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

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March 2009

Working paper ENSM-SE CMP WP 2009/2

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 in order 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.

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January 26, 2009

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 in order 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.

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 [75]. 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 [14], [39]. There are different EPC formats; 64 bits, 96 bits or 128 bits... EPC of 96 bits can identify more than 268 million manufacturers, more than 16 million types of objects and almost 69 billion articles for each manufacturer [14]. 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 [34], [36]. 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 [70]. 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 [105] 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) [62]. 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 [74]. Thus, applications of RFID in supply chain have increased. Bagchi *et al.* [8] reported the prediction of RFID growth as from $1 billion in 2003 to $4 billion in 2008 to $20 billion in 2013.

Current applications of RFID focus on inventory management, logistics and transportation, assembly and manufacturing, asset tracking and object location, environment sensors, etc [37]. Some sectors have more opportunity to gain from the various RFID applications, such as retail, healthcare, textile, automotive and luxury good industries [70].

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. Table 1 presents a general classification of papers according to the main approaches and the main topics of the publications on RFID applications in supply chains.

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

Publications	Main Approaches	Main Topics
Practical papers	Pilot projects	Inventory management
	Case studies	Logistics and Transportation
	ROI analyzes	Assembly and Manufacturing
		Asset tracking and Object location
		Environment sensors
Academic papers	Analytical approach	Inventory inaccuracy
	Simulation approach	Bullwhip effect
	ROI analyzes	Replenishment policies
	Literature review	

Table 1: Classification of publications

Practical papers generally deal with pilot projects, case studies and ROI analyzes 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 of IBM about improving product availability at the Retail Shelf by using Auto-ID technologies, Alexander *et al.* [3] 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 [51], Chappell *et al.* [22] [21], Tellkamp [104] and Lee *et al.* [67]. The white paper of Bitkom [41] presents an overview of numerous applications of RFID systems in Germany. 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 in supply chain problems that RFID technologies have the possibility to solve. Inventory inaccuracy (Kang and Gershwin [52], Atali *et al.* [6], Fleisch and Tellkamp [32]...), bullwhip effect (Joshi [50], Lee *et al.* [66], Fleisch and Tellkamp [32]...), and replenishment policies (Kok and Shang [59], Lee *et al.* [66]...) 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 [65], Rekik *et al.* [87]...), simulation approach (Brown *et al.* [16], Leung [69]...), case studies and experiments (Lefebvre *et al.* [68], Wamba *et al.* [113], Bottani and Rizzi [13]...). 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.* [67], Kang and Koh [53]...).

Literature review papers of RFID technologies on supply chains are limited. In a literature review on Build-to-Order Supply Chain (BOSC) management, Gunesekaran and Ngai [42] highlight RFID technology as one of the important information technologies for BOSC that increases efficiency and accuracy. Extending this study, Ngai *et al.* [78] 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. Németh *et al.* [79] present a state-of-the-art on RFID systems and the challenges and possibilities of the integration to supply chains. Chao *et al.* [20] review the literature on trends and forecast of RFID technologies from 1991 to 2005 by a historical review method and bibliometric analyze. They focus on the RFID innovation, deployment by enterprises and market diffusion in supply chain management. Recently, Delaunay *et al.* [27] present a survey on the causes of inventory inaccuracy in supply chain management. Dolgui and Proth [29] 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.

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.

The remaining of this review is organized as follows. In Section 2, a brief survey of potential benefits of RFID technologies in supply chains is presented in three parts; (1) the benefits of RFID improving inventory accuracy, (2) dealing with the bullwhip effect and (3) replenishment policies in supply chains. Section 3 describes different approaches such as analytic modeling, simulations, case studies and experiments. ROI analyzes are reviewed in Section 4. In the last section, some concluding remarks and research perspectives are presented.

2 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.* [95], Michael and McCathie [76]). Thus, RFID can improve the traceability of products and the visibility throughout the entire supply chain, and also can make reliable and speed up tracking, shipping, checkout and counting processes, which leads to improved inventory flows and more accurate information (Chow *et al.*, Tajima). Leung *et al.* [69] present the benefits if RFID as in Figure 1 in three main groups; revenue, operating margin, capital efficiency.

However, as mentioned before, the objective of RFID implementation is not just to improve current systems. Reorganizing processes using this new technology can

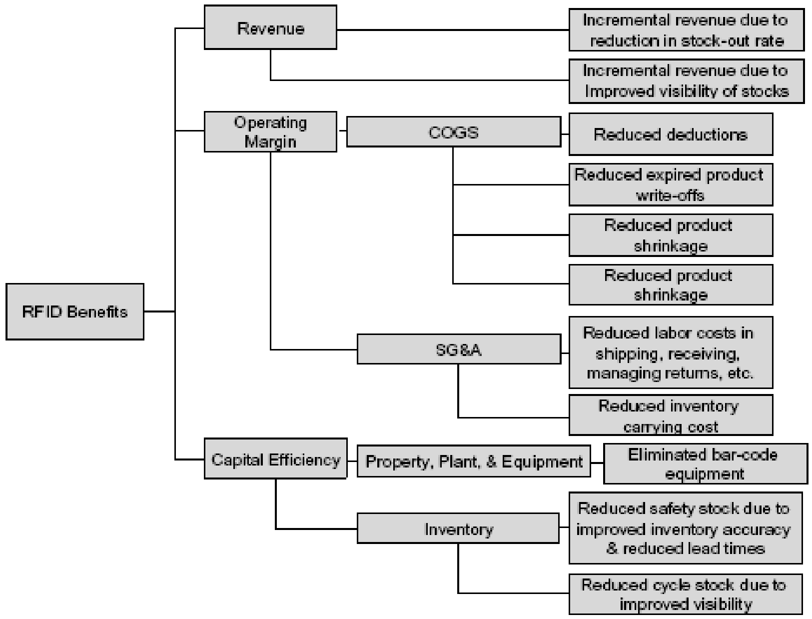

Figure 1: RFID benefits tree

also lead to large gains in the overall supply chain effectiveness (McFarlane *et al.* [75], Agarwal [1], Langer *et al.* [63]). Bottani and Rizzi [13] conclude that reengineering models highlight possible benefits gained through RFID for all processes of distribution centers and retailers.

There are not many real supply chain application yet. Enterprises generally conduct pilot projects to validate this technology in a limited environment. According to Chappell *et al.* [22] the purposes 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 [8]. In 2005, Wal-Mart asked their 100 first suppliers to tag all their pallets and cases [115], [70], [118]. 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% [13]. Roberti [89] 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.* [113] 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 [116] 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.

2.1 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 [52]. The difference between these inventory levels is called inaccuracy and can deeply affect the performance of firms. DeHoratius and Raman [26] 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.* [84] 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 Inglehart and Morey [49], 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 Inglehart and Morey [49]. Several authors followed this study (Krajewski *et al.* [61], Brooks *et al.* [15]...). Transaction errors include shipment errors, delivery errors, scanning errors [83] and also incorrect identification of items [66]. Shipping errors can be very expensive; customers who receive wrong items can demand a refund or the supplier has to pay double transportation costs [83]. Delivery errors were explained such as delivery quantities from suppliers that are different than the required quantities [65]. The deliveries of wrong products or deliveries to the wrong directions are also delivery errors [4]. 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 [1].

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 [18], Brooks *et al.* [15]...). According to a retail survey report of the University of Florida, shrinkage errors represent 1.69% of sales for retailers [43]. Shrinkage errors include employee theft, shoplifting, administration and paperwork errors, vendor fraud [22] [21] and unavailable products for sale [53]. 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

	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
Inglehart and Morey [49]	*												
Bullard and Resnik [18]						*	*						
Krajewski *et al.* [61]	*		*										
Brooks *et al.* [15]	*		*	*		*	*						
Yano and Lee [119]													*
Raman [84]	*	*		*									
Lightburn [71]						*		*					
Alexander *et al.* [3] [4]	*	*	*	*		*	*	*					*
Kang and Koh [53]						*							
Chappell *et al.* [22] [21]											*	*	
Kok and Shang [59]	*												
DeHoratius and Raman [26]	*	*		*							*	*	
Wong and McFarlane [117]	*		*			*	*				*	*	
Tellkamp *et al.* [103]	*			*		*	*		*	*			
Lee *et al.* [66]	*				*	*					*		
Kang and Gershwin [52]	*				*	*	*						
Fleisch and Tellkamp [32]	*		*			*	*	*			*	*	
Kleijnen and Van Der Vorst [58]						*							
Sahin [90]	*					*	*	*			*	*	
Lee and Ozer [65]	*		*	*		*	*	*	*		*	*	
Bensoussan *et al.* [12]						*		*					*
Camdereli and Swaminathan [19]											*	*	
Atali *et al.* [6]	*			*		*	*	*			*	*	
De Kok *et al.* [60]	*					*					*	*	
Ketzenberg and Ferguson [54]						*		*					
Rekik *et al.* [85] [87] [88] [86]	*	*		*		*	*	*		*	*	*	*
Tellkamp [104]	*	*	*	*		*	*	*	*	*	*	*	
Basinger [11]	*	*		*	*	*	*	*	*		*	*	
Doerr *et al.* [28]	*	*				*							
Kim *et al.* [57]						*							
Tajima [102]						*	*	*					
Leung *et al.* [69]	*		*		*	*	*	*			*		
Delaunay *et al.* [27]	*					*						*	*
Uçkun *et al.* [108] [107]	*					*						*	
Sarac *et al.* [92] [93]						*	*	*				*	

Table 2: Survey on the causes of inventory inaccuracy

total sales (2000 Retail Survey University of Florida [21], the National Supermarket Research Group for 2001 [32]). The products unavailable for sale are called unsaleable by Tellkamp [103]. Lightburn [71] 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.* [22] call unsaleable products as write-offs. They explain that one of its 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.* [66], Camdereli and Swaminathan [19]...). Employees can put products in wrong shelves or customers can set an item that they took from a shelf to another shelf [53]. It can also happen in the back room store [117]. This inaccessible inventory can be found later and be ready to be sold again. If the items are seasonal, and they are found after the season, retailers can discount the price to sell the products [87]. If misplaced items are found too late and become out of date, mode or season, the inaccessible products become unsaleable products and thus cannot be sold [52]. Raman *et al.* [84] present a case study where misplaced items reduced profits by 25%.

Literature on supply errors are limited (Yano and Lee [119], Bensoussan *et al.* [12]...). Product quality, yield efficiency and supply process can affect inventory accuracy [85].

Recently Delaunay *et al.* [27] present a survey on the causes of inventory inaccuracy in supply chain management. 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 its real time data capture properties that enable improvements in the supply chains against these inventory inaccuracy errors [66]. It is in particular very successful to eliminate transaction errors [123]. Although RFID cannot eliminate all errors, they can be detected quickly and by considering the existence of this problem in planning processes, they can be dealt with effectively. Several authors were interested in RFID technologies to be able to eliminate these errors. They analyzed the impact of RFID technologies on inventory inaccuracy due to different errors. Kang and Gershwin [52], Fleisch and Tellkamp [32], Lee *et al.* [66], Sahin *et al.* [91], Rekik [85] and Gaukler [36] are some of them. These papers will be detailed in the next section.

2.2 Bullwhip effect

The bullwhip effect is an important phenomenon of supply chain management that has been studied for about fifty years. It was explained by Stevenson [100] 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 [33]. 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, 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.

Numerous authors followed Forester; Buffa and Miller [17] deal with the bullwhip effect in planning and control. Sterman [99] 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 *et al.* present a study of Philips Semiconductor bullwhip effects [59]. 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 showed important savings; minimum yearly savings of around US $5 million from $300 million yearly turnover.

More recently, Lee *et al.* deal with this subject [66]. They present two main sources of bullwhip effect such as selling seasonal items and batching orders by participants. The sharp variance of customer demand for seasonal items complicates the downstream actors' purchasing. Batching continuous orders in the periodic ordering systems cause demand variance up to the supply chain. He also reports that the bullwhip effect can significantly be reduced through information sharing. Yucesan [121] 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. According to Huang *et al.* [46], 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.* [23] 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.* [30] 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 than choosing the wrong assembler or supplier. Zhou [122] analyzes the benefit of RFID item-level information visibility using a manufacturing example in 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.* [2] 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 ([50], [97] and [32]). We detail these papers in the next section.

2.3 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 stock-out 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. Kok and Shang [59], Lee *et al.* [67] and Kang and Gershwin [52] 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 scope with. RFID can improve supply chain performances by increasing inventory availability, improving coordination, saving labor cost, reducing inventory levels... 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 in order 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.

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

There are several methods to study a system. Law and Kelton [64] present these methods as showed in Figure 2 in two groups; experiments with the actual system and experiments with a model of the system that contains physical and mathematical models.

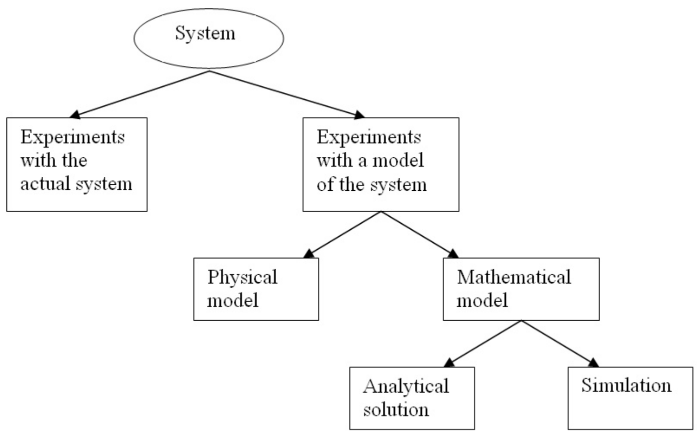

Figure 2: Methods to study a system

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.

3.1 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 3 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 [49]. 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, in order to correct inaccurate data, and safety stocks in order to protect the system against out-of-stocks.

	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 [49]	*		*		*		*		(s,S)
Lee and Ozer [65]	*		*		*		*	*	(s,S), (Q,R)
Kang and Gershwin [52]	*		*				*		(Q,R)
Gaukler *et al.* [35]						*			(Q,R)
Atali *et al.* [6]	*		*		*			*	
Kok *et al.* [60]			*		*			*	(R,S)
Sahin *et al.* [91] [90]	*		*		*		*		Newsvendor model
Rekik *et al.* [85] [87] [88] [86]	*	*	*		*		*		Newsvendor model
Tellkamp [104]	*	*	*		*			*	(s,S) (s,Q)
Gaukler *et al.* [38] [36]	*	*	*		*			*	(Q,R)
Sounderpandian *et al.* [98]		*		*	*			*	(s,Q)
Szmerekovsky and Zhang [101]	*	*			*	*	*		
Uçkun *et al.* [107]	*	*	*		*		*		Newsvendor model
Sarac *et al.* [92]	*		*		*		*		Newsvendor model

Table 3: Characteristics of analytical modeling papers

In a recent paper, Lee and Ozer [65] 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. 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 [52] 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.* [35] 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.

Atali *et al.* [6] 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 and, in the second model, they integrate RFID in order 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. They conclude that RFID can eliminate some of the error sources, but not all of them.

Kok *et al.* [60] 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. 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 increase investment dramatically if the item value and the theft rate are high.

Sahin [90] 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.* [91] develop a single-period model where inventory inaccuracies occur because of the data capture process. In this model, demand and errors are uniformly distributed, and the impact of inaccuracies on the inventory system performance is evaluated. They also focus on 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%.

The previous study is again extended by Rekik *et al.* ([85], [87], [88] and [86]). The authors perform several analyzes in order 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.* [86] 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.

Tellkamp [104] 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 [36] studies the effects of RFID technologies on supply chains at three decision levels; strategic, tactical and operational. He develops an analytical model in order 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%.

In a recent paper, Gaukler *et al.* [38] 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, 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 analyzes 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 in order to maximize the retailer and the supply chain profit which depends on the retailer's power to mandate the manufacturer a lower profit.

Sounderpandian *et al.* [98] 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. They assume that the RFID technology is applied at item, case, and pallet levels. They consider that 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 a 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.

Szmerekovsky and Zhang [101] 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. They indicate that it should be interesting to consider also the fixed costs of RFID.

Uçkun *et al.* [107] 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, Uçkun *et al.* [108] 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.

DeHoratius *et al.* [25] analyze a multi-period inventory system for a single item with periodic review. 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.

Sarac *et al.* [92] 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 their efficiencies increase with the costs of RFID technologies. An analytic model is proposed in order 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 in order to analyze its performances and behavior over time. In the next subsection we present simulation models that consider RFID integrations in supply chains.

3.2 Simulation models

Simulation provides 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.* [9] present these steps as in Figure 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 must be verified if it performs efficiently and the model has to be validated if it represents the actual system behavior. In the next step, production runs and their analysis are used in order 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 analysis must clearly be saved.

The literature of simulations on RFID applications in supply chains has increased in the last few years. One of the first studies on supply chain simulation is performed in Krajewski *et al.* (1987) [61]. Authors simulate an MRP based production environment in order 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.* [16] also simulate a 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.

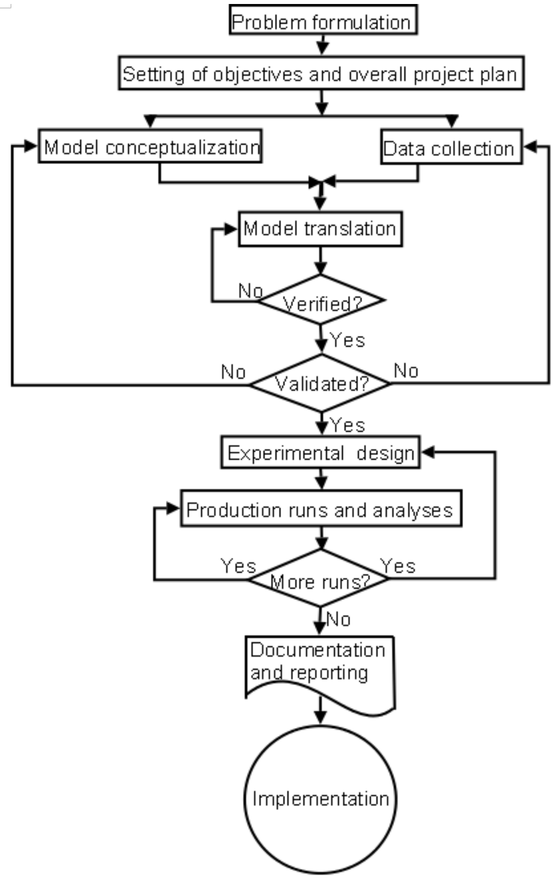

Figure 3: Steps in a simulation study

Joshi [50] 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.

Kang and Koh [53] 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 stock-out 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 [52] also study the impact of shrinkage errors on inventory management. They consider indirect costs 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 in order 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 methods have different limitations.

Lee *et al.* [67] 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 distribution center inventory level by 23% and eliminate completely backorders. They conclude that RFID can also provide a reduction in order quantity that can reduce distribution center inventory level by up to 47%.

Fleisch and Tellkamp [32] simulate a one-product three-level supply chain in order 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 of 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%.

Basinger [11] develops a simulation of a single item, three-level supply chain subject to inventory inaccuracy and its impact on supply chain performance. He finds that dominance factors of inaccuracy are the order policy, stock-out/backlog policy, theft and supply chain synchronization. The results show that the stock-out/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.

Leung *et al.* [69] 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.

Saygin [94] 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.* [93] analyze the impacts of RFID technologies, particularly their economical impacts and ROI analyzes 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 were 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 the economical impacts and also ROI analyzes depend on the chosen technology, the tagging level and the characteristics of the products.

Wang *et al.* [115] 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 agents supply chain where an automatic inventory replenishment policy (s, S) is enabled with and without RFID technology. Their results 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.* [56] 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 use RFID technology to provide real time information automatically. Their simulation study results show that the integration 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.

Yoo *et al.* [120] develop a simulation model of a three-level closed loop supply chain in order 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.

Vrba *et al.* [110] 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 proposed model was verified in the lab environment using the Manufacturing Agent Simulation Tool system.

Ustundag and Tanyas [109] 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 augment in 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 in product value and the decrease in the demand uncertainty augment almost equally the cost savings for the distributor and manufacturer.

Wamba *et al.* [111] 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. They show that RFID technologies can support the redesign of business process, improve data quality, real-time data collection, synchronization and information sharing between the 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.

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.

3.3 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.* [96] 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.

Lefebvre *et al.* [68] 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.* [112] 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 the 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.* [106] analyze the business value of RFID technology implementation in health care 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 health care 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 in order to maximize the efficiency of RFID technology implementations.

Wang *et al.* [114] 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 [45] develop an empirical study through questionnaires and interviews in order 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 different models with varying complexity and provide quantitative cost and benefit analyzes of RFID technologies integration.

Ergen *et al.* [31] 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 environments. 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. 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.

Chuang and Shaw [24] focus 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 or a real deployment.

Lin *et al.* [72] 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.* [48] 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 [47] 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.* [73] conducted an RFID application project in an automotive industry supplier company in order to improve the efficiency of the production process. Through the functional experiment, they were able to observe the advantages of RFID system and to analyze the operational experience and the actual implementation cost.

Mourtzis *et al.* [77] 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 to delivery time so that customization orders can be realized in spite of market variation.

Baars *et al.* [7] 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 contains 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 Centre (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 [13] analyze the economical impact of RFID technology on the fast-moving consumer goods (FMCG) supply chain. They focus on a three-echelon supply chain which contains manufacturers, distributors and retailers of FMCG. They collected quantitative and qualitative data of the logistics processes of each actor through a questionnaire survey in order to examine the feasibility of RFID and EPC adoption, for each echelon of the chain and for the whole chain. Their results 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 [80] 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.* [55] compare the benefits of RFID technology on supply chain management of U.S and Korean retailers. Through the interviews of numerous U.S. 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 U.S. 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 U.S. and Korean retailers.

Hossain and Prybutok [44] 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 [81] 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.* [82] 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. They first study the actual environment of the warehouse they are studying. Then, they analyze various RFID technologies, by considering that the sizes, costs, reading performances, and application domains of these technologies vary. 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. In this phase, they integrate 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 either 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) analyzes can be carried out to determine the economical impacts of RFID deployments. The next section surveys the literature on ROI analyzes related to RFID applications in supply chains.

4 Return-On-Investiment (ROI) analyzes of RFID implementation in supply chains

ROI analyzes are conducted to evaluate whether an investment is profitable on a period of time. They have often been studied through analytical models, simulations, case studies and experiments. 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 [118]. However, the cost of RFID is still larger than current identification technologies [124], and companies must decide whether to invest or not to acquire RFID technologies. Hence, ROI analyzes are helpful to support decisions on the feasibility of RFID deployments [32]. The literature on this subject is still limited.

Goel [39] 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.

ROI analyzes compare the costs and benefits of RFID implementations. 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 [37] 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 [10]. In the last years, positive ROIs have been observed from closed-loop RFID implementations in manufacturing and asset management [102].

A positive ROI also depends on the benefits that RFID can provide [28]. Classical ROI analyzes focus on direct benefits, while new RFID analyzes are also interested in indirect benefits [69], [67]. 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 [5] 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.* [38] indicate that sharing the cost of RFID between a manufacturer and retailer 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 their suppliers [115].

ROI analyzes are limited. IBM and Accenture developed an ROI calculator [103]. 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.* [40]). 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 analyzes 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 [93].

5 Conclusion and Perspectives

This survey covered potential benefits of RFID technologies in supply chains. We first focused on cost reduction and value creation, particularly related to inventory inaccuracy and the bullwhip effect. Then, we surveyed 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 were presented.

This survey showed that RFID technologies can provide several advantages in supply chain management through better traceability and improved visibility of products and processes all along the chains. Increase of efficiency and speed of processes, improvement on information accuracy, reduction of inventory losses are some of these advantages. There have been important implementations conducted by pioneer companies such as Wal-Mart, Metro, Mark and Spencer, Tesco, Gillette and Procter & Gamble. However, real applications of RFID technologies are still limited because 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 prefer to start with pilot projects and ROI analyzes to evaluate the cost and profits.

This review showed that most of the analytical and simulation models proposed in the literature are limited to one product, one retailer, one manufacturer, etc. In further investigations, it would be interesting to conduct research work for multiple items and multiple actors of the supply chain. Moreover, the vast majority of the studies in the literature consider that RFID technologies are perfect and can eliminate all errors in the supply chains. However, there are 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. This survey shows that choosing the right technology and environment is a critical decision for companies to gain the most out of RFID technologies.

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