Strategic Aspects of Cross-company Item-level RFID Usage - A Game Theoretic Analysis

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Abstract—We propose an economic supply chain model that accounts for typical inefficiencies resulting from low visibility of the flow of consumer goods. Using realistic numerical input values for the model, we illustrate how the profit distribution among manufacturer and retailer changes as item-level RFID is used for different purposes along the consumer goods supply chain. Applying basic Game Theoretic tools, we analyze the incentives of manufacturers and retailers to use item-level RFID cooperatively. Our results suggest that, if RFID helps to prevent typical supply chain inefficiencies such as delivery errors and replenishment inefficiencies, a full and cooperative RFID rollout is the most likely outcome of the "RFID usage game".

I. INTRODUCTION

The core vision of the industry consortium EPCglobal is the use of standardized item-level RFID along the supply chain of consumer products [1]. In particular, they propose the standardized Electronic Product Code (EPC) which can be used as unique product identifier. To date, however, most manufacturers and retailers of consumer goods have not reached a consensus on whether it is profitable to use item-level RFID instead of traditional identification technology such as the bar code. In many cases the current cost of RFID transponders is indeed high to justify if one only considers the automation value that can be derived from it. Stated otherwise, the payback period of the initial investment into the RFID reader infrastructure and required process changes is infinite (variable costs exceed benefits) or considered too long. However, RFID is expected to also yield information and transformation value, which may very well exceed its variable cost and also lead to a competitive ROI [2]. The discussion has been taken up by researchers which has resulted in a number of publications on the profitability of RFID, e.g. [3], [4], [5], and [6]. The cross-company use of RFID in consumer goods supply chains implies that manufacturers and retailers use the same RFID transponders which calls for standardization of the corresponding hardware and product identification codes. RFID-related standardization has been advanced by EPCglobal and affiliated organizations for many years now. Apart from the specification of the EPC, their effort has lead to the creation of standards for a number of other crucial infrastructure components such as standards for reader protocols, data storage [7], and data access [1]. Although the benefit of using RFID to monitor the movement of single products in supply chains has often been stressed [8], it is still far from being fully explored or realized in practice. Apart from early trials, for instance the one conducted by apparel manufacturer Gerry Weber and the retail store chain Kaufhof in 2003 [9], we are not aware of any cross-company application of item-level RFID. One possible explanation for this observation may be a lack of economic incentives. In fact the prevailing consensus in practice is that retailers realize most of the value from item-level RFID whereas their suppliers, i.e. the manufacturers and distributors of consumer products, do not gain substantial benefits [10]. Manufacturers are more interested in tracking cases or pallets of the products they deliver to the retailer’s distribution centers or outlets, whereas retailers are expected to gain substantial benefit from individual-product tracking on their shelves [10], [11]. Since item-level tags are usually placed within the single product’s carton or even sewn into products in the case of apparel, it makes economic sense to tag at the manufacturers’ location. Otherwise all recipients of the product who want to use item-level RFID would have to operate tag placing and encoding equipment at all of their distribution centers or retail stores. The initial conflict of item-level RFID adoption thus becomes clearer. Whereas the supplier usually incurs the cost of tagging products, the economic potential is expected to lie on the retailers’ side [12].

The focus of the work presented in this paper is the analysis of the economic incentives of manufacturers and retailers to use item-level RFID. By use we mean the local storage and processing of RFID data, not just the attachment of transponders. This distinguishes our work from related quantitative work that investigates a similar setting, in particular [5]. As we outlined previously, the use of item-level RFID not only in retail stores but also at the sites where products are made, stored, and shipped is a crucial precondition for realizing the full potential of RFID. The benefits expected from advanced supply chain applications (e.g. SCEM [13], efficient product recalls [14], or product authentication [15]) can only be realized if RFID data is collected, stored, and made accessible along the supply chain and not just within retail stores. To date, the academic literature investigating the economic incentives for using item-level RFID along the
supply chain is sparse. Academic work that addresses related issues includes [5] who investigate tag cost allocation using a supplier-retailer supply chain model based on the Newsvendor model. [16] uses a quantitative modeling approach to show that inventory record accuracy exacerbates the inefficiencies resulting from double marginalization in supplier-retailer supply chains. In particular, they demonstrate how RFID can improve supply chain coordination. [8] review literature on the EPCglobal network’s value proposition; they provide an excellent overview of case studies and industry reports on proposed ways to leverage a supply chain wide RFID infrastructure. [17] follow a qualitative research approach in order to propose cost-benefit sharing schemes for RFID. Related industry publications include [10] and [18], both of which document the importance of incentive problems regarding the adoption of RFID. None of the cited publications addresses the strategic implications of supply chain wide RFID usage in the light of execution problems along the supply chain. We address this research gap by proposing an economic model that captures the combined impact of picking errors and shrinkage as well as inefficient retail store execution on the incentives of both manufacturers and retailers to use RFID cooperatively. By cooperation we mean the minimum of using a uniform tag format so that both organizations can use the data stored on the transponders independently. We therefore explicitly do not consider collaborative scenarios, e.g. SCEM, product recalls, or product authentication, although these applications would without doubt allow the supply chain participants to derive further value from a common tag format. To the best of our knowledge, the particular focus of this work adds a new dimension of execution problems along the supply chain.

II. THE MODEL

A. General Assumptions

The model we use to demonstrate the value and strategic impact of item-level RFID in the supply chain has one manufacturer $M$ and one retailer $R$. We use the term manufacturer only for convenience. It simply denotes the upstream business partner of the retailer which could also be a distributor or wholesaler. The manufacturer delivers a single product to the retailer. After the retailer has placed an order with the manufacturer, the manufacturer picks the corresponding amount of products from her stock and delivers it to the distribution center or directly to a major outlet of the retailer before the start of the sales period. Making or buying this product costs her $c_M$. The per unit revenue she earns by selling the product to $R$ is $r_M$. Thus her profit per unit of product sold is $r_M - c_M$ and the corresponding markup is $m_M = (r_M - c_M)/r_M$. The variable transportation cost that is incurred by the manufacturer is assumed to be included in the production cost.

The retailer sells the product to the end customers. Her profit per unit sold is $r_R - c_R$ where $c_R$ is the purchase cost. The purchase cost is assumed to be equal to the supplier’s revenue per unit, i.e. $c_R = r_M$. We assume that the product is sold for $r_R$ at the retail stores. Thus, the retailer’s relative markup is $m_R = (r_R - c_R)/r_R$.

The retailer makes her order decision according to a one period Newsvendor framework (cf. [19], p. 241). The Newsvendor model is a widely accepted standard for modeling supply chains, especially if simple models for more strategically oriented analyses are required [20]. If the ordered quantity $Q$ in one period is smaller than the number of units $D$ requested by the end consumers during this period, the retailer incurs lost sale costs equal to $(D - Q)m_R r_R$. In case the consumers demand less product units than ordered by the retailer, the remaining products can be salvaged for $s$ per item (e.g. by selling it at a discount at the end of the sales period). If the product cannot be used after the sales period, $s$ is equal to zero. The unit salvage value $s$ lies somewhere in between the unit purchasing price of the retailer, i.e. $(1 - m_R)m_R$, and zero. Equation 1 provides the formula used to obtain the unit salvage value.

$$s = h(1 - m_R)r_R$$

We assume that the "true" consumer demand $d$ during one sales period is a random variable that follows the Normal distribution $N(\mu_d, \sigma_d)$. If the sum of the period demand for a product at all retail stores is sufficiently high, the Normal distribution is an acceptable model of consumer demand because the probability of negative values becomes negligible. Let $F$ be the Cumulative Density Function (CDF) of $N(\mu_d, \sigma_d)$, and let $F^{-1}$ be its inverse CDF. Define $f_1(x)$ to denote the standard Normal Probability Distribution Function (PDF) corresponding to $F^{-1}$. The optimal order quantity according to the Newsvendor model can be computed using the following formula (cf. [19], p. 244):

$$Q = F^{-1}\left(\frac{c_a}{c_o + c_a}\right)$$

In Equation 2 $c_a$ represents the "underage cost" and $c_o$ the "overage cost" per unit. The retailer incurs underage cost if the stocked product quantity does not suffice to satisfy consumer demand. If consumer demand is higher than the number of available stock, she incurs overage cost. In our model the basic underage cost per item is $c_a = r_R - c_R$ and the unit overage cost is $c_o = c_R - s$.

B. RFID Tagging

We assume that if the retailer decides to tag her products, she has to pay for the entire tagging cost. Only if the manufacturer uses RFID and the retailer does not, the tagging cost is incurred by the manufacturer. According to the results of Gaukler [12] this is a reasonable assumption if the retailer is not powerful enough to make the manufacturer give up the corresponding profit margin. The per unit RFID tagging cost is denoted by $t$. This cost encompasses the price of the RFID transponder itself as well as the cost of attaching the tag to the product and virtually associating the unique identifier with the product type. If the retailer orders tagged products, the tagging cost $t$ is included
in the unit purchase price. Therefore the optimal order quantity also depends on \( t \) [12].

C. RFID’s Impact on Store Efficiency

Similar to [12] and others we use the ”shelf stock/back room stock” paradigm to model the in store shelf management process. The back room stock is replenished each time a shipment from the manufacturer or the retailer’s own distribution center arrives at the retail store. Products are replenished from the back room to the shelves whenever necessary. Back rooms exist in most retail settings since the space on the actual sales floor is usually limited. The frequency of replenishments depends on the daily demand and other factors such as the availability of personnel responsible for restocking. Similar to [12] and others we assume that the penalty for empty shelves is lost sales.

Item-level RFID is expected to allow for ”smarter” shelf restocking and thus to help preventing lost sales. We assume that its usage on the sales floor increases the shelf replenishment process to 100 percent. This also implies the usage of an information system that indicates the need for action and helps store personnel to devise replenishment priorities. The cost of purchasing and implementing such a system is deliberately not part of our model. We assume that if the retailer does not use RFID for item-level tracking, she incurs a lost sale every time a customer willing to buy or an inquired sales person does not find it on the shelves. In particular, we assume that without RFID the effective demand \( \bar{d} \) that can be satisfied is only \( 100(1-\alpha)\% \) of the true demand \( d \). If the effective demand \( \bar{d} \) for the considered product decreases, the corresponding demand distribution changes from the distribution of the true demand \( N(d) \) to \( N(\bar{d}(1-\alpha)\mu_d, \sqrt{(1-\alpha)\sigma_d}) \). Let \( F_{\bar{d}}^{-1} \) denote the corresponding inverse function and \( f_{{\bar{d}}}(x) \) denote its PDF (cf. [12], p. 18). Thus, if the retailer does not order RFID-tagged products and therefore cannot exploit its advantages on the sales floor, she maximizes her profit by ordering quantity \( 3 \).

\[
Q_0 = F_{\bar{d}}^{-1}\left(\frac{r_R-c_R}{r_R-s}\right)
\]

If the retailer uses RFID in the stores, she orders quantity 4 (cf. [12], p. 19):

\[
Q_1 = F_{\bar{d}}^{-1}\left(\frac{r_R-c_R-l}{r_R-s}\right)
\]

D. Delivery Errors

The delivery errors we refer to throughout this paper are solely quantity errors. We assume those delivery errors have two main underlying causes: picking errors and shrinkage. Picking errors occur at the manufacturer’s warehouse or distribution center when shipments destined for the retailer are picked and assembled to shipments. Shrinkage can occur at many steps during the delivery process. Products can be misplaced, stolen or spoilt. According to industry reports, employee theft represents one of the most important sources of shrinkage in consumer good supply chains. We model the effect of delivery errors using two random variables: \( y \) for the picking error and \( z \) for the shrinkage.

The random variable \( y \) is assumed to be distributed according to the Normal distribution \( N(\mu_y, \sigma_y) \) with zero mean. Thus, according to our model assumptions, picking errors sometimes result in more and sometimes less items than ordered leaving the manufacturer’s warehouse. Let \( g(y) \) denote the PDF of \( y \) in the following. The standard deviation \( \sigma_y \) of this distribution is assumed to multiplicatively depend on the order size in the following way.

\[
\sigma_y = \theta_y Q_{\{0,1\}}
\]

The parameter \( \theta_y \) scales the variance of over and under deliveries and will be used in the subsequent analyses.

The random variable \( z \) is used for modeling the total amount of shrinkage occurring between the production step and the hand over of shipments at the retailer’s location. We assume that this shrinkage is distributed according to the Poisson distribution \( P(\lambda_z) \). The reason for choosing the Poisson distribution is that undiscovered shrinkage is usually small relative to the ordered quantity and always positive (in contrast to the picking error). According to [19], the Poisson distribution is a useful model for low demand. Let \( h(z) \) denote the PDF of \( z \) in the following. The parameter \( \lambda_z \) of \( P \) represents both the mean and the variance of the distribution (cf. [21]).

The mean and variance of the shrinkage occurring in the supply chain are assumed to multiplicatively depend on the order size in the following way.

\[
\lambda_z = \theta_y Q_{\{0,1\}}
\]

The actual quantity that reaches the retailer’s distribution center is the quantity ordered plus the picking error minus the shrinkage.

\[
Q_{\{0,1\}} = Q_{\{1\}} + y - z
\]

E. RFID Usage in the Supply Chain

The manufacturer tags the products during or right after production. We assume that this approach makes economic sense, whether the manufacturer only ”slaps and ships” or uses the transponders in her own processes. Thus, the RFID system can support the following delivery processes of the manufacturer:

1) Put away process (movement of items from production facility to the manufacturer’s stock)
2) Picking process (assembly of retailer orders and forwarding to the packing station)
3) Packing process (packing of single items into cartons, onto pallets, etc. and preparation of shipments)
4) Goods issue process (movement of shipments to loading bay)
5) Loading process (movement of shipments onto trucks)
6) Transportation process (transportation of retailer order to the retailer’s distribution center or stores)

In each of the mentioned processes, the correct allocation of products to stocking locations and shipments can be validated.
in real time using RFID. For instance, during the picking process the RFID-based system can continuously compare picked products with the items listed on the picking list. The use of RFID readers installed on the loading platform of trucks enables quantity checks while the products are in transit to the retailer’s location. Thus, both picking errors and shrinkage can be detected immediately. The ability to efficiently prove the time and place of product loss can already enable the manufacturer to reduce the financial loss resulting from shrinkage. In particular, we assume that the manufacturer can use RFID monitoring data to obtain financial compensation from the employees who are responsible for certain process, the third party logistics contractor responsible for the delivery, or the insurance company. The retailer can install RFID readers at the goods receipt of her distribution center or outlet. This enables her to conduct a 100 percent count of incoming shipments. Without RFID this is usually not possible, especially at large distribution centers where trucks arrive in minute cycles. We assume that the actual correction of delivery errors is no longer possible at this point. Products that have not been picked may have already been used to fill orders of another customer. Missing products cannot be recovered because they have either been stolen or are in a non-usable state. Although the retailer may be able to detect product shortage later in the distribution process (e.g. when products get forwarded to the stores) she may not be able to convince the manufacturer or any third party that the product was not received in the first place, i.e. that it has not been lost by their own mistake. Furthermore, trade law usually requires that received shipments are inspected immediately and buyers are not entitled for compensation otherwise. We assume that if RFID is implemented, the retailer can immediately prove under deliveries to the manufacturer. Thus, she can obtain the corresponding financial compensation in case too few items of a particular product type have been received.

F. Scenarios

Depending on who uses RFID for which purpose, the outcome in terms of cost incurred and benefits obtained from its use differ. Table I provides an overview of the considered RFID usage scenarios. Assuming that tagging single items at the retailer’s location does not make economical sense, we exclude these cases from the analysis. Moreover, we exclude scenarios where the manufacturer tags her products and offers them at no additional cost to the retailer since this would not be individually rational.

III. NUMERICAL STUDY

A. Setup

The complexity of the many interdependencies implied by our model makes a purely mathematical treatment of the impact of picking errors and shrinkage and thus the expected value of RFID difficult. Hence we resorted to a simulation-based computation of the profit functions, in particular numerical integration. Numerical integration can be used to compute the profit functions for fixed parameter configurations.

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Table II lists the parameters and corresponding values that we used as input for our model. We focus on rather high priced products which is reflected by the considered retail price range ($20 to $60). This range covers typical average prices of DVDs, books, apparel, footwear and certain types of consumer electronics. Since the average unit RFID tag price is currently about 5 Cents, the range of the tagging cost should reflect reality relatively well. The chosen range of the mean consumer demand $\mu_d$ should be regarded as the retailer’s mean estimated demand for one stock keeping unit (SKU) during the entire sales season, i.e. the aggregate demand for this SKU at all outlets operated by the retailer for as long as the product is sold there. The values chosen for the standard deviation of consumer demand $\sigma_d$ vary in a moderate range around the standard deviation of the Poisson distribution which is often used to describe demand distributions in the Operations Management literature (cf. [22], p. 179). The factor $\alpha$ is used to scale the degree of store efficiency. [6] estimate the efficiency of the retail replenishment process from back room to shelf at 90-93%; surveys by ECR Europe carried out by [23] quote similar numbers.

B. Results

We present the results of the numerical study in two steps. First we provide both the absolute profit levels of the supply chain participants in the different scenarios described above. This allows for comparisons of RFID’s impact depending on its usage along the supply chain. We fix the parameters that describe the general supply chain setting at their respective default values and only change the intensity of the error sources, i.e. $\theta_y$ and $\theta_z$.

Figure 1(left) shows the combined impact of picking errors and shrinkage on the profit of the manufacturer in the different scenarios. Only the profit in the "full rollout" scenario remains unaffected by the total delivery error since both picking errors and shrinkage are completely prevented in this case. Due to the manufacturer’s ability to prevent over-delivery, her profit in the scenarios "proprietary tag format" and "manufacturer and store

<table>
<thead>
<tr>
<th>Parameter Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_R$ [20, 40, 60]</td>
<td>Unit sales price</td>
</tr>
<tr>
<td>$m_R$ [20%, 30%, 40%]</td>
<td>Percentage retail markup</td>
</tr>
<tr>
<td>$m_M$ [20%, 30%, 40%]</td>
<td>Percentage wholesale markup</td>
</tr>
<tr>
<td>$h$</td>
<td>0.02, 0.4</td>
</tr>
<tr>
<td>$t$</td>
<td>0.05, 0.1, 0.15</td>
</tr>
<tr>
<td>$\mu_d$ [500, 1000, 1500]</td>
<td>Mean end consumer demand</td>
</tr>
<tr>
<td>$\sigma_d$ [50, 100, 150]</td>
<td>Standard deviation of end consumer demand</td>
</tr>
<tr>
<td>$\theta_y$ [0%, 0.1%, ..., 1%]</td>
<td>Factor of the standard deviation of the yield error $y$ (cf. Equation 5)</td>
</tr>
<tr>
<td>$\theta_z$ [0%, 0.1%, ..., 1%]</td>
<td>Factor of the mean and variance of shrinkage in the supply channel $z$ (cf. Equation 6)</td>
</tr>
<tr>
<td>$\alpha$ [0%, 0.25%, 5%]</td>
<td>Demand lost due to inefficient store processes</td>
</tr>
</tbody>
</table>

TABLE II

MODEL PARAMETERS (* INDICATES DEFAULT VALUE)
We record the following results. At positive values of \( \theta_y \) and/or \( \theta_z \):

1) the manufacturer’s profit in scenario E (“manufacturer and store use”) is greater than in scenario C (“store use only”)

2) the manufacturer’s profit in scenario F (“full rollout”) is greater than in scenario D (“full retailer use”)

3) the retailer’s profit in scenario A (“status quo”) is greater than in scenario B (“proprietary tag format”)

4) the retailer’s profit in scenario F (“full rollout”) is greater than in scenario E (“manufacturer and store use”)

C. Sensitivity Analysis

To make sure that the results presented in section III-B are sufficiently robust within the range of considered parameter values and to show the effect of the different parameters on the value of RFID, we conduct the following sensitivity analysis: All profits are recalculated for the lowest and highest value of every considered model parameter while keeping all remaining parameters at their default value respectively. The levels of picking errors and shrinkage are set to their highest respective value in order to render the profit differences visible. In summary, the sensitivity analysis shows that the results obtained in Section III-B do not depend on the value of the input parameters. However, the profit differences between the scenarios vary based on those values.

IV. Strategic Implications

In this section we analyze the strategic implications of the results presented in the two preceding sections. In particular, we predict the degree of item-level RFID usage in the supply chain by applying basic tools from game theory. Considering the strategic interaction of stakeholders is crucial since in many real world situations the decision of one player can influence the utility of another player and vice versa. In the absence of such externalities or spill-over effects it
In the following we introduce some definitions of non-cooperative game theory tailored to the RFID usage game. We assume that the strategic interaction of the manufacturer and the retailer starts in the status quo. Furthermore, we assume throughout the game theoretic analysis that both players possess complete information. Complete information in the context of our supply chain model implies that the supplier and the retailer know each others profit functions and options for action regarding the use of RFID. Although this is a very strong assumption, this is a useful first step to understand the strategic implications of RFID usage in supply chains.

Games can be fully characterized by the set of players $N = \{1, 2, ..., n\}$, the possible strategies of the players $S_i = \{s_{1i}, s_{2i}, ..., s_{ni}\}$ and the profit of each player $i$ that results from all possible strategy vectors $s \in (S_i)$ [24]. Using game theoretic notation, the RFID usage game can thus be formally described as follows.

**Definition 1:** RFID usage game The supplier $M$ and the retailer $R$ are the players of the RFID usage game. $N$ denotes the set of players, i.e. $N = \{M, R\}$. The utility functions of the players are given by $\Pi_M(s_M, s_R)$ and $\Pi_R(s_M, s_R)$. The strategy space of player $M$ is $S_M = \{s_1M, s_2M, s_3M, s_4M\}$ (cf. Table I). The strategy space of player $R$ is $S_R = \{s_1R, s_2R, s_3R\}$. The game can be fully characterized by the tuple $(N, S_M, S_R, \Pi_M, \Pi_R)$.

In the following we sometimes use the scenario indices A-F to characterize profit functions, i.e. we write for instance $\Pi_M^{A}$ instead of $\Pi_M(s_M, s_R)$. As one can see from the definition of the RFID usage game and also Table I, the applicability of strategies is interdependent. If player $R$ does not request tagging, player $M$ can only chose between $s_1M$ and $s_2M$. Thus, if $M$ does not cooperate with respect to RFID tagging, the $R$ cannot chose strategies $s_2R$ and $s_2R$. These interdependencies require a decomposition of the RFID usage game into subgames. In order to make the analysis of the game more transparent we consider its extensive form in the following analysis. Figure 2 shows the extensive form representation of the RFID usage game if the retailer is first to move. The RFID usage game has three subgames. Subgame 1 is the entire RFID usage game. Subgame 2 begins either if the retailer choses not to request tagging, or if the retailer requests tagging but the manufacturer defects. The only player who can work in the following way: first one considers the last actions of the entire game in extensive form and determines

**TABLE III**

| Parameter | Player Prop. Store Full Man. Full | Ret. tag use use are and rollout |
|-----------|----------------------------------|---------------------------------|---------------------------------|---------------------------------|
| value     |                                  |                                 |                                 |                                 |
| $p = \$20$ | Man. 2.1% 2.6% 1.2% 6.0% 5.0% | Ret. -1.0% 1.8% 4.7% 0.7% 4.5% |                                 |                                 |
| $p = \$60$ | Man. 2.5% 2.6% 1.2% 6.0% 5.0% | Ret. -1.0% 2.1% 5.0% 1.0% 4.9% |                                 |                                 |
| $m = 20\%$ | Man. 2.3% 2.5% 1.2% 6.0% 5.0% | Ret. -1.8% 1.4% 6.4% -0.5% 6.1% |                                 |                                 |
| $m = 40\%$ | Man. 1.9% 2.5% 1.1% 5.9% 4.9% | Ret. -0.7% 2.0% 3.9% 1.3% 3.8% |                                 |                                 |
| $h = 0\%$  | Man. 4.0% 2.6% 1.0% 8.5% 6.8% | Ret. -1.0% 1.8% 4.7% 0.7% 4.5% |                                 |                                 |
| $h = 0.4\%$ | Man. 1.2% 2.6% 1.3% 4.7% 4.1% | Ret. -1.0% 2.1% 4.7% 0.7% 4.5% |                                 |                                 |
| $t = \$0.05$ | Man. 2.7% 2.6% 1.2% 6.0% 5.0% | Ret. -1.0% 2.2% 5.1% 1.2% 5.0% |                                 |                                 |
| $t = \$0.15$ | Man. 1.5% 2.5% 1.1% 5.9% 4.9% | Ret. -1.0% 1.8% 4.7% 0.7% 4.5% |                                 |                                 |
| $\mu_1 = 600$ | Man. 2.1% 2.4% 1.0% 5.9% 4.9% | Ret. -1.1% 1.9% 5.1% 0.7% 4.9% |                                 |                                 |
| $\mu_4 = 1500$ | Man. 2.1% 2.5% 1.2% 5.9% 5.0% | Ret. -1.0% 1.8% 4.6% 0.7% 4.5% |                                 |                                 |
| $\sigma_d = 50$ | Man. 2.1% 2.6% 1.2% 6.0% 5.1% | Ret. -1.0% 1.7% 4.5% 0.7% 4.5% |                                 |                                 |
| $\sigma_d = 150$ | Man. 2.1% 2.5% 1.1% 5.9% 5.0% | Ret. -1.1% 1.8% 4.8% 0.7% 4.6% |                                 |                                 |
| $\alpha = 0\%$ | Man. 2.1% -0.1% -1.4% 3.2% 2.3% | Ret. -1.0% -0.9% 1.9% -1.9% 1.8% |                                 |                                 |
| $\alpha = 5\%$ | Man. 2.1% 5.3% 3.8% 8.8% 7.8% | Ret. -1.0% 4.6% 7.6% 3.5% 7.5% |                                 |                                 |

suffices to find the maximum profit of a stakeholder provided her own action alternatives in order to predict her decision. As the previous analysis has revealed, there exist significant spill-over effects regarding the deployment of item-level RFID along the supply chain. For instance, if the manufacturer does not tag products, the retailer cannot use them to make store operations more efficient. Depending on the “natural” level of store inefficiency, the decision of the manufacturer can thus have a negative impact on the retailer’s profit. We speak of negative externalities in this case. The spill-over effect can also be observed in the opposite direction, i.e. actions of the retailer can affect the manufacturer’s profit. For instance, if the retailer can increase shelf availability by using RFID in her stores, the manufacturer benefits from the higher demand of the retailer. Since the choice of the retailer to use RFID in the stores has a positive impact on the manufacturer’s profit, we speak of positive externalities. Another example for a negative externalities is when the manufacturer uses RFID unilaterally for preventing over-deliveries. In this case the retailer suffers from the manufacturer’s exclusive use of the technology. The existence of measurable externalities motivates the game theoretic analysis presented in this section.
which strategy the final mover has to implement in order to maximize her profit. One then supposes that the last mover will implement this strategy, and considers the second last mover, again choosing the strategy that maximize that player’s profit. This process continues until one reaches the first move of the game. The remaining strategies are all subgame perfect equilibria. In order to determine the subgame perfect equilibria of the RFID usage game we carry out backward induction using the extensive form of the game shown in Figure 2.

To begin with we determine the Nash equilibrium of subgame 2. The formal definition of Nash equilibria is provided in Definition 2.

**Definition 2**: Nash Equilibrium The strategy vector \( e^{NE} \) is a Nash equilibrium of the game \((N, (E_i), (\Pi_i))\) if\[
\Pi_i(e_i^{NE}, e_{-i}) = \Pi_i(e_i \neq e_i^{NE}, e_{-i}) \quad \text{for all players } i \in N.
\]

Translated into human language, the outcome of a game is a Nash equilibrium if no player has an incentive to unilaterally deviate from it by choosing a different strategy. Since only the manufacturer has a choice to make in this game, the solution is simple. She picks strategy \( s1_M \) if \( \Pi_M(s1_M, s1_R) > \Pi_M(s2_M, s1_R) \) and \( s2_M \) otherwise. The corresponding outcome is the Nash equilibrium of subgame 2. The results of Section III show that from certain values of \( \theta_y \) onwards \( \Pi_M^F > \Pi_M^E \) is true and that otherwise the opposite is true. Thus, the Nash equilibrium of subgame 2 depends on the intensity of the delivery error.

Next we determine the Nash equilibrium of subgame 3. It can easily be shown that this approach is equivalent to solving the subgame by backward induction under complete information. Given results (i-iv) of Section III-B which state that \( \Pi_M^E > \Pi_M^C \), \( \Pi_R^F > \Pi_R^E \), and \( \Pi_M^F > \Pi_R^F \) for all positive values of \( \theta_y \) and/or \( \theta_z \), it can be shown that the strategy configuration \( (s4_M, s3_R) \) (“full rollout”) is the only one that fulfills the conditions of a Nash equilibrium in subgame 3. This result implies that in case the game reaches the point where subgame 3 begins, the manufacturer will seek to completely prevent delivery errors by using RFID technology for monitoring the picking and shipping process and the retailer will use RFID both in her stores and at the goods receipt.

Given the unique Nash equilibrium of subgame 3 the backward induction can continue. When the game reaches the stage at which the manufacturer has to decide whether to cooperate or not, she is can choose to cooperate and obtain a profit of \( \Pi_M^F \) (the unique Nash equilibrium of subgame 3) or to defect and realize a profit of either \( \Pi_A^M \) or \( \Pi_B^M \) (the unique Nash equilibrium of subgame 2). The numerical results presented in Section III-B show that \( \Pi_M^F \) is always greater than both \( \Pi_A^M \) and \( \Pi_B^M \) for the considered value ranges. However, as can be inferred from Figure 1, \( \Pi_B^M \) steadily increases with \( \theta_y \) and/or \( \theta_z \) whereas \( \Pi_A^M \) remains constant. Therefore \( \Pi_M^F \) can theoretically become greater than \( \Pi_B^M \) if picking errors occur more frequently than considered in the numerical study or if the retailer cannot substantially increase the efficiency of her store processes using RFID (cf. Table III).

Based on the above information we can infer the decision problem of the retailer at the beginning of the RFID usage game. If she decides not to request tagging, the manufacturer can still decide to use RFID unilaterally which is a plausible strategy if the total delivery error is sufficiently high. This outcome would make the retailer strictly worse off than in the status quo if the manufacturer prevents over-deliveries resulting from picking errors but permits under-deliveries. If she decides to request tagging, she will thus either realize \( \Pi_A^M \), \( \Pi_B^M \), or \( \Pi_F^M \). Provided the knowledge gained from the numerical study, the chances are fairly high that \( \Pi_F^M \) is greater than both \( \Pi_A^M \) and \( \Pi_B^M \) and will therefore constitute the unique equilibrium of the RFID usage game. The scenario "proprietary tag format" can be an equilibrium whether the retailer takes action or not. Hence, by asking the manufacturer to tag products the retailer simply adds the advantageous "full rollout" scenario to the possible outcomes of the RFID usage game. The retailer’s optimal strategy is thus to request tagging in the first stage of the RFID usage game if her profit in the "full rollout" scenario is greater than in the status quo.

If the manufacturer is first to move in the RFID usage game, the subgame perfect equilibrium obtained does not differ from the one obtained if the retailer moves first. The game then simply starts at the node where the manufacturer decides to cooperate or to defect.

**V. LIMITATIONS**

Our results have to be seen against the background of a number of limitations mentioned in this section. Similar to previous model-based work on RFID value (e.g. [5]), we do not consider the fixed costs of RFID readers, infrastructure, and further IT investments that are necessary to implement item-level RFID. These costs can be estimated fairly well in practice and do not depend on the other model parameters (unlike the tagging cost). Furthermore, the implemented RFID infrastructure is used for not only one type of
product but for all tagged products that move through the supply chain. Thus, the ultimate return on investment resulting from the usage of item-level RFID can be calculated by taking the profit values resulting from our model and comparing these to the estimated fixed costs, e.g. by conducting a net present value analysis.

In order to calculate the benefits obtained from monitoring the supply chain, we had to make a number of assumptions regarding the business conduct of the considered RFID stakeholders. First of all, we assume that the business partners act in their own self-interest and therefore strive to increase their profits even if this means to reduce the profits of the respective business partner. In some business environments this assumption may not be justified, for instance because the retailer does not want to strain the business relationship with the manufacturer.

Publicly available information about execution errors in different types of supply chains is sparse. Whereas empirical research on store efficiency is becoming increasingly available, the accuracy of picking and delivery operations still seems to be a well-kept secret. In particular the amount of shrinkage due to employee theft is a delicate topic. Since most RFID benefits in the supply chain result from the detection and prevention of errors, it is crucial for companies evaluating RFID to collect reliable data on the frequency and dimension of such errors.

VI. CONCLUSIONS

The main research questions treated in this paper are whether cross-company item-level RFID makes economical sense and how strategic reasoning affects the economic incentives for a cooperative RFID rollout. In order to answer these research questions, we have proposed an economic model regarding the business conduct of the considered RFID stakeholders.

The emergence of the predicted RFID usage equilibrium can lead to a visible increase of the individual profits of both manufacturers and retailers. Thus our results put the need to cost sharing arrangements into perspective. Both, the predicted deployment of standardized RFID infrastructures along the supply chain as well as the non-existence of economic incentives to restrict sharing RFID data in supply chain partnerships are preconditions of the eventual full realization of RFID benefits.

REFERENCES