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FOCUS THEME

Benchmarking RFID profitability in complex retail distribution systems

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Abstract Radio Frequency Identification (RFID) can improve the performance of distribution systems in a major way by providing full inventory visibility. Before adopting a new technology, however, one needs to benchmark the new approach to alternative and possibly more traditional solutions—such as transshipments of product stock between retail outlets. In this paper we develop and demonstrate the use of a simulation framework for comparing the use of RFID with other means to improve the responsiveness of distribution systems in a comprehensive manner. In order to compare the combined effect of various inventory error sources (in particular shrinkage, misplacements, and transactions errors), we have conducted extensive simulations. Our results show that the performance gains achieved by different responsive supply chain practices, such as the use of RFID for increased stock visibility or transshipments, depend on the reliability of inventory data and can also be highly interdependent. The value of RFID can be significantly lower in more responsive distribution systems. A sensitivity analysis confirms the robustness of the observations made. Our work confirms the need for more sophisticated methods to evaluate new supply chain information technologies and practices.

Keywords Value analysis · RFID · Retail · Distribution · Simulation

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Introduction

The most fundamental trade-off in supply chain management exists between *efficiency* and *responsiveness* (Chopra and Meindl 2004). Efficiency in the supply chain context refers to the minimization of production and distribution cost; responsiveness refers to the degree to which a supply chain is able to efficiently cope with demand uncertainty (Lee 2002). The trade-off exists because responsiveness has to be paid for, e.g. in the form of higher safety inventory or the acceleration of transportation. The introduction of new information technology can have consequences regarding both efficiency and responsiveness. For instance, if it enables the reduction of labour cost in a distribution centre it has an impact on efficiency. If it enables or improves supply chain practices that reduce the exposure to demand risks it has an impact on responsiveness.

In this article we address performance improvements resulting from improved responsiveness that can be achieved by using Radio Frequency Identification (RFID) in retail distribution systems. RFID is an information technology whose impact on supply chain management has been rising steadily (Günther et al. 2008). It allows for the contactless and concurrent identification of multiple objects carrying an RFID transponder and can therefore significantly increase the efficiency and accuracy of data collection in supply chain processes. Wal-Mart has mandated their major suppliers to attach RFID transponders to pallets in order to increase the efficiency of their distribution centre processes (Mah 2008). Others are still hesitating to introduce the technology, mainly because of the high transponder prices and uncertain benefits. The uncertainty of RFID's value in supply chain management has lead many researchers from the operations research and information systems community to investigate methods to support the RFID investment decision. Hitherto the focus of this research has been on considering RFID's value independent of other possibilities to improve the cost/benefit performance of goods distribution. If basic *efficiency* issues are considered, such as the reduction of labour costs due to higher automation, the calculation of the returns of different investment alternatives can be carried out separately because the achievable value gains are additive. However, if a technology like RFID is evaluated in combination with or instead of other measures for making goods distribution more *responsive*, such as transshipments, the financial returns of all measures and possible combinations should be assessed within the same model framework. This approach is advisable because the impact of different managerial practices on the responsiveness of a distribution system can be highly complex and interrelated. In particular they can be non-additive. As our results show, RFID-enabled visibility affects a system's performance by improving its responsiveness. Therefore RFID's relative financial impact depends on the existing degree of distribution system responsiveness. The returns of other techniques for improving responsiveness in turn depend on the degree of existing visibility. These two relationships establish a complex cost/benefit trade-off that can only be analyzed using advanced research methods.

We show that measuring the value of RFID and possible investment alternatives within the same conceptual framework is especially advisable if a company plans to deploy RFID in connection or on top of another technology or supply chain practice used to increase responsiveness. We concentrate on transshipments as a competing supply chain practice because their use, just like the use of RFID technology, can only be profitable in the distribution of high-value products: both item-level RFID tagging and item-level transshipments are relatively expensive given current price levels and therefore require sufficiently high overstocking and stock-out penalties. This commonality motivates the analysis of both practices within one model framework.

Related literature

Transshipments

A recent survey by Chiou (2008) provides a comprehensive overview of the current state of research on transshipments. Numerous articles have investigated the value of transshipments in service part distribution systems (e.g. Lee 1987). Since the demand for service parts (e.g. machine components) is usually low and highly uncertain and because of the high value of such parts, an optimal transshipment policy can often increase the efficiency of such systems. Recently, transshipments have also been considered as a measure to improve the responsiveness of consumer product distribution. Their use is especially promising for high-priced products (e.g. apparel, toys, etc.) whose demand is highly uncertain (cf. Rudi et al. 2001).

Transshipment policies can be of the emergency and preventive type (cf. Chiou 2008). The applicability of either type of policy primarily depends on the whether customer demand is backlogged or not. In many retail settings demand is not backlogged since customers are not willing to wait for a particular product. Instead they may want to buy a substitute product in the same retail outlet, buy from a competing retailer, or they do not buy at all (cf. Corsten and Gruen 2003).

The determination of the optimal timing and quantities of transshipments has turned out to be highly complex. Optimal policies with limited generalizability have been proposed among others by Robinson (1990), Rudi et al. (2001), Jonsson and Silver (1987), and Bertrand and Bookbinder (1998). Whereas the work of Robinson (1990) and Rudi et al. (2001) is on emergency transshipments, Jonsson and Silver (1987) and Bertrand and Bookbinder (1998) consider preventive transshipments. Interestingly, none of these authors have explicitly investigated the lost sales case.

Some authors have analysed transshipment policies using numerical optimization models and simulation (e.g. Herer et al. 2006). Their optimization procedures are sufficiently comprehensive to take the complex trade-off between inventory holding, stock-out and transportation costs into account. The work of Banerjee et al. (2003) compares two different types of preventive transshipment policies: (i) ad-hoc transshipments for preventing pending shortages and a (ii) transshipment policy based on system-wide inventory balancing which is performed once per review cycle. They come to the conclusion that the first policy type is more effective in preventing stock-out incidents. Other authors have specified and evaluated the performance of less sophisticated transshipment mechanisms that do not implicitly optimize all relevant cost tradeoffs (e.g. Lee and Özer 2007a).

The implementation of transshipment operations naturally requires a high degree of inventory visibility across the entire distribution system. Since the product quantities that need to be transshipped at any given date are computed based on the respective inventory levels at the different retail outlets, the accuracy of this data can have a substantial effect on the quality of allocations and in turn on the efficiency of transshipment operations.

Value of visibility and RFID in distribution systems

A number of authors have investigated the potential of RFID for increasing the accuracy and accessibility of inventory information and thereby indirectly improving the effectiveness of supply chain management practices (cf. Lee et al. 2007b). Inventory inaccuracy can come into existence for different reasons, e.g. theft, misplacements, transaction errors, unreliable delivery processes, and quality problems (Raman et al. 2003, DeHoratius and Raman 2008). The effect of inventory inaccuracy on the performance of typical inventory order policies was analyzed by several authors (e.g. Rekik et al. 2008; Atali et al. 2006; Thiesse and Fleisch 2007).

Atali et al. (2006) for instance quantified its impact on the performance of stock management of a retailer. The only work we are aware of that investigates the effect of inventory error sources on a whole supply chain is of Fleisch and Tellkamp (2005) who simulated a typical retail supply chain and analyzed the impact of inventory record inaccuracy caused by different error sources on the its overall performance.

To the best of our knowledge, the impact of RFID-enabled stock visibility in distribution systems subject to inventory inaccuracies has not been compared to other means that can help to increase the efficient response to consumer demand. We have begun to close this research gap by proposing a simulation-based framework for benchmarking the impact of RFID against other approaches, in particular transshipments.

The model

Our model of a distribution system comprises one depot and N retail outlets that belong to the same company. The demand for a product has to be satisfied immediately from the on-hand stock available at the outlets. Customers walk away if they do not immediately find the product they search for. Each lost sale results in a penalty c_p for the company. Holding one unit of stock causes holding costs of c_h per day.

We assume that the amount of the product stored in the distribution centre is sufficient to fill retailer orders of arbitrary size. The retailers follow a simple reorder point policy: if the inventory level of the product falls short of a certain reorder point R at any of the outlet locations, it places an order of size Q with the depot. The order arrives after a deterministic lead time of L days irrespective of the outlet location. There is no fixed order cost. The order size Q is exogenous. It may be subject to exogenous constraints such as the capacity of vehicles or contractual terms such as minimal order quantities.

The actions during a day are performed in the following predefined order.

1. The retail outlets receive outstanding orders and incur order costs.
2. Daily demand occurs at the retail outlets.
3. The product stock at all retail outlets is audited if the audit interval has elapsed.
4. If the reorder point is undercut at a particular retail outlet, the outlet places an order with the depot.
5. Inventory holding and shortage costs are incurred.
6. If allowed, transshipments between retail locations are conducted and the corresponding costs are incurred.

Customer demand and inventory inaccuracy

Total daily demand D for the product at each of the retail outlets follows a Poisson distribution with rate λ, i.e. the mean demand is λ items per day with a standard deviation of $\sqrt{\lambda}$ items. Included in this demand are the share D_α of paying customer demand, the share D_β of shrinkage and the share D_γ of misplacements. Shrinkage refers to the unwanted loss of stock, e.g. due to theft or spoilage. It leaves the virtual inventory level unchanged but reduces the physical stock. Misplacements come into existence because customers or employees remove products from the place from which they can be taken to fill demand. We assume that misplaced products are recovered when inventory audits are conducted. Misplacements leave the total physical stock unchanged but reduce the sales-ready inventory temporarily. The probability distribution for paying customer demand D_α, shrinkage D_β, and misplacements D_γ can thus be obtained by the following formula (cf. Atali et al. 2006):

$$\Pr\{D_i = k\} = \sum_{d=k}^{\infty} \Pr\{D_i = k | D = d\} \Pr\{D = d\}$$

Mean daily paying customer demand λ_α, shrinkage λ_β and misplacements λ_γ during a day can be expressed as a fraction of the mean total daily demand λ using the parameters α, β, and γ respectively.

Another reason for inaccurate inventory levels apart from shrinkage and misplacements are transaction errors. They occur if the flow of goods is documented incorrectly. Following Atali et al. (2006) we introduce this kind of error in our model by adding an additional source of demand represented by a Normal distribution with mean and standard deviation σ.

The simulation model needs to keep track of three different types of inventory levels: (i) the total physical stock S_i^{tp}, which reflects the amount of products stocked at retail location i, (ii) the 'sales-ready' amount of products at location i S_i^{sr}, and (iii) the virtual stock level S_i^{vi} which is made available by the company's information system.

We assume that the time between subsequent inventory audits is Δt_α. After each audit the virtual inventory level S_i^{sr} as well as the sales-ready inventory level S_i^{sr} are set back to the total physical inventory level S_i^{tp} at every retail outlet i.

The transshipment algorithm

As outlined in the Related Work section of this paper, transshipment mechanisms in a retail setting usually have to be of the preventive type in order to be effective: since customers are assumed to walk away instead of waiting for a product, emergency transshipments are not applicable. In contrast to all previous research on preventive transshipments that we are aware of, we consider a setting where the time of order placement depends on the reorder point R_i only, i.e. the order cycles of the N retail outlets are *not* synchronized. The applied transshipment mechanism is based on the idea of preventive but 'informed' equalization of outlet inventories and apart from the differences with respect to the assumptions made in this article (asynchronous order placement, lost sales) is similar to transshipment policies proposed by other authors (e.g. Lee et al. 2007b or Banerjee et al. 2003).

We assume that transshipments are performed 'over night', i.e. outlets with excess stock can transship products to locations with pending shortages in the time between the daily sales periods. The cost of transhipping one unit of stock is c_t . The optimal transshipment quantities from outlet i to outlet j at time t are determined according to the following algorithm where the transshipments scheduled by the algorithm at time t are represented by the $N \times N$ integer matrix M_{ij}^t.

Initialize values of transshipment matrix by setting $M_{ij}^t = 0$ for all i and j;
Repeat:

For all outlets o:

Compute the expected marginal cost of adding one more unit MC_o^t to the inventory of outlet o *at time t;*

Determine outlet i with the highest and outlet j with the lowest marginal cost;

If $\left(MC_i^t - MC_j^t\right) > c_t$:

Increase scheduled transshipments from outlet i to j by one unit, i.e. $M_{ij}^t = \left(M_{ij}^t + 1\right)$;

Otherwise:

Terminate;

We determine the marginal cost of adding one more unit to the stock of a retail outlet using a newsvendor-style computation. The total cost function for the single period newsvendor problem according to Nahmias (2005, p. 242) is

$$C(S) = c_o \int_0^S (S - x)f(x)dx + c_u \int_S^\infty (x - S)f(x)dx \quad (1)$$

where S is the available stock, c_o and c_u the cost that over- and underage cost per unit respectively, and $f(x)$ is the

Table 1 Simulation parameters (* indicates default value)

Parameter	Values	Description
c_h	{0.05, 0.1*, 0.15}	Daily unit holding cost
c_p	{20, 40*, 60}	Unit stock-out penalty
c_t	{1, 2*, 3}	Unit transshipment cost
c_r	{0.5, 0.1*, 0.15}	Unit RFID transponder cost
λ	{2, 6*, 10}	Mean total daily demand at each retailer
N	{2, 6*, 10}	Number of retail outlets
Q	{INT(2λ), INT(6λ)*, INT(1Oλ)}	Order quantity
L	{2, 6*, 10}	Lead time in days
β	{0%, 1%, 2%, 3%, 4%, 5%}	Shrinkage rate
γ	{0%, 1%, 2%, 3%, 4%, 5%}	Misplacement rate
σ	$\{0, 0.1\sqrt{\lambda}, 0.2\sqrt{\lambda}, 0.3\sqrt{\lambda}, 0.4\sqrt{\lambda}, 0.5\sqrt{\lambda}\}$	Standard deviation of transaction error
ε	{0, 1, 2, 3, 4, 5}	Total error source
Δt_a	{10, 20*, 30}	Audit interval in days
I_t	{0, 1}	Use of transshipments (no, yes)
I_p	{0, 1}	Use of RFID (no, yes)

density function of demand. The marginal cost of adding one unit to S is

$$\frac{dC(S)}{dS} = c_o \int_0^S 1 f(x)dx + c_u \int_S^\infty (-1) f(x)dx = c_o F(S) - c_u (1 - F(s)) \quad (2)$$

where $F(x)$ is the cumulative distribution function (cdf) of demand.

Since the regular lead time is assumed to be deterministic in our model and we assume the total demand follows a Poisson process, the demand occurring at a retailer i until the next regular replenishment also follows a Poisson distribution with rate parameter $\lambda(\Delta t_i - 1)$ where Δt_i denotes the period of time in days until the next replenishment arrives at retailer i. Using Eq. (2) we can construct an approximation of the expected cost of adding one unit to the inventory of retail outlet i.

$$\begin{aligned} MC_i^t\left(S_i^v\right) &= (c_h \Delta t) F\left(S_i^v\right) - c_p\left(1 - F\left(S_i^v\right)\right) \\ &= (c_h \Delta t + c_P) F\left(S_i^v\right) - c_p \end{aligned} \quad (3)$$

where $F(x)$ is the cdf of the Poisson distribution with rate parameter $\lambda(\Delta t_i - 1)$.

As indicated in Eq. 3 the marginal cost is determined based on the *virtual*, not on the actual *physical* inventory level at the retail outlet. Thus, there may occur situations where there is not enough stock available to transship the quantity computed by the transshipment algorithm. In those cases all remaining units are transshipped.

The proposed transshipment policy is only near-optimal since it cannot be guaranteed that stock will be transshipped back and forth several times without preventing stock-outs. However, as our empirical evaluations have shown, the chances that this happens given our model assumptions are extremely low.

Simulation study

Experimental setup

We have implemented a simulation model in the programming language Java using the SSJ library for stochastic simulation (L'Ecuyer and Buist 2005). In order to obtain a good overview of the impact of a number of crucial parameters a factorial design was used. Table 1 lists the parameters and corresponding values that were provided as input to the simulation model. The chosen cost parameters can best be explained by using a handy example of the type of product we are considering. The current retail price of an iPod classic is 250 Euros. Assuming a retail margin and yearly holding cost of 20% both, we obtain a daily holding cost (c_h) of approximately 0.11 Euros $(200 \times (1 - 0.2) \times 0.2/360)$ and a lost sale cost (c_p) of 50 Euros $(250{\times}0.2)$. The unit Euros transshipment cost c_t is geared to typical spot market prices for national packet delivery (e.g. the prices offered on the DHL website) considering batch consolidation as well as corporate and quantity rebates. The

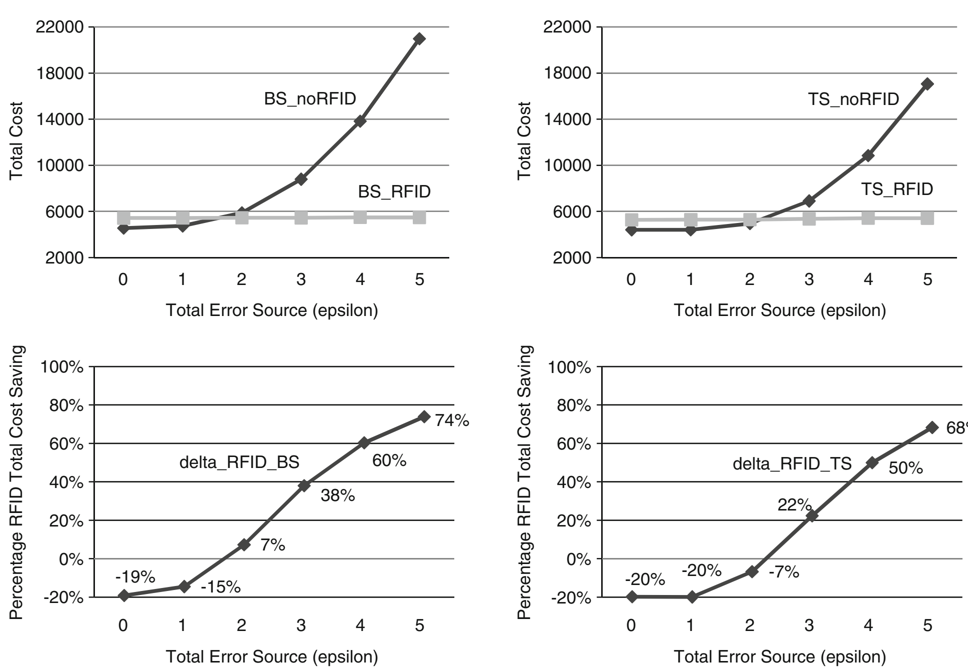


Fig. 1 Effect of different levels of the error source on total costs in the basic distribution system (**a**) and the distribution system with transshipments (**b**); percentage total cost savings achieved by RFID for the basic distribution system (**c**) and the distribution system with transshipments (**d**)

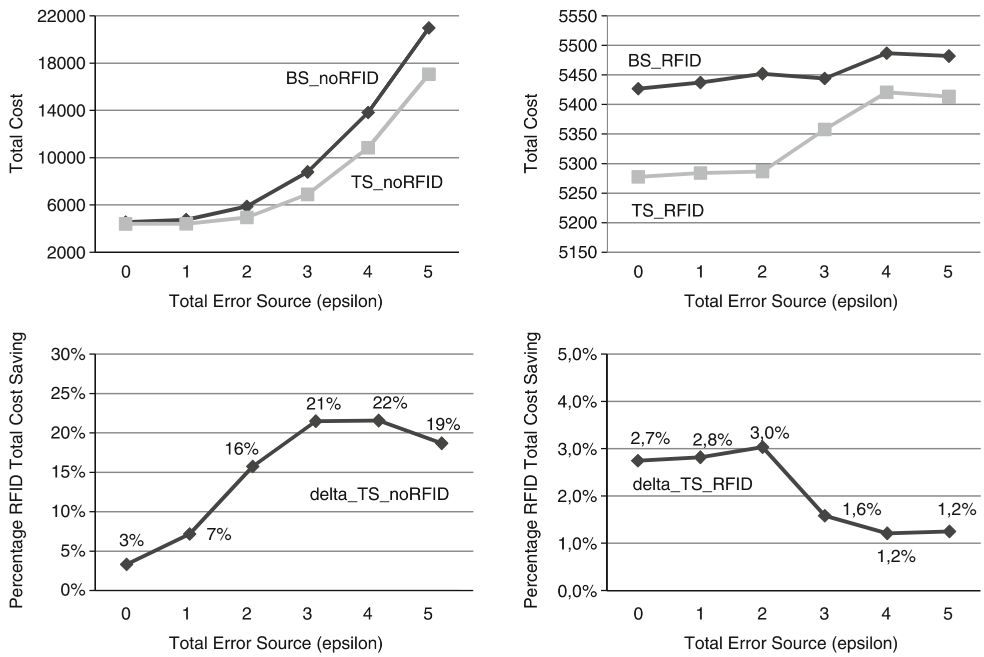


Fig. 2 Effect of transshipments on total costs in the distribution system without RFID (**a**) and the distribution system with RFID (**b**); percentage total cost savings for the distribution system without RFID (**c**) and with RFID (**d**)

chosen tag costs (c_r) cover the current market price range of passive RFID transponders. The remaining parameters ranges are partly based on the literature (cf. (Atali et al. 2006) for daily demand λ and Lee et al. (2007b) for lead time L), partly are they supposed to cover the whole range of possible values (such as the different error sources).

The parameter ε was introduced to measure the combined impact of all sources of inventory inaccuracy on the performance of the distribution system. For ε=0 there exists no error source, for ε=1 the parameters β and γ are set to 1% and parameter a is set to $0.1\sqrt{\lambda}$ and so fourth. Studying the aggregated impact of all possible error sources reflects the fact that they coexist in practice (cf. Atali et al. 2006; Lee and Özer 2007).

In a first step the optimal reorder points for the retail outlets were computed using a simulation-based linear search technique. The reorder points used in the RFID setups are optimal with respect to full visibility, i.e. the physical stock level was used as input during the simulation. The reorder points of the non-RFID setups are ignorant of the additional stock level variance caused by inventory discrepancies: the mean shrinkage and misplacement rate is taken into account at order time (λ includes λ_β and λ_γ) but the order policy does not use all information on the different error sources because they are not known in practice (in contrast to the order policy used by Atali et al. 2006).

In a second step the entire distribution system including transshipments was simulated using the optimal reorder points as input. Each experiment was repeated 1,000 times in order to assure the statistical significance of the results.

Results

In order to quantify the performance improvements resulting from the use of RFID and/or transshipments in the defined distribution system we compare four distinct

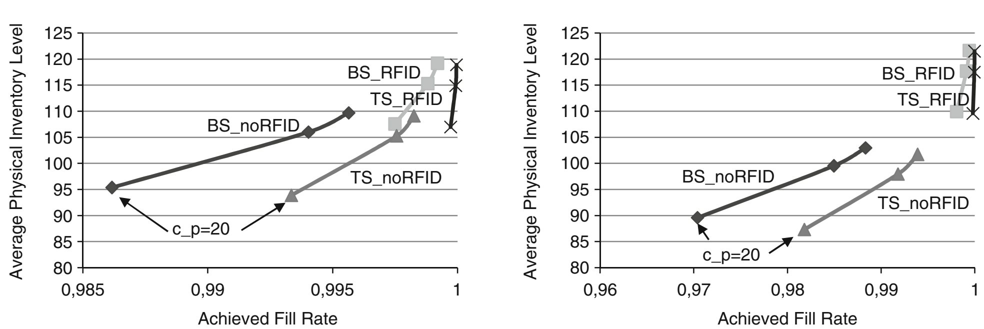


Fig. 3 Effect of different error source levels on the trade-off between average inventory and achieved fill rate for different distribution systems (left diagram: ε=2, right diagram: ε=3). We plotted three trade-off points (connected by lines) that represent different levels of lost sale cost for each of the considered distribution systems

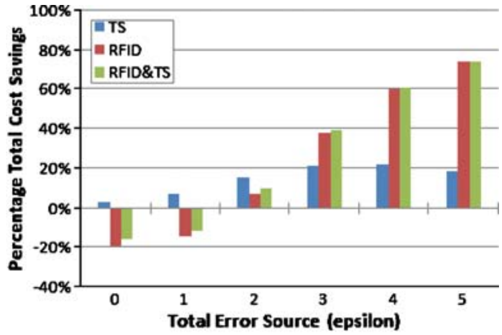


Fig. 4 Comparison of RFID and transshipment cost savings at different levels of the total error source

distribution system setups: the *basic* distribution system (*BS*) without transshipments and the distribution system with transshipments (*TS*), with and without the use of RFID respectively.

For the initial comparison all simulation parameters were set to their default values (indicated by * in Table 1) while the different sources of inventory record inaccuracy—i.e. shrinkage, misplacements, and transaction errors—were varied to reveal their effect on the total distribution cost.

The utility of RFID can be expressed as the percentage improvement when switching from the system BS_{noRFID} to BS_{RFID} (denoted by $\Delta RFID_{BS}$) and from system TS_{noRFID} to TS_{RFID} (denoted by $\Delta RFID_{TS}$).

In order to make sure that the observed differences between the total cost values are statistically significant, we computed their 95% confidence intervals. The confidence intervals do not overlap for different parameter choices.

Figure 1 shows the total cost figures for different levels of ε and the corresponding percentage cost savings that can be realized using RFID in the distribution system with and without transshipments.

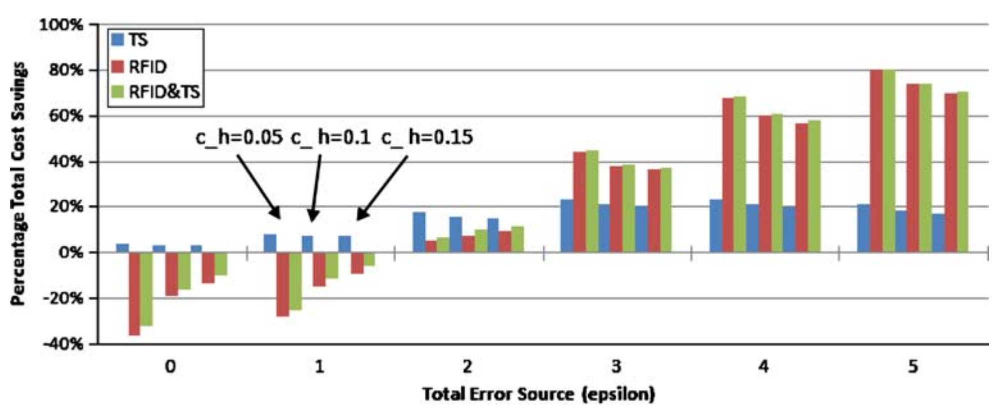
Diagrams (a) and (b) of Fig. 1 indicate that without full inventory visibility the total costs quickly increase while the total cost of the system with visibility stays at a relatively constant level.

The percentage cost savings due to RFID usage provided by Diagrams (c) and (d) really take off from a total error source of ε=3 onwards. The comparison of Diagrams (c) and (d) of Fig. 1 reveals that RFID has a more positive impact on the total costs of the basic distribution system in terms of relative improvement: at a total error source level of 2 the total cost saving in the basic system is already 7% while the tag break even in the system with transshipments is not reached resulting in a negative return of −7%.

Figure 2 shows how the use of transshipments improves the performance of the distribution system with imperfect and full visibility (abbreviated with ΔTS_{noRFID} and ΔTS_{RFID} respectively). As Diagram (c) indicates, the savings achieved by the transshipments can be significant even if the stock levels that transshipment decisions are based on inaccurate stock levels; in fact, the profitability of transshipments even increases until a total error source of 4. In the system with RFID, the profitability of transshipments declines with increasing levels of ε (see Diagram (d)). This observation can be explained by the fact that the transshipment policy does not take the side-effects of inventory error into account, in particular the changes in the demand pattern that is caused by the stochastic inventory error. Its performance therefore slowly decreases with higher values of the inventory error source.

Figure 3 reveals how the different distribution systems realize value from visibility and the ability to swap stock between retail outlets. It shows the trade-off between the average inventory and the achieved fill rate for a total error source of three and different lost sale costs. The distribution systems with imperfect inventory visibility use slightly less stock than the RFID-enabled systems but also achieve significantly lower fill rates. Transshipments reduce stock-outs while using approximately the same average amount of products; a reduction of lost sales is traded against increased transportation cost. The RFID-enabled systems use slightly more stock and achieve higher fill rates than the systems with imperfect visibility. The RFID-enabled distribution system with transshipments achieves a slightly

Fig. 5 Sensitivity of percentage total cost savings with respect to unit time holding cost



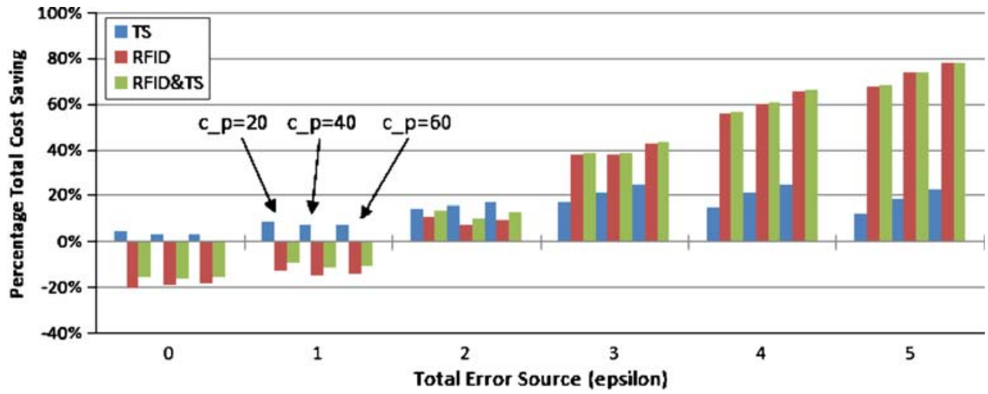


Fig. 6 Sensitivity of percentage total cost savings with respect to unit lost sale cost

higher fill rate than the RFID-enabled system without transshipments using the same amount of stock on average.

In summary, both the use of transshipments and the introduction of RFID translate into fewer out-of-stock situations and thereby realize value. At lower levels of the total error source, the distribution system with transshipments achieves approximately the same fill rate as the RFID-equipped system without transshipments.

Figure 4 shows the percentage total cost savings at different levels of the total error source if either RFID or transshipments (TS) or both are used in the distribution system specified by the default parameter values. It turns out that up to a certain error level the use of transshipments alone is more efficient for increasing the responsiveness of the system. Furthermore, the use of transshipments is profitable at all considered error levels in contrast to the introduction of RFID. Furthermore, the additional percentage cost saving that can be realized by using transshipments in an RFID-enabled distribution system declines with higher levels of the error source because RFID eventually becomes more efficient as a means to reduce stock-outs than the use of transshipments.

Sensitivity analysis

To make sure that our results are sufficiently robust with respect to the choice of input parameters, we have conducted an extensive sensitivity analysis. We observed the changes to the percentage RFID-enabled total cost improvement when decreasing and increasing the value of one model input parameter while keeping all other input variables at their default values (indicated by * in Table 1).

As Fig. 5 indicates, higher unit time holding costs make both transshipments and RFID less profitable. This result can be explained by the fact that holding costs are computed based on the physical stock level in our model. Therefore the shrinkage component of the total error source causes inventory holding costs to decline at higher levels of ε regardless of whether RFID or transshipments are used.

Figure 6 indicates that the effect of unit lost sale cost on the profitability of both transshipments and the use of RFID is predominantly positive; this result is intuitive because higher lost sale costs increase the relative value of stock-out prevention irrespective of how it is achieved.

The unit transshipment cost only has an impact on the profitability of transshipments, of course. As Fig. 7 indicates an increase of the transshipments costs leads to a higher winning margin of RFID at higher levels of ε.

Higher transponder prices naturally reduce the profitability of using RFID to provide stock visibility. As Fig. 8 shows, the effect of a five cent decrease or increase of the unit RFID transponder cost has a significant effect on the percentage cost savings achieved by RFID—in particular if the level of the total error source is relatively low. At higher

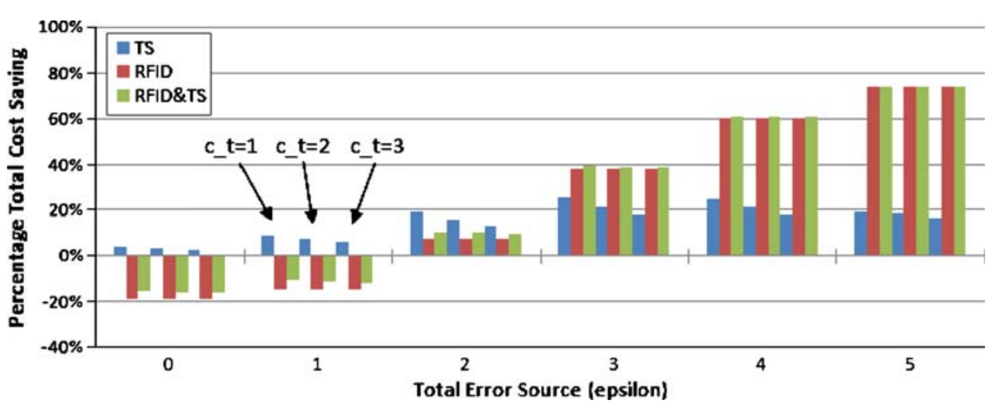


Fig. 7 Sensitivity of percentage total cost savings with respect to unit transshipment cost

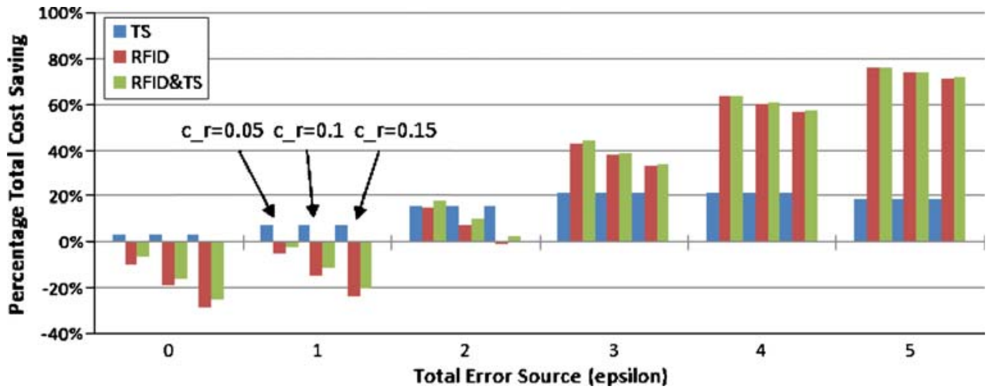


Fig. 8 Sensitivity of percentage total cost savings with respect to RFID transponder cost

error levels the benefits of full visibility begin to dwarf the considered transponder cost effect.

Daily demand has a significant influence on both the value of transshipments and RFID (see Fig. 9). Higher demand rates make transshipments less profitable and RFID more profitable from a certain level of the error source onwards.

The number of retail outlets in the distribution system has a positive impact on the profitability of transshipments (see Fig. 10), whereas its effect on RFID's profitability is negative.

At low levels of ε, increased order sizes have a negative impact on the profitability of transshipments and a positive impact on the profitability of RFID (see Fig. 11). These relationships are reversed at higher error rates.

The longer the order lead times, the lower the profitability of RFID (see Fig. 12). This effect is due to the fact that shorter lead times allow for a reduction of safety stock which increases the dependency of the system on the correct time of ordering and thus also on the accuracy of inventory data.

The effect of the length of the inventory audit interval shown in Fig. 13 is straightforward: it has a direct impact on the level of additional visibility provided by RFID. More frequent audits significantly reduce the value of being able to observe stock movement in real time. The inventory audit frequency also has a significant impact on the profitability of transshipments. As described in the previous section of this article, the effect of the inventory error source on the performance of transshipment operations is mixed. On the one hand, transshipments are also effective in the presence of inventory inaccuracy as far as stock-out prevention is concerned; on the other hand their efficiency in terms of the transshipment costs incurred relative to the number of prevented stock-outs also diminishes with increasing levels of the error source.

In summary, the sensitivity analysis has shown that the fundamental observations stated in the preceding section are indeed robust with respect to changes of the input parameters.

Conclusion

We have proposed a simulation-based framework for evaluating the effect of inventory error on the performance

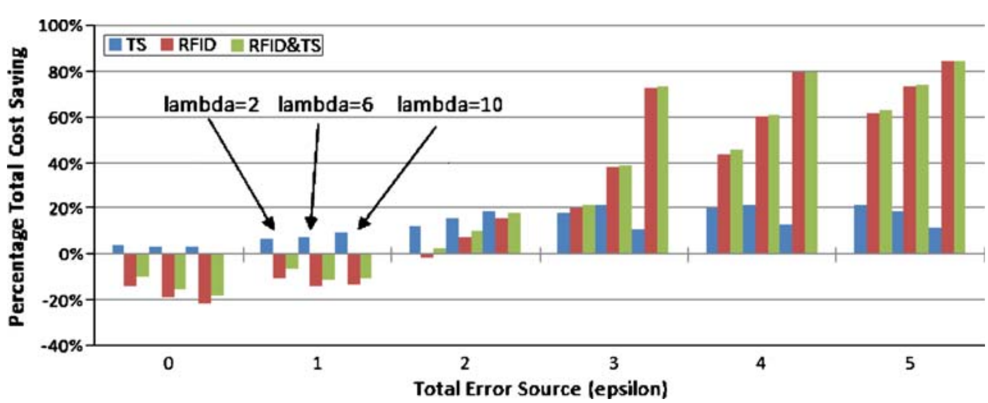


Fig. 9 Sensitivity of percentage total cost savings with respect to daily demand rate

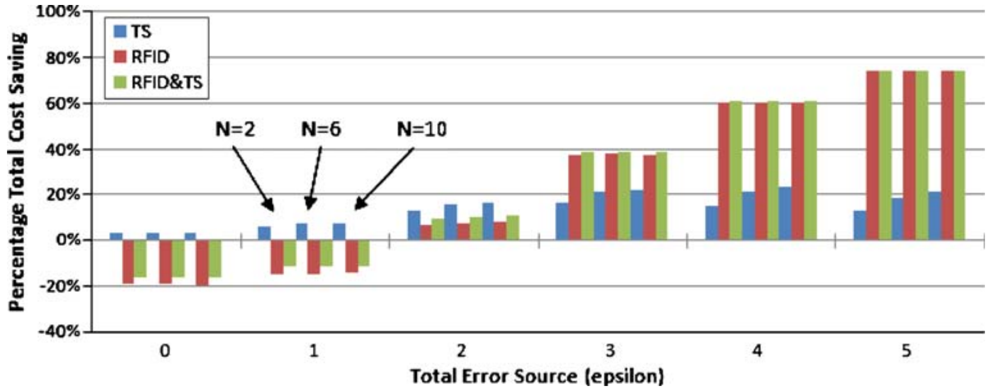


Fig. 10 Sensitivity of percentage total cost savings with respect to number of retail outlets

of complex distribution systems. The framework allows for comparing the profitability of using RFID for inventory tracking at retail outlets to other managerial measures for increasing the responsiveness of retail distribution systems. We focus on transshipments which is one possible option in this context.

The impact of full RFID-enabled inventory visibility turned out to be substantial in many of the analysed settings. At a realistic total inventory error (2% of demand) it ranges between 0% and 33% of the total distribution costs depending on the chosen parameter configuration. The degree of performance improvements that can be achieved with RFID depends on the characteristics of the product to be tagged. It is affected positively by the unit lost sale cost and the size of daily demand; it is influenced negatively by the unit holding cost, the distribution lead time, the RFID transponder prices, and the frequency of inventory audits.

The preventive transshipment policy whose value we compare to the RFID-enabled full inventory visibility performs well even at high levels of the total inventory error source. Moreover, in contrast to RFID it leads to positive returns at all considered error rates. The profitability of the transshipment mechanism is positively correlated to unit lost sale cost and the number of retail outlets. It is negatively influenced by unit holding cost and unit transshipment cost.

Our results imply that if transshipments are currently not used, they can be introduced in combination with RFID in order to hedge against the risk of overestimating the value of full inventory visibility because the combined use of transshipments and RFID turns out to be always at least as profitable as using RFID alone. Furthermore, synergies with respect to efficiency may result from the combined use of RFID and transshipments that have not been addressed in this article. For instance, the additional handling overhead caused by transshipments could be partly compensated by RFID: RFID has repeatedly been praised as an instrument to reduce the related costs, e.g. by using automated picking lists (cf. Thiesse and Fleisch 2007).

There exist many levers to increase the responsiveness of distribution systems apart from RFID (e.g. lead time reduction, the reduction of order batch sizes, or more effective inventory audits). As the example of transshipments shows, managers should carefully consider using these levers instead or in combination with an investment in RFID. In particular, the relative performance gains from RFID-enabled stock visibility may be significantly lower if other responsive supply chain practices are already in place.

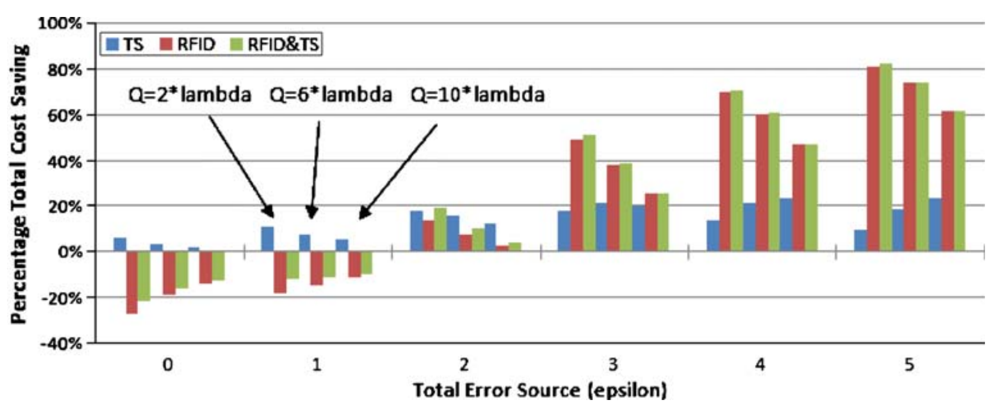


Fig. 11 Sensitivity of percentage total cost savings with respect to order quantity

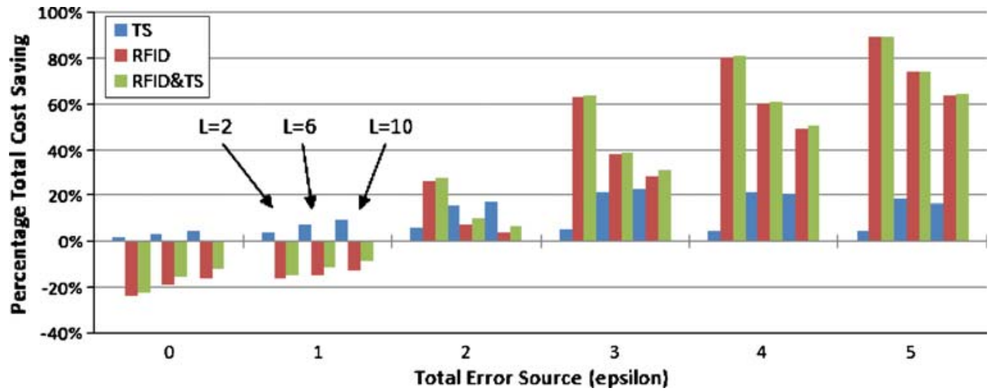


Fig. 12 Sensitivity of percentage total cost savings with respect to lead time

We only consider RFID-based tracking of high value products such as expensive consumer electronics and apparel. As previous work has shown (e.g. Atali et al. 2006; de Kok et al. 2006), the RFID transponder prices that are necessary to make the tagging of typical low-value items profitable are unrealistic—at least in the foreseeable future.

The total distribution cost metric considered in our analysis only includes the obvious variable costs. Fixed costs associated with the use of RFID transponders include the purchase and/or operation of the required RFID reader infrastructure at the retail outlets which are shared across all tagged products. Transshipments cause substantial additional handling costs after the shops have closed and may require specialized transportation service contracts that include a higher fixed cost component. Those fixed costs of both RFID investment and transshipments were left aside since their range can only be realistically assessed on a case by case basis. Among other things, they depend on factors not included in our study, e.g. the number of different products that are being tagged and/or transshipped. However, since fixed costs are additive, they can easily by included into our cost/benefit framework if necessary.

The same limitations to comprehensive assessment apply to the benefit side: the recent hype about RFID has lead to manifold value propositions, for instance product-related after-sale services or the role that RFID can play in supporting theft prevention efforts. In spite of these limitations, we believe that our approach can provide valuable insights into RFID's impact on the responsiveness of complex distribution systems.

We have chosen to use a computer simulation as a method to demonstrate the effect of RFID and transshipments on the cost of goods distribution. Simulation has the advantage that it can be used to analyse even highly complex systems in a perfectly controllable environment. Its disadvantage in contrast to more formal methods is the high computational effort involved in conducting comprehensive simulation studies. Furthermore, the impact of certain parameters on the system's performance as a whole cannot be described mathematically like in less complex formal models. Therefore we have conducted an extensive sensitivity analysis with respect to all considered model parameters to make sure that our results are sufficiently robust.

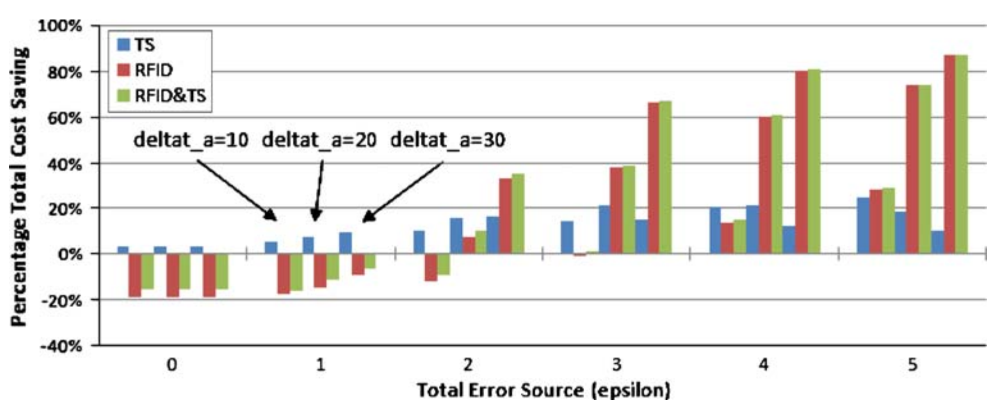


Fig. 13 Sensitivity of percentage total cost savings with respect to inventory audit interval

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