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Review

A literature review on the impact of RFID technologies on supply chain management

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ABSTRACT

RFID technologies may improve the potential benefits of supply chain management through reduction of inventory losses, increase of the efficiency and speed of processes and improvement of information accuracy. Various RFID systems can be obtained by combining different tags, readers, frequencies and levels of tagging, etc. The cost and potential profit of each system change in a wide range. In this paper, a state-of-the-art on RFID technology deployments in supply chains is given to analyze the impact on the supply chain performance. Potential benefits, particularly against inventory inaccuracy problems, the bullwhip effect and replenishment policies, are briefly surveyed. Various works addressing analytic modeling, simulations, case studies and experiments as well as ROI analyses are reviewed. Finally, conclusions and future research perspectives are presented.

Contents

1. Introduction

Radio frequency identification (RFID) is an automatic identification and data capture technology which is composed of three elements: a tag formed by a chip connected with an antenna; a reader that emits radio signals and receives in return answers from tags, and finally a middleware that bridges RFID hardware and enterprise applications (McFarlane et al., 2003). According to EPC-Global standards, the chip memory contains an Electronic Product Code (EPC) which allows the identification of each product in a unique way (Brock, 2001; Goel, 2007). There are different EPC formats, e.g. 64, 96, 128 bits (Lahiri, 2005). EPC of 96 bits can identify more than 268 million manufacturers, more than 16 million types of objects and almost

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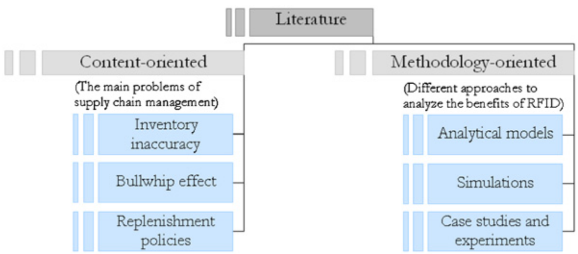

Fig. 1. Methods to classify publications.

69 billion articles for each manufacturer (Brock, 2001). Through radio waves, RFID technologies provide a real-time communication with numerous objects at the same time at a distance, without contact or direct line of sight (Garcia et al., 2007; Gaukler, 2005). These advanced identification and communication characteristics of RFID can improve the product traceability and the visibility among supply chains. For example, RFID technologies can increase accuracy, efficiency and speed of processes. It can also reduce storage, handling and distribution costs and improve sales by decreasing the number of stockouts (Li et al., 2006). The contribution of RFID to supply chains is not only in increasing the efficiency of systems but also in supporting the reorganization of the systems that become more efficient. Thonemann (2002) reported that after the deployment of RFID technologies, Procter & Gamble and Wal-Mart simultaneously reduced inventory levels by 70%, improved service levels from 96% to 99%. They also reduced administration costs by re-engineering their supply chains.

RFID technologies have gained significant interest from supply chain industries and academics in recent years. However, RFID is not a new technology. According to AIM,[1] the first applications marked during the Second World War were created to differentiate friendly planes from enemy planes (IFF System, Identification Friend or Foe) (Landt, 2001). RFID technologies have made headway through the recent improvements in data processing and microelectronics. The components of this technology are becoming smaller and smaller, less expensive and more effective (Maxwell, 2007). Thus, applications of RFID in supply chain have increased. Bagchi et al. (2007) reported the prediction of RFID growth as from $1 billion in 2003 to $4 billion in 2008 to $20 billion in 2013.

Current studies of RFID in supply chains focus on inventory management, logistics and transportation, assembly and manufacturing, asset tracking and object location, environment sensors, etc. (Gaukler and Seifert, 2007). Some sectors have more opportunity to gain from RFID applications, such as retail, healthcare, textile, automotive and luxury good industries (Li et al., 2006). Automobile industry, particularly in the assembly process, is one of the most popular RFID applications in USA and Canada (Hedgepeth, 2007). Additionally, RFID technologies can improve the efficiency and effectiveness of healthcare operators in numerous ways, such as smarter physical flows (patients, beds, etc.), accuracy of information flows (patient's history, treatment records, etc.) and better inventory management (medicine linens, beds, etc.) (Banks et al., 2007).

By surveying the literature, we observe that the main areas that RFID can deal with are inventory inaccuracy, the bullwhip effect and replenishment policies. Analytical models, simulations, case studies and experiments are the main approaches that were developed to analyze the impact of RFID technologies on supply chain management. Hence, we classify the publications according to two criteria: content oriented and methodology oriented. Fig. 1 illustrates our classification method.

The remainder of this paper is organized as follows. We present a general overview of literature on RFID technologies in supply chains in Section 2. Section 3 surveys content oriented publications, which deal with the main problems of supply chain management that can be improved by RFID technologies. The methodology oriented papers are discussed in Section 4. Section 5 reviews ROI analyses. In the last section, some concluding remarks and research perspectives are presented.

2. General overview of literature on RFID technologies in supply chains

The literature on RFID applications in supply chains is limited. Most of the existing studies were published in the last few years. We can separate these publications in two groups; practical papers (white papers, technical reports) and academic papers. In these studies, several subjects are analyzed through different approaches. Table 1 presents a general classification of papers according to the most used approaches and the main topics of the publications on RFID applications in supply chains.

Practical papers generally deal with pilot projects, case studies and ROI analyses of RFID implementations in supply chains. Companies deploy pilot projects to test this new technology in a small and simple environment to observe the difficulties and the efficiencies of its integration, to analyze the associated costs and profits and to facilitate the complete integration in the whole company if they decide to implement it. In a white paper by IBM about improving product availability at the Retail Shelf by using Auto-ID technologies, (Alexander et al., 2002a) focus on the difficulties for enterprises to adopt RFID systems through the consumer retail value chain. They illustrate the impact of the Auto-ID system on specific problems faced by companies in the consumer retail value chain. Similar papers on the value of RFID in supply chains were published by Kambil and Brooks (2002), Chappell et al. (2003a, 2003b), Tellkamp (2006) and Lee et al. (2004). The white paper of Bitkom presents an overview of numerous applications of RFID systems in Germany Bitkom RFID Project Group, 2005. This paper focuses on four case studies such as logistics processes at Hewlett-Packard GmbH, flexible automotive processes at BMW, mobile maintenance solution in airport industry at Fraport AG, and logistics processes in the retail supply chain at Metro Group. One of the results of these case studies showed that, in Metro Group, RFID technology decreased losses during transit by 11–14%, improved the availability of items in stores by about 14%, and reduced costs in merchandise distribution centers by 11%.

Recently, numerous academic papers deal with potential benefits of RFID in supply chains. Authors were mostly interested

Table 1
Types of publications.

Publications	Most used approaches	Main topics
Practical papers	Pilot projects Case studies ROI analyzes	Inventory management Logistics and transportation Assembly and manufacturing Asset tracking and object location Environment sensors
Academic papers	Analytical approach Simulation approach Case studies ROI analyzes Literature review	Inventory inaccuracy Bullwhip effect Replenishment policies

[1] The Association for Automatic Identification and Data Capture Technologies.

in supply chain problems that RFID technologies have the possibility to solve. Inventory inaccuracy (Kang and Gershwin, 2004; Atali et al., 2006; Fleisch and Tellkamp, 2005), bullwhip effect (Joshi, 2000; Lee et al., 2005; Fleisch and Tellkamp, 2005), and choosing the optimal replenishment policy (de Kok and Shang, 2007; Lee et al., 2005) are some of these problems. In order to analyze the impact of RFID on supply chain systems, four main approaches are investigated: analytical approach (Lee and Ozer, 2007; Rekik et al., 2007a), simulation approach (Brown et al., 2001; Leung et al., 2007), case studies and experiments (Lefebvre et al., 2006; Wamba et al., 2007; Bottani and Rizzi, 2008). Generally all of them are followed by a return on investment (ROI) study to quantify the economic impact of RFID in supply chains (Lee et al., 2004; Kang and Koh, 2002).

In the literature, different state-of-the-art on RFID technologies on supply chains are presented. Gunesekaran and Ngai (2005) review the literature on build-to-order supply chain (BOSC) management. They aim to highlight RFID technology as one of the important information technologies for BOSC that increases efficiency and accuracy. Extending this study, Ngai et al. (2008) review and classify the literature on RFID technologies that was published between 1995 and 2005. They analyze qualitative and quantitative development of the knowledge in this area. This study includes a content-oriented classification of the RFID literature. Németh et al. (2006) present a state-of-the-art on RFID systems and the challenges and possibilities of the integration to supply chains. This paper gives only an overview on current development of RFID technology and processes. Chao et al. (2007) review the literature on trends and forecast of RFID technologies from 1991 to 2005 by a historical review method and bibliometric analyses. They focus on the RFID innovation, deployment by enterprises and market diffusion in supply chain management. This survey classifies the RFID literature according to several criteria, such as publication country, institution, year, document type, language, subject category, etc. However, we observe the lack of critical analyses on these publications. Recently, Delaunay et al. (2007) present a survey on the causes of inventory inaccuracy in supply chain management, and give a perspective to future studies on the impact of RFID technologies on inventory inaccuracy in supply chains. Dolgui and Proth (2008) also present a literature review on RFID technology in supply chain. They focus on the advantages of RFID technologies in inventory management. They also analyze some problems and present perspectives dealing with privacy and authentication properties of RFID technologies. The authors give a general point-of-view on RFID applications by analyzing a limited number of publications in the literature. This study thus may not give readers a complete overview of the literature. Moreover, their survey does not contain recent publications.

In this paper, we present a state of the art on the impacts of RFID deployments in supply chains. We categorize the literature regarding the methods that have been used; such as analytic modeling, simulations, case studies, experiments and ROI analyzes. Potential benefits against inventory inaccuracy problems, the bullwhip effect and replenishment policies are the main topics that we focus on. Contrarily to other relevant surveys, we present a complete review of the literature through statements and critical analyses of related publications and also by giving significant discussions on the impacts of RFID technologies on supply chain management.

3. Research methodology

This study reviews the literature of the economic and physical impacts of RFID technologies on supply chains. We aim at discussing these impacts to develop an effective overview of the challenges and benefits related to integrating RFID in supply chains.

The literature was mainly collected from journals on supply chain management, operations research, information systems and production economics. *European Journal of Operational Research*, *Manufacturing and Service Operations Management*, *Production and Operations Management*, *International Journal of Production Economics* and *Decision Support Systems* are some of these journals. In order to obtain a general overview on the literature, book chapters, dissertations, working papers, technical reports and conference papers are also included. Most of the technical papers are published by the Auto-ID center. In total, we kept 142 references that we believe are the most relevant on the impacts of RFID technologies on supply chain management since 1958 up to 2009.

Each article is reviewed through statements and critical analyses and also discussions on the impacts of RFID technologies on supply chain management. The publications are classified according to two criteria; content oriented and methodology oriented. Fig. 1 illustrates our classification method.

The content oriented publications, which deal with the main problems of supply chain management that can be improved by RFID technologies, are surveyed in Section 4. The methodology oriented papers, which contain different approaches to evaluate the benefits of RFID technologies in supply chains, are discussed in Section 5.

4. Potential benefits of RFID technologies in supply chains

RFID technologies offer several contributions to supply chain through their advanced properties such as unique identification of products, easiness of communication and real-time information (Saygin et al., 2007; Michael and McCathie, 2005). The progress through RFID can be observed in different types of supply chains such as warehouse management, transportation management, production scheduling, order management, inventory management and asset management systems (Banks et al., 2007).

RFID can improve the traceability of products and the visibility throughout the entire supply chain, and also can make reliable and speed up operational processes such as tracking, shipping, checkout and counting processes, which leads to improved inventory flows and more accurate information (Chow et al., 2006; Tajima, 2007). Companies integrate and store the more accurate data obtained through RFID technologies in their information technology systems for better supply chain planning and management (Whitaker et al., 2007). There is thus a strong link between IT applications and RFID technologies.

Through these numerous benefits, RFID technologies can provide cost reduction, increased revenue, process improvement, service quality, etc. Banks et al. (2007) show a list of general quantitative and qualitative key factors for RFID implementations.

However, as mentioned before, the objective of RFID implementation is not just to improve current systems. Reorganizing processes using this new technology can also lead to large gains in the overall supply chain effectiveness (Agarwal, 2001; Langer et al.; McFarlane et al., 2003). Bottani and Rizzi (2008) indicate that reengineering models increase possible benefits gained through RFID for all processes of distribution centers and retailers. Dutta et al. (2007) conclude that RFID integration through new business architectures provides more benefits than technology integration in current business processes.

There are not many real supply chain applications yet. Enterprises generally conduct pilot projects to validate this technology in a limited environment. According to Chappell et al. (2003a), the goals of pilots are to validate the technology for reduced-scale and to prepare the systems for full-scale implementation and integration. The US Department of Defense, Wal-Mart, the Food & Drug Administration, Mark and Spencer, Tesco, Gillette are some of the pioneers of RFID technologies users (Bagchi et al., 2007). In 2005, Wal-Mart asked their 100 first suppliers to tag all their pallets and cases (Wang et al., 2008; Li et al., 2006; Wu et al., 2006). Through this innovative attempt, Wal-Mart provided a considerable acceleration to RFID implementations in supply chains. According to the analysis of the University of Arkansas, Wal-Mart succeeded in adopting the RFID technology and reduced out-of-stocks by 16% (Bottani and Rizzi, 2008). Roberti (2003) shows that out-of-stock items with RFID were replenished three times faster than items using standard barcode technology. He also concludes that Wal-Mart experienced a 10% reduction in manual orders resulting in a reduction of excess inventory. Mark & Spencer is also employing RFID technologies in its refrigerated food supply chain. Wamba et al. (2007) report that they are tracking 3.5 million reusable trays, dollies and cages using RFID, and about 70% of the products are perishable in this chain. Wilding and Delgado (2004) show that, through RFID technologies, Mark & Spencer gained 83% reduction in reading time for each tagged dolly, 15% reduction in shrinkage, a reduction in lead time and also an improvement of inventory management.

In this section, we present potentials benefits of RFID technologies in supply chains. We are particularly interested in three main problems of supply chain management that can be improved through RFID; inventory inaccuracy, the bullwhip effect and replenishment policies.

4.1. Inventory inaccuracy problem

Inaccuracy problems in inventory management are important in supply chain management. Although many companies have automated their inventory management using information systems, inventory levels in information systems and the real physical inventory levels often do not match (Kang and Gershwin, 2004). The difference between these inventory levels is called inaccuracy and can deeply affect the performance of firms. DeHoratius and Raman (2008) report that 65% of the inventory records in retail stores were inaccurate. The result was obtained in a case study, by examining about 370,000 inventory records from 37 stores of an important retailer (Gamma). Raman et al. (2001) report that such inaccuracies could reduce the profit of retailers by 10% due to higher inventory cost and lost sales.

Since the earliest paper of Iglehart and Morey (1972), there are numerous papers in the literature that have considered the impact of inventory inaccuracy and its causes. Table 2 represents a survey on the different causes of inventory inaccuracy. We can classify them in four groups; transaction errors, shrinkage errors, inaccessible inventory and supply errors.

Transaction errors were introduced in inventory management by Iglehart and Morey (1972). Several authors followed this study (Krajewski et al., 1987; Brooks and Wilson, 1993). Transaction errors include shipment errors, delivery errors, scanning errors (Raman, 2000) and also incorrect identification of items (Lee et al., 2005). Shipping errors can be very expensive; customers who receive wrong items can demand a refund or the supplier has to pay double transportation costs (Raman, 2000). Delivery errors were explained such as delivery quantities from suppliers that are different than the required quantities (Lee and Ozer, 2007). The deliveries of wrong products or deliveries to the wrong directions are also delivery errors (Alexander et al., 2002b). Scanning errors generally occur when a customer wants to buy two similar items with the same price. In order to accelerate the payment process, checkout employee often scans one item twice as if they were identical, which leads to inventory inaccuracy for both items (Agarwal, 2001). In a recent study, Sahin and Dallery (2009) propose an analytic model to analyze the impact of inventory inaccuracy due to scanning errors.

Shrinkage (named also stock loss) errors include all types of errors that cause loss of products ready for sale. There are several studies on this subject (Bullard and Resnik, 1983; Brooks and Wilson, 1993). According to a retail survey report of the University of Florida, shrinkage errors represent 1.69% of sales for retailers (Hollinger and Davis, 2001). Shrinkage errors include employee theft, shoplifting, administration and paperwork errors, vendor fraud (Chappell et al., 2003a, 2003b) and unavailable products for sale (Kang and Koh, 2002). Theft represents an important part of shrinkage errors. There are several studies on internal and external theft in supply chains. According to the previous studies, theft levels represent about 1–2% of total sales (2000 Retail Survey University of Florida Chappell et al., 2003b, the National Supermarket Research Group for 2001 Fleisch and Tellkamp, 2005). The products unavailable for sale are called unsaleable by Tellkamp (2003). Lightburn (2002) reports that the causes of unsaleable products are damage with 63%, out-of-code with 16% and discontinued items with 12%. He also mentions that according to the results of a survey which included about 65 manufacturers and retailers, the cost of unsaleable food takes 1% of US sales. Chappell et al. (2003a) call unsaleable products as write-offs. They explain that one of the causes is spoilage, caused by time or temperature exposure, and applies to many products in retail supply chains as well as some types of prescription medications.

Inaccessible inventory can be explained as products which are not in the correct place and are not available for customers. Inaccessible inventories, called also misplaced items, have been studied by many authors (Lee et al., 2005; Camdereli and Swaminathan, 2005). Employees can put products on wrong shelves or customers can set an item that they took from a shelf to another shelf (Kang and Koh, 2002). It can also happen in the back room store (Wong and McFarlane, 2005). This inaccessible inventory can be found later and be ready to be sold again. If the items are seasonal and are found after the season, retailers can discount the price to sell the products (Rekik et al., 2007a). If misplaced items are found too late and become out of date, fashion or season, the inaccessible products become unsaleable products and thus cannot be sold (Kang and Gershwin, 2004). Raman et al. (2001) present a case study where misplaced items reduced profits by 25%.

Literature on supply errors is limited (Yano and Lee, 1995; Bensoussan et al., 2005). Product quality, yield efficiency and supply process can affect inventory accuracy (Rekik, 2006).

A recent survey on the causes of inventory inaccuracy in supply chain management is presented by Delaunay et al. (2007). They were interested in the errors of supply chain such as shrinkage, misplacement, supply and transactions errors. They classify the papers in the literature according to the type of errors, the structure of the error modeling (additive, multiplicative or fixed error modeling), the structure of the supply chain (centralized or decentralized) and the objective of the paper (evaluate the impact of errors or optimize the supply chain model).

RFID technologies provide better product traceability through real-time data capture properties that enable improvements in the supply chains against these inventory inaccuracy errors (Lee et al., 2005). It is in particular very successful to eliminate transaction errors (Zipkin, 2006). Although RFID cannot eliminate all errors, they can be detected quickly and by considering the

Table 2
Survey on the causes of inventory inaccuracy.

	Transaction errors	Shipment errors	Delivery errors	Scanning errors	Incorrect identification	Shrinkage errors	Theft	Unavailable for sale	Vendor fraud	Administrative errors	Inaccessible inventory	Misplacement	Supply errors
Iglehart and Morey (1972)	*												
Bullard and Resnik (1983)						*	*						
Krajewski et al. (1987)	*		*										
Brooks and Wilson (1993)	*		*	*		*	*						
Yano and Lee (1995)													*
Raman et al. (2001)	*	*		*									
Lightburn (2002)						*		*					
Alexander et al. (2002a, 2002b)	*	*	*	*		*	*	*					*
Kang and Koh (2002)						*							
Chappell et al. (2003a, 2003b)											*	*	
de Kok and Shang (2007)	*												
DeHoratius and Raman (2008)	*	*		*							*	*	
Wong and McFarlane (2005)	*		*			*	*				*	*	
Tellkamp (2003)	*			*		*	*		*	*			
Lee et al. (2005)	*				*	*					*		
Kang and Gershwin (2004)	*				*	*	*						
Fleisch and Tellkamp (2005)	*		*			*	*	*			*	*	
Kleijnen and Vorst (2005)						*							
Sahin (2004)	*					*	*	*			*	*	
Lee and Ozer (2007)	*		*	*		*	*	*	*		*	*	
Bensoussan et al. (2005)						*		*					*
Camdereli and Swaminathan (2005)											*	*	
Atali et al. (2006)	*			*		*	*	*			*	*	
Kok et al. (2008)	*					*					*	*	
Ketzenberg and Ferguson (2006)						*		*					
Rekik (2006) and Rekik et al. (2007a–2007c)	*	*		*		*	*	*		*	*	*	*
Tellkamp (2006)	*	*	*	*		*	*	*	*	*	*	*	
Basinger (2006)	*	*		*	*	*	*	*	*		*	*	
Doerr et al. (2006)	*	*				*							
Kim et al. (2008a)						*							
Tajima (2007)						*	*	*					
Leung et al. (2007)	*		*		*	*	*	*			*		
Delaunay et al. (2007)	*					*						*	*
Uckun et al. (2008, 2007)	*					*						*	
Sarac et al. (2008a, 2008b)						*	*	*				*	

existence of this problem in planning processes, they can be dealt with effectively. Several authors were interested in RFID technologies to eliminate these errors. They analyzed the impact of RFID technologies on inventory inaccuracy due to different errors. Kang and Gershwin (2004), Fleisch and Tellkamp (2005), Lee et al. (2005), Sahin et al. (2008), Rekik (2006) and Gaukler (2005) are some of them. These papers will be detailed in the next section.

4.2. Bullwhip effect

The bullwhip effect is an important phenomenon in supply chain management that has been studied for about fifty years. It was explained by Stevenson (2007) that the demand variations of the customer become increasingly large when they diffuse backwards through the chain. The bullwhip effect was first introduced by Forrester (1958). He observed a fluctuation and amplification of demand from the downstream to the upstream of the supply chain. He stated that the variance of the customer demand increases at each step of the supply chain (customer, retailer, distributor, producer and supplier). Furthermore, he concluded that the main cause of this amplification is the difficulties in the information sharing between each actor of the supply chain.

Including Forrester's approach, several authors analyze the sources of bullwhip errors and the factors to control the bullwhip effect. Lee et al. (1997) present the main sources of bullwhip effect such as demand forecast, order batching, price fluctuation and gaming principle. Wang et al. (2008) conclude that lead time, market sensitivity and resource allocations in supply chains can cause bullwhip effect.

Geary et al. (2006) review the literature on bullwhip effect and analyze the previous approaches and conclude that the main cause of bullwhip errors is poor material flow. Wamba et al. (2008a) indicate that controlling the bullwhip effect can optimize material resources by decreasing unnecessary locations or safety stocks along the supply chains. Metters (1997) quantifies the bullwhip effect in supply chain by comparing the effects of increased demand seasonality and forecast error of demand distortion. They show that eliminating the bullwhip effect can increase profits by an average of 15–30%.

Information sharing is indicated as one of the main factors to control the bullwhip effect. Chen et al. (2000) develop an analytical approach in order to evaluate the impacts of information sharing between supply chain actors on the bullwhip effect. Holweg et al. (2005) also indicate that supply chain collaboration and the visibility of information flow can reduce the bullwhip effect that improves service quality, decreases inventory levels and reduces stockouts.

Several authors conclude that Auto-ID technologies such as RFID can reduce the bullwhip effect and improve supply chain performance. Bottani and Rizzi (2008) indicate that an automated information system can improve the inventory visibility that can thus reduce safety stocks and the bullwhip effect. Wang et al. (2008) conclude that RFID integrations into supply chains can reduce bullwhip effect and improve inventory replenishment management performance. Imburgia (2006) indicates that RFID technologies can prevent the bullwhip effect through more accurate forecasting. Zaharudin et al. (2006) indicate that Auto-ID technologies can reduce the bullwhip effect through information sharing between all supply chain actors by accessing information in a single way. Saygin et al. (2007) conclude that RFID can reduce the bullwhip effect by a better visibility obtained through real-time information of items and locations. However, they highlight that having too much visibility is equivalent to having no visibility because having a lot of unusable data can worsen supply chain performance.

Table 3
List of publications on the bullwhip effect.

Authors	Year	Main topic
Buffa and Miller (1979)	1979	Bullwhip effect in planning and control systems
Sterman (1989)	1989	Beer game: an effective method to understand the bullwhip effect
de Kok and Shang (2007)	2007	Philips Semiconductor bullwhip effects
Yucesan (2007)	2007	Main sources of bullwhip effect
Huang et al. (2003)	2003	Impacts of information sharing
Choi et al. (2008)	2008	The importance of information sharing in a virtual enterprise chain
Emerson et al. (2009)	2009	The information sharing in a dynamic supply chain
Zhou (2009)	2009	Benefits of RFID information visibility using a manufacturing example
Agrawal et al. (2009)	2009	Impact of information sharing and lead time on the bullwhip effect

Numerous authors analyze the bullwhip effect. A short list of the publications is given in Table 3.

Buffa and Miller (1979) deal with the bullwhip effect in planning and control. Sterman (1989) describe an effective method to understand the bullwhip effect named as "beer game". It is a useful teaching tool where each participant represents an actor of a beer supply chain such as retailer, wholesaler, distributor and manufacturer. This game has been played many times by numerous students, professionals and managers. Every time, the same results are obtained; a small change in a consumer demand is translated into considerable fluctuation in both orders and inventory upstream. This fluctuation is caused by the lack of information sharing among the entire chain.

de Kok and Shang (2007) present a study of Philips Semiconductor bullwhip effects. In 1999, Philips conducted a project on bullwhip effects in some of its supply chains and developed a collaborative-planning tool to reduce inventory and increase customer service levels. The results of this project show important savings; minimum yearly savings of around US $5 million is from $300 million yearly turnover. This study presents an insight into complex stochastic problems, such as multi-item multi-level inventory control.

More recently, Yucesan (2007) writes that the main cause of the bullwhip phenomenon is the deficiency in information sharing, communication, and collaboration throughout the supply chain that causes information failure as well as delays in information and material flows. Huang et al. (2003) review the literature of the impacts of shared information on supply chain dynamics. They also discuss how to share information (information, time, people, format, etc.) to maximize the benefits for supply chains. According to them, more shared information leads to more efficient decisions on ordering, on capacity allocation and on production planning for each supply chain actor.

Choi et al. (2008) focus on the importance of information sharing through a new virtual enterprise chain collaboration framework. They analyze the impacts of enterprise collaboration on three aspects: business processes, service components and technologies that are essential for the collaboration of virtual enterprises.

Emerson et al. (2009) focus on the information sharing in a dynamic supply chain. They consider that the actors of a supply chain can update the knowledge independently when they need to keep the partners informed. They use a knowledge base framework in order to analyze the effects of inventory constraints on the performance dynamics of supply chains. They indicate that neither static nor dynamic configurations are consistently dominant. They show that dynamically choosing a supplier or assembler does not always optimize the profits, but it can be more profitable by choosing the right supplier.

Zhou (2009) analyzes the benefit of RFID item-level information visibility using a manufacturing example on multiple periods. He considers the reduced uncertainty as a key factor to increase the benefit in both static and dynamic scenarios. The analysis shows that the benefit due to item-level visibility increases through the improvement of the information system. The results also show that the information visibility in multiple periods can provide improved decision making.

Agrawal et al. (2009) analyze the impact of information sharing and lead time on the bullwhip effect and inventory levels in a two-level supply chain. They showed that, even if the information is shared inter and intra echelon, it cannot completely eliminate the bullwhip effect. Their results show that lead time reduction is more interesting to reduce the bullwhip effect than information sharing.

RFID technologies can deal with the bullwhip effect by considering supply chain as a whole as well as by reducing drastically the information distortion through data capture and real-time communication properties. There are several simulation studies conducted on this subject to analyze the impact of RFID technologies on the bullwhip effect (Joshi, 2000; Simchi-Levi et al., 2000; Fleisch and Tellkamp, 2005). We detail these papers in the next section.

4.3. Replenishment policies

In inventory management, replenishment policies are very important methods for determining the frequency and the size of orders to maximize customer satisfaction with low ordering, holding and stockout costs. There are several replenishment policies under continuous or periodic review inventory systems. Companies try to choose the best policy for them. Inventory replenishment decisions are made based on inventory levels in the information system. Real-time inventory information obtained by RFID technologies ensures the accuracy of these levels. Hence, companies may change their replenishment strategies. The effects of RFID technologies on replenishment policies have been studied by many authors. de Kok and Shang (2007), Lee et al. (2004) and Kang and Gershwin (2004) are some of them. These papers will be detailed in the next section.

In this section, we focused on the main problems of supply chains that RFID technologies can deal with. RFID can improve supply chain performances by increasing inventory availability, improving coordination, saving labor cost, reducing inventory levels, etc. Therefore, companies should rethink their important decisions, such as order policies, replenishment from the backroom processes, inventory locations, taking into account new inventory levels, safety stock levels and sharing information among the entire supply chain.

In the next section, we review the literature according to the methods used to analyze the impact of RFID technologies on supply chain performances and potential benefits of RFID technologies against the problems encountered in supply chains such as inventory inaccuracy problems, bullwhip effect, replenishment policies, etc.

5. Different approaches to evaluate the benefits of RFID technologies in supply chains

There are several methods to study a system. Law and Kelton (2000) present these methods as showed in Fig. 2 in two groups;

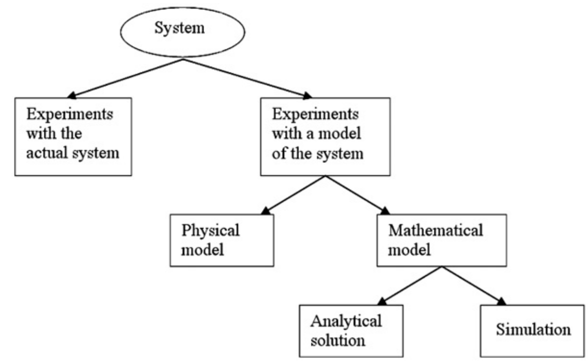

Fig. 2. Methods to study a system.

experiments with the actual system and experiments with a model of the system that contains physical and mathematical models.

In this section we focus on analytical models and simulations of mathematical models as well as case studies and experiments of physical models subject to potential benefits of RFID technologies.

5.1. Analytical models

Analytical models correspond to the simplifications of a real system through mathematical expressions in order to analyze and optimize the system according to an objective function. Analytical models have been studied in supply chain for about four decades. However, the literature on analytical modeling of RFID technologies in supply chain is limited. The main topics that analytical models often deal with are inventory systems with different replenishment policies and Newsvendor models. Table 4 summarizes the characteristics of the papers presented in this section.

The first analytical modeling approach on inventory inaccuracy due to transaction errors was presented by Iglehart and Morey (1972). They study a single-item, periodic-review inventory system with a reorder point up-to-level replenishment policy (s, S). They propose a formula to optimize the frequency of physical inventory counting, to correct inaccurate data, and safety stocks in order to protect the system against out-of-stocks.

In a recent paper, Lee and Ozer (2007) extend the model of Iglehart and Morey, and they observe that random distribution of transaction errors and uncertain demands make this approach an approximation. They integrate RFID technology to this model. The originality of this study is that, contrary to classical approaches, they do not consider RFID as a perfect technology; they assume that RFID can reduce transaction errors by 90%. They observe that, depending on the error and the demand, this reduction can reduce by around 5.9% the inventory cost related to transaction errors.

Kang and Gershwin (2004) also develop an analytical and simulation model of a single item inventory system under a regular replenishment order (Q,R) policy. They have shown that even a small rate of inaccuracy due to undetected stock loss can disrupt the replenishment process and creates severe out-of-stocks. The results are presented in the next section.

Gaukler et al. (2008) also model the impact of RFID on supply visibility in the (Q,R) policy. They propose a model to analyze how a retailer can use order progress information obtained by RFID in an uncertain replenishment lead time and uncertain demand environment. Based on numerical experiments, they conclude that 47–65% cost savings are gained on the order progress information. They obtain interesting results. However, this study is limited to a single-item and simple supply chain.

Table 4
Characteristics of analytical modeling papers.

	Centralized supply chain	Decentralized supply chain	Single item	Multiple items	Periodic review inventory system	Continuous review inventory system	Single period	Multiple periods	Replenishment policy
Iglehart and Morey (1972)	*		*		*		*		(s,S)
Lee and Ozer (2007)	*		*		*		*	*	(s,S), (Q,R)
Kang and Gershwin (2004)	*		*				*		(Q,R)
Gaukler et al. (2008)						*			(Q,R)
Atali et al. (2006)	*		*		*			*	
Kok et al. (2008)			*		*			*	(R,S)
Sahin et al. (2008) and Sahin (2004)	*		*		*		*		Newsvendor model
Rekik (2006) and Rekik et al. (2007a–2007c)	*	*	*		*		*		Newsvendor model
Sahin and Dallery (2009)			*		*		*		Newsvendor model
Tellkamp (2006)	*	*	*		*			*	(s,S), (s,Q)
Gaukler et al. (2007) and Gaukler (2005)	*	*	*		*			*	(Q,R)
Heese (2007)		*	*		*		*	*	Newsvendor model
Karaer and Lee (2007)	*		*		*			*	Base-stock policy
Sounderpandian et al. (2007)		*		*	*			*	(s,Q)
Szmerekovsky and Zhang (2008)	*	*			*	*	*		
Uckun et al. (2007)	*	*	*		*		*		Newsvendor model
DeHoratius et al. (2008)	*			*	*			*	(s,S)
Sarac et al. (2008a)	*		*		*		*		Newsvendor model

Atali et al. (2006) study a single-item, periodic-review inventory problem on inventory accuracy due to shrinkage (such as thefts and damages), misplacement and transaction (scanning) errors. They develop two models. In the base model, they focus on the impacts of errors on the inventory management. In the second model, they integrate RFID to deal with these errors. They try to analyze whether RFID technologies can improve inventory visibility and if they can eliminate or reduce some of the causes for inventory inaccuracy. The originality of this study is that they consider that RFID can eliminate some of the error sources, but not all of them. Their analyses are limited to a single-stage and single-item supply chain.

Kok et al. (2008) propose an analytic model to study the impact of RFID technology on inventory management with shrinkage errors. They quantify the potential gains of using RFID against shrinkage errors. The cost-benefit analysis deals in particular with the cost of the technology and the inspection cycle length. Finally, they conclude that the price of the item and the fraction of demand have the largest impact on the break-even costs for RFID tags. The originality of this study is that they indicate that the effect of inspection cycle length depends on the item value and its theft rate. They observe that a long inspection cycle can drastically increase investment if the item value and the theft rate are large. Considering that RFID technologies provide 100% accuracy and not considering the fixed cost (e.g. the reading equipment, etc.) are the limitations of this study.

Sahin (2004) focuses on the impact of inventory inaccuracy on the performance of supply chain inventory management. She studies the reasons for inaccuracy and develops a general Newsvendor model in order to analyze inventory inaccuracies and to quantify the cost of errors. Furthermore, she analyzes the economic effect of implementing an advanced Auto-ID technology such as RFID. Following this study, Sahin et al. (2008) develop a single-period model where inventory inaccuracies occur because of the data capture process. In this study, they evaluate the impact of inaccuracies on the inventory system performance and also analyze additional overage and shortage costs. They conclude that not correcting inaccuracies, even if error rates are small, may induce large costs. Furthermore, they observe that, when inaccuracy occurs in inventory management, the cost of having errors may be up to 80%. Analyzing a single-period simple supply chain and considering that RFID technologies provide 100% accuracy are the limitations of this study.

The previous study is again extended by Rekik (2006) and Rekik et al. (2007a–2007c). The authors analyze several models to quantify the impact of inventory inaccuracy on inventory management. They define separately the factors for inventory inaccuracy such as transaction errors, misplaced items, theft, damage and spoilage and supply errors. They deal with each factor separately and analyze the effect of RFID technology on supply chain inventory through a newsvendor model. They consider RFID as a perfect technology that can eliminate all errors. In a recent paper, Rekik et al. (2007c) analyze a single manufacturer, single retailer, single product Newsvendor model subject to execution problems such as losses in the backroom and misplacements in the store. They analyze two models; in the first model, supply chain actors are aware of the errors and take them into consideration in their order decisions and, in the second model, they integrate RFID technology within the store to eliminate errors. They observe that, when more errors occur in the system, RFID provides more benefits for both manufacturer and retailer as well as for the entire supply chain. They conclude that the benefits are larger with RFID technology when shelf availability is poor. These studies are limited to a single-product and single-period supply chain. Considering inventory errors separately makes their models not realistic enough.

Sahin and Dallery (2009) also study a Newsvendor model in which inventory inaccuracy occurs because of data recording errors. They consider that actors of the studied chain use barcode labels and scanners in order to obtain inventory-level information. They analyze the economic impacts of inventory inaccuracy by comparing two models. In the first, inventory errors are ignored. In the second model, they consider that a new data capture technology such as RFID is integrated that eliminates the recording errors. The originality of this work lies in the study of the economic impacts of inventory inaccuracy in terms of overage/underage costs and the savings through error elimination and introducing a new cost factor, i.e. shortage penalty, related with demands that were accepted by the actor but could not be satisfied. They present interesting results that are, however, limited to single-period and single-item inventory models.

Tellkamp (2006) proposes an analytical model to analyze the potential impact of RFID on product availability. According to the author, providing inventory accuracy and reorganizing the replenishment are the most interesting subjects. Through the analytical model, he finds that inventory inaccuracy decreases service level by about 7% and also decreases the values of reorder points.

Gaukler (2005) studies the effects of RFID technologies on supply chains at three decision levels; strategic, tactical and operational. He develops an analytical model to analyze the cost of RFID technology and also its benefits. He assumes that the price of RFID technologies can be shared by all actors of the supply chain. He also considers the use of these technologies to improve stock control policies as well as inventory replenishment policies. A numerical study is conducted to evaluate the cost savings due to a more effective reorder point replenishment policy. The results show that RFID can reduce costs by about 2.8–4.5%. He develops significant analyses, but only considers a single-product and simple supply chain which is the limitation of this study.

In a recent paper, Gaukler et al. (2007) analyze the benefits and the costs of an item-level RFID application in a supply chain which contains one manufacturer and one retailer. They develop two analytical models; a centralized case with and without RFID at item level and a decentralized case with item-level tagging RFID where the manufacturer and the retailer try to optimize their own profit without cooperation. The centralized model is first studied and the level of tag prices which make item-level RFID economically feasible is estimated. The service level is considered to be a key performance factor, because a high tag price decreases the retailer's backroom inventory level which can in turn reduce the service level. The impact of an item-level RFID implementation on the decentralized model is then studied in order to evaluate how the tag cost should be shared between the supply chain actors. Their analyses show that, when the manufacturer is dominant, sharing RFID costs between the actors is not a matter. However, they also indicate that, when the retailer is the driving force, there exists an optimal sharing of the tag cost to maximize the retailer and the supply chain profit which depends on the retailer's power to mandate the manufacturer a lower profit. They present interesting analyses. However, this study is limited to a "simple" two-level supply chain.

Heese (2007) analyzes the impacts of inventory accuracy and RFID adoption in a decentralized supply chain. Similarly to most papers in literature, he considers that RFID technologies can eliminate all shrinkage errors. However, he indicates that RFID technologies are more beneficial in decentralized supply chains.

Karaer and Lee (2007) focus on the value of inventory visibility obtained through RFID technologies in the reverse channel management. They analyze the coordination of the reverse and forward chain at the distribution center of a manufacturer. The results of their analytical approach show that RFID technologies provide several benefits that depend mainly on the volatility of product return and the duration of the reverse channel processes.

Sounderpandian et al. (2007) are interested in the costs and benefits of implementations of RFID technologies in a supply chain that contains a manufacturer, a distributor, a retailer and consumers. They develop an analytic approach in order to estimate the load rate of RFID employment by the retailers and the cost benefits obtained through RFID applications for shelf replenishment. The main originality of this study is that they consider RFID technology application at item, case, and pallet levels and the costs of RFID implementation include tag reader costs, communication costs and other infrastructure costs. They note that RFID can improve the automatic checkout process at retail store, so it can reduce inventory costs as a result of more efficient shelf replenishment. They also observe some additional benefits of RFID such as reduction losses due to shoplifting and increased use of point of sale applications. They analyze a simple supply chain. However, practical supply chains are more complicated. They would obtain more realistic results by analyzing supply chains with multiple actors.

Szmerekovsky and Zhang (2008) analyze the impacts of RFID technologies on a vendor managed inventory (VMI) system using an analytical approach. They develop two single-period models with one manufacturer and one retailer. The first model considers a basic inventory management system under a periodic replenishment policy and, in the second model, an RFID system is integrated and a continuous review replenishment policy is used. They first determine the optimal policies and then compare the performances of these models in a centralized system where the objective is to maximize the overall supply chain profit. They show that implementing RFID can increase sales and inventory levels. They add that the efficiency of RFID depends on the tag price and available shelf space. They also analyze the effect of RFID on the manufacturer and the retailer in a decentralized system. They observe the utility of sharing the tag cost between the manufacturer and the retailer. In their model, they only consider the variable costs associated with RFID technology. Analyzing a simple two-level and single-period supply chain and not considering the fixed costs of RFID are the main limitations of this study.

Uckun et al. (2007) use an analytic model to study the deployment of RFID technologies in a two-level supply chain which contains a supplier and a retailer. They analyze the optimal investment levels of RFID, the benefits of RFID gained through more accurate inventory, the system parameters that make the investments more profitable and the effect of inventory sharing on the investment decision. As an extension to this study, Uckun et al. (2008) focus on the optimal investment level that maximizes the profit in both centralized and decentralized supply chains. Through a single-period newsvendor analytic approach, they study a three-level supply chain that contains a retailer, a supplier and multiple warehouses. They first develop a model under two scenarios. In the first one, inventory sharing between the warehouses is allowed whereas, in the second scenario, sharing is not allowed. Their model deals with inventory inaccuracy problems due to shrinkage and misplacement errors and they consider that RFID technologies can eliminate these errors. They then study several extensions of this model; asymmetric warehouse parameters, demand and inventory correlation and imperfect RFID implementation. The numerical results show that the profit difference between the decentralized and the centralized system is sharp when the profit margin of the retailer is low and inventory sharing is not allowed. They also observe that, if there is no inventory sharing between warehouses, making an investment to decrease inventory accuracy is more beneficial. Finally, they characterize the important factor for the investment decision as low fixed investment costs and small demand variances. They present interesting analyses that are, however, limited to a simple supply chain. RFID technologies are again considered as perfect technologies.

DeHoratius et al. (2008) analyze a two-level, multi-period inventory system. The originality of this study is that they consider an intelligent inventory management tool using a Bayesian analysis of the physical inventory level. They assume that records can be inaccurate and excess demands are lost and unobserved. They demonstrate that a Bayesian inventory record is an efficient alternative method that can provide good replenishment policies and the required parameters can be estimated from existing data sources. Their results are limited to a simple two-level supply chain.

Sarac et al. (2008a) analyze the impacts of RFID technologies on a newsvendor model that contains inventory inaccuracy because of out of stocks due to misplacements, thefts, expired and obsolete products. This study considers, contrary to numerous papers in the literature, that RFID technologies are not perfect and that their efficiency increases with the associated costs. An analytic model is proposed to examine how RFID technology can decrease the inventory inaccuracy and to calculate the most profitable technology cost. The results show that there is a certain RFID cost that makes the profit optimum. This cost is proportional to the price of the product as well as its ordered quantity.

In this subsection, we reviewed the analytical models dealing with RFID applications in supply chains. Most of these models consider simplified supply chains that contain a single product, a single period, a single manufacturer, etc. Furthermore, the majority of these models consider RFID technologies as a perfect technology that can eliminate all problems.

In analytical models, various hypotheses and approximations are considered. Thus the results of these models are limited. However, simulations provide better observation of a real system to analyze its performances and behavior over time. In the next subsection we present simulation models that consider RFID integrations in supply chains.

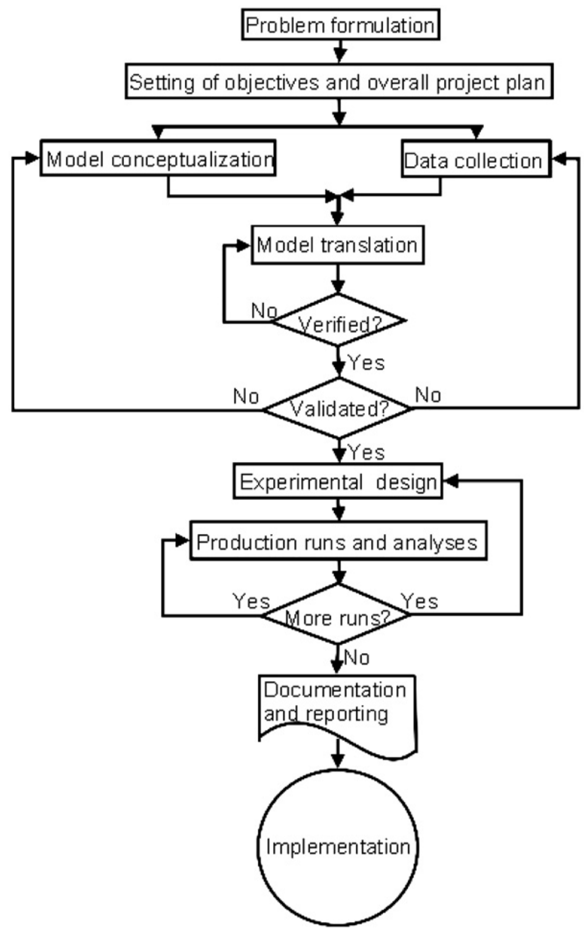

Fig. 3. Steps in a simulation study.

5.2. Simulation models

Simulation provides a better understanding of complex models with a sense of dynamics of the systems. Numerous authors review the necessary steps to perform a simulation study. Banks et al. (2005) present these steps as in Fig. 3.

According to this approach, the model should first be formulated with the statement of objectives and of alternative systems. The model is conceptualized and the required input data is collected. The model is then programmed in a simulation language. In order to pass the experimental design step, the selected computer program efficiency must be verified and the model has to be validated if it represents the actual system behavior. In the next step, production runs and their analyses are used to evaluate the performance measures for the system design. Additional runs are performed if it is necessary. At the end, in order to obtain a successful implementation, the results of all analyses must clearly be saved. We notice that, through several verification steps, simulation studies can provide more realistic analyses of systems than analytic models.

The literature of simulations on RFID applications in supply chains has increased in the last few years. Table 5 presents a short list of the publications analyzed in this section.

One of the first studies on supply chain simulation is performed in Krajewski et al. (1987). Authors simulate an MRP based production environment to analyze the factors of inventory management performance. They use some performance measures such as inventory level, percentage of late orders, etc. More recently, Brown et al. (2001) also simulate an MRP environment in order to analyze the impact of inventory inaccuracy. They focus on the frequency, the magnitude and the location of errors that cause inventory inaccuracy; which represent, respectively, the number of time periods of inaccuracy, the percentage of inaccuracy and the processes where inaccuracy occurs. They conclude that the frequency of errors is the main factor of inventory performance. However, the magnitude and the location of errors can also affect the supply chain performance.

Joshi (2000) uses a simulation approach to evaluate the value of information visibility in a supply chain using RFID. He underlines that information visibility is one of the success factor of software implementations. He deals with the "bullwhip effect", and he simulates a simple supply chain with different scenarios. He varies the degree of information visibility and collaboration between supply chain actors as if RFID technologies were deployed in the system. The results he obtains show that information visibility and collaboration provide 40–70% reduction in inventory costs. He also concludes that the reduction in lost sales improves customer service due to timely order deliveries and real-time traceability. Analyzing a simple supply chain is the main limitation of this study.

Kang and Koh (2002) simulate a retailer inventory system. The model includes an automatic reorder point replenishment policy, random demand and inventory inaccuracy due to shrinkage errors. They show that 2.5% increase of shrinkage can increase stockout rate by about 50%. They also conclude that the indirect cost of uncounted shrinkage errors that cause stockouts is 30 times greater than the direct cost of shrinkage errors.

Kang and Gershwin (2004) also study the impact of shrinkage errors on inventory management. They consider indirect costs

Table 5
List of publications that develop simulation analyses.

Authors	Year	Title
Krajewski et al. (1987)	1987	Kanban, MRP, and shaping the manufacturing environment
Brown et al. (2001)	2001	Measuring the effects of inventory inaccuracy in MRP inventory and delivery performance
Joshi (2000)	2000	Information visibility and its effect on supply chain dynamic
Kang and Koh (2002)	2002	Applications research
Kang and Gershwin (2004)	2004	Information inaccuracy in inventory systems-stock loss and stockout
Lee et al. (2004)	2004	Exploring the impact of RFID on supply chain dynamics
Fleisch and Tellkamp (2005)	2005	Inventory inaccuracy and supply chain performance: a simulation study of a retail supply chain
Basinger (2006)	2006	Impact of inaccurate data on supply chain inventory performance
Leung et al. (2007)	2007	A tool set for exploring the value of RFID in a supply chain
Saygin (2007)	2007	A systems approach to viable RFID implementation in the supply chain
Sarac et al. (2008b)	2008	A simulation approach to evaluate the impact of introducing RFID technologies in a three-level supply chain
Wang et al. (2008)	2008	The simulated impact of RFID-enabled supply chain on pull-based inventory replenishment in TFT-LCD industry
Kim et al.	2008	Value analysis of location-enabled radio-frequency identification information on delivery chain performance
Yoo et al. (2009)	2009	Service-level management of non-stationary supply chain using direct neural network controller
Vrba et al. (2008)	2008	Using radio frequency identification in agent-based control systems for industrial applications
Ustundag and Tanyas (2009)	2009	The impacts of radio frequency identification (RFID) technology on supply chain costs
Wamba et al. (2008b)	2008	RFID-Enabled warehouse optimisation: Lessons from early adopters in the 3PL industry

such as losses of potential customers that occur because of unexpected out-of-stocks and also direct costs due to inventory losses. They simulate a single item inventory model with a periodic review system under a (Q,R) policy to analyze the effects of shrinkage errors on lost sales. In this simulation, they observe that even a 1% shrinkage error can cause an out-of-stock level at 17% of the total lost demand, as well as 2.4% of shrinkage can increase the out-of-stock level to 50%. To eliminate inaccuracy, they also examine several inventory management methods such as safety stock, manual inventory verification, manual reset of the inventory record, constant decrement of the inventory record, Auto-ID technologies and they conclude that each method has different limitations. However, assuming that Auto-ID provides perfectly accurate inventory and studying a single-item model is not realistic enough.

Lee et al. (2004) realize a quantitative analysis to demonstrate the potential benefits of RFID in inventory reduction and service-level improvement. They conclude that RFID can impact some performance factors of the supply chain. They focus on analyzing the effect of factors such as inventory accuracy, shelf replenishment policy and inventory visibility. They show that RFID implementation can reduce the distribution center inventory level by 23% and completely eliminate backorders. They conclude that RFID can also provide a reduction in order quantity that can reduce the distribution center inventory level by up to 47%. Again, in this study, RFID technologies are considered to provide 100% accuracy.

Fleisch and Tellkamp (2005) simulate a one-product three-level supply chain to analyze the impact of different causes for inventory inaccuracy on supply chain performance. They develop two models. In the base model, inventory inaccuracy occurs because of some factors such as low process quality, theft, and items becoming unavailable for sale and there is not any alignment policy to adjust the wrong information on inventory level. In the modified model, inventory inaccuracy is still present but, at the end of each period, inventory records are aligned. The result of their simulation indicates that an elimination of inventory inaccuracy can reduce out-of-stock level and supply chain cost even with a small initial inventory inaccuracy of 2%. They show interesting results that are, however, limited to a one-product supply chain.

Basinger (2006) develops a simulation of a single item, three-level supply chain subject to inventory inaccuracy and studies its impact on supply chain performance. He finds that dominance factors of inaccuracy are the order policy, "stockout/backlog" policy, theft and supply chain synchronization. The results show that the "stockout/backlog" policy has the most impact on the service level, followed by the order policy. He reports that physical inventory counting is a method frequently used to align physical and recorded inventory levels. He concludes that RFID is a new method for real-time alignment of the data that can improve the accuracy of supply chain inventory. Single-item modeling and single setting for the expected demand conditions are the limitations of this study.

Leung et al. (2007) develop a simulation to analyze the impact of RFID on supply chain management. They focus on shrinkage errors that cause inaccuracy. They simulate two models; with and without RFID. They assumed that RFID can eliminate the inaccuracy by 100%. The results obtained show that the backorder quantity decreases by 1% and the average inventory increases by 20%. They also observe that RFID can decrease inventory levels. The originality of this study is that they detail the investment data of RFID technology and its benefits related to inventory shrinkage. However, this study is limited again by considering RFID as a perfect technology and focusing only on the logistics of the supply chain.

Saygin (2007) deals with RFID technology implementations on the inventory management of time-sensitive materials in a simulation environment. He compares four inventory models in order to analyze the impacts of RFID technologies in a complex decision-making manufacturing system. The models are simulated through the Rockwell Arena simulation package and, in each model, the statistical analysis of the performance are obtained by using Analysis of Variance (ANOVA). He demonstrates that RFID technologies can provide important benefits by decreasing manufacturing costs with a higher service level and lower inventory and waste levels. In this study, he considers that RFID technology provides 100% visibility of inventory levels.

Sarac et al. (2008b) analyze the impacts of RFID technologies, particularly their economical impacts and ROI analyses on supply chain performances. They develop a simulation model of a three-level supply chain with inventory information inaccuracies because of thefts, misplacements and unavailable items for sale. The effects of different RFID technologies and with different tagging levels for different product types are examined. The main originality of this research is that various RFID systems of different costs and potential profits are analyzed and the possibility of RFID errors is not ignored. The results show that different technologies can improve the supply chain performance at different ratios, and that the economical impacts and also ROI

Table 6
List of publications that conduct case studies and experiments.

Authors	Year	Title
Lefebvre et al. (2006)	2006	RFID as an Enabler of B-to-B e-Commerce and its Impact on Business Processes: A Pilot Study of a Supply Chain in the Retail Industry
Tzeng et al. (2008)	2008	Evaluating the business value of RFID: Evidence from five case studies
Wang et al. (2007)	2007	Dynamic mobile RFID-based supply chain control and management system in construction
Hou and Huang (2006)	2006	Quantitative performance evaluation of RFID applications in the supply chain of the printing industry
Ergen et al. (2007)	2007	Life-cycle data management of engineered-to-order components using radio frequency identification
Ngai et al. (2007)	2007	Mobile commerce integrated with RFID technology in a container depot
Chuang and Shaw (2007)	2007	RFID: Integration stages in supply chain management
Lin et al. (2006)	2006	Using RFID in supply chain management for customer service
Huber et al. (2007)	2007	Barriers to RFID adoption in the supply chain
Huber and Michael (2007)	2007	Vendor perceptions of how RFID can minimize product shrinkage in the retail supply chain
Manik et al. (2007)	2007	Analysis of RFId application through an automotive supplier's production processes
Delen et al. (2007)	2007	RFID for better supply-chain management through enhanced information visibility
Mourtzis et al. (2008)	2008	Supply chain modeling and control for producing highly customized products
Baars et al. (2008)	2008	Combining RFID technology and business intelligence for supply chain optimization—scenarios for retail logistics
Bottani and Rizzi (2008)	2008	Economical assessment of the impact of RFID technology and EPC system on the fast-moving consumer goods supply chain
O'Leary (2008)	2008	Supporting decisions in real-time enterprises: Autonomic supply chain systems
Kim et al. (2008b)	2008	Comparison of benefits of radio frequency identification: Implications for business strategic performance in the US and Korean retailers
Hossain and Prybutok (2008)	2008	Consumer acceptance of RFID technology: An exploratory study
Pigni and Ravarini (2008)	2008	RFId in the fashion industry: Evidences and lessons learnt from an anti-counterfeiting project
Poon et al. (2009)	2009	A RFID case-based logistics resource management system for managing order-picking operations in warehouses

analyses depend on the chosen technology, the tagging level and the characteristics of the products.

Wang et al. (2008) analyze the impacts of RFID technology in the thin film transistor liquid crystal (TFT-LCD) industry. They develop a simulation model of a pull-based multi-agent supply chain where an automatic inventory replenishment policy (s,S) is enabled with and without RFID technology. They obtain interesting results which show that RFID technology integration to the automatic replenishment policy can reduce the total inventory cost and increase the inventory turnover rate.

Kim et al. deal with the value of RFID real-time information for vehicle deployment and shipment process on delivery chain performance. They develop three simulation models. In the first model, data for vehicle deployment and shipment are collected manually. RFID technology is integrated in the second model to collect real-time data. In the third model, they propose a new planning algorithm that uses RFID technology to provide real-time information automatically. Their simulation study results show that the integration of RFID technology to the tracking system can improve customer satisfaction by decreasing dwell time and can reduce labor cost by increasing labor utilization. They also indicate that RFID-based information systems can provide better decision-making using real-time information. Their analyses are interesting but limited to a simple three-level supply chain.

Yoo et al. (2009) develop a simulation model of a three-level closed loop supply chain to analyze the value of RFID real-time information on the performance of a direct neural network controller. They indicate that a neural network controller is an intelligent decision maker that aims to keep the actual service level close to the target level under an unstable customer demand. They consider that RFID technology can provide the required data for the neural network controller during the operations of the supply chain. Their simulation results show that, using RFID technology, the direct neural network controller can make the actual service level reach the target level in a short time with small average errors. The originality of this study is that they analyze a supply chain that contains multiple actors. However, they consider that RFID technologies provide 100% information accuracy.

Vrba et al. (2008) analyze the deployment of RFID technologies in industrial applications for the real-time programmable logic controller (PLC)-based manufacturing control. They develop a simulation model of RFID integration to an agent based control system. Special RFID agents were introduced as mediators between the physical readers and other control agents. The RFID data was used by resource agents such as machines, transport system components to discuss the details of production and transportation. The originality of this study is that the proposed model was verified in the lab environment using the Manufacturing Agent Simulation Tool system.

Ustundag and Tanyas (2009) perform a simulation study to analyze the benefits of RFID system integration on a three-echelon supply chain. They consider that RFID systems can improve the efficiency, accuracy, visibility, and security level in supply chains. They focus on the product value, lead time, and demand uncertainty as the cost factors of the chain. Their simulation results show that the increase of the product value increases the total supply chain cost saving and the increase of demand uncertainty decreases the cost savings. They also show that supply chain actors do not gain equally from RFID integration and the retailer has the highest cost savings. The increase in lead time decreases the cost saving of the retailer. The increase of the product value and the decrease of demand uncertainty augment almost equally the cost savings for the distributor and manufacturer. The limitation of this study is that RFID technologies completely delete thefts, misplacements and shipment errors.

Wamba et al. (2008b) focus on RFID technologies in the picking and shipping process of one warehouse in third party logistics companies. They perform a simulation study to analyze the impacts of RFID technologies integration on business processes. The originality of this study is that they show that RFID technologies can support the redesign of business processes, improve data quality, real-time data collection, synchronization and information sharing between actors. In their study, they consider that the tagging process is done during the picking process. They conclude that the full benefits of RFID technology can be obtained through its integration in all supply chain actors.

Tu et al. (2009) analyze the performance of RFID technologies in a healthcare system. They propose and simulate different algorithms for locating RFID tagged objects and they analyze RFID benefits on this system. The originality of this study is that, contrarily to most publications, they consider that the RFID technology performance depends on environment properties, tag orientations, etc. They present interesting results that are, however, limited because of simplified assumptions.

In this subsection, we reviewed simulation models of RFID deployments in supply chains. Most of these studies focused on single item, single manufacturer and single retailer supply chains. Through simulation methods, dynamic behavior of the systems can be analyzed. However, simplified models may lead to worst results. In the next subsection, we consider case studies and experiments that can point out key factors of RFID deployments in supply chains.

5.3. Case studies and experiments

Case studies and experiments are tests of RFID technologies in small or simple environments. They help companies to show the difficulties and the efficiency of the integration. Moreover, companies can also evaluate some of the associated costs and profits. These applications facilitate the implementation decision as well as the complete integration in the company. Silver et al. (1998) highlight the importance of realistic models as an important tool for decision making.

There are numerous industrial applications. However, in this section, we focus on the academic papers that deal with case studies and experiments. In the literature, questionnaires and interviews are frequently used in case study papers in order to analyze the point of view of the supply chain actors on the RFID technology, the feasibility and the difficulty of its adoption.

Numerous authors conduct case studies and experiments to analyze the impacts of RFID technologies on supply chains. Table 6 is a short list of the publications detailed in the following.

Lefebvre et al. (2006) develop a pilot study to analyze RFID deployment in the warehouse of a specific supply chain. They collected empirical data from four inter-related firms from three echelons of the supply chain. Their results show that RFID technology can be difficult for the actors to apply because it can improve the existing processes, can provide a new business model and can increase the communication between supply chain actors.

Wamba et al. (2008a) analyze the impacts of integrating RFID technologies and EPC network on mobile business to business e-commerce. They carried out a pilot project by testing various scenarios based on empirical data that was obtained from four different companies. They indicate that RFID–EPC network can enhance operational processes such as shipping, receiving and put-away processes. They note that RFID adoption forces supply chain actors to change their business processes through automated activities, a high-level information sharing and a better synchronization between supply chain actors.

Tzeng et al. (2008) analyze the business value of RFID technology implementation in healthcare industry. They discuss five case studies with five hospitals in Taiwan in order to identify the organizational effects, strategic impacts and business values of RFID in healthcare systems. They indicate that RFID employment can significantly change processes and human resources of the organizations, enhance customer satisfaction and improve efficiency and flexibility of process redesign. They note that re-engineering application optimizes systems but its effectiveness is difficult to estimate because of the uncontrollable factors and psychological elements of the organizations. They also highlight the importance of collaboration and cost sharing between all actors of the healthcare supply chain to maximize the efficiency of RFID technology implementations.

Wang et al. (2007) focus on how RFID technologies can improve the information flow of a construction supply chain environment. They analyze a high-tech factory building in Taiwan in order to verify the proposed RFID-based dynamic construction supply chain model and to test the effectiveness and efficiency of information sharing for project control in the construction phase. They demonstrate that, through real-time information, RFID technology can significantly improve supply chain control and construction project management by improving the efficiency of operations and also by providing a dynamic control.

Hou and Huang (2006) develop an empirical study through questionnaires and interviews to analyze the costs and benefits of RFID applications in the supply chain of the printing industry. They examine the feasibility of RFID deployments through interviews of eight main actors of the Taiwanese printing industry. They propose interesting models with varying complexity and provide quantitative cost and benefit analyses of RFID technologies integration.

Ergen et al. (2007) study intelligent components in engineered-to-order (ETO) management. They propose to use RFID technologies so that intelligent components can communicate their identity, location and history with their environment. In order to analyze the technical feasibility of RFID technology for the intelligent components in construction supply chains, they applied three experiments in three types of components. The originality of this study is that, by using various components under several scenarios, they demonstrate the technical feasibility of RFID technology in supply chains. They also indicate that active UHF RFID technology is efficient to create intelligent components.

Ngai et al. (2007) analyze a case study on RFID technology integration in a mobile commerce system. In this study, they conduct the research and development of an RFID prototype system on a local depot to analyze the impacts of the RFID system on locating, tracking and managing the containers in the depot. Through this case study, they observe that RFID technologies improve visibility, decrease errors and accelerate operational processes that enhance customer service quality and save operational, return and pick-up costs. This study presents interesting analyses, but they could evaluate the economical impacts of RFID technologies, for example through ROI analyses.

Chuang and Shaw (2007) focus on the RFID integration in supply chains. Three different stages of RFID implementation are proposed; functional, business and inter-company RFID integration. They indicate that these stages have different risk and benefit degrees. For each stage, they analyze a company RFID adoption case in order to demonstrate the difficulties and the benefits of a real deployment.

Lin et al. (2006) analyze an RFID business adopting, and the relationship between RFID and customer relationship management (CRM). They propose an RFID–CRM model in supply chain management and show that RFID technologies can improve customer satisfaction.

Huber et al. (2007) focus on the impact of RFID on the shrinkage problem for tracking goods, in particular at case-level and item-level. They analyze the challenges and the difficulties of the adoption of RFID technologies in supply chains using interviews of RFID vendors.

Huber and Michael (2007) study how RFID can decrease shrinkage problems in the retail supply chain. Interviews with nine Australian RFID vendors and associations are used in this research. The results show that RFID can minimize losses in the supply chain. They indicate that the visibility of stocks is the main shrinkage factor that RFID can improve. The authentication capacity is also defined as a key factor of RFID during recalls, identifying products and against fraud acts. They note that the automation of supply chain processes by RFID technology minimizes human errors. They also add that RFID can decrease the retailer loss by recognizing damaged products because of incorrect temperatures in storage and transportation, expiration dates of products, etc.

Manik et al. (2007) conducted an RFID application project in an automotive industry supplier company to improve the efficiency of the production process. Through the functional experiment, they observe the advantages of the RFID system and analyze the operational experience and the actual implementation cost.

Delen et al. (2007) conduct a case study to analyze the impacts of RFID technologies on supply chain management. They focus on a simple retailer supply chain in which the retailer uses an RFID technology to collect the data of the cases shipped by its major suppliers. They indicate that RFID technologies can improve the performance of the entire supply chain. They note that the key factor of the efficiency is not only the technology itself but also the creative use of the data obtained by this technology. The main originality of this study is that they show that RFID is not a perfect technology. They also highlight the importance of the data filtering process to improve the efficiency of RFID implementations.

Mourtzis et al. (2008) deal with the use of RFID technology in a highly customizable production supply system in order to dynamically assure the communication between actors by using real-time information to verify the availability of parts required for production. Through a case study in the automotive industry, they demonstrate a software system to analyze the feasibility of RFID integration in the automotive supply chain. They indicate that RFID significantly reduces the order delivery time so that customization orders can be realized in spite of market variation.

Baars et al. (2008) analyze the feasibility of a decision support system based on RFID technology and the business intelligence in supply chain management. They use a case study of a three-level retail supply chain which includes Chinese manufacturers, a consolidator who deals with the bundling and the shipment of products in containers from different suppliers in China, and a goods distribution center (GDC) in Germany. They indicate that cooperation between the business intelligence and RFID technologies enhances supply chain operations, but a cost-benefit analysis should be realized.

Bottani and Rizzi (2008) analyze the economical impact of RFID technology on the fast-moving consumer good (FMCG) supply chain. They focus on a three-echelon supply chain which includes manufacturers, distributors and retailers of FMCG. They collected quantitative and qualitative data of the logistics processes of each actor through a questionnaire survey to examine the feasibility of RFID and EPC adoption, for each echelon of the chain and for the whole chain. The originality of this study is that they show that RFID and EPC deployment is still not profitable for all of the actors. They indicate that, both in the integrated and non-integrated scenarios, RFID technologies at pallet-level can provide benefits for all echelons. However, manufacturers cannot obtain positive revenues because of the high cost of case-level tagging.

O'Leary (2008) highlights RFID technologies as one of the technologies and architectures that can provide real-time information and autonomic supply chain. Knowledge-based event managers, intelligent agents, database and system integration, and enterprise resource planning systems are the other reviewed technologies. They analyze two applications of Procter and Gamble and tainted dog food and spinach that demonstrate real-time decision support systems and autonomic system architectures.

Kim et al. (2008b) compare the benefits of RFID technology on the supply chain management of US and Korean retailers. Through the interviews of numerous US and Korean retailers, they estimate a path model to analyze technological infrastructure, RFID benefits and business strategic performance. Their results indicate that data system automation is a key factor to improve inventory management for both countries. They note that hardware and software applications influence RFID benefits in inventory management for US retailers while, for Korean retailers, it can improve the efficiency of store operation and demand management. They also show that business strategic performance is a main RFID benefit factor for both US and Korean retailers.

Hossain and Prybutok (2008) analyze the factors of consumer acceptance of RFID technology. They develop and test a theoretical model with a technology acceptance model. Through interviews of consumers, they indicate that convenience, culture, and security are significant elements of the consumer acceptance of RFID.

Pigni and Ravarini (2008) analyze the effects of RFID technologies in the fashion industry. They perform a case study in the Italian fashion industry that includes the gray market and the product distribution. They show that RFID technology integration improves the system business process and provides an inter-organizational information system that improves the efficiency and effectiveness of the entire supply chain.

Poon et al. (2009) analyze and perform a case study on RFID technology integration in a warehouse in order to facilitate the collection and sharing of inventory data. They aim to formulate and suggest the most effective RFID solution in a warehouse environment. The originality of this study is that they study the actual environment of the warehouse and they propose various RFID technologies (different sizes, costs, reading performances, and application domains) according to properties of the environment. They evaluate the reading performances of active and passive RFID technologies through four tests (orientation, height, range and material). The results of these tests help to select the most efficient RFID equipment and to install the equipment in the most suitable locations for data collection in the warehouse environment. They also verify the data capture capability of the selected RFID technology in three steps; data collection, data storage and data management. They propose three technologies that improve the efficiency of the warehouses by facilitating real-time information sharing and solving communication problems along the supply chain, also by transferring raw data to material handling solutions. Finally, they practice the proposed system in a real working case with three main objectives; simplifying RFID integration, improving the visibility of warehouse activities and the performance of the warehouse.

In this section, we presented the literature on RFID applications in supply chains using analytical models, simulations, or case studies and experiments. These methods can be used in conjunction to analyze impacts, difficulties and effectiveness of RFID technologies in supply chains. In addition to all of these methods, return-on-investment (ROI) analyses can be carried out to determine the economical impacts of RFID deployments. The next section surveys the literature on ROI analyses related to RFID applications in supply chains.

6. Return-on-investment (ROI) analyses of RFID implementation in supply chains

ROI analyses are conducted to evaluate whether an investment is profitable over a period of time. They have often been studied through analytical models, simulations, case studies and experiments. However, the literature on this subject is limited. In this section, we first highlight the importance of ROI analyses. We then present how we can calculate ROI and how a positive ROI can be obtained. Finally, we present some ROI applications on RFID projects.

6.1. Why are ROI analyses so important?

As mentioned before, RFID technologies can provide several benefits on supply chains; cost reduction such as labor cost, inventory cost, process automation, or efficiency improvements and value creation such as increase in revenue, or increase in customer satisfaction (Wu et al., 2006). Leung et al. (2007) present the benefits of RFID as in Fig. 4. This figure shows the benefits of RFID in three main groups; revenue, operating margin, capital efficiency. We observe that there are several benefits of RFID technologies through the increase in revenue, the decrease in operating costs and expenses and the improvement in capital through the reduction of property, plant and equipment costs and inventory costs.

However, the cost of RFID is still larger than current identification technologies (Zipkin, 2007). Furthermore, RFID implementations require large costs, that Banks et al. (2007) divide into six groups; hardware costs, software costs, system integration costs, installation services costs, personnel costs and business process reengineering costs. Fig. 5 shows the main costs of RFID implementations.

The discussion above shows that there are several significant costs and benefits of RFID implementations. Thus, companies must decide whether to invest or not to acquire RFID technologies. Hence, ROI analyses are helpful to support decisions on the feasibility of RFID deployments (Fleisch and Tellkamp, 2005).

6.2. How to calculate ROI?

Eq. (1) recalls the simplest formula to calculate ROI:

$$\mathrm{ROI} = \left(\frac{\text{The final monetary yield of the project}}{\text{The investment required by the project}} - 1\right) * 100 \qquad (1)$$

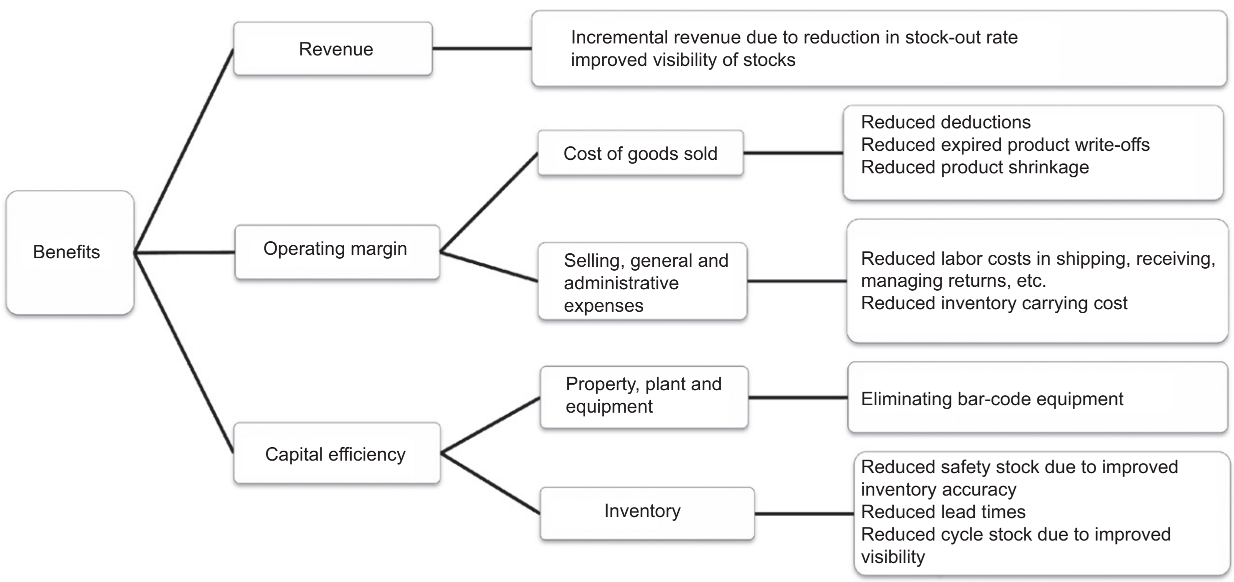

Fig. 4. RFID benefits (Leung et al., 2007).

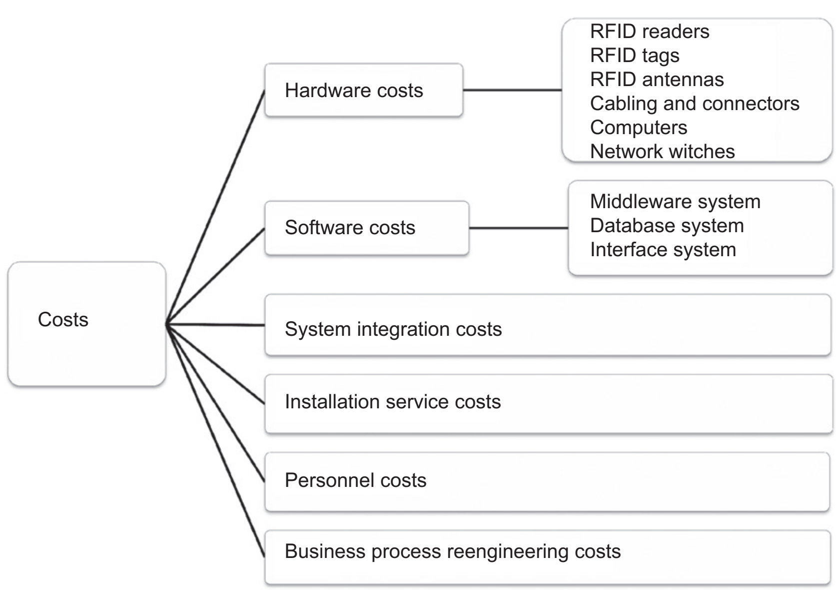

Fig. 5. RFID implementation cost tree (Banks et al., 2007).

However, this is a simplified formula that cannot provide the real economical visibility of RFID implementations. RFID projects are analyzed over multiple time periods, days, months or years. These time periods force companies to take into account the time value of money. The following equation presents the ROI formula considering the time value of money (Banks et al., 2007):

$$\mathrm{ROI} = \left(\frac{\sum_{t=1}^{n} \frac{V_t}{(1+D)^t}}{V_i} - 1 \right) * 100 \qquad (2)$$

where t is the time period, n is the number of periods, V_i is the investment required by the project, V_t is the monetary yield of the project at the end of time period t, and D is the discount rate for the time value of money.

ROI analyses will be positive if the project is profitable, or negative for unprofitable projects.

6.3. Key factors to obtain a positive ROI

Goel (2007) reports that, to understand the ROI of RFID implementation, an organization must analyze the economic justification of RFID. He also concludes that they must first understand RFID technology, then understand potential uses of RFID in their environment and finally decide how to make the investment.

A positive ROI depends on the technology costs; price of tags, readers and middleware, implementation costs, maintenance service cost, etc. The level of RFID tagging is an important cost factor. Case/pallet-level tagging cost is lower than item-level tagging cost which can provide more benefits. Gaukler and Seifert (2007) report that there is no positive ROI of item-level tagging for manufacturers while a positive ROI can be attained for retailers. Tag cost is also less important in a closed loop because tags can be used many times while, in an open loop, tags are used one time (Barbier and Lecosse, 2007). In the last years, positive ROIs have been observed from closed-loop RFID implementations in manufacturing and asset management (Tajima, 2007).

A positive ROI also depends on the benefits that RFID can provide (Doerr et al., 2006). Classical ROI analyses focus on direct benefits, while new RFID analyses are also interested in indirect benefits (Leung et al., 2007; Lee et al., 2004). Direct benefits of RFID technologies include increase of sales and/or decrease of lost products that can be observed and quantified. Indirect benefits consider non-financial benefits such as improved customer satisfaction and shortened customer response times, etc. These improvements cannot be quantified by a direct economical calculation but they can increase direct benefits later.

Angeles (2005) reports that choosing the right technology is very important for positive ROI. He writes that three factors have to be considered when choosing RFID technology; the needs of enterprises, the needs of their partners and the needs of the industry.

Deployment of RFID technologies on entire supply chains is another important factor. If all the actors of a chain share the cost of RFID, implementation becomes easier for each of them. In a recent paper, Gaukler et al. (2007) indicate that sharing the cost of RFID between manufacturers and retailers can maximize the total supply chain profit. For example, Wal-Mart asked its 100 largest suppliers to use RFID at the pallet and case levels in 2005. Wal-Mart shared the RFID deployment cost with its suppliers (Wang et al., 2008).

6.4. ROI analyses on RFID projects

ROI analyses are very important for companies to determine whether an RFID investment will repay the investor. ROI analyses on RFID projects in the literature are still limited because of the current stage of the RFID technology and because companies that conduct successful analyses want to hide their results from their competitors (Banks et al., 2007).

IBM and Accenture developed an ROI calculator (Tellkamp, 2003). This calculator focuses on a supply chain that includes manufacturer, distributor, retailer, etc. The tagging level (item, case and pallet), decrease in labor cost, reduced inventory levels, more detailed information about the firm's processes are the main subjects that they are interested in. The companies can use this calculator by changing the nature and the number of variables.

IBM Business Consulting Services conducted an "EPC Forum survey" with over 60 sponsor and non-sponsor companies of the Auto-ID center. The aim of this study is to give an early indication of directions and priorities to the companies (Gramling et al., 2003). Procter & Gamble, Wal-Mart, Target and Johnson & Johnson are the main sponsors of this work. The participants have a wide range of functions; finance, supply chain, marketing and technology. Furthermore, the companies are from Europe, South America and the US. The majority of participants are manufacturers. This survey shows that most of the end users expect to drive attractive ROI results from case and pallet-level implementation. They also write that over 70% of retailers expect to be rolling out full implementation of Auto-ID by the end of 2004; while about 50% of manufacturers expect to reach rollout at the end of 2004.

In this section, we reviewed ROI analyses of RFID deployments in supply chains. The literature on this subject is limited. RFID technologies can provide important benefits to companies. However, because of their high costs, integrating RFID technologies in companies still require important investigations. Furthermore, every company should perform its own ROI analysis, because an RFID technology can be more beneficial for a company than another technology and/or for another company environment (Sarac et al., 2008b).

7. Conclusion and perspectives

This survey covers potential benefits of RFID technologies in supply chains. We analyze the literature according to two criteria; the problems for which RFID can improve efficiency and the methods used to analyze the impacts of RFID technologies. Thus, we first focus on cost reduction and value creation, particularly related to inventory inaccuracy, the bullwhip effect and replenishment policies. Then, we survey analytical models, simulations, case studies and experiments that were developed to analyze the impact of RFID technologies on supply chain management. Finally, some ROI analyzes are presented.

This survey showed that RFID technologies can provide several advantages in supply chain management. The main advantages of RFID technologies in supply chains are:

- Improvement of traceability and visibility of products and processes.
- Increase of efficiency and speed of processes.
- Improvement on information accuracy.
- Reduction of inventory losses.
- Facilitation of management through real-time information.

Important implementations have been conducted by pioneer companies such as Wal-Mart, Metro, Mark and Spencer, Tesco, Gillette and Procter & Gamble. RFID applications have marked significant progress in some industries such as automobile industry, cattle ranching, healthcare, manufacturing, military, payment transactions, retailing, transportation, warehousing and distribution systems (Banks et al., 2007). However, real applications of RFID technologies are still limited because of various technical and economical obstacles. Metal and liquid environment can disturb reading performances of RFID technologies. Numerous tests are conducted to obtain optimum technologies according to the environment. Lack of international standards is another disadvantage. For example, there are important differences between the UHF frequency in Europe and USA. Furthermore, the costs of RFID are still often much larger than the costs of current identification technologies. RFID technologies have been attractive in numerous contexts and for numerous companies, but most of them still prefer to start with pilot projects and ROI analyzes to evaluate costs and profits. However, we indicate that real RFID implementations in a complete system for several products and process, when all actors of the supply chain can provide strong collaboration and cost sharing, can significantly improve performance of supply chains and thus increase benefits.

The originality of this study is that we present a complete review of the literature through statements and critical analyses of selected publications. However, this survey is limited by the number of analyzed publications.

In surveying the literature, we observe that there are four main limitations:

- Most of the previous research considers RFID as a perfect technology which can eliminate all inaccuracy problems in supply chains.
- We also point out that these studies are limited to provide a complete analysis of the impacts of RFID technologies on supply chains performances and economical issues. Most of the studies analyze single-level supply chains and/or on a single time period and/or for a single product type.
- Most of the previous studies only develop analytical models. These models do not support a dynamic analysis, and so are not capable to fully estimate the impacts of real-time information provided by RFID technologies.
- We notice that most of the studies consider the integration of RFID technologies as replacement of current technologies. Actual supply chains have been designed during long years according to the characteristics and the working issues of current technologies such as bar codes.

Conducting research for multiple items and multiple actors can provide more realistic analyses of supply chains. Thus, we believe that future studies should aim at studying more complex supply chains.

There are also numerous different RFID systems obtained by combining different types and numbers of tags, frequencies and readers, tagging levels, open/closed loops, environment sensors. The costs and potential benefits of these technologies vary in a wide range. Although some studies take into account that RFID technologies are not perfect and their performances increase with their costs, many research opportunities still remain.

Choosing the right technology for an environment is a key decision factor for companies to gain the most out of RFID technologies. Analyzing the environment and defining their objectives, constraints, strengths, weaknesses, opportunities, and threats are as important as analyzing different RFID technologies in order to choose and implement the most efficient technology.

We also want to highlight the importance of reengineering through RFID technologies. In this survey, we present numerous publications that show that RFID technologies improve supply chains. However, reorganizing supply chains using these new technologies can significantly increase gains. So, it would be relevant in future studies to consider new reengineering possibilities to optimize the benefits of RFID technologies in supply chains.

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