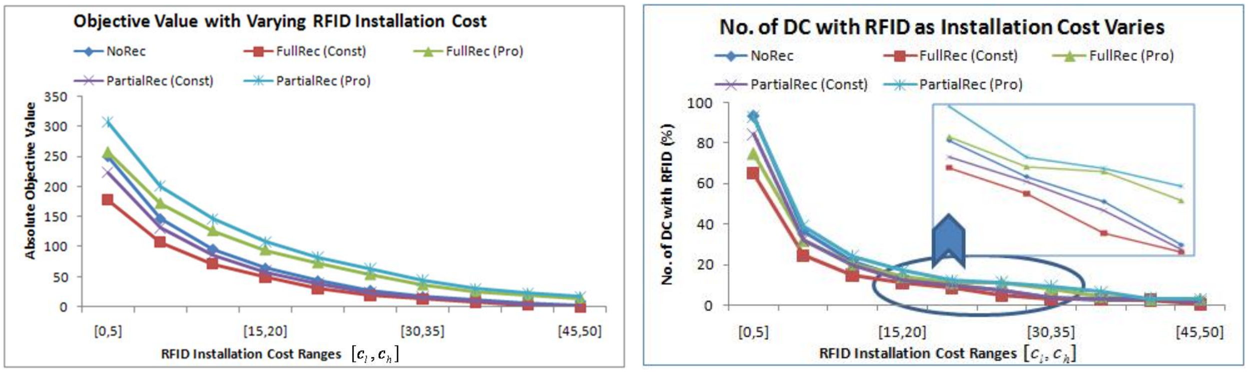

Figure 7: The objective values and number of RFID location when installation costs vary

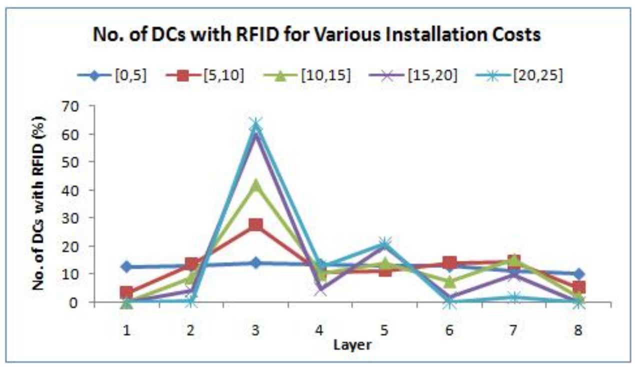

Figure 8: The number of RFID installations in each layer

locations are *not* selected 66.4% of the time, indicating that simple selection strategies are unlikely to be optimal.

5.5 Overlap Probability of DCs in the Path

The fourth experiment provides a more systematic analysis of the impact of overlapping routes by varying the overlap parameter $p_{overlap}$. Increasing the value of this parameter increases the commonality among paths. Recall that a path for each commodity is chosen randomly, but some of the locations are selected from a pool of previous locations with probability $p_{overlap}$. We vary $p_{overlap}$ from 0 to 1. The value of $p_{overlap} = 0$ implies that locations on each path are randomly and independently selected, while $p_{overlap} = 1$ is a significant though not necessarily complete overlap.

Figure 9 shows the lead time reductions and the installation costs when path commonality is varied. Not surprisingly, the lead time benefits $\sum_{k \in K} r_k(L_k(\phi) - L_k(S))$ increase as paths overlap more. This indicates that an RFID installation is more beneficial in environments where a location serves multiple commodities. It appears, however, that the level of overlap has little impact on the optimal RFID configurations: the total installation cost remains relatively steady, which means that there is little variation in the number of locations where RFID is installed.

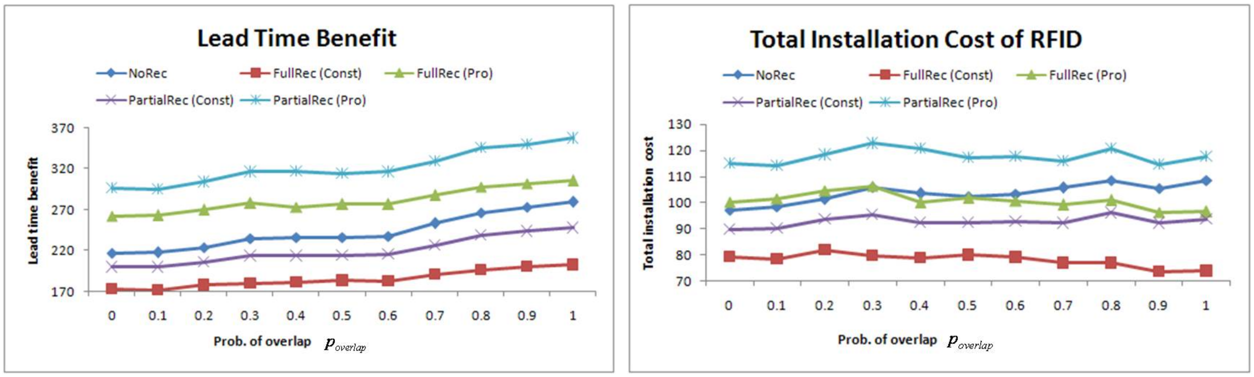

Figure 9: The impact of increasing route overlap

6 Summary and Conclusions

In this paper, we introduced novel approaches to evaluate benefits of RFID in a supply chain. Given that RFID deployments can present a substantial cost, we proposed models to determine an appropriate level of visibility by optimizing the number and locations of RFID systems in the network. To evaluate the potential benefits of an installation strategy, we considered its impact on the effective lead times in the system. Our framework allows for a variety of alternatives to address different system characteristics and recovery strategies. We solve the resulting problems using methods that employ dynamic programming techniques within a branch-and-price framework.

Our computational study illustrates the trade-offs that arise when establishing a deployment strategy. First, the location of RFID balances the benefits of early discovery of losses with the number of losses that can be captured. Other factors that influence the location strategies are the number of commodities served by each location, as well as other system and process characteristics.

As stated in the introduction, the main objective of our paper is to analyze how different RFID deployment levels can impact supply chain performance. Our results show that RFID investments can yield (potentially significant) benefits even when the RFID systems do not reduce the likelihood of losses or increase the likelihood of recovery. This illustrates the value of increased visibility, which allows for the early detection of losses and an increased ability to pinpoint where items have been lost. Moreover, our results indicate that the optimal RFID *configuration* is largely driven by the system's loss probabilities prior to the installation of RFID, even though accuracy improvements can have a substantial impact on the actual *benefits*. As stated before, this may provide an important insight for the management of RFID implementations. Initial implementation efforts should focus on the RFID configuration; afterward, attention could be directed to increasing accuracy at each RFID location to increase benefits. The optimal RFID configurations themselves, however, are quite sensitive with respect to the cost parameters. Specifically, our results show that the optimal number of RFID installations varies substantially according to the magnitude of the installation costs (relative to the monetary value of the per unit reduction in the lead time). Given that these costs may vary substantially in practice, we believe that the deployment of RFID requires careful consideration in each individual implementation effort and basic rules of thumb or ad-hoc analysis will be insufficient. In summary, we believe that the deployment decision can be a critical component in the justification of RFID investments that has been somewhat overlooked.

Finally, we also believe that evaluating the aggregated RFID benefits as considered here offers several interesting opportunities for further research. One area of research, for example, could be to address the impact of reductions in lead time variability that result from RFID.

Another direction is tied to the observation that our approach cannot be extended in a straightforward way to assembly type situations. In such a case the commodities would not follow single paths and thus the dynamic program to generate columns would be much more involved.

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A Nomenclature

$G = (N, A)$	The transportation network along which commodities are routed
d_{ij}	The transportation time between locations i and j
K	The commodities routed through the transportation network
$P(k)$	The path followed by commodity k within the transportation network
$L_k(S)$	The expected effective lead time when RFID is installed at the locations in set S
$R_k(S)$	The expected supply chain benefits when RFID is installed at the locations in set S
p	The probability that an item is lost at a location without RFID ($q = 1 - p$)
p_0	The probability that an item is lost at a location with RFID ($q_0 = 1 - p_0$)
$\hat{p}_0$	The probability that an item is lost at a source or destination ($\hat{q}_0 = 1 - \hat{p}_0$)
r	The probability that an item is recovered (given that it has been lost) at a location without RFID
r_0	The probability that an item is recovered (given that it has been lost) at a location with RFID
$\hat{r}_0$	The probability that an item is recovered (given that it has been lost) at a source or destination
$\bar{p} = p(1 - r)$	The probability that an item is lost and cannot be recovered at a location without RFID ($\bar{q} = 1 - \bar{p}$)
$\bar{p}_0 = p_0(1 - r_0)$	The probability that an item is lost and cannot be recovered at a location with RFID ($\bar{q}_0 = 1 - \bar{p}_0$)
$\tilde{p}_0 = \hat{p}_0(1 - \hat{r}_0)$	The probability that an item is lost and cannot be recovered at a source or destination location ($\tilde{q}_0 = 1 - \tilde{p}_0$)
T	The time spent searching for a lost item at a single location
c_i	The per period amortized cost of installing and maintaining RFID at location i
ρ_k	The monetary value of the per unit reduction in the lead time of a request of commodity k in a single period.
$\mathcal{D}_k$	Demand of commodity k.