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RFID TECHNOLOGY IN SUPPLY CHAIN MANAGEMENT: STATE OF THE ART AND PERSPECTIVES

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Abstract: This paper provides a state of the art on RFID technology in Supply chain management. It presents technical characteristics of existing RFID systems, a guideline for RFID deployment, and some applications in Supply chains. The paper summarizes the advantages of RFID technology for inventory control and introduces some challenging problems and perspectives dealing with, in particular, privacy and authentication. In addition, there is a carefully selected recent bibliography in this domain. *Copyright ©2008 IFAC*

Keywords: Supply Chain, RFID technologies, Inventory control, Information sharing, Privacy, Authentication.

1. INTRODUCTION

RFID has been around for decades. The RFID concept was introduced during World War 2 to distinguish allied aircrafts from the enemy (Stockman, 1948; Want, 2006). But only recently have the convergence of low cost, increasing capabilities and the creation of electronic product code (EPC) made this technology more and more attractive.

EPC is the standard designed to assign a unique identifier to each item. EPC consists of four sequences of binary digits: an eight-bit header, the EPC manager (28 bits), the product type (24 bits) and the serial number of the product (36 bits). The EPCglobal Inc. oversees the development of the standard. EPCglobal is a joint venture of the UCC, which regulates bar code use in the US and EAN that is in charge of the regulation in the rest of the world.

RFID can be defined as an automatic identification technology composed of:
- Tags incorporated into or attached to any kind of object (products, tools, animals, goods, human being, etc.),
- A specialized RFID reader which reads the information stored in the tags and transfers them to a processing device (a computer for instance).

RFID systems can be considered as the successors of bar codes. They are several key differences between RFID and bar code:

- Unlike bar codes, data are not gathered manually and, since companies have a great number of products, using RFID leads to a drastic reduction in workload.
- When using a bar code, the operator has to scan the items one by one, while the RFID reader can automatically receive information from the tags.
- RFID scanning can be done at greater distances than bar code. The scanning distance of RFID depends on the type of system as explained hereafter.
- The constraints that apply to the positioning of the tags are much weaker than the constraints to satisfy when bar codes are concerned. Tagged objects can be read in different orientations at high speed. Orientation sensitivity depends on antenna design.
- Tags can store more data than bar codes.
- RFID readers can communicate with multiple tags. As a consequence, it is possible to capture the information concerning an entire shipment.

Another comparison of RFID to bar codes is reported in (Penttilla et al., 2004) where main characteristics of the existing RFID devices are also presented.

One of the main objectives of this paper is to provide an overview of the recent developments in RFID. Numerous applications of RFID already exist (Chappell et al., 2002) and some of them are presented in this paper. A particular attention will be paid to supply chains (Sahin, 2004; Gaukler, 2005; Gunasekarana and Ngai, 2005). It will be show in the next sections how using RFID better deals with process complexity, product variety, market uncertainty and data inaccuracy. This, in turn, results in the reduction of: labor cost; number of discrepancies between invoices and deliveries; product shrinkage (loss of products due to theft, misplacement of items in the storage area, inaccurate handling information, etc.); fraud by reducing the counterfeiting of high value products; to quote only a few.

Contrarily to certain states of the art, this article is not compiled from short abstracts of publications, but presents the authors' analysis and point of view on the domain. It contains a meticulously selected bibliography of the more interesting recent papers. The authors recommend reading most of these papers before any project on RFID implementation for Supply chain management. Note: a complementary literature review which gives also the number of publications on RFID in different scientific journals is presented in (Ngai et al., 2007).

The remainder of this paper is organized as follows. Section 2 presents in general the technical characteristics of RFID, Section 3 deals with the implementation of RFID with a guideline provided. In Section 4, several possible applications of RFID for Supply Chain management are suggested and analyzed. Section 5 summarizes the advantages of RFID technology and Sections 6 and 7 are dedicated to challenging aspects as privacy and authentication. Finally, concluding remarks are given in Section 8.

2. TECHNICAL OVERVIEW

2.1. General description

As aforementioned, an RFID system consists of a reader (also known as *interrogator*) and a tag (or *transponder*), which is a silicon chip connected to an antenna. When a tag passes through the field covered by a reader, the information stored in the tag is transmitted to the reader.

A tag can be *passive* or *active*. An RFID system based on passive tags is as follows. The antenna of the reader creates an electronic magnetic field (EMF) within the antenna of the tag. The antenna of the tag draws energy from this field and stores it in a capacitor (inductive coupling) which releases this energy into a coil embedded in the tag, which, in turn, allows the tag to emit radio waves that are transformed into digital information representing the EPC.

An RFID based on active tags contains a battery that provides the energy to the antenna, which is necessary to send encoded radio waves to the reader. A third type of tags, called semi-passive tags, contains a battery that provides energy to the chip but the reader field is still used for the transmission from tag to reader. Active and semi-passive tags are used to track high value items that have to be scanned over longer distances. For more details on RFID principles see (Finkenzeller, 1999; Want, 2006).

As outlined by (Prater et al., 2005; Smith, 2005), RFID technology makes it possible automatic data capture and identification. As mentioned before, RFID technology is the successor of the well-known bar codes. Please keep in mind that the two main advantages of RFID over bar code are as follows:
- RFID goes a step further for the information related to an item, emitting a unique identifier for each item, which distinguishes it from other identical items.
- RFID tags are readable without precise positioning and line-of-sight contact as opposed to bar codes which require carefully positioned items and line-of-sight contact with the reader.

2.2. Properties

The cost of passive tags is less than 0.2 euros each, with an objective of 0.05 euros in the near future. Their data storage capacity is low (less than 256 bytes), which is just enough to store an item identification and a limited history. One advantage of passive tags is their size which is less than the size of a dime, which makes them easy to incorporate or attach to items. These advantages, low cost and reduced size, occur at the expense of read range. The read range of a tag depends on both the power of the reader and the frequency used to communicate. A higher frequency increases the tag's read range, but this requires more energy from the reader. The read range of a passive tag can not exceed 5 meters using stationery based readers at a frequency ranking from 860 Mhz to 930 Mhz, and 20 centimeters using hand held readers. Furthermore, any metal surface is an impassable barrier for reading a passive tag.

Passive tags are the most widely used in RFID applications and their life expectancy is much longer than active tags. Nevertheless, they are still too expensive to be used on a massive scale. Therefore, passive tags are mainly attached to reusable pallets or cases, making it impossible, for the time being, to track every single item. Item-level tagging is the next step of RFID deployment. For the consumer side, security and privacy issues will be concerns, as will be explained further.

Semi-passive tags have a battery built in, which allows them to function with much lower power provided by the reader's field. As a consequence, they have a read range of up to 100 meters.

Active tags are totally energy independent from the reader. This allows them to communicate at distances of several kilometers. Furthermore, a metal surface is no longer an impassable barrier. Active tags can remain dormant until they exposed to the field of the reader. Moreover, they can constantly broadcast a signal. Currently, active tags have a memory capacity from 32 to 128 Kb. One drawback of these tags is that the quality of the embedded battery is difficult to evaluate, which results in a random lifetime of the tag. Another problem is the cost of active tags, this cost resulting mainly from the build-in battery. For the same reason, the size is quite important: the size of a playing card.

The ship included in the tag can be either read-write or read-only. Indeed, read-write tags are much more expensive than read-only tags, but the application range is broader. In particular, a read-write tag is convenient when the information concerning the items change according to their production stage. For a long time, readers were supposed to take care of a limited flow of tags containing a low volume of data. The current and new tendency is to develop readers to treat large numbers of tags containing a high volume of data each.

A major issue with readers has to do with the frequency in which they communicate with the tags. Frequencies are regulated by governments, and a frequency available for RFID in one country may be unavailable in another.

As mentioned before, the cost of tags is a parameter that will play a major role for the development of RFID. As commonly accepted, the 5 cents a tag is the limit below which wide adoption of RFID technology will occur. The only way to reach this limit is to find alternative tag designs and more efficient tag manufacturing processes.
Most of the attempts in the alternative tag design evolve around chipless tags. Among others, it can be mentioned:

- Chipless tag that uses surface acoustic waves technology (SAW) that propagates radio frequency acoustic waves on the surface of polished crystals.
- Chipless tag that uses nanotechnology genomes.

Apart from reducing the cost, the chipless technology is more easily applicable near metal and liquid, which are impassable barriers for passive tags. Improving tag packaging is another way of research for specific uses of tags and for reducing manufacturing cost.

2.3. Parameters of importance when selecting tags

The selection of tags depends on the work to be done. The communication distance is certainly the first parameter to consider. The size of the tag is another important parameter: it is constrained by the type of item to which it should be attached (or incorporated). The environment is another parameter of importance. The following questions should be answered: what will be the temperature exposures? Will the environment be harsh (corrosion, humidity, steam, dust …)? May the environment be disturbing for communication between readers and tags (presence of other radio devices or electrical noises, proximity to other tags)? May metal disturb communications?

It is also necessary to check if tags must be reusable and what are the constraints related to the orientation of the tags in relation to the orientation of the reader. Other parameters to consider are the communication protocols (EPC) and the operating frequency (LF, HF or UHF) that depends on the application and may be constrained by regulation.

Indeed, the volume of data to be carried by the tags (the *granularity*) and the speed of the items carrying the tags are of utmost importance.

It is also necessary to mention data security and anti-collision aspects (How many tags are in the field of the reader at the same time? Do signals emitted by different readers interfere?). Thus, anti-collision is related to avoiding confusion between data carried by different tags when they are in the reading environment of the same reader, but also interference of signals of different readers. The number of tags that can be identified "simultaneously" depends on the protocol used and the frequency of electromagnetic waves. Typically, this number ranges from 50 tags / second for HF to about 200 tags / second for UHF.

Finally, the selection of the reader will depend on the tags to be treated.

2.4. The Auto-ID Center (Auto-ID Labs)

Founded in 1999, the Auto-ID Center is a unique partnership between almost 100 global companies and seven of the leading research universities: the Massachusetts Institute of Technology (MIT) in the US, the University of Cambridge in the UK, the University of Adelaide in Australia, Keio University in Japan, the University of St. Gallen in Switzerland, Fudan University in China and Daejeon ICU University in Korea, for more details, see: www.autoidlabs.org.

The Auto-ID Center has developed an EPC global network system, which is an Automatic Identification, Data Capture and Sharing (AIDCS) system that combines RFID with several other technologies in order to be able to track items through a supply chain and share information between the participants to the supply chain using Internet (Chappell et al., 2002; Kang and Gershwin, 2005).

To avoid interferences between signals issued from different readers. This new global network system uses the Time Division Multiple Access (TDMA): the readers are programmed to read tags at different times instead of simultaneously.

To avoid the problem that arises when a reader has to read several tags in the same field, the Auto-ID Center developed a system that ask tags to respond only if their first digits match the digits emitted by the reader.

To solve the frequency problem, the Auto-ID Center has designed reference specifications that allow reading chips of different frequencies (agile readers). This saves the cost of having a specific reader for each frequency.

3. GUIDELINE FOR RFID DEPLOYMENT

Some information have been previously given concerning the choice of tags, but an effective use of RFID needs a perfect integration of the techniques in the environment of the company and, particularly, in the IT infrastructure.
In this section, some of the most important factors, which should be considered when introducing RFID in a production system, more precisely, in a supply chain, are emphasized.

3.1. Choice of the technology

As mentioned in the *RFID Journal*, March 31, 2003, decision makers have to take into account the following three general aspects:
(i) The needs of their corporate environment. This has to do with the evolution of the corporate environment regarding RFID, and thus to competitiveness,
(ii) The needs of their trading partners. For instance, the well known example of Wal-Mart shows that a powerful customer can force his providers to use RFID,
(iii) The needs of the industry that is concerned, and thus of the production performed by the company. For instance, valuable goods or time-dated products may require specific abilities from the RFID.

Some other aspects are discussed in (Sbihli, 2002; Violino, 2003).

3.2. Analysis of the problem that may happen

Some problems have already been mention in section 2.3 as far as tags are concerned.

Some other problems may result from an inappropriate handling of items. To face this kind of problems, it is usually necessary to establish handling procedures. The collision problems already mentioned in section 2.4 should be also included in this analysis.

3.3. Matching RFID with IT

As mentioned before, introducing RFID in a supply chain is not only a technical problem. The RFID technology has some characteristics that may oblige the company to reorganize and, possibly, redesign its IT system.

The first characteristic of importance is the volume of data to handle, due to:
- The real time data exchange related to the use of RFID which force to automate some of the activities that were previously performed by employees. Thus, the expertise of some employees and managers should be analyzed and translated into software, which also drastically increases the volume of data to be processed.
- The tendency to increase the *granularity* (i.e. the volume of information concerning an item) in order to develop more automated applications related to maintenance, security, quality, real time management, etc.
- The automation of the integration of the new system with upstream and downstream

applications. This will also require a huge analysis and programming work.

This usually requires redesigning the whole data processing and communication system. Thus, the implementation of RFID applications requires expanded, and even new, IT infrastructure. New computers, application programs, tag readers and antenna will be disseminated in distribution centers, transportation resources, factory floors and warehouses. This will create new services around IT.

4. RFID APPLICATIONS

4.1. Application to inventory systems

4.1.1 Causes of inventory inaccuracy
Retailers are rarely perfectly aware of the number of items in their inventory (Brown et al., 2001). At least once a year, a physical count of SKUs (Stock Keeping Units) is conducted on the occasion of drawing up the inventory. Comparing the actual quantities stored with the quantities in the inventory records is often surprising. As mentioned in (Kang and Gershwin, 2005), the best situation is the one where 75 to 85% of inventory records match perfectly the actual inventory.

The reasons of inventory inaccuracy fall usually in four categories:
- ***Stock loss***, which is apparently the category that contains the most usual explanations of the discrepancy between actual inventory and recorded inventory. Stock loss is called *shrinkage* in industry. It may be due to defects caused by inappropriate handling, theft, out of date when time-dated items are concerned, to quote only a few. Undetected shrinkage does not lead systematically to updating inventory records. As a consequence, further decisions are made based on false data.
- ***Transaction errors*** (Dolgui et al., 2005). For instance, this may happen when the shipment records are taken for granted and do not reflect the physical inputs of the inventory. It is the case when the employees in charge of inventory management rely on shipment records to reduce work load. Other transaction errors are label errors or approximate checkouts. It can be also mentioned in this category the case of items that are introduced in the inventory without being recorded.
- ***Inaccurate location*** of items in the inventory or inaccessible items (for instance, heavy items such as truck engine stored behind other engines).
- ***Incorrectly labeled items.*** This may happen when wrong labels are attached to items.

4.1.2. An illustrative example
In the following example, it will be shown that inventory inaccuracy may lead a substantial loss in the bottom-line profit. This example concerns a unique item.

Well in advance, the wholesaler orders a quantity q_0 to the provider. The deadline accepted by the wholesaler is *t*. At the same time, the wholesaler makes a commitment to the retailers, informing them that a quantity q_0 will be available at time *t*. The selling activity will take place on a unique period (one month, for instance), and there is no supply option (i.e. no replenishment can take place during the selling period).

The quantity q_1 that will be really available at time *t* is different from q_0. It will be assumed that $q_1 < q_0$, due to stock loss, inaccurate location or incorrectly labeled item in wholesales stocks. Nevertheless, the inventory costs should be computed based on q_0 (and not q_1) since q_0 items have been delivered to the wholesaler.

To simplify the formulation, it is considered that $q_1 = q_0 \times (1-\alpha)$, $1 > \alpha > 0$. The total demand of the retailers is random and function of q_0. More precisely, the demand is a random variable *X* that takes its values on $[\ 0, q_0\ ]$. The demand is supposed to be continuous. The density of probability of *X* is $f_X\ (x) = \exp\ (a \times x) - 1$, with $a > 0$. Indeed, $\int_0^{q_0} f_X\ (x)\ d\ x = 1$, which leads to the value of a by solving:

$$\int_0^{q_0} [\ \exp\ (a \times x) - 1]\ d\ x = \frac{1}{a} [\ \exp\ (a \times q_0\ )\ ] - q_0 = 1$$

For instance, for $q_0 = 4$, $a = 0.107711$.

Two costs should be taken into account:
- The inventory cost *IC* that is computed as follows: $IC = ic \times [\ q_0 + q_0 - x\ )\ ] / 2$, where x is the demand and *ic* of the inventory cost of one unit during the selling period. This expression is based on the assumption that the flow of items sold is constant during the selling period. This assumption is common in inventory management,
- The backlogging: $BC = -bc \times Min\ (q_1 - x, 0)$, where bc is the backlogging cost of one unit during the selling period. In this expression, $-Min\ (q_1 - x, 0)$ is the demand that is not satisfied at the end of the selling period.

For each value of α, 1000 simulations have been made, and the mean values of *IC* and *BC*, denoted by $\overline{IC}$ and $\overline{BC}$ respectively, have been computed, as well as the total average cost $\overline{TC} = \overline{IC} + \overline{BC}$. The results for $\alpha = 0, 0.01, \ldots, 0.19, 0.2$ are given in Figure 1.

In this example, $q_0 = 10$, the inventory cost is $ic = 2$ and the backlogging cost is $bc = 25$. As you can see, the greater α, the greater the backlogging cost, but the inventory cost remain the same because, even if an item is lost, inaccurately located or incorrectly labeled, it belongs to the store and participates to the inventory cost.

Assume now that a tag is attached to each item. In this case, it is hard to lose items since locating a reader at the place items should be stored would prevent them to be misplaced and theft would become very difficult using readers at the right places. In fact, the only possible error would be to store wrong information in the tags, which is rare if the initial information is double checked.

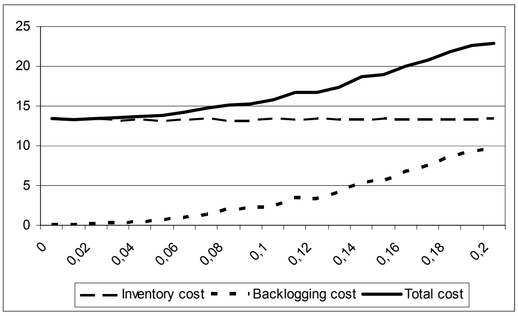

Figure 1: Cost versus α

As foreseen, the backlogging cost increases as α increases: this represents the cost resulting from the inaccurate inventory or, in other words, from shrinkage. Thus, introducing an RFID system would reduce this cost and improve retailers' service, which is of utmost importance from a commercial point of view. Indeed, the cost of introducing an RFID system remains to be evaluated.

The objective of this simple example was to give an insight of RFID use in inventory management. Some other interesting examples are given in (Lee et al., 2004; Kang and Gershwin, 2005; Fleisch and Tellkamp, 2005; Lee and Ozer, 2007; de Kok et al, 2007; Rekik et al., 2007). Additional applications are currently emerging as, for instance, real-time shipment processing and automated inventory updating at distribution centers (Garcia et al., 2006) and e-supply chain in grocery retailing (Prater et al., 2005).

4.2. RFID in Supply Chains

4.2.1. A three echelon supply chain

To illustrate the influence of RFID on supply chains, a simple three echelon supply chain that is composed of a manufacturing system (MS), a distribution center (DC) and *n* retailers is considered.

The daily production of the MS is shipped to the DC once a day. One day is required to transfer products from MS to DC. This includes the packaging, the transportation, the physical assignment in the DC and, if applicable (that is if RFID is not used), the registration of the transfer.

A retailer is composed of a storage facility, called backroom (BR), and a shelf (SH) to display the products. Two days are required to transfer products from the DC to anyone of the retailers' BR. The replenishment of a shelf decided at day *j* takes effect at day *j*+1. Only one product is concerned in this example.

The dynamics and management of the supply chain can be summarized as follows:

- Every single day, shelf *i*, $i \in \{1, 2, \ldots, n\}$, has to meet the demands of customers. The sum of the demands during one day is the value taken by a random variable that obeys to a Poisson rule of parameter λ_i.
- The replenishment of shelf *i* is based on a (s_i, S_i) policy: as soon as the number x_i of products in the shelf becomes less than s_i, a quantity $S_i - x_i$ is taken from the BR and transferred to the shelf. This quantity will be available to customers the next day.
- The replenishment of backroom *i* is based on a (ss_i, SS_i) policy, and replenishments are ordered from the DC.
- Every evening, each retailer *i* informs the MS of the quantities d_i sold during the day. The MS will launch the total demand, that is $D = \sum_{i=1}^{n} d_i$, in production the next day. It is assumed that the MS is flexible enough to perform the production of D units in one day.

The model is represented in Figure 2.

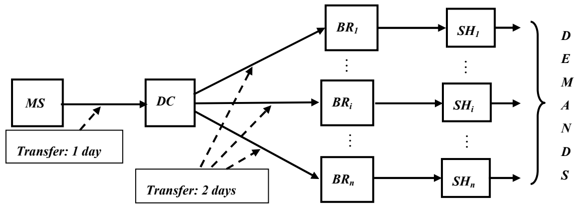

Figure 2: A supply chain with three echelons

Assume that:

- At the MS level, the manufacturing problems (lack of quality, for instance) are solved by the end of the same day. In other words, the efficiency of the MS can be considered as being perfect,
- The shrinkage in the DC is equal to *a*% of the items that are present in DC at the beginning of the day.

This percentage includes the shrinkage during the transfer between MS and DC,
- The shrinkage in the backroom of retailer i is equal to v_i % of the items in this backroom at the beginning of the day. This percentage includes the shrinkage during the transfer between DC and the backroom,
- The shrinkage in the shelf of retailer i is equal to w_i % of the items in the shelf at the beginning of the day. This percentage includes the shrinkage during the transfer between the backroom and the shelf.

It is also assumed that a stock taking is done once every *Js* days in the BRs and SHs and every *Jd* days in the DC. When a retailer does a stock taking, he / she observes that the quantities in the shelves and the backrooms are less than the registered quantities (i.e. the quantities stored in the computer). This is due to the shrinkage. As a consequence, the numbers of items in the shelves and the backrooms, which are stored in the computer, should be reduced to fit with the real values provided by the stock taking. Due to the management of the system presented above, i.e. using the (*s*, *S*) policy, additional items are automatically ordered by the shelves to the backrooms, and by the backrooms to the DC. The management of the DC is slightly different: when a stock taking happen, the total shrinkage from the previous stock taking is added to the quantity to be manufactured by the MS the next day.

4.2.2. Deployment of RFID

Let an RFID be deployed and tags introduced at the item level (in other words, one tag is attached to each item). Thus, each single item is tracked in the supply chain, which ensures that each item that disappears from the system is detected the same day. Indeed, some undetected shrinkages (for instance, shrinkages due to lack of quality) exist; It is the case of items belonging physically to the inventory, but not usable, when completed, for lack of quality.

Finally, when an RFID is not deployed, the existence of shrinkage is detected and corrected only periodically, at the time a stock taking is performed. In the meantime, the system is managed based on the data stored in the computer, which are inaccurate. This leads to stock shortage and delays to customers. To face shrinkages, the solution is to increase the initial inventory level of the shelves, the backrooms and the DC. The numerical examples presented in the next section will illustrate these remarks.

4.2.3. Illustrative examples

The three echelon supply chain presented in Figure 3, with three retailers is considered. The daily demands to the retailers are the same and follow a Poisson rule of parameter 2, which means that the mean daily demand to a retailer is 2. Let *Js* = 100 and *Jd* = 300.

Simulations of 15 000 days have been performed to evaluate the number of stock shortages at the different levels of the supply chain according to percentage of undetected shrinkages. The (*s*, *S*) replenishment policy is (15, 20) for the shelves and (20, 30) for the backrooms. Note that the behaviors of retailers are identical on the average.

As shown in Figures 3, 4 and 5, when the proportion of shrinkage increases, there is more and more often stockouts at each level of the supply chain. To face this situation when RFID is not in use, it is possible to postpone deliveries and / or keep inventories to avoid stock shortages. Another solution is to increase the frequency of stock takings.

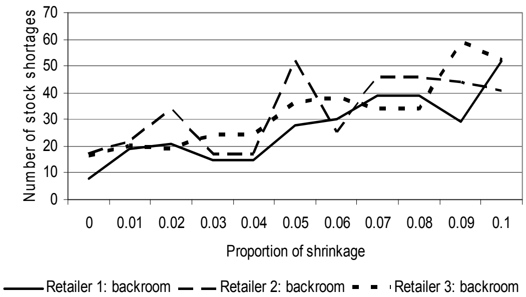

Figure 3: Stock shortage in the shelves according to the proportion of undetected shrinkages

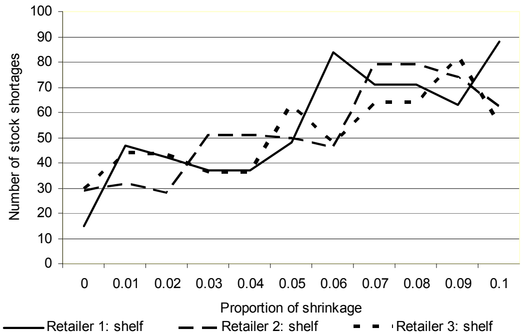

Figure 4: Stock shortage in the backrooms according to the proportion of undetected shrinkages

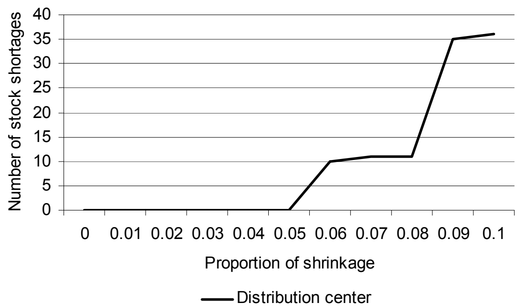

Figure 5: Stock shortage in the DC according to the proportion of undetected shrinkages

The best behavior of the supply chain arises when stock takings are performed every day: it is what RFID makes possible, at least partially.

This example illustrates the interest of using RFID for the case of shrinkages. McFarlane and Sheffi (2003) presented some other challenging aspects of RFID in supply chain operations and introduced the main elements of using such a system. A study on the economical assessment of the impact of RFID for a special case of supply chain is reported in (Bottani and Rizzi, 2007). An interesting work on the valuation of RFID technology in military applications for ordnance inventory is exposed in (Doerr et al, 2007).

4.3. Applications related to movement tracking

Applications related to movement tracking are varied (Brewer et al., 1999). In this section, some of these applications in different activity domains are presented.

In some hospitals, tags are attached to newborn babies in order to prevent kidnapping and to secure the identity of babies. Another application in hospitals is to track equipments as they move from room to room. This reduces theft and facilitates resource and maintenance management. A third application consists of associating tags to surgical patients and storing the surgical procedures in the tags: this prevents surgical mistakes.

Some schools required children to wear bracelets in which tags are incorporated to monitor attendance and locate children.

In Taiwan, RFID is under study to improve delay in import cargo customs clearance in air cargo terminal. This is motivated by a study of the International Air Transport Association (IATA) that found that flying account for only 8% of total transport time while clearance requires 92% of the time. For more details on baggage tracking, see for example (Croft, 2004ab). An interesting approach on the design of an automated warehouse for air cargo is presented in (Oudheusden and Boey, 1994).

Similar applications can be found in car shipment yards where RFID is used to build the shipment loads. The fact that information are provided in real time by the wireless tracking system allows reducing drastically vehicle dwell time, improve customer satisfaction and increases transportation resource utilization.

Numerous companies use RFID to track item movements. Three well-known examples are mentioned hereafter:
- Unilever uses RFID to track its customer products in the warehouses.
- The port of Singapore implemented RFID in conjunction with an electronic data interchange (EDI) to track containers in the port and to manage their arrival and departure.
- The Mexican Ford Motor Company facility uses RFID for the routing of vehicles through the automated manufacturing systems.

An analysis of the practical benefits of RFID in the context of a re-entrant manufacturing process in a semiconductor fab is reported in (Thiesse and Fleisch, 2007).

Some unusual applications are mentioned in the literature as, for instance, the following ones:
- In 2004, members of the Baja Beach Club of Barcelona received syringe-injected RFID tag implants, which enabled them to pay for their drinks automatically, without being obliged to reach their credit card or their wallet.
- In some golf clubs, tags are incorporated into the balls, so that balls can be located easily by means of portable readers.

Numerous applications already exist in the everyday life such as:
- Proximity cards (cards used to enter protected areas, for instance).
- Automated tool payments transponders.
- Ignition keys of some vehicles. They include RFID tags and are able to reduce theft risk.

Putting imagination at work, the following applications are conceivable:
- If tags are incorporated in clothes, they can communicate with the washing machine and transfer the characteristics of the clothe material so that the machine can select automatically the appropriate washing cycle.
- If tags are incorporated in the packages of some perishable food product (milk, soup, processed food, etc.), they can make the products communicate with the refrigerator that will warn the customer if the product is over the use-by date.
- If tags are incorporated at the item level in retail shops, the invoices can be established automatically at the point-of-sale terminal and, even, automatically charge the customers' payment devices.
- Still in the case when tags are implemented at the item level, returning defective items would be easy.
- This technology can also be used to check if medications are taken on time, or to help elderly to navigate in their home, etc.

The RFID technology opens also possibilities for the development of context-aware computer systems (Selker and Burleson, 2000; Selker and Holmstrom, 2000).

The cases mentioned in this section are a tiny part of the applications currently in use in the world. Larger applications are forecasted in a near future in volume retailers. In the next section, the main advantages of RFID technology are reported.

5. MAIN ADVANTAGES OF RFID

Readers (interrogators) can read multiple tags instantaneously, this reduces drastically item identification. This allows the automation of many time-consuming tasks such as scanning inventory inputs and outputs, as well as checking inventory levels, which can be done in real time using RFID technology. This results in lower inventory levels and less out of stock occurrences which, in turn, leads to the physical flow speeding up; this aspect is of utmost importance in supply chains. Indeed, inventory costs and labor costs decrease accordingly.

RFID technology allows following items in real time across the supply chain, thus increasing competitiveness by faster response to customer demands, reduction of delivery disputes, reduction of uncertainty on factors causing fluctuations in process, improvement of the readability of the quantity and quality of items produced, improvement of safety (in particular, reduction of counterfeiting) and reduction of waste and theft. A precise knowledge of the state of supply chains simplifies warrantee claim management.

It should also be noticed that RFID technology increases security when used in domains like food supplies (when goods are perishable) or potentially hazardous substances (Kärkkäien, 2003; Li et al., 2006). Tracing food "from farm to fork", which is now mandatory for large spectrum of food products at least in Europe, is another domain of application of RFID technology.

Other RFID technology advantages are as follows:
- Reducing administrative errors, due to the automation of data transfer.
- Simplifying production management, due to the ability to track work-in-progress in real time.
- Reducing rework, due to early information related possible production problems.
- Being able to start business relations with major clients who require RFID use from their providers.
- Controlling the quality of items when they move along the supply chain. RFID technology permits the collection, in real time, of information that influences quality. For instance, tags can monitor temperature, bacteria density, degree of humidity, etc. Indeed, active or semi-active tags are required to perform monitoring.
- Managing yards, warehouses and factories. For instance, tags may be used to direct trucks to the most efficient drop-off locations.
- Robustness of tags is another important aspect of RFID technology. RFID can work in dirty, wet, oily, warm or harsh environment. Also, passive tags can last for extensive period, making the technology safe.

To conclude, RFID technology guarantees labor reduction, precise management, safety, efficient management of assets, and thus drastic reduction of production costs. Reduction of production cycle is another aspect that benefits from this technology.

RFID technologies combined with software agents can provide the means of adding intelligence to manufactured products and this can enable a truly distributed and intelligent manufacturing control systems, see for example (McFarlane et al., 2003). Real-time enterprise planning, scheduling and control processes based on information provided by RFID sensing systems are also studied in (Kohn et al. 2005) and (Kim et al., 2007).

6. PRIVACY CONCERNS

6.1. Main privacy concerns

Several aspects of the privacy and authentication are considered in (Juels and Pappu, 2003; Juels, 2004; Juels et al., 2005, Juels, 2006).

Considering the problems passive tags have to face (in particular, the impassable metal barrier and the cost) they are unlikely to appear on each consumer item for some more years, but the objective of item-level tagging remains fresh in everybody mind due to the numerous advantages of RFID technology that have been mentioned in the previous section. Nevertheless, item-level tagging raises an important privacy concern that is clandestine tracking and inventorying. Basically, RFID tags respond to any reader requirement assuming that the read range allows it, thus making possible clandestine tracking and inventorying.

Indeed, tags broadcast only a fixed serial number, but this serial number can be combined with personal information in some circumstances. For instance, it may be the case when a customer pays his / her purchase with a credit card: the vendor may establish a link between the identity of the customer and the serial number, making it possible to use this information to design the customer profile.

A tag may also contain information about the product to which it is attached. This may be of great interest to competitors since they could be informed about volumes sold and stock turnover rates. Thus, RFID technology that enhances supply chain visibility and, as a result, facilitates management and improves competitiveness may also play a negative role.

Concerning private person, clandestine reading may inform about the products he / she is carrying. If these products are medications, it is possible to derive from the information what illness the person suffers, which can be used at different levels of the everyday life (insurance, hiring, etc.).

The clandestine tracking and reading is still quite limited, due to the fact that RFID infrastructure development is limited. But privacy concerns will certainly become of utmost importance in the future.

RFID privacy is already of concern in some cases:
- Recently, RFID enabled passports became mandatory to enter some countries. Tags incorporated in these passports can be read clandestinely. They contain private information concerning the owner of the document and can be used by unauthorized persons.
- In some library, due to the cost of books, tags are incorporated in books in order to control inventory, facilitate check out and avoid thefts. These may potentially be used for marketing purpose and, more precisely, for establishing the profile of some consumers.
- Human implementation for medical purpose (implemented tag that contains the medical record of the patient) is obviously of concern, as well as tool payment transponders already mentioned in this paper as a common application.

6.2. How to protect privacy?

Several solutions are conceivable to protect privacy when item level tagging will be of common use and RFID infrastructure well developed:
- ***Tag killing***. This solution consists in deactivating tags when their usefulness vanishes. To avoid accidental deactivation of tags, the killing command is PIN-protected.
An example: in supermarkets, RFID tags on purchased items are deactivated automatically when the invoice is established and paid. In this case, tag killing is effective for privacy protection, but the benefits for after sale services like management of item return or maintenance are lost. Also, it is impossible to use this solution in some domains like rental activities (books, cars, etc.) or when tracking items is mandatory (food distribution, for instance).
- ***Putting tags to sleep*** is another type of solution. The solution consists in rending tags temporarily inactive. Indeed, this solution requires the ability to deactivate and reactivate tags in due course, which could be difficult to manage. Furthermore, a very effective control (using PIN) should be put in place to avoid unauthorized reactivation of tags.
- ***Renaming tags*** is a third type of solutions that this currently proposed. It consists in changing tag identifiers over time.
- ***Distance measurement*** consists in introducing additional (and low-cost) circuitry in tags so that they can achieve a rough measurement of the distance to the reader that tries to connect itself to the tag. Depending on the comparison of this distance with some predefined distances, the tag will deliver more or less information to the reader.
- ***A blocking scheme*** is also available. It consists of introducing a so-called *privacy bit* in the tags. If the value of this bit is "0", the scanning is limited to the identifier. Further information is delivered only if the privacy bit is equal to "1".

Other solutions exist but, whatever the solution selected to protect privacy, limitations appear. The higher the protection, the lower the benefits of RFID technology and / or the more complex the activity of the tag, which leads to increasing cost.

7. AUTHENTICATION

As cleverly mentioned in (Juels, 2006), "*RFID privacy concerns the problem of misbehaving readers harvesting information from well-behaving tags. RFID authentication, on the other hand, concerns the problem of well-behaving readers harvesting information from misbehaving tags, particularly counterfeit ones*".

Basic RFID tags, as well as EPC tags, are vulnerable to counterfeiting: replicating such tags requires little expertise. In principle, the EPC of a target tag can simply be skimmed and "pasted" in a counterfeit tag. Thus, counterfeit tags may appear on the market and facilitate counterfeiting since tags may carry information that does not guarantee the authenticity of the item they are attached to.

Achieving counterfeiting resistance is a difficult task, but some possibilities exist. For instance, a unique numbering of items can be efficient to fight counterfeiting in a "closed loop" RFID system: if two items or pallets carry tags with the same serial number, counterfeiting is obvious. Another way to fight counterfeiting is to repurpose the kill function in the EPC; the kill PIN can be used to authenticate the tag to the reader.

To conclude, a well stabilized set of solutions does not exist yet to guaranty authenticity, but several research projects are under development.

8. CONCLUSION

RFID technology is profitable in "closed loop" organizations. A "closed loop" organization is a system (warehouse, supply chain, etc.) where the infrastructure that encapsulates RFID is well developed and able to connect the different components of the system.

The main advantages of RFID technology in a supply chain are:

- Increased speed of the physical flows.
- Drastic reduction of work load.
- Reduction of Work-in-Progress (WIP) and inventories.
- Easier management, due to real-time information.
- Reduction of shrinkages.
- Reduction of counterfeiting.
- Overall visibility in supply chains, which helps maintaining competitive edge.
- Reduction of theft.

Numerous "indirect" advantages can be listed such as reduction of rework, possibility of becoming provider of major clients that require the use of RFID technology, reduction of internal administrative error, simplification of warrantee claim management. These advantages lead to a drastic reduction of production costs. Other domains take advantage of RFID technology. It is the case of food industry where tracking some products "from farm to fork" is mandatory. Nevertheless, many problems are still waiting for solution.

The cost of tags is still too high to adopt item-level tagging for consumer products. Reducing the cost of tags requires a new step forward in technology and, probably, alternative tag design. Another open problem is the difficulty of implementing RFID technology in "open loop" environment. Furthermore, standards are still not stabilized, which slow down the dissemination of RFID technology.

The day item-level tagging will become economically acceptable, privacy concerns will arise, and solving this problem is of utmost importance. Finally, the cost of implementing RFID technology in an organization depends on the development state of this organization. The cost of integrating RFID in a coherent IT infrastructure (that must be adapted and even redesigned) and connecting it with upstream and downstream applications vary from an implementation to the next one.

Thus, the return of investment can probably not be achieved in short term, but the dissemination of RFID technology in the every day life is inescapable, as were the dissemination of data processing and communication systems in the seventies.

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