THE VALUE OF RADIO FREQUENCY IDENTIFICATION TECHNOLOGY FOR MANAGING POOLS OF RETURNABLE TRANSPORT ITEMS

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ABSTRACT

THE VALUE OF RADIO FREQUENCY IDENTIFICATION TECHNOLOGY FOR MANAGING POOLS OF RETURNABLE TRANSPORT ITEMS

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Limited asset visibility is a key problem in the management of returnable transport items (RTIs) like reusable containers, pallets and kegs. One tool to increase asset visibility is radio frequency identification (RFID) technology. However, RFID requires high investment cost and intensive efforts for implementation. In this study, we investigate the added value of using RFID technology for the management of the RTI pool in a closed-loop supply chain setting considering both costs and benefits. We have conducted a case study in a company which has recently started an RFID application in its closed-loop supply chain of RTIs. The aim of this case study is to identify and understand how an existing RTI pool is managed and the impact of using RFID technology on the management of such an RTI pool. In order to quantify the added value of RFID technology in RTI pool management, we search for the minimum cost solutions both without and with the use of RFID technology in a problem environment similar to that of our case study using the simulation optimization method. We also analyze the impact of using RFID technology on RTI pool management in terms of several performance measures, including RTI pool size, RTI lifetime, RTI trippage and the cycle time for RTIs to complete one trip in the closed-loop supply chain.

In our study, we develop a number of discrete event simulation models of the identified closed-loop supply chain of RTIs operating with our predetermined decision rules for the RTI pool management using the simulation software Arena. We then develop our simulation optimization model in OptQuest for Arena in which the discrete event simulation models are embedded. The results from the simulation optimization method show that the added value of using RFID technology is mostly positive and it depends on the severity of the problematic issues in the closed-loop supply chain, as well as on the extent of improvements that RFID brings about.

Keywords: Closed-Loop Supply Chains, Discrete Event Simulation, Radio Frequency Identification (RFID), Reusable Containers, Returnable Transport Items, Simulation Optimization

ÖZ

RADYO FREKANSLI TANIMA TEKNOLOJİSİNİN YENİDEN KULLANILABİLİR KONTEYNER HAVUZLARININ YÖNETİMİ İÇİN DEĞERİ

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Varlık takibinin kısıtlı olması palet, konteyner, fıçı ve varil gibi yeniden kullanılabilir taşıyıcı varlıkların yönetiminde önemli bir sorundur. Varlık takibini artırmak için bir araç, radyo frekanslı tanıma (RFID) teknolojisidir; fakat bu teknolojinin uygulanması, yoğun çaba ve yüksek yatırım maliyeti gerektirir. Bu çalışmada, RFID teknolojisinin yeniden kullanılabilir konteyner havuzlarının yönetimine sağladığı katma değeri, bir kapalı devre tedarik zinciri ortamında, hem maliyet hem de fayda kalemlerini dikkate alarak araştırmaktayız. Çalışmamız kapsamında, yeniden kullanılabilir konteynerlerin kapalı devre tedarik zincirinde RFID uygulamasını yeni başlatmış olan bir işletmede bir vaka analizi gerçekleştirdik. Bu vaka analizinin amacı, var olan bir yeniden kullanılabilir konteyner havuzunun nasıl yönetildiğini; ve bununla birlikte RFID teknolojisinin böyle bir havuzun yönetimindeki etkisini belirlemek ve anlamaktır. Yeniden kullanılabilir konteyner havuzlarının yönetiminde RFID teknolojisinin katma değerini ölçmek amacıyla; hem RFID teknolojisiyle, hem de bu teknolojinin yokluğunda maliyeti en aza indiren çözümleri, benzetimle eniyileme yöntemi ile aramaktayız. Bununla birlikte, RFID teknolojisinin yeniden kullanılabilir konteyner havuzlarının yönetimindeki etkisini; konteyner havuzunun büyüklüğü, konteyner ömrü, konteynerin toplam kullanım sayısı, konteynerin kapalı devre tedarik zinciri içindeki dönüş süresi gibi başarı ölçüleri ile de incelemekteyiz.

Bu çalışmada, belirlediğimiz konteyner havuzu yönetimi karar kuralları ile işleyen kapalı devre tedarik zincirinin ayrık olaylı benzetim modellerini, Arena benzetim yazılımını kullanarak geliştirmekteyiz. Daha sonra, içine ayrık olaylı benzetim modellerinin gömüldüğü benzetim eniyilemesi modelini oluşturmaktayız. Sonuçlar, RFID teknolojisinin katma değerinin çoğunlukla pozitif olduğunu; ve bu katma değerin, kazanılan iyileştirmenin derecesine ve tedarik zincirindeki sorunların ciddiyetine bağlı olduğunu göstermektedir.

Anahtar Kelimeler: Ayrık Olaylı Benzetim, Benzetim Eniyilemesi, Kapalı Devre Tedarik Zincirleri, Radyo Frekanslı Tanıma (RFID), Yeniden Kullanılabilir Konteynerler

To my family

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ABBREVIATIONS

AIDC:	Automatic identification and data capture
CDF:	Cumulative distribution function
CLSC:	Closed-loop supply chain
DC:	Distribution center
DES:	Discrete-event simulation
EOQ:	Economic order quantity
EPC:	Electronic product code
FMCG:	Fast moving consumer good
ID:	Identity
ISO:	The International Association for Standardization
MIT:	The Massachusetts Institute of Technology
RFID:	Radio frequency identification
RPC:	Returnable product container
RPM:	Returnable packaging material
RTI:	Returnable transport item
RTLS:	Real time location system
SRU:	Shelf ready unit

CHAPTER 1

INTRODUCTION

Returnable transport items (RTIs) are defined as all means to assemble goods for transportation, storage, handling and product protection in the supply chain which are returned for further usage, including pallets, reusable crates, trays, boxes, roll pallets, barrels, trolleys, pallet collars and lids (ISO, 2005). They are the key elements for the efficient logistics operations and the protection of goods as well during transport, storage and handling (Ilic et al., 2009). They may bring significant benefits over the traditional single use packaging (Johansson and Hellström, 2007). Firms have been adopting RTIs for:

- operational benefits such as improved protection and security of products, improved ergonomics, more efficient handling and cube utilization, and reduced use of one-way packaging materials (Witt, 1999; Maloney, 2001; Twede and Clarke, 2004; Johansson and Hellström, 2007); and
- government regulations requiring to reduce packaging waste (Livingstone and Sparks, 1994; Kroon and Vrijens, 1995; Johansson and Hellström, 2007).

The supply chain management of RTIs includes the management of both forward and reverse channels. Forward channel refers to the development, production, distribution and delivery of products and services to the end users. Reverse channel refers to the collection of returns, reuse, recycling, remanufacturing, and disposal of products (Karaer and Lee, 2007). Specifically, it refers to the collection of returns and reuse of transport items in a supply chain of RTIs. The combination of forward and reverse channels is referred to as the ‘closed-loop supply chain’ (CLSC) (Flapper et al., 2005).

RTI management is challenging, since it requires accurate counting, reporting and shared information among organizations (Twede and Clarke, 2004; Johansson and Hellström, 2007). Current RTI management processes are based on estimates about where, when and how RTIs are utilized, because it is often unknown where the individual RTIs are and in what condition they are in at any specific point in time. This limited visibility constitutes the key problem in RTI management. Due to this limited visibility, organizations feel less responsible for the proper management of RTIs. Consequently, high lost rates, breakages and unavailability of RTIs bring unnecessary costs (Ilic et al., 2009).

RTIs are often managed with limited visibility or control, although they are often of high value, vulnerable to theft or misplacement, and critical for production and distribution (McKerrow, 1996; Twede, 1999; Witt, 2000; Johansson and Hellström, 2007). Due to these characteristics of RTIs, the management of RTI fleets is expected to suffer seriously from the absence of systems which keep track of individual RTIs and present timely and relevant information on their whereabouts. Tracking systems are required to manage and control where and how RTIs are moving, and to reconcile RTI supply with demand (Johansson and Hellström, 2007).

One way of tracking assets and increasing asset visibility is radio frequency identification (RFID) technology. RFID can be utilized as a tool to assist in RTI management. However, RFID technology requires high investment cost and intensive efforts for implementation. In this respect, our goal is to find out the value of using RFID technology for the management of RTI pools in a CLSC considering both its costs and benefits. The technical details of RFID technology can be found in Appendix A. Appendix B presents the comparison of this technology with an older technology, barcoding; while Appendix C presents the disadvantages and the advantages of using RFID technology.

RTI pool operator, manufacturer and retailer are the key RTI stakeholders. Figure 1.1 shows the domain boundaries of these key stakeholders which describe their responsibilities and interests in the RTI management process. It also denotes the minimum set of points for the setup of RFID readers (three inbound and three outbound RFID read points) for any form of automation using RFID technology.

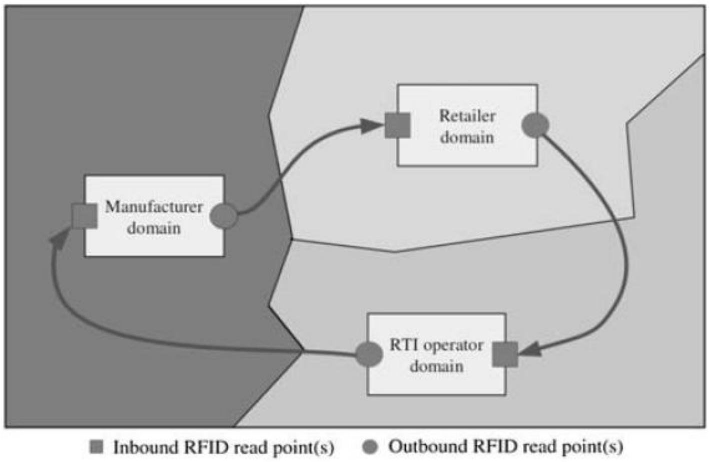

Figure 1.1: The three domains of responsibility and interest for RTI management (Ilic et al., 2009)

According to Üstündağ and Tanyaş (2009), RFID is regarded as a promising technology for the optimization of supply chain processes, since it improves manufacturing and retail operations from forecasting demand to planning, managing inventory, and distribution. As indicated by Tzeng et al. (2008), RFID has received considerable attention and is considered to be the next wave of the IT revolution due to its 'MOST' (mobility, organizational, systems and technologies) characteristics. Heinrich (2005) points out that RFID is likely to be the one of the most exciting and fastest-growing technologies in terms of scope of application in the next generation of business intelligence. Curtin et al. (2007) state that the emergence of RFID is expected to significantly affect a number of industries and impact their strategic management. Investing in RFID technology is found to be promising and an excellent long-term capital investment (Karkkainen, 2003; Kumar and Budin, 2006; Regattieri et al., 2007; Ngai et al. 2008b).

Ngai et al. (2008a) state that RFID has become a new and exciting technological development area, and it is receiving an increasing amount of attention. According to Üstündağ and Tanyaş (2009), the use of RFID technology has increased as costs in the semiconductor industry fall and data communication standards enhance. RFID technologies are currently catching such cost and functionality levels that make them practical for various service applications. Industry analyst IDTechEx forecasts a strong growth over the next decade both in RFID tag sales and in the breadth of application sectors (Heim et al., 2009). Total RFID market is expected to grow from over \$5 billion in 2008 to over \$25 billion in 2017 (Das and Harrop, 2008; Sheng et al., 2008).

As indicated by Ngai et al. (2008b), RFID technology has been widely applied in many industries, including the airline industry (Wyld et al., 2005; O'Connor, 2006), cattle industry (Mennecke and Townsend, 2005), construction (Jaseiskis and Ei-Misalami, 2003; Song et al., 2006), logistics (Ngai et al., 2007b), healthcare (Collins, 2005), and manufacturing (Swedberg, 2006). According to Heim et al. (2009), many service sectors are also deploying RFID applications including hospitals and health care providers, airlines and transportation services, postal services, libraries, veterinarian services, banking, and government services. Large consumer-packaged goods manufacturers including The Gillette Co., Procter & Gamble, and Johnson & Johnson, and also logistics service providers including United Parcel Service, and DHL also have experimented with RFID (Heim et al., 2009; Sliwa, 2002; Vijayan and Brewin, 2003). Tzeng et al. (2008) point out that the applications of RFID are actually not new. The British Royal Air Force used an RFID-like technology in World War II to distinguish between the enemy and the friendly aircraft (Asif and Mandviwalla, 2005).

In this study, we aim to investigate the value of using RFID technology for the management of RTI pools in a CLSC setting. Our general research question can be stated as follows:

What is the added value of using RFID technology for the management of an RTI pool in a CLSC setting when both costs and benefits of RFID technology are considered?

We now explain the importance of our problem both in practice and in the current literature and how our problem choice is positioned in the current literature.

According to Lee (2007), RFID deployment has made a moderate progress until today despite the optimism that high numbers of white papers, reports and trade articles about the value that RFID can bring. Several companies are still at their pilot stages and high hopes for value realization have not been attained. This current situation gives rise to the question of whether RFID's potential value is a hype or not. Lee and Özer (2007) state that a credibility gap has emerged due to this current situation. They argue that concrete quantification of benefits is necessary instead of guesses and rough estimates in order to close this credibility gap.

Dutta et al. (2007) point out that a very small number of companies would implement a new technology such as RFID based purely on faith. Rather, they would prefer to perform value assessment studies, tests or experiments, and benchmarking. Therefore, there is a need for research on value assessment exercises as well as on modeling the economics of RFID systems in order to guide their planning and implementation. Particularly, this need makes our study important especially for practice.

As stated by Johansson and Hellström (2007), RTIs have increasingly been introduced in various industries. This means that our problem can be widely seen in practice. Some examples of RTIs include beer kegs, special reusable containers for shipping glasses, large wooden bobbins of cables, cylinders for liquid gases. They also indicate that RTIs are often of high value and an RTI fleet is often characterized with a significant initial capital investment and shrinkage which brings considerable operating costs. Asset visibility is expected to be more important for higher value assets since it can provide higher cost savings and eventually higher benefits. Considering the high shrinkage rates, the importance of asset visibility is expected to increase. In a survey of

233 enterprises in consumer-oriented industries undertaken by the Aberdeen Group (2004), one quarter of the respondents report that they lose more than 10% of their RTI fleet annually, with 10% of the respondents losing more than 15%. Angeles et al. (2005) claim that monitoring the location and the usage of product handling and storage assets throughout the supply chain can decrease detention and demurrage charges for the third-party-owned assets by as much as 80%. Therefore, it is worthwhile to explore the potential value that can be realized by the asset visibility.

As stated by Ngai et al. (2008a), ‘RFID is an exciting area for research due to its relative novelty and exploding growth’. According to past publication rates, they predict substantial development in this area in the future, with a significant increase in research and published literature. In addition, Dutta et al. (2007) indicate that there are numerous white papers, reports and trade articles on the value that RFID can provide. However, they also indicate that measuring the value of RFID has several challenges and it is not clear if the value claims performed in the literature are actually sound. Therefore, reliable value quantification examples are needed in the literature in order to show whether RFID is profitable or not and in which conditions.

According to Dutta et al. (2007), many of the industry reports and white papers indicate what is obvious with lack of much quantification. For instance, there are many reports stating that RFID can decrease inventory and improve customer service. However, they do not provide details of how, nor did they give more specifics or quantification. Concrete quantification is needed instead of available guesses and rough estimates (Lee and Özer, 2007). In addition, Johansson and Hellström (2007) also state that the most of the research on asset tracking and asset visibility has focused on the potential benefits and has been largely theoretically explorative (Shayan and Ghotb, 2000; Luedtke and White, 2004). These findings in the literature point out a gap of reliable quantification for the value of using RFID technology.

In this study, we quantify the added value of using RFID technology for the management of RTI pools. In order to make a fair quantification, we compare the optimal RTI pool management in the absence of any asset tracking technology with the same in the presence of RFID technology. We have conducted a case study in a company which has recently started an RFID application in its CLSC of RTIs. The aim of this case study is to identify and understand how an existing RTI pool is managed as well as the impact of using RFID technology on the management of such an RTI pool. Based on the problem environment that we have observed during this case study, we define our problem environment in which we search for the minimum total cost of RTI pool management. The minimum total cost of RTI pool management is searched for using the simulation optimization method. This method firstly requires the simulation models of the CLSC operating with the decision rules of RTI pool management. It secondly requires minimizing the total cost of RTI pool management, which is an output of the simulation models, by changing a set of decision variables.

This study is conducted according to the framework presented in Figure 1.2. Our research is started with the decision of our research question which determines our type of problem choice. Next, a case is chosen and studied to clearly define our problem. The required analysis and diagnosis are completed in the case study in order to understand how an existing RTI pool is managed as well as the impact of using RFID technology on the management of such an RTI pool. We simulate the plan of action and the intervention steps. Finally, the results are gathered with the help of simulation optimization method.

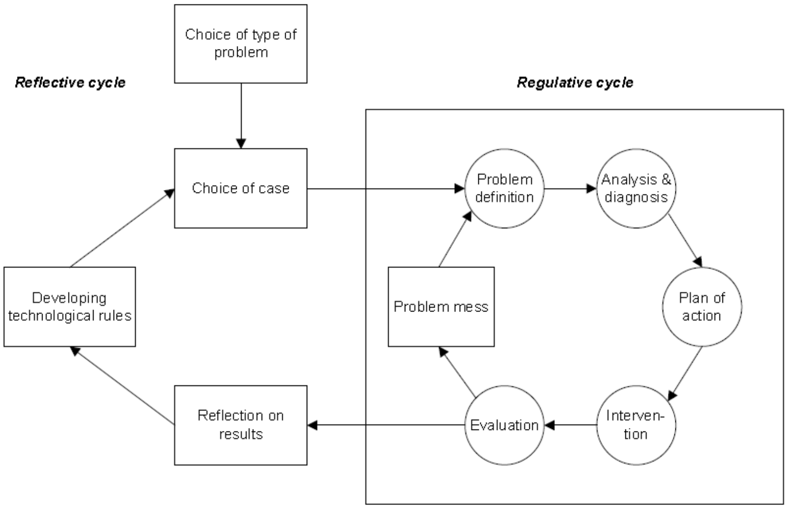

Figure 1.2: Research design (Van Aken et al., 2007; Van Strien, 1997)

The rest of the study is organized as follows: In Chapter 2, we present the studies relevant to our research question in the literature. In Chapter 3, we list the potential benefits and the potential costs of using RFID technology in a CLSC of RTIs. In Chapter 4, we show how the added value of RFID technology can be quantified using the benefit and the cost lists given in Chapter 3. In Chapter 5, we give detailed information on our case study. In Chapter 6, we provide the details of our proposed approach and method to quantify the value of using RFID technology in the cases similar to the one in our case study. In Chapter 6, we also give the details of the problem environment in which the optimal RTI pool management is searched for. In Chapter 7, we present the experimental results for the added value of using RFID technology together with the generation of scenarios, the input analysis, the verification and the validation of the simulation optimization study. In Chapter 7, we also discuss the implementation issues related with the software used in this study. Finally, the study is concluded in Chapter 8.

CHAPTER 2

LITERATURE STUDY

In this chapter, an overview of the relevant literature is provided. In section 2.1, we introduce the current status and contemporary trends in RFID research. In section 2.2, we present some of the related academic studies on the value of information, the added value of RFID technology, and the value of asset visibility. By added value, we mean the additional value that RFID technology brings in monetary terms; in order words, it is the benefits of using RFID technology after its costs are subtracted. In section 2.3, we mention the relevant studies on RTI pool management and the CLSC of RTIs.

2.1 The Current Status and Contemporary Trends in RFID Research

According to Ngai et al. (2008a), it is essential to understand the current status of RFID research and to examine contemporary trends in the research domain for the advancement of knowledge in this area. Additionally, they also state that it is important to determine the main concerns of the current RFID research, namely technological, application related, and security related. Therefore, we find it suitable to start with a discussion on the literature review on RFID research which can give a more comprehensive idea about the current status of this research area.

Ngai et al. (2008a) present a literature review of 85 journal papers that were published on RFID between 1995 and 2005. These studies are divided into four main categories according to their main focus. These categories are technological issues, application areas, policy and security issues, and other issues.

According to this review, the applications of RFID are many and varied as they span 14 different industries. In most cases of RFID studies on retailing, the articles present a general view of RFID use in retail and supply chains or mention the potential of using RFID technology, the perceived benefits, effects and challenges for retailers, how consumers are likely to react to the technology and the market drivers in the grocery industry for RFID implementation (Eckfeldt, 2005; Karkkainen, 2003; Jones et al., 2005; Prater et al., 2005).

Ngai et al. (2008a) also discuss the future research questions and directions. They believe that future research effort is needed to offer 'useful guiding principles for practitioners for the RFID system design, development, implementation and evaluation'. Many different research directions are suggested. The following three future research directions are the ones that are the most related to our study:

- The economic performance of RFID systems in terms of their 'cradle to grave' cost. This includes the costs of designing, developing, maintaining, controlling, and updating the systems.
- The formulation of technical and economic decision rules to guide practitioners in selecting the appropriate RFID system for implementation.
- The impact of RFID systems on companies and organizations in various industrial situations and the generation of business models for the adoption of RFID.

It is found important for the researchers of production and operations management, information technology and information systems to make sure that the future research directions are managerially useful with an emphasis on studies including design, implementation and deployment of RFID technology. Here, the words of John Williams, director of the MIT Auto-ID Labs should be noted: "There is simply an enormous amount of applied research that needs to be done to move RFID forward and realize the dream of creating the 'internet of things'".

2.2 The Added Value of RFID and Asset Visibility

Johansson and Hellström (2007) propose a framework of the potential benefits of asset visibility with regard to the costs associated with RTI systems. They base this framework on the general tracking and visibility literature. With the help of this framework, they explore the effect of asset visibility on the management of RTI systems through a combined case and simulation study. The case study shows that a tracking system with inadequate data analysis and reporting capabilities provides limited visibility. It is about a company (The Arla Foods Group) which distributes its fresh products directly to the retail outlets in RTIs (roll containers). The company has experienced difficulties in managing and controlling its RTIs. It loses a large number of RTIs each year. It estimates that approximately 10% of its RTIs are lost annually as a result of misplacement and theft. There is no information about how many RTIs are in circulation or in stock at various points in the supply chain. In the simulation study three scenarios are developed:

1. Operation of the system without a tracking system
2. Operation of the system based on the collected data from the tracking system
3. Operation of the system when asset visibility is accompanied by proper management actions

In the mentioned tracking system, there are three different identification locations to gather data about container locations. A single data transaction contains ID of the container, its location, customer ID, or route number, along with a date and a time stamp. As a result of this simulation study, the appropriate fleet size can be calculated and insights into the effects of changes in different parameter values such as cycle times and demand on the system are gained. It suggests that the investment cost in RTI and total costs can be reduced significantly (52% and 34% respectively in the Arla case) if asset visibility is accompanied with the proper managerial actions. The authors emphasize that asset visibility for RTI systems is not sufficient. It requires proper actions and continuous management attention to gain savings. They also emphasize the importance of shrinkage and its impact on the operating costs of an RTI system. They claim that the findings are likely to be valid for other systems with high RTI shrinkage where a central organization supplies RTI without deposits or rental charges.

Ilic et al. (2009) explore the impact of increased asset visibility on the RTI management processes. They define the key problem in RTI management as the reality that the location and the condition of an individual RTI at any specific point in time is often unknown. They argue that RTI visibility together with a proper management approach is needed to improve process efficiency and RTI control. They present the potential benefits of visibility at different points in a CLSC of reusable pallets. They estimate the decrease in the trip fee (the fee for an RTI to make one cycle) with improved visibility.

According to Thoroe et al. (2009), the benefits of the use of RFID technology for tracking RTIs have so far hardly been undertaken from a theoretical perspective. In order to help to fill this gap, they analyze the impact of RFID on RTI management using a deterministic inventory model. Their model misses some important aspects of the use of RFID technology (e.g. the setup cost of RFID) and RTI management (e.g. stochasticity of losses). With their deterministic inventory model, they make suggestions for the batch sizes and the frequency of the procurement of new RTIs and the refurbishment process.

Leung et al. (2007) offer a tool for quantifying the business value of RFID for different participants in a manufacturing-retail supply chain in order to enable the development of business cases to support the decision on whether and when to adopt the technology. Their tool consists of two parts which are linked to each other, namely a business value model and a business process model. They classify the benefits of RFID as direct and indirect. Their business value model calculates the value of the direct benefits (e.g. the decrease in inventory shrinkage). On the other hand, their business process model calculates the value of the indirect benefits (e.g. the use of real-time inventory information to redesign inventory replenishment process) which may be overlooked with the traditional return on investment analysis.

Thiesse and Fleisch (2008) analyze the practical benefits of the location information provided by real-time location systems (RTLSs) in complex manufacturing processes. This analysis is based on the case example of an RFID-based RTLS implementation which combines the flexibility of manual production processes with a high level of visibility and the control of conventional automation technologies in a facility of semiconductor fabrication. The main achievements of the project are reduced cycle times, prevention of handling faults and reduction of non-value-adding activities by making the entire production process visible and thus controllable with the help of RTLS. Therefore, they examine the value of RTLS information on the location of physical objects in a production system for the problem of efficient scheduling using a simplified simulation model. With this simulation model, they experiment on the RTLS-enabled dispatching rules that they propose and compare them with the conventional rules that do not make use of any location information. The results show that the use of RTLS technology offers new levels of process visibility and control in comparison to the conventional material-tracking systems. It also offers both significant improvements with regard to some process performance indicators such as cycle time and machine utilization, as well as opportunity to develop novel dispatching rules considering real-time information from the logistic processes on the shop floor.

According to Dutta et al. (2007), the ability of RFID –as with any new technology– to deliver business value depends not just on the technical factors, but also on the economic and the organizational ones. Their objective is to identify some selected research issues arising from these factors themselves and their interaction. Hence, three dimensions of the value proposition of RFID are examined and areas for further research are proposed. The first dimension is the architecture of RFID implementations in which the focus is on issues that would be relevant to management in adopting this technology and obtaining business value from it. The second dimension is the measurement issues related to value assessment. Academic research on assessing the value of RFID mainly utilizes three categories as tools, namely empirical-based research (field studies), simulation and analytical operations-research models. The third and last dimension focuses on incentives for achieving diffusion through the entire supply chain.

As indicated by Van Dalen et al. (2005), the Heineken Group started the Chip in Crate pilot at the Brand brewery in April 2000. The objective of the project is to measure total circulation time of Brand crates through returnable packaging materials (RPM) logistic chain. For the calculations of optimum amount of RPM, the measurement results of the project are used as input. Existing information about storage duration of crates at the brewery (based on daily counts of full and empty RPM) is complemented by the Chip in Crate information. The united information sources give information about total circulation times and about the time crates spend in the market. This information is necessary for both long-term decisions about RPM investments and for short-term forecasts of RPM returns to the brewery. Besides, it gives Heineken the opportunity to initiate efforts on control the return of RPM. The resulting information shows that the return pattern of empty crates is S-shaped and it can be conveniently used to forecast RPM returns in a specific week. An investment model based on the Chip in Crate data suggests that implementation of the project brings a saving opportunity between 5 and 10 million Euro for RPM worldwide, which makes the Chip in Crate project to be appreciated as a highly successful experiment.

Van Dalen et al. (2008) state that Heineken chose to use the read-only chip to keep the process simple and affordable. The chips, which could only be observed with scanning, were baked into the crates. Reading the information from the chips was performed crate by crate. The scanners were placed alongside the production belt. Chips carried information regarding tag numbers which were uniquely linked with individual chips in crates, the dates and the times when they passed the scanners. Samples were drawn from chips in crates in order to check whether chips were still functioning and whether the data output was correct. It was observed that all chips functioned properly and that the performance of the scanners at the production belt was less satisfactory since occasionally no chips were registered while passing the scanners.

According to Üstündağ and Tanyaş (2009), several researchers have examined the impact of RFID technology on inventory and supply chain management. Generally, the research studies have mainly interested in the inventory function and the effect of taking inventory discrepancies into account. Literature having an analytical assessment of RFID technology is quite limited. On the other hand, there are some studies focusing on the cost-benefit analysis of RFID implementation. Several RFID researchers concentrating on inventory management handled the impact of inventory errors on supply chain performance and examined how reducing inventory inaccuracy with RFID technology affects performance measures. Besides, they note that most studies in this area have used the simulation method to determine the impact of inventory inaccuracy on supply chain performance.

Üstündağ and Tanyaş (2009) perform a simulation study to calculate the expected benefits of an integrated RFID system on a three-echelon supply chain gained by means of performance increases in efficiency, accuracy, visibility and security level. This study fills a gap in the literature by examining the effect of product value, lead time and demand uncertainty on the benefits of RFID integrated supply chain in terms of cost factors at the echelon level using a simulation model. It is shown that the factors of product value and demand uncertainty have significant influence on the expected benefits of RFID integrated systems. As the product value increases, total supply chain cost savings increases and as the demand uncertainty increases, total supply chain cost savings decreases. Additionally, simulation study reveals that not each member of the supply chain benefits equally from the RFID integration.

De Kok et al. (2008) determine an inventory policy by considering shrinkage and the impact of RFID technology. The situation with RFID is compared with the one without RFID in terms of costs. As a result, an exact analytical expression is derived for the break-even prices of an RFID tag. Using these expressions in a full factorial design, it is shown that these break-even prices are closely linked to the value of the lost items, the shrinkage fraction, and the shrinkage after implementation. Additionally, a simple rough-cut approximation for the determination of the maximum amount of money that a manager should be willing to invest in RFID technology is offered. It should be noted that, fixed investment costs of RFID technology are not taken into account in this study and they are left for potential future research.

Bottani and Rizzi (2008) quantitatively assess the impact of RFID technology and electronic product code (EPC) system on the main processes of the Fast Moving Consumer Goods (FMCG) supply chain. The impact of these technologies on the FMCG industry is quantified on a three-echelon supply chain composed of manufacturers, distributors and retailers. Firstly, a questionnaire survey is conducted, and both quantitative and qualitative data about logistics process of each supply chain player are collected. Then a quantitative feasibility study which includes the costs and benefits of such technologies is performed to quantify the economical profitability of the implementation and to justify technology investments. This study reveals that RFID and EPC implementation is still not profitable for all echelons. Although RFID adoption with pallet level tagging gives positive revenues for all supply chain players, case level tagging produces negative economic results especially for manufacturers. Additionally, the break-even prices for RFID tags are estimated.

Heim et al. (2009) investigate how customer value may be affected by deploying RFID technologies in service environments. Although business articles point out operational cost savings and improved inventory management as key benefits of RFID deployment, this study shows that customers recognize far more value from RFID applications than these key benefits. Firstly, they develop a conceptual framework of RFID service applications derived from three potential user groups involved in an RFID-enabled service process: customers, service firms, and suppliers (Lee et al., 2008). The framework is used to structure a value-focused thinking study (Keeney, 1992; 1999) to identify a list of RFID value dimensions. Then, how the proposed RFID value dimensions relate to the framework structure is investigated. In short, the study analyzes the qualitative survey responses on the value gained from RFID to identify a broad list of value objectives —benefits and drawbacks—associated with RFID service applications. This article contributes to the literature by identifying a broad set of value dimensions related with RFID applications, and additionally, by this means constructing a foundation for subsequent empirical study of RFID in service applications. As a practical contribution, service managers can use the developed framework and empirical findings to aid in design and improvement of their service operations.

According to Karaer and Lee (2007), the most of the studies about inventory management with reverse channel dynamics focus on finding the optimal inventory policy regarding the reverse channel by addressing possible correlation between demand and return streams, and possible negativity of net demand. These studies concentrate on the major challenges of the reverse channel dynamics with the assumption of full visibility in the whole system. Different from those studies, Karaer and Lee (2007) focus on the benefit of information and visibility in the reverse channel pipeline in coordination with the regular product procurement, with some practical assumptions regarding the reverse channel dynamics.

Karaer and Lee (2007) examine the inventory decisions of a manufacturer who has ample production capacity and also uses returned products to satisfy customer demand. Therefore, the focus is the coordination of the reverse and the forward chain at the distribution center of a manufacturer. Among the product return classes, namely end of life, end of use, reusable items, and commercial returns (Krikke, Le Blanc, and Van de Velde 2004), the concern of the study is the commercial returns. All commercial returns enter an evaluation process to make the decision of disposal, direct selling, or rework according to a predetermined procedure. They quantify the value of information and visibility on the reverse channel for the manufacturer by making comparisons among the following three approaches:

1. *Naive approach:* The naive manufacturer neither has visibility on his reverse channel nor utilizes general characteristics of the return flow in his inventory management.
2. *Enlightened Approach:* The enlightened manufacturer knows the statistical characteristics of the return flow. Although he is aware of the reverse channel

(i.e., the pipeline of negative demands in the reverse channel); he does not have visibility on it.

3. *Full Visibility:* The manufacturer has full visibility on his reverse supply chain, i.e., he can monitor the number of products at every step of the chain. However, he cannot foresee beforehand exactly how many units out of the returned products batch will be disposed of, reworked, or sold as is.

For quantification, Karaer and Lee (2007) use a basic model with many simplifying assumptions (e.g. constant production and rework time, and no capacity constraints in production and rework). As a result, they find that “the value of visibility increases with the comparative length of the reverse channel and volume, volatility, and usability of returns”. Besides, they conclude that “the smarter the manufacturer, the less benefit visibility brings to the system”. Most important part for us is that they quantify the visibility savings of RFID in the reverse channel as a candidate visibility enabler technology and show that RFID can also have benefits to the reverse channel.

Langer et al. (2007) investigate the benefits of RFID with a field study with GENCO, a third party logistics company which deploys RFID technology in the outbound logistics operations of one of its return centers. Its purpose is to improve the warehouse operational accuracy and quality of material flow, to enhance customer responsiveness and to diminish shipment errors. It places the RFID tags containing information regarding the pallet, its contents, and order details. on the pallets. Besides, each forklift is equipped with a reader and a screen in order to ensure correct loading onto trucks and locate lost pallets within the facility more easily. In order to assess the impact of RFID on customer claims, they conduct statistical analyses. They estimate a profit model by using the claims as the dependent variable and RFID, transaction intensity-specific parameters, shipment characteristic variables, and buyer-specific parameters as the explanatory variables. Therefore, they confirm that the RFID implementation has a significant impact on the accuracy of GENCO’s outbound logistics process and RFID is a key factor that contributes to several positive results. Following its deployment, the number of claims has fallen substantially due to reduction in errors in loading, as well as acting as a deterrent to fraudulent claims. Additionally, they emphasize that GENCO has barcoded all of its outgoing shipments, however this has provided no benefits due to its technical (e.g. problems in reading) and human limitations.

2.3 RTI Pool Management

Bowman et al. (2009) propose a contextual model for the management of reusable assets. They classify reusable assets into two categories. The first category covers a broad range of assets that remain within a site during its useful lifetime. The second category is named as RTIs, which are generally used within the supply chains. The list of the reusable items that can be called as RTIs according to the ISO hierarchy is as follows:

- Air cylinders
- Collapsible crates
- Dollies (rolling quarter pallets)
- Folding plastic security containers
- Kegs
- Liquid intermediate bulk containers
- Meat containers
- Pallets (wooden & plastic)
- Plastic diary crates
- Returnable product containers (RPCs)
- Roll cages
- Shelf ready units (SRUs)
- Stillages
- Totes

Bowman et al. (2009) present two main RTI models widely used in the reusable asset management context, namely the exchange (closed-loop) model and pooling (open-loop) model. An example to the exchange model can be seen in the CLSC of a manufacturer that has its own RTI pool and supplies the demand of its customers from its RTI pool. An example to the pooling model can be seen in the case of a pool operator which owns the RTI pool and ensures that its RTI pool is enough to satisfy the RTI need of its supply chain partners. They give detailed information about wooden pallet, plastic pallet, keg and folding plastic security container management.

Lange and Semal (2010) consider the management of the return flows of empty logistics containers that accumulate at the sites of customers and must be brought back to the factories. They try to answer the following questions raised by the management of return flows with a strategic perspective:

- To which factory should each customer return the containers?
- At which frequency should they be returned?
- How many containers are needed in the network?

Del Castillo and Cochran (1996) also deal with the subject of reusable containers. They are also interested in optimizing production planning and transportation of containers throughout the system. They try to address three interrelated decision sets as follows:

1. Production planning: What products should be made, in what lines, and for how long?
2. Product distribution: How many of each product should be distributed to each depot and during which shifts?
3. Return of containers: From which depots should containers be returned to each plant and in which shifts, and how many of each type of container is needed?

Del Castillo and Cochran (1996) model the reusable bottle production and distribution operations of a large soft-drink producer. They use hierarchical models to assist in decision making with referring to Hax and Meal (1975). In order to form the overall optimization system, two types of models are combined. A framework and a mathematical formulation for process control and material management in reusable container industries are proposed. Improvements have resulted in significant market gains for the soft-drink producer after the proposed models are implemented.

There are some early studies related with the management of RTIs. Kelle and Silver (1989a) study on forecasting the returns of reusable containers, which is important in giving the decision of new container acquisitions. They propose four forecasting methods, each of which requires a different level of information to forecast the net demand, i.e. the demand minus the returns. One of the forecasting methods assumes that the containers are individually identified and the records are kept when they are issued and returned. In other words, this method assumes that the containers are tracked and traced with a suitable technology like RFID. They compare these methods on a wide range of simulated data and conclude that the use of additional information improves the forecasting performance. In addition, they use the method which assumes tracking and tracing of individual containers as a best-case benchmark for the evaluation of other forecasting methods that need less data.

In another study, Kelle and Silver (1989b) propose a stochastic mathematical model of the optimal purchasing based on net demand with a chance constraint for the target service level. They conclude that this stochastic problem is equivalent to the usual dynamic lot-sizing problem which can be exactly solved by the Wagner-Whitin dynamic programming algorithm.

Goh and Varaprasad (1986) study on the life-cycle characteristics of reusable containers including parameters such as trippage (the number of trips made by a container in its lifetime), trip duration, loss rate and expected useful life. They also describe a data analysis and modeling approach to find out the needed parameters. They argue that accurate estimation of life cycle parameters is required for pricing a product, effective inventory and production control, financial control and accounting for losses.

CHAPTER 3

THE VALUE OF USING RFID TECHNOLOGY IN A CLOSED-LOOP SUPPLY CHAIN OF RETURNABLE TRANSPORT ITEMS

Both the potential benefits and the potential costs of RFID technology should be determined in order to assess the added value of using RFID technology. In section 3.1, the potential benefits of RFID technology are explored in detail; while in section 3.2, the potential costs of RFID technology are analyzed.

3.1 The Potential Benefits of Using RFID Technology in a Closed-Loop Supply Chain of RTIs

In general, RFID is seen as an enabling technology that a company can adopt to enhance asset visibility and improve operations, like improving receiving and picking accuracies, and reducing human errors (Ngai et al., 2007a). The four benefit factors of RFID technology is defined as operational efficiency, accuracy, visibility, and security (Singer, 2003). Though beginning as a tool to achieve operational efficiency, some practitioners believe that RFID could become the next major weapon for organizations to gain strategic competitive advantage (Tzeng et al., 2008).

RFID is expected to bring various benefits changing according to its application setting, which makes the right focus essential. Our focus is on the benefits of RFID technology in a CLSC setting in which RTIs are in use. The following benefits related to our focus have been found with the help of literature review and the insights gained through our case study:

1. RFID provides timely information of manufacturer's actual RTI stock. Therefore, the manufacturer's replenishment process and stocks can be optimized based on the actual information for RTI stock (Ilic et al., 2009).

2. The flow of RTIs in the supply chain becomes more predictable with asset visibility (Ilic et al., 2009). Uncertainty in quantity, quality and timing of returns is decreased (Karaer and Lee, 2007). Increased visibility of return process can be seen as similar to having advance negative demand information since inventory in the return channel can be seen as future negative demands (Lee and Özer, 2007). In that sense, more accurate forecasting methods can be used for returns and replenishment process can be improved with better return forecasts. Therefore, increased visibility allows more proactive decisions (Dutta et al., 2007). This can help to reduce buffer stocks and stockouts.

3. The unique identification of each RTI can guarantee clear accountability of each of the RTIs and can help in assessing the number of outstanding RTIs kept by each stakeholder accurately (Ilic et al., 2009). RFID provides an accurate reading of the quantity of stocks in the system, avoiding the problem of inventory discrepancies due to shrinkage, misplacement and transaction errors (Dutta et al., 2007). This eventually brings reduction in inventory and stockouts as well (Lee and Özer, 2007).

4. With unique serial identification associated with the RTIs, it is possible to trace the source of the damaged pallets to the originator. As a result, it is expected that RTI damages are decreased (Ilic et al., 2009).

5. With the help of track and trace capability, it is also possible to identify any systematic losses including theft within the supply chain (Ilic et al., 2009). As a result, it is expected that RTI losses are decreased.

6. With the help of track and trace capability, it is also possible to identify slow moving locations and excessive holding areas in the supply chain. Cycle time can be decreased and rotation rate can be increased with the determination of slow moving locations and taking action when possible. Cycle time and rotation rate can be further improved with the elimination of delays due to manual data acquisition processes. This benefit is revealed in our case study.

7. The accurate recording of inventory by quantity and by location can help in making use of the contents that RTIs are filled before they are outdated, especially when they are perishable items (Dutta et al., 2007). RFID can create value in the presence of important concerns of food and drug industries like counterfeit prevention, facilitation of product recall and traceability (Lee and Özer, 2007).

8. The lifetime information and repair history can be kept for individual RTIs. As a result, RTI maintenance decisions and corresponding actions can be automated and speeded up. Such efficiency can provide quicker update of the usable RTI stock count and thus help to minimize buffer stocks or emergency purchases (Ilic et al., 2009). Besides, RFID enables automatic handling of preventive maintenance and disposal of RTIs which have exceeded their best-use-before dates. Improved maintenance brings extended use life of RTIs. With the repair history of all fleet, which type of repair is done with which frequency can be found out. Most vulnerable parts of the RTI can be determined. This information can be used for improvement of the RTI design, if possible (Johansson and Hellström, 2007).

9. The availability of dynamic RTI stock and movement data, the load utilizations of the delivery vehicles can be improved. It also helps in avoiding or at least decreasing emergency deliveries (Ilic et al., 2009). In addition, where to collect is also known in case of emergencies.

10. Due to automatic RTI identification and notification upon reaching a drop point, the collection of RTIs from the drop points (customer locations) can be better scheduled. Collection route optimization is also possible (Ilic et al., 2009). Besides, RFID brings decrease in or elimination of erroneous shipments, since RFID readers placed on gates or forklifts can scan the shipments and give signals in case of errors (Johansson and Hellström, 2007).

11. Labor savings can be achieved in the receiving operations or inventory audits since multiple RFID tags can be scanned together without manually scanning the objects one by one (Dutta et al., 2007). RTIs can be counted and found in an efficient manner when necessary due to automatic read count and identification (Ilic et al., 2009). RFID enables automatic sorting, handling, and cleaning procedures, which also brings labor cost savings (Johansson and Hellström, 2007). In addition, costly data acquisition processes such as extracting data from invoices can be avoided (Ilic et al., 2009).

12. Asset visibility brings cycle time reduction, increase in rotation rate, damage and loss reduction. Therefore, investment in RTI fleet can be decreased with minimal sizing and configuration of RTI fleet through asset visibility (Johansson and Hellström, 2007; Frazelle, 2002).

13. Several flexible billing models can be made possible. For example, the end user can be charged for each damaged and lost RTI within his domain of responsibility. In addition, deposit charging can also be possible due to automatic identification of RTIs (Ilic et al., 2009).

14. RFID can decrease information asymmetries and incentive problems arising between different parties. Two main sources of information asymmetry for a supply chain are costs and forecasts (Lee and Özer, 2007).

15. RFID systems make it possible to use a more systemic view of managing the production function and indeed business organization as a whole. By systemic, it is meant that the production function is seen as a structured collection of technical and organizational components that interact with the operating environment and react to changing conditions. (Dutta et al., 2007)

16. Any data errors due to manual data entry can be eliminated (Ilic et al., 2009).

The first twelve benefits can be directly related to RTI management operations, since we are able to establish the link between them and some operational characteristics of a CLSC like cycle time and RTI pool size. As a result, we are able to quantify these benefits. On the other hand, we have decided not to quantify the benefits 13-16 for the following reasons:

Benefit 13: There are various billing models and the formula of systemwide costs of a CLSC can greatly differ from one billing model to another. It is possible to build a different cost formula for each billing model. However, this option results in a cost formula dependent on the billing model. We do not want this to happen, since our aim is not to deal with billing models in detail.

Benefit 14: There can be countless different situations of information asymmetries arising between different parties of the supply chain. Likewise benefit 13, it is not possible to make generalizations for quantification of this benefit.

Benefit 15: It is not possible for us to establish a clear link between this benefit and operational characteristics, since there is not a clear and one way that this benefit can bring a change in supply chain. In other words, it is not clear how systemic view can help us to make improvements in which parts of the supply chain separately.

Benefit 16: It is not possible to quantify this benefit without knowing the consequences of errors in manual data entry. These consequences can be countless. Therefore, it is not possible to make generalizations for the quantification of this benefit.

3.2 The Potential Costs of Using RFID Technology in a Closed-Loop Supply Chain of RTIs

The costs of an RFID application should be analyzed with the following cost classification:

1. Setup costs: Initial investment cost of RFID implementation incurred only one time
2. Periodic costs: Costs that are incurred periodically

The cost items belonging to each cost class are listed below. It is important to note that one item can be included in both classes.

3.2.1 Setup Costs

Setup costs are as follows:

1. Training costs: The cost for training the employees who use RFID technology.
2. Administration costs: The cost of labor devoted to administering the implementation of RFID technology. This can include the fee for consultancy taken for RFID implementation.
3. Installation cost: The cost for setting up the necessary working environment for an RFID application.

4. Tag costs: This cost item covers both purchasing and placing RFID tags.
5. Software costs: The cost for purchasing the necessary software including the construction of a database in which RFID data can be stored and the software for readers.
6. Hardware costs: The cost for purchasing the necessary hardware including RFID readers, and personal computers to access the database.
7. Other costs: The costs attributable to the RFID implementation and cannot be included in one of the above cost items.

3.2.2 Periodic Costs

Periodic costs are as follows:

1. Administration costs: The cost of labor devoted to the operations necessary for RFID application. For example, using manual readers to scan the shipments should be included in this cost item.
2. Tag maintenance costs: This cost item covers the cost of replacing damaged and fallen tags.
3. Software maintenance costs: The maintenance cost for keeping the software (including the database) up to date and running. For example, if there is a periodic fee for using the database, this should be included in this cost item.
4. Hardware maintenance costs: The maintenance cost for keeping the hardware up to date and running. This also includes renewal of hardware which becomes obsolete.
5. Other costs: The costs attributable to the RFID application and cannot be included in one of the above cost items.

CHAPTER 4

QUANTIFICATION OF THE ADDED VALUE OF USING RFID TECHNOLOGY

Firstly, in section 4.1, we establish the links between the potential benefits given in section 3.1 and the operational characteristics of a CLSC. With the help of these links, we find out how and which operational characteristics can be affected with an RFID implementation. In section 4.1, we also show how to quantify the change in operational characteristics due to the use of RFID technology. Here, it should be noted that by operational characteristics, we mean the variables which can give some indication about the operational efficiency of a supply chain like cycle time, fleet size, and inventory level. In section 4.2, we propose formulas to quantify the total cost of RFID technology using the potential costs listed in section 3.2. Finally, in section 4.3, we give the formula of the added value of using RFID technology.

4.1 Quantification of the Potential Benefits of Using RFID Technology

Lee and Özer (2007) argue that bottom-up approaches are needed to obtain a better assessment of the value of RFID. According to them, the best approach is to start with the most fundamental operational characteristics and observe how the technology initiates a chain of improvements and accordingly values. Therefore, analytical models connecting underlying operational characteristics to control decisions, and finally performance measures are needed to be developed. Such operational models can describe the way that RFID affects the operation of processes. With such a description, the quantification of RFID's impact can be accurately performed (Dutta et al., 2007).

Table 4.1 shows how and which operational characteristics of a CLSC of RTIs are affected with the use of RFID technology. It also shows the links between the benefits (the benefits 1-12) chosen for quantification in section 3.1 and the operational characteristics. This table constitutes a framework for quantification of these focused benefits. The first column of this table shows the number of the benefit in our benefit list given in the section 3.1. The second column answers the question of what RFID technology makes possible. For example, RFID makes tracking and tracing RTIs possible, which brings several benefits which can be found in Table 4.1. The third column of the table shows the yield of what is given in the second column. For example, timely information of actual RTI stock brings replenishment process improvement/optimization (as it is given in the row for benefit 1). Finally, the last column shows the final results of the benefits in terms of some operational characteristics. The results presented in Table 4.1 are arrived with the help of the studies for which references are given in the list of potential benefits in section 3.1.

Table 4.1: How and which operational characteristics of a CLSC of RTIs are affected with the use of RFID technology

Benefit	What RFID makes possible?	What this brings?	What final important outcomes are brought?
1	- Timely information of actual RTI stock	- Replenishment process improvement/optimization - Improvement/optimization in/of stock levels	- Decrease in new RTI purchases - Decrease in inventory - Increase in RTI availability - Decrease in stockouts/lost sales/backorders - Increase in vehicle utilization - Decrease in emergency shipments
2	- Increased visibility of return process	- More predictable return flow(s) - More accurate return forecasting	- Decrease in new RTI purchases - Decrease in inventory - Increase in RTI availability - Decrease in stockouts/lost sales/backorders - Increase in vehicle utilization - Decrease in emergency shipments
3	- Unique identification of RTIs - Track and trace capability	- Clear accountability of stocks - Decrease in inventory discrepancies	- Decrease in inventory - Decrease in stockouts/lost sales/backorders - Decrease in new RTI purchases

Benefit	What RFID makes possible?	What this brings?	What final important outcomes are brought?
4	- Unique identification of RTIs - Track and trace capability	- Tracing source(s) of damages	- Decrease in RTI damages - Increase in RTI availability - Decrease in new RTI purchases
5	- Unique identification of RTIs - Track and trace capability	- Tracing source(s) of systematic losses/ thefts	- Decrease in lost/stolen RTIs - Increase in RTI availability - Decrease in new RTI purchases
6	- Unique identification of RTIs - Track and trace capability	- Identification of slow moving locations/operations - Identification of excessive holding areas	- Cycle time reduction - Increase in RTI availability - Increase in rotation rate - Decrease in the RTI fleet size
7	- Unique identification of RTIs - Track and trace capability	- Tracing lifetime information of the RTI contents - Facilitation of product recall - Counterfeit prevention	- Decrease in the amount of outdated RTI contents - Decrease in penalty cost of outdated RTI contents reaching the end user

Benefit	What RFID makes possible?	What this brings?	What final important outcomes are brought?
8	- Storing RTI lifetime information - Storing RTI repair history	- Automatic handling of preventive maintenance - Ensuring disposal of RTIs completing their lifetime - Repair frequency information of the RTI fleet - Improvement opportunities in the RTI design	- Increase in useful lifetime of RTIs - Decrease in new RTI purchases - Decrease in RTI damages - Decrease in penalties of outdated RTIs
9	- The availability of dynamic RTI stock and movement data	- Better scheduling of the RTI shipments - Information about where to collect RTIs in case of emergencies	- Decrease in emergency shipments - Increase in vehicle utilization
10	- Automatic RTI identification and notification	- Better scheduled RTI collection - Collection route optimization	- Decrease in erroneous shipments - Decrease in the transportation cost - Cycle time reduction - Increase in rotation rate
11	- Automatic read and count	- Easier inventory audit - Elimination of manual data acquisition processes - Automatic sorting	- Decrease in labor cost - Cycle time reduction
12	- Asset visibility	- Improvement opportunities for the sizing and configuration of the RTI fleet	- Decrease in the RTI fleet size - Decrease in the RTI fleet investment

Although all of the changes in the operational characteristics listed in the last column of Table 4.1 are possible with the use of RFID technology, not all of them have a direct effect on the total cost of RTI pool management. For example, the availability of RTIs to satisfy the demand for empty RTIs is expected to increase with the use of RFID technology; however, this does not directly influence cost. Due to an increase in RTI availability, we expect a decrease in the number of lost sales (or backorders) in satisfying the full RTI demand, which has a direct effect on penalty cost. This means that the increase in RTI availability influences costs through the decrease in the number of lost sales (or backorders). As a result, the decrease in total cost due to the increase in RTI availability should be calculated based on the decrease in the number of lost sales (or backorders).

The changes in operational characteristics listed in the last column of Table 4.1 are expected to (directly or indirectly) bring changes in the following cost items. The operational characteristics having a direct effect on the cost items are written in bold in the following set of cost formulas. The superscript *i* differentiates between the time before (*i*=1) and after (*i*=2) the use of RFID technology. Total number of RTIs prepared for reuse in the planning horizon is expected to increase due to the less RTI shrinkage with the use of RFID technology. The unit transportation cost may be decreased, since the number of emergency shipments may be reduced with the use of RFID technology. Besides, the number of truck trips may also be decreased due to possible decreases in erroneous and emergency shipments.

$$TC^{i}_{administration} = c_{labor}\boldsymbol{H^{i}_{RTI\ management}} \tag{4.1}$$

$$TC^{i}_{inventory} = h_e\boldsymbol{E^{i}} + h_f\boldsymbol{F^{i}} \tag{4.2}$$

$$TC^{i}_{new} = K_{order}\boldsymbol{N^{i}_{order}} + c_{new}\boldsymbol{N^{i}_{new}} \tag{4.3}$$

$$TC^{i}_{penalty} = c_{penalty}\boldsymbol{L^{i}} \tag{4.4}$$

$$TC^{i}_{preparing} = \boldsymbol{c^{i}_{sorting}} \boldsymbol{R^{i}} + c_{repair} \boldsymbol{r^{i}_{repair}} \boldsymbol{R^{i}} + c_{dispose} \boldsymbol{r^{i}_{disposal}} \boldsymbol{R^{i}} \\ + c_{cleaning}(1 - \boldsymbol{r^{i}_{disposal}}) \boldsymbol{R^{i}} \tag{4.5}$$

$$TC^{i}_{transportation} = \boldsymbol{c^{e,i}_{transportation}} X + \boldsymbol{c^{f,i}_{transportation}} Y \tag{4.6}$$

or $TC^{i}_{transportation} = \sum_{a,b} c^{trip}_{ab} \boldsymbol{Tr^{i}_{ab}}$ (4.7)

where,

$c_{cleaning}$: The unit cleaning cost of RTIs

$c_{dispose}$: The unit disposal cost of RTIs

c_{labor}: The unit labor cost of RTI pool management

c_{new}: The unit price of RTIs

$c_{penalty}$: The penalty cost of one unit of lost sales

c_{repair}: The cost of repairing one RTI

$c^{i}_{sorting}$: The unit sorting and checking for damage cost of RTIs

$c^{e,i}_{transportation}$: The unit transportation cost of an empty RTI

$c^{f,i}_{transportation}$: The unit transportation cost of a full RTI

c^{trip}_{ab}: The fixed trip cost of a shipment from location a to location b

E^{i}: The average empty RTI stock level in the whole CLSC during the planning horizon

F^{i}: The average full RTI stock level in the whole CLSC during the planning horizon

h_{e}: Inventory holding cost of one empty RTI for T periods

h_{f}: Inventory holding cost of one full RTI for T periods

$H^{i}_{RTI\,management}$: Total amount of administrative labor hours spent in RTI management operations in the planning horizon

K_{order}: The fixed cost of new RTI orders

L^{i}: The total number of lost sales occurred in the planning horizon

N^{i}_{new}: The total number of RTIs purchased in the planning horizon

N_{order}^{i}: The total number of new RTI orders in the planning horizon

R^{i}: The total number of RTIs prepared for reuse in the planning horizon

$r_{disposal}^{i}$: The disposal rate ($r_{disposal} = \frac{RTI\ disposals}{RTI\ returns}$)

r_{repair}^{i}: The repair rate ($r_{repair} = \frac{Repaired\ RTIs}{RTI\ returns}$)

T: The number of periods in the planning horizon

Tr_{ab}^{i}: Total number of truck trips made between location x and y in the planning horizon

$TC_{administration}^{i}$: The total administration cost of RTI pool management (including administration for new RTI purchases, planning RTI shipments, and taking action in case of low level of returns)

$TC_{inventory}^{i}$: The total inventory holding cost

TC_{new}^{i}: The total cost of new RTI purchases

$TC_{penalty}^{i}$: The total penalty cost of lost sales

$TC_{preparing}^{i}$: The total cost of preparing for reuse operation of RTIs

$TC_{transportation}^{i}$: The total transportation cost

X: The total number of empty RTIs transported in the planning horizon

Y: The total number of full RTIs transported in the planning horizon

The total value of the benefits of using RFID technology is the decrease in the total cost:

$$TB_{RFID} = TC^{1} - TC^{2} \tag{4.8}$$

In equation 4.8, TB_{RFID} is the total benefit of RFID and TC^{i} is the total cost of RTI pool management which can be found with the following equation:

$$\begin{aligned} TC^{i} = {} & TC_{administration}^{i} + TC_{inventory}^{i} + TC_{new}^{i} + TC_{penalty}^{i} + TC_{preparing}^{i} \\ & + TC_{transportation}^{i} \end{aligned} \tag{4.9}$$

Using the formula of TC^i given in equation 4.9, equation 4.8 can be rewritten as follows:

$$\begin{aligned} TB_{RFID} = {} & (TC^1_{administration} - TC^2_{administration}) \\ & +\left(TC^1_{inventory} - TC^2_{inventory}\right) \\ & +(TC^1_{new} - TC^2_{new}) \\ & +\left(TC^1_{penalty} - TC^2_{penalty}\right) \\ & +\left(TC^1_{preparing} - TC^2_{preparing}\right) \\ & +(TC^1_{transportation} - TC^2_{transportation}) \end{aligned} \tag{4.10}$$

In conclusion, the total cost saving provided by RFID technology can be found with the following equation:

$$\begin{aligned} TB_{RFID} = {} & \left[c_{labor}\left(\boldsymbol{H^1_{RTI\ management}} - \boldsymbol{H^2_{RTI\ management}}\right)\right] \\ & +\left[h_e(\boldsymbol{E^1} - \boldsymbol{E^2}) + h_f(\boldsymbol{F^1} - \boldsymbol{F^2})\right] \\ & +\left[K_{order}(\boldsymbol{N^1_{order}} - \boldsymbol{N^2_{order}}) + c_{new}(\boldsymbol{N^1_{new}} - \boldsymbol{N^2_{new}})\right] \\ & +\left[c_{penalty}(\boldsymbol{L^1} - \boldsymbol{L^2})\right] \\ & + \Big[(\boldsymbol{c^1_{sorting}R^1} - \boldsymbol{c^2_{sorting}R^2}) + c_{repair}(\boldsymbol{r^1_{repair}R^1} - \boldsymbol{r^2_{repair}R^2}) \\ & \qquad + c_{dispose}\left(\boldsymbol{r^1_{disposal}R^1} - \boldsymbol{r^2_{disposal}R^2}\right) \\ & \qquad + c_{cleaning}\left(\left(1 - \boldsymbol{r^1_{disposal}}\right)\boldsymbol{R^1} - \left(1 - \boldsymbol{r^2_{disposal}}\right)\boldsymbol{R^2}\right)\Big] \\ & + \Big[(\boldsymbol{c^{e,1}_{transportation}} - \boldsymbol{c^{e,2}_{transportation}})X + (\boldsymbol{c^{f,1}_{transportation}} - \boldsymbol{c^{f,2}_{transportation}})Y\Big] \end{aligned} \tag{4.11}$$

The last term can be changed with the right hand side of the following equation:

$$TC^1_{transportation} - TC^1_{transportation} = \textstyle\sum_{a,b} c^{trip}_{ab}\,\boldsymbol{Tr^1_{ab}} - \sum_{a,b} c^{trip}_{ab}\boldsymbol{Tr^2_{ab}} \tag{4.12}$$

4.2 Quantification of the Potential Costs of Using RFID Technology

The following assumptions are made in this cost quantification.

- There is no salvage value of any item purchased for RFID application.
- All the costs of using RFID technology can be separated from the costs of any other activities. For example, if the same database stores both RFID and non-RFID data, it is assumed to be possible to separate the database cost related with using RFID.

The total setup and the total periodic costs can be found as follows:

$$TSC = SC^{adm} + SC^{ins} + SC^{hw} + SC^{oth} + SC^{sw} + SC^{tag} + SC^{tra} \tag{4.13}$$

$$TPC_t = PC_t^{adm} + PC_t^{hw} + PC_t^{oth} + PC_t^{sw} + PC_t^{tag} \quad for\ t = 0,1,2 \ldots, T \tag{4.14}$$

$$TC_{RFID} = TSC + \sum_t TPC_t \quad \text{without discounting} \tag{4.15}$$

$$TC_{RFID} = TSC + \sum_t \frac{TPC_t}{(1+r)^t} \quad \text{with discounting} \tag{4.16}$$

where

PC_t^{adm}: Periodic administration cost of RFID technology
PC_t^{hw}: Periodic hardware (maintenance) costs of RFID technology
PC_t^{oth}: Periodic other costs of RFID technology
PC_t^{sw}: Periodic software (maintenance) cost of RFID technology
PC_t^{tag}: Periodic tag (maintenance) cost of RFID technology
$r_{interest}$: The interest rate used for discounting
SC^{adm}: The administration cost for the setup of RFID technology
SC^{ins}: The installation cost of RFID technology
SC^{hw}: The initial hardware cost of RFID technology

SC^{oth}: The other setup costs of RFID technology

SC^{sw}: The initial software cost of RFID technology

SC^{tag}: The initial tagging cost of RFID technology

SC^{tra}: The cost for training the employees who use RFID technology

T: The number of periods in the planning horizon

TC_{RFID}: Total cost of the RFID application

TPC_t: Total periodic costs of the RFID application in period t

TSC: Total setup cost of the RFID application

4.3 The Added Value of Using RFID Technology

The added value of using RFID technology is equal to its benefits which are the total of cost savings introduced by RFID technology, minus the total cost of using this technology.

$$Added\ value\ of\ RFID = TB_{RFID} - TC_{RFID} \tag{4.17}$$

The RFID application can be evaluated as profitable if the following condition is satisfied:

$$Added\ value\ of\ RFID \geq \pi_{profit} TC_{RFID} \tag{4.18}$$

In equation 4.18, π_{profit} is the profit margin determined by the organization which initializes the RFID application.

CHAPTER 5

PROBLEM ENVIRONMENT OF THE CASE STUDY

It is already mentioned that a case study is conducted in a company which has recently started an RFID application in its CLSC of RTIs. The aim of this case study is to identify and understand how an existing RTI pool is managed, as well as the impact of using RFID technology on the management of such an RTI pool. In this chapter, we give information related with this case study. In section 5.1, we introduce the key stakeholders and their roles. In section 5.2, we describe the CLSC of RTIs in this case study. In sections 5.3 and 5.4, we present the problems in RTI pool management and RFID application as a possible solution to these problems, respectively. In section 5.5, we give the potential benefits of using RFID technology in the case under study. Finally, we summarize the path for realizing the value of using RFID technology in section 5.6.

5.1 Key Stakeholders

The key stakeholders are CHEP, Company A, and Company B. CHEP is the supplier of the RFID technology. Company A is the owner of the RTI pool and the manufacturer of the product which is sold in a single type of RTI. Company B is the customer of Company A and the only end user of the product sold in this type of RTI.

CHEP is a third party logistic provider which issues, collects, conditions and reissues more than 300 million pallets and containers from a global network of service centers, helping manufacturers and growers transport their products to distributors and retailers. It is the global leader in pallet and container pooling services serving many of the world's largest companies. It handles pallet and container supply chain logistics for customers in the consumer goods, produce, meat, home improvement, beverage, raw materials, petro-chemical and automotive industries by combining superior technology, decades of experience and an unmatched asset base. As a result, it provides a valuable service to 345,000 customers in 46 countries (CHEP official website, 2010).

Company A fills RTIs with its product and keeps them in its full RTI stock. The distribution centers (DCs) of Company B demand full RTIs from Company A in order to ship them to the end users of Company B. After being emptied in one of the end users, RTIs are collected by the same DCs and brought to a facility in which they are cleaned and repaired if necessary. After the completion of the preparing for reuse operation, they are shipped to the filling facility of Company A. The RTIs complete one cycle when they enter the filling facility again. This whole chain constitutes a CLSC of RTIs. This CLSC is explained in detail in section 5.2. The role of CHEP here is to supply RFID technology and consult Company A on the management of its RTI pool with the help of an application of RFID technology in this CLSC.

CHEP started the application of RFID technology with a pilot project. The concern of the pilot project is the core business of CHEP Material Intelligence. If this pilot project turns out to be successful, there is an opportunity of its worldwide application in different companies which have the similar complaints as Company A. Because of these reasons, this project is important for CHEP both for its current business with Company A and its long term business opportunities.

5.2 The Closed-Loop Supply Chain of RTIs

Figure 5.1 demonstrates the CLSC of RTIs. The life of an RTI starts with its purchase. A newly purchased RTI (entering the stock point 1) is brought to the facility in which it is filled. Firstly, it enters the stock of empty and clean RTIs which wait to be filled (the stock point 1). After the filling operation, it enters the stock of full RTIs (the stock point 2). After waiting in this stock, it is shipped to one of the DCs (the transportation 1) in a truck sent from the DC to which the RTI is shipped. This DC delivers it (from its stock point 3 to the stock point 4) to one of the end users (the transportation 2). It enters the empty RTI stock of this end user when it is emptied (the stock point 5). After waiting in this stock, it is collected by one of the DCs in order to bring it to the empty RTI stock of this DC (the transportation 3). When it arrives in this DC, it is placed at (one of) the stock point(s) for the RTI returns (the stock point 6). Then, it is shipped (to the stock point 7) to the facility of preparing for reuse (the transportation 4). In this facility, it is checked to see whether it has a damage or not, and whether the damage is repairable or not. If it has a non-repairable damage, it is disposed. Otherwise, it is prepared for reuse after repairing if necessary. Following the preparing for reuse operation, it enters the stock of ready-for-reuse RTIs (the stock point 8). From this stock, it is transported to the facility in which it is filled (the transportation 5) by Company A. After this transportation, it completes the cycle and continues with its next cycle with filling again. It continues cycling until it is lost at one of the stages of the CLSC or disposed due to a non-repairable damage.

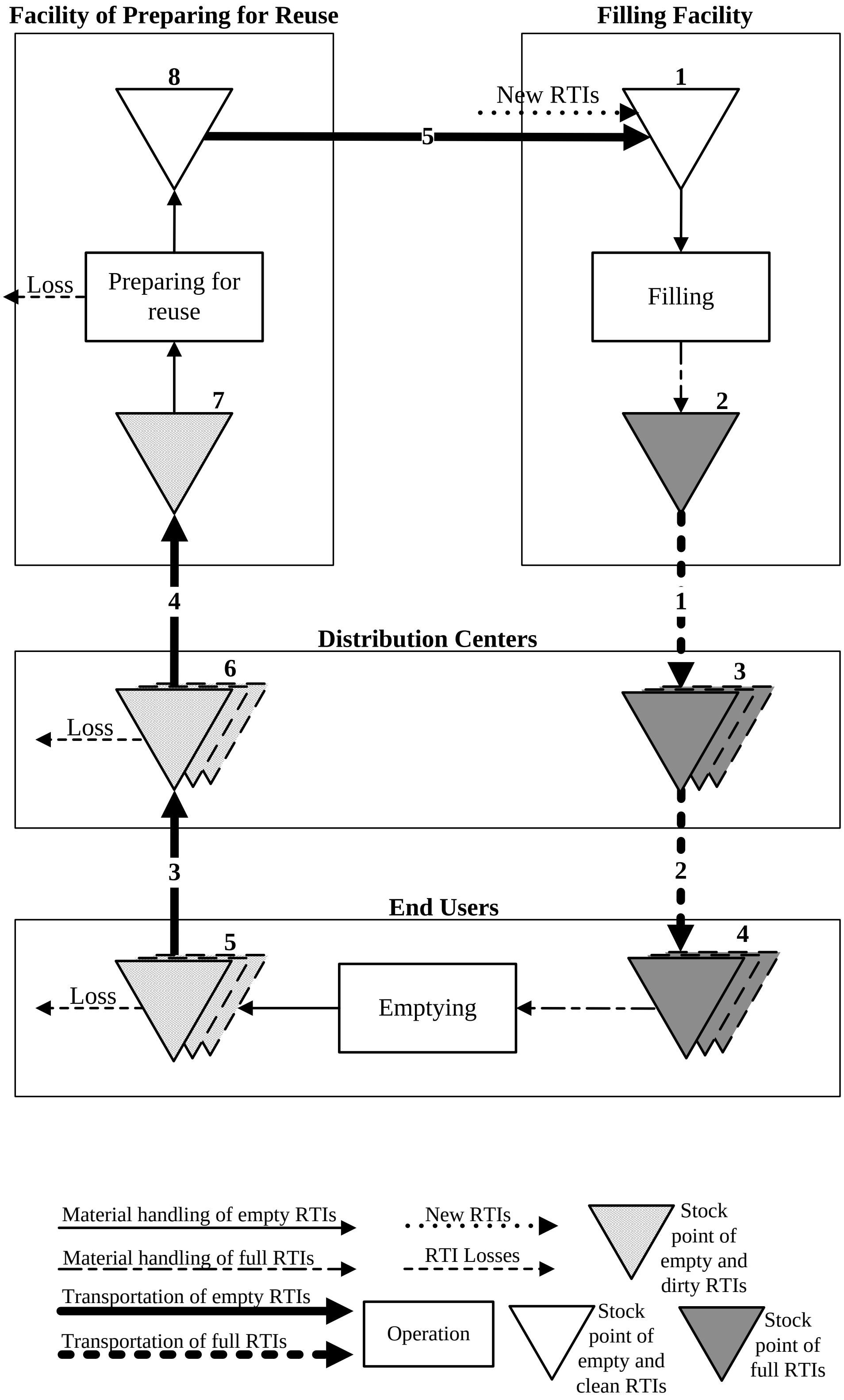

Figure 5.1: The CLSC of RTIs in the case under study

5.3 The Problems in RTI Pool Management

Company A has troubles regarding the RTI returns from DCs. The speed of return is slow (or not fast enough), which brings difficulties in meeting the empty RTI demand of the filling facility. In order to satisfy this empty RTI demand, Company A purchases new RTIs with a high rate. Besides, damages which are either require repair or result in RTI disposals are frequently seen in RTI returns. Both new RTI purchases and repairs of RTI returns are expensive since these RTIs are assets with high value.

In order to help Company A, CHEP started an RFID application in this CLSC for a better RTI pool management. The answers of the following questions were unknown before the use of RFID technology, since the RTIs did not have unique identity numbers and there were no tracking and tracing:

- How many RTIs are there in this CLSC in total?
- What is the actual cycle time of RTIs?
- Where do excess holding periods occur in the CLSC?
- How many RTIs get lost periodically?
- At which points do RTIs get lost?
- What are the benefits associated with improved RTI pool management?

In summary, the size of the RTI pool, actual cycle time, the points and the amounts of RTI damage/lost/theft in the supply chain were unknown and making the RTI pool management harder and more costly. Because of this reason, RFID technology has been implemented in order to estimate the unknown parameters and improve RTI pool management.

5.4 The Application of RFID Technology

CHEP is a leader in all aspects of RFID – from customer trials and testing to global compliance and technology (CHEP official website, 2010). RFID technology has been fully implemented with three shipment scan points since September 2009. These three scan points are located as defined below:

1. Just before shipping full RTIs from Company A
2. Just after receiving empty RTIs in the facility of preparing for reuse
3. Just before shipping empty RTIs from the facility of preparing for reuse to Company A

Besides, scanning has also been performed in the facility of preparing for reuse in order to record repair history of RTIs. Figure 5.2 shows the currently used scan points in the CLSC.

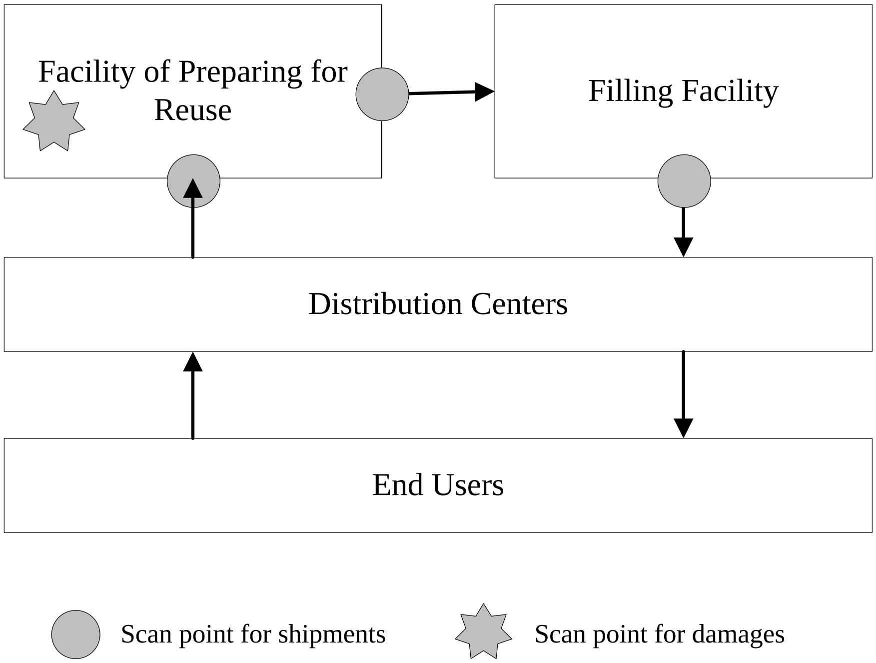

Figure 5.2: RFID scan points

RFID database reports provide information on,

- The identities of RTIs in circulation in the CLSC,
- Cycle time, i.e. time for an RTI to complete a whole cycle or a part of a cycle,
- Open cycle time (for RTIs in the field, i.e. in the part of the CLSC consisting of DCs and end users), i.e. the length of time that passes since an RTI sent to the field,
- The time, the destinations and the contents of RTI shipments,
- The location of RTIs (whether they are in the field, at the filling facility, or at the facility of preparing for reuse), and
- Damage history of RTIs.

The information of the identities of RTIs in circulation makes possible to find out the size of the RTI pool. Open cycle time information can be used to detect the RTI losses in the field. The ingredient carried by the RTIs has a limited shelf life and can only be used before its shelf life ends. As a result, it is expected that the return of an RTI to the facility of preparing for reuse should be started after the end of ingredient's shelf life at the latest. This makes possible to calculate the maximum time that an RTI can spend in the field. If the open cycle time of an RTI is found to be more than this maximum time, than Company A assumes that the RTI is lost in the field by the DC that it is lastly sent to. Company A also assumes that the responsible for an RTI damage (whether it is repairable or not) is the DC that the damaged RTI is lastly sent to.

5.5 The Potential Benefits of Using RFID Technology for the Chosen Case

From the list of benefits given in Chapter 3, the following benefits are found to be the most relevant to our case study:

- The flow of RTIs in the supply chain becomes more predictable with asset visibility (Ilic et al., 2009). Uncertainty in quantity, quality and timing of returns is decreased (Karaer and Lee, 2007). More accurate forecasting methods can be used for returns and replenishment process can be improved with better return forecasts.

- With unique serial identification associated with the RTIs, it is possible to trace the source of the damaged pallets to the originator. As a result, it is expected that RTI damages are decreased (Ilic et al., 2009).

- With the help of track and trace capability, it is also possible to identify any systematic losses (including theft (Dutta et al., 2007)) within the supply chain (Ilic et al., 2009). As a result, it is expected that RTI losses are decreased.

- With the help of track and trace capability, it is also possible to identify slow moving locations and excessive holding areas in the supply chain. Cycle time can be decreased and rotation rate can be increased with the determination of slow moving locations and taking action when possible.

- Currently, emergency deliveries occur since the return flow is slow. The decrease in damages, and losses as well as the identification of excessive holding areas can help to increase the speed of return flow. Therefore, RFID can help in avoiding or at least decreasing emergency deliveries between the facility of preparing for reuse and the filling facility.

- Asset visibility brings cycle time reduction, increase in rotation rate, damage and lost reduction. Therefore, investment in RTI fleet can be decreased with minimal sizing of RTI fleet through asset visibility (Johansson and Hellström, 2007; Frazelle, 2002).

In this master thesis study, we have decided to quantify all of these benefits except the first benefit given in the reduced benefit list. The quantification of this benefit is in the context of advance supply information.

5.6 The Path for Value Realization

This pilot project has started with RFID implementation. The goal of CHEP was to ensure that the pilot project went live and has been continuing for a long time. This could only be achieved by making the potential value of RFID technology real. Therefore, the ultimate step that the pilot project should reach is the realization of value. Figure 5.3 shows the path for value realization starting with RFID implementation as a first step. In order to reach the ultimate step of value realization, there are questions to be answered at every step. These questions are written in word balloons in this figure. Studies have been conducted related with all of these questions during the case study. Figure 5.3 is given in order to summarize what we have done in this pilot project. At the end, we have achieved to turn the pilot project into a long-term RFID application.

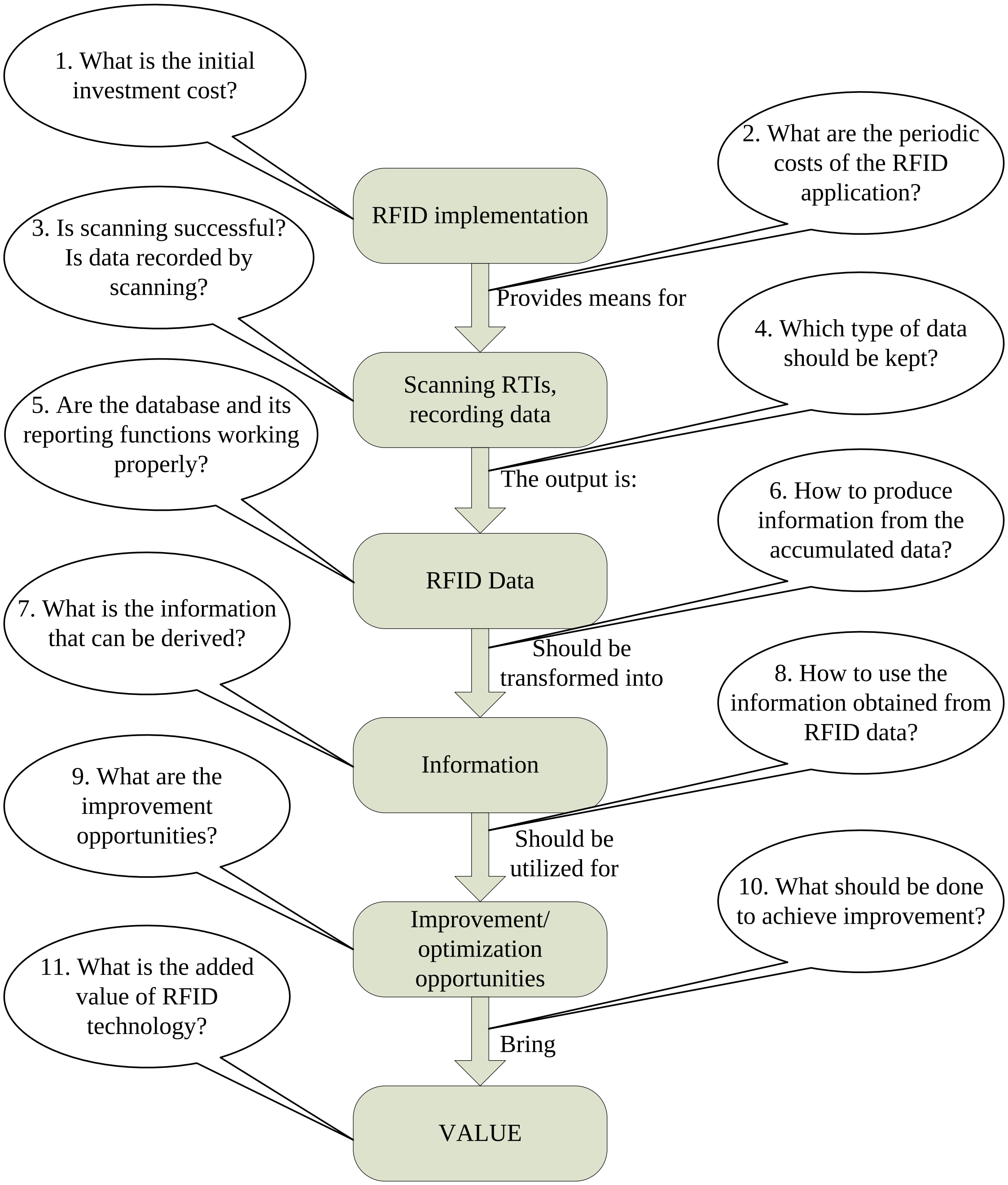

Figure 5.3: The path for value realization

CHAPTER 6

THE PROPOSED APPROACH AND SIMULATION OPTIMIZATION STUDY

In sections 6.1 and 6.2, we explain the details of the proposed approach to quantify the added value of using RFID technology. In section 6.3, we give the problem environment for value quantification. We present the performance measures of RTI pool management used in this study in section 6.4. In sections 6.5 and 6.6, we provide the details related with the efforts to find the optimal RTI pool management. In section 6.7, we present our simulation optimization study.

6.1 Introduction

Our aim is to explore the value of using RFID technology on RTI pool management. For this purpose, we need to investigate the two cases, namely with and without the use of RFID technology. In both cases, the manager of the RTI pool may or may not have the optimization effort. As a result, there exist four situations for the management of an RTI pool. These situations are summarized in Table 6.1. Atali et al. (2006) have a similar summary for the situations for the management of an inventory system under inventory inaccuracy.

		VISIBILITY	
		Without (No use of RFID technology)	With (RFID-enabled)
OPTIMIZATION EFFORT	Without	Situation 0: Ignorant situation	Situation 2: Situation of not fully utilizing RFID
	With	Situation 1: Optimal situation without RFID	Situation 3: Optimal situation with RFID

Table 6.1: Four situations in RTI pool management

Situation 0 refers to RTI pool management in which both a possible optimization opportunity and a possible means for visibility (RFID) are ignored. Therefore, this situation is referred to as the *ignorant situation*. The initial situation in our case study can be considered to be an *ignorant situation*. *Situation 1* refers to the way of management when possible optimization opportunities are exploited in the absence of RFID technology. *Situation 2* is the RTI pool management when RFID technology is applied; however, there is no optimization effort to make further improvements with the additional information provided by this technology. Since such a way of management is somehow irrational, we do not deal with *Situation 2* in our study. Finally, *Situation 3* refers to the way of management when possible optimization opportunities are utilized in the presence of RFID technology and the additional information and visibility it provides. In order to be fair, we compare *Situation 1* and *Situation 3* in order to obtain the true impact of using RFID technology.

6.2 Main Steps of the Proposed Approach

In order to find out the impact of using RFID technology, the following three main steps should be completed:

Step 1. Modeling *Situation 1*: We need to find the optimal RTI pool management in the absence of RFID technology.

Step 2. Modeling *Situation 3*: We need to find the optimal RTI pool management in the presence of RFID technology. At this step, we make the following assumptions:

- RFID data is transformed into useful information and this additional information is used in order to find out
    - The sources of damages,
    - The sources of systematic losses, and
    - Excessive holding areas.
- Action is taken in order to decrease and eliminate the sources of damages, the sources of systematic losses, and excessive holding areas.

Step 3. Comparing *Situation 1* and *Situation 3*.

At the strategic level, RTI pool management requires the design of the CLSC including the locations and the numbers of facilities that serve the end users, as well as the structure of collection and distribution system. At the tactical level, RTI pool management requires determining the pool size which in turn determines the level of capital investment. At the operational level, it is necessary to decide on quantity and timing of new RTI purchases in order to maintain the RTI pool, as some RTIs are never returned and some are disposed due to the non-repairable damages. Besides, emergency shipments should be organized at the operational level when there are not enough empty RTIs to fulfill the demand of full RTIs. These decisions should be made according to a prescribed service level of satisfying the demand of full RTIs.

In our study, strategic level decisions are taken as given. Our aim is to deal with the following tactical and operational level decisions:

- The size of the RTI pool
- The determination of quantity and timing of new RTI purchases by the manufacturer

- The decision of emergency shipments from DCs to the manufacturer

There are other decisions at the operational level like,

- timing and quantity of return collection,
- timing and lot sizes of the preparation for reuse operation, and
- timing and lot sizes of the filling operation.

The rules for these decisions are taken as given, because our focus is only on the decisions that RFID can have an impact and the RTI manager can have an effect on.

6.3 The Modeled Closed-Loop Supply Chain

Before starting with the modeling of *Situation 1* and *Situation 3*, we need to define the CLSC in the case study as we conceive it and do some additional simplifying assumptions.

In our case study, we have reached the detailed information only about the operations of the manufacturer. There is not enough reliable information about the operations of DCs and end users. It is not clearly known how distribution and collection operations are carried out between DCs and end users. Because of these reasons, we model the part of the CLSC that involves DCs and end users as a *black box*. Related with this *black box*, we only observe the deliveries of full RTIs to DCs, the receipts of empty RTI returns from DCs at the manufacturer and the level of empty RTI stock at DCs when there is a need for emergency shipment by contacting with them. In addition, we combine the preparing for reuse facility and the filling facility as a single facility, since the distance between them (which takes 1 hour with trucks) is negligible when modeling is done at the day level and there is no limit on the number of trucks required. As a result, we conceive the CLSC in our case study as shown in Figure 6.1.

In our case study, we have observed that the manufacturer rarely needs to emergently ship RTI returns from DCs. These emergency shipments help the manufacturer to increase RTI availability for the filling operation, because it reduces the time that empty RTIs need to wait at DCs to form a full truck load of RTI returns. On the other hand, they result in dispute between the manufacturer and DCs, because they require additional effort of DCs. There can be such cases that it may not be possible to make an emergency shipment, because DCs are reluctant to cooperate with the manufacturer for such shipments. As a result, we have considered the following possible settings related with the emergency shipments from DCs in our modeling:

1. Emergency shipment is not allowed by DCs.
2. Emergency shipment is allowed by DCs and the manufacturer decides on it.

We now define the parties involved in the CLSC together with how they operate and the RTIs circulating in the CLSC together with how they are managed.

The Manufacturer

- There is a single manufacturer whose aim is to minimize the undiscounted total cost of RTI pool management.
- The manufacturer produces various products. Only one of them is under consideration.
- The manufacturer sells the product under consideration in a single type of RTI.
- The manufacturer is the owner of the RTI pool.
- The manufacturer holds two kinds of RTI stock, namely empty and clean RTI stock (ready to enter filling operation), and full RTI stock (waiting to be delivered to DCs).
- The manufacturer is responsible for purchasing new RTIs, the preparing for reuse and the filling operations.

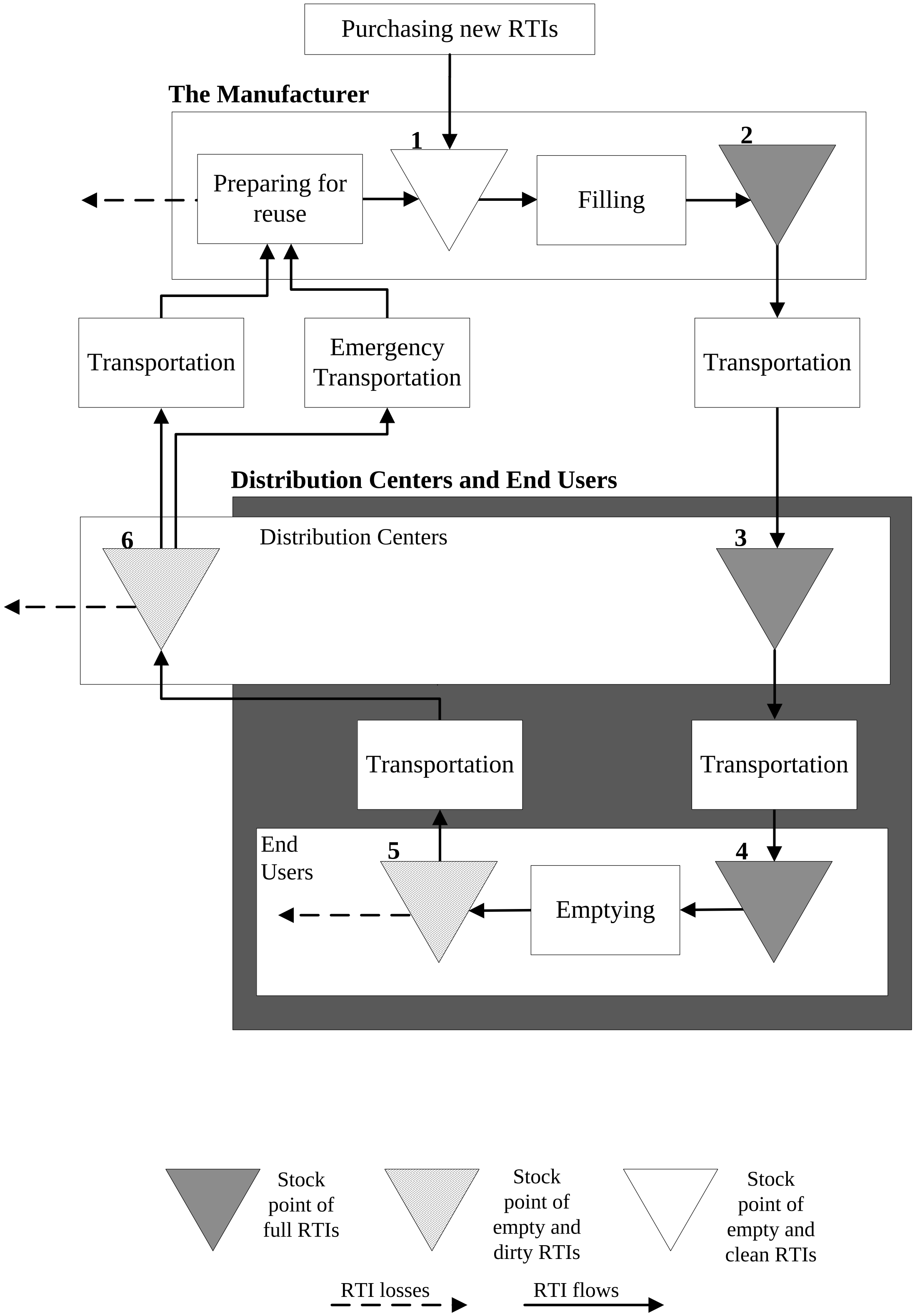

Figure 6.1: The simplified version of the CLSC of RTIs in the case under study

RTIs

- All RTIs in the pool are identical and interchangeable.
- RTIs can be damaged; however they do not deteriorate through time. As a result, there is no useful lifetime limit for RTIs.
- Possible causes of RTI losses are disposals due to non-repairable damages and never being returned.
- An RTI cannot be damaged or lost at the manufacturer.
- An RTI may never be returned after it is sent to one of DCs. This probability of never being returned, i.e. being lost in the field, has a binomial distribution.
- The RTI losses in the preparing for reuse operation as well as at the empty RTI stock points in DCs and end users are not negligible. The total of these losses constitutes the RTI shrinkage.

New RTI Purchases

- The purchasing of new RTIs is carried out by the manufacturer according to a periodic (weekly) review.
- The decisions regarding new RTI purchases are given such that there will be no need for the emergency shipments of empty returns from DCs, when emergency shipment is allowed. The emergency shipments bring additional transportation cost and planning effort to the manufacturer. Besides, they result in dispute with DCs because they require additional effort of DCs at each occasion of contacting with DCs for their planning. Most importantly, the manufacturer does not want to take the risk regarding empty RTI availability. When the manufacturer needs to make an emergency shipment, it is not certain that there will be enough empty RTIs in DCs to satisfy the need.
- The purchasing of new RTIs is carried out according to the target service level of 99% fill rate for satisfying the empty RTI demand of the filling operation.

- The quantity and timing of new RTI orders are determined by the manufacturer according to its inventory policy for the stock of reusable empty RTIs (including the ones in the preparing for reuse operation) at the manufacturer.
- The inventory policy of the manufacturer for reusable empty RTI stock is reorder-point, order-quantity (s, Q) policy.
- There is no limit for the order quantities of new RTI purchases.
- There is a positive ordering cost of new RTI purchases. This is the cost of transportation of new RTIs from the supplier of RTIs to the manufacturer in trucks with limited capacity.
- There is a positive, fixed and known lead time (the time between order and delivery) for new RTI purchases which is independent of the order quantity.
- The unit price of new RTIs is constant and known. It does not depend on order quantity (no quantity discounts) and the time of ordering (no promotion periods).
- The price of new RTI purchases is paid upon delivery to the manufacturer.

The Empty and Clean RTI Stock at the Manufacturer

- The RTIs leaving the preparing for reuse operation enter the empty and clean RTI stock at the manufacturer.
- A newly purchased RTI is ready for use. Therefore, it enters the CLSC at the empty and clean RTI stock at the manufacturer.
- There are no storage space restrictions for the empty and clean RTI stock at the manufacturer.

The Filling Operation

- Only prepared for reuse RTIs (at the empty and clean RTI stock of the manufacturer) can enter the filling operation.

- The production of ingredients is decoupled from the filling operation. There is always enough substance to fill the RTIs.
- Only the lack of RTIs can interrupt the filling operation.
- The manufacturer has abundant capacity for the filling operation.
- Once a week, filling lot size is determined according to on hand full RTI stock and demand forecasts. After determining filling lot size, the filling operation is performed.
- If emergency shipment is allowed, the time between the determination of filling lot size and the start of the filling operation is enough to make an emergency shipment when it is found to be necessary. Otherwise, if emergency shipment is not allowed, the filling operation is started just after the determination of filling lot size.
- If the level of on hand empty and clean RTI stock is less than the need of the filling operation (filling lot size) at the start of the filling operation, the operation is started and all of the RTIs at the empty and clean RTI stock are filled.
- There is a positive and fixed lead time for the filling operation.
- The setup cost and the setup time of the filling operation are negligible.
- The filling operation is always successful with no defectives.

The Full RTI Stock at the Manufacturer

- There are no storage space restrictions for the full stock at the manufacturer.
- The inventory policy of the manufacturer for its full RTI stock is periodic-review, order-up-to-level (R, S) policy.
- The target service level for satisfying the full RTI demand of DCs is set as 95% fill rate.
- The full RTI demand that cannot be immediately satisfied from full RTI stock at the manufacturer is backordered.
- The RTIs leaving the filling operation enter the full RTI stock at the manufacturer and wait for demand arrivals from DCs if there is no full RTI backorders.

Otherwise, if there is a full RTI backorder, RTIs leaving the filling operation are sent immediately to satisfy the outstanding backorders.

- When more than one DC have a backorder, firstly a backorder of the DC having the maximum level of backorders is satisfied. If the levels of backorders are equal, backorders are satisfied according to the following rationing policy: Priority of DC-1 > Priority of DC-2 > Priority of DC-3. The manufacturer continues to satisfy full RTI backorders until either there are no outstanding backorders left or there are no full RTIs left to satisfy outstanding backorders.

DCs and End Users

- There are three DCs demanding full RTIs from the manufacturer, namely DC-1, DC-2, and DC-3.
- The demand from DCs for full RTIs is stationary.
- The distributions of the demand interarrival times and the order quantities of DCs are known and different for DCs.
- There are no upper or lower limits imposed by the manufacturer for the order quantities of DCs given in total in a time period.
- The size of each order can be from a set of possible order sizes with finite size. Each possible order size has a discrete probability for a DC.
- Full RTIs are distributed to the end users through DCs. There is no direct shipment from the manufacturer to the end users.
- Empty RTIs are collected from the end users through DCs. There is no direct shipment from the end users to the manufacturer.
- Once an RTI is sent to a DC, it is distributed to and collected from an end user by the same DC.

The Transportation between DCs and the Manufacturer

- The transportation cost of the full RTI shipments from the manufacturer to DCs belongs to DCs.
- It is not possible to combine full RTI shipments to DCs. So, there is no milk run from the manufacturer to DCs.
- An RTI is brought back to the manufacturer by the same DC that it is lastly sent to.
- It is not possible to combine the shipments of empty RTI returns from DCs to the manufacturer.
- Each DC returns the empty RTIs when their returns stock is enough to fill a truck completely. In other words, every ordinary shipment of returns from DCs to the manufacturer has full truck load.
- Transportation is carried out by the identical trucks for the empty and the full RTIs. The truck capacity for carrying empty RTIs is larger than the capacity for full RTIs due to legal weight limit for truck loads.
- The transportation between the manufacturer and a DC has a positive and fixed lead time regardless of whether the truck carries full or empty RTIs.
- When the level of empty RTI stock at the manufacturer is lower than the need of the filling operation, the manufacturer decides whether or not to do emergency shipments according to the amount of empty RTI shortage if emergency shipment is allowed.
- The emergency shipments are started immediately after their decision is given.
- It is not possible to combine emergency shipments of different DCs. The emergency shipment of a DC cannot wait a truck coming from another DC since emergency shipments are started immediately after their decision is given.
- When the amount of empty RTI shortage is enough to make an emergency shipment, i.e. when it is greater than a threshold value, the manufacturer contacts with DCs. The aim of contact is to find out whether or not a shipment of returns is in the pipeline and also the amount of the returns stock at DCs.
    - If there is not any shipment of returns on the way, the manufacturer makes the emergency shipment from the DC having the maximum level of returns stock if

  its level is worth to make an emergency shipment, i.e. if its level is greater than the minimum amount of emergency shipment. If the manufacturer decides to make an emergency shipment, it recalculates the amount of empty RTI shortage by considering the amount of emergency shipment. Then, it makes the necessary number of emergency shipments as long as the recalculated amount of empty RTI shortage and the level of returns stock at the DCs is enough to make an emergency shipment.

  - If there is a shipment of returns on the way, the manufacturer recalculates the amount of empty RTI shortage by considering the total amount of RTI returns on the way. If the amount of shortage is not still greater than the threshold value, the manufacturer does not make an emergency shipment. Otherwise, it makes the emergency shipment from the DC having the maximum level of returns stock if its level is worth to make an emergency shipment. In that case, it recalculates the amount of empty RTI shortage by considering the amount of emergency shipment. Then, it makes the necessary amount of emergency shipments, as long as the recalculated amount of empty RTI shortage and the level of returns stock at the DCs is enough to make an emergency shipment.
- When the amount of empty RTI shortage is enough to make an emergency shipment (after including the RTI returns which are currently on the way to the manufacturer, if there are any) and there is more than one DC having equal levels of returns stock which worth to do an emergency shipment, emergency shipment(s) should be carried out according to the following preference ranking: DC-1 > DC-2 > DC-3.
- The cost of the ordinary shipments is in the responsibility of DCs. On the other hand, the cost of the emergency shipments is in the responsibility of the manufacturer.
- The transportation time is the same for both ordinary and emergency shipments.

The Preparing for Reuse Operation

- The RTIs returned to the manufacturer are immediately sent to the preparing for reuse operation.
- The condition of RTIs when they are returned from DCs has a general discrete distribution with three different outcomes and a known probability mass function. RTIs can be in three different states, namely good (not damaged), reparably damaged, and non-reparably damaged.
- The preparing for reuse operation has abundant capacity.
- There is a positive and fixed lead time for the preparing for reuse operation.
- The setup cost and the setup time of the preparing for reuse operation are negligible.
- In the preparing for reuse operation, RTIs are firstly checked for their damages, repaired if necessary and possible, and then cleaned.
- RTIs entering the preparing for reuse operation are checked to determine:
  - Whether they have a damage or not, and
  - If they have a damage, whether it is repairable or not.
- The RTI returns having non-repairable damages are disposed immediately.
- The RTI returns having repairable damages are repaired at a fixed unit repair cost.
- Repair is always successful with no defectives and repaired RTIs become as good as new.
- Cleaning is always successful with no defectives. Once cleaned, an RTI cannot be dirty again before being used again.

The Costs Included

In RTI pool management, we are only interested in the following costs for the manufacturer:

- The purchasing cost of RTIs (including ordering cost and the price of RTIs)

- The cost of preparing for reuse (including the costs of cleaning, checking for damages, repair, and disposal)
- The transportation cost of emergency shipments
- The cost of labor devoted to the planning of operations related with the RTI pool
- The penalty cost of full RTI backorders
- Inventory holding cost (including the cost of capital tied in the RTI pool and on hand full RTI stock)
- Material handling cost at the site of the manufacturer.

Among the above cost items, some of them are (almost) fixed costs, i.e. they do not seem to be (significantly) changed due to an improvement in RTI pool management. These costs are the costs of cleaning and checking RTI returns, the cost of labor devoted to the planning of operations related with the RTI pool, the inventory holding cost of full RTIs and material handling cost at the site of the manufacturer. Besides, the penalty cost of backorders is not expected to change significantly given the same service level for satisfying the demand of full RTIs. In addition, some of the cost items are small enough to be considered as negligible (e.g. disposal cost). When all of these cost items are removed, we are left with the following cost items:

- The purchasing cost of RTIs (including ordering cost and the price of RTIs)
- The cost of repair
- The transportation cost of emergency shipments
- Inventory holding cost (only including the cost of capital tied in the RTI pool)

6.4 Performance Measures of the Closed-Loop Supply Chain

We need to determine the performance measures that can be used to find the optimal RTI pool management in *Situation 1* and *Situation 3* and to compare these situations with each other. The life-cycle characteristics of reusable containers given by Goh and Varaprasad (1986) as well as the lists of RTI key performance indicators and RTI management metrics given by Bowman et al. (2009) have guided us to come up with the presented list of performance measures. In addition, the insights that we have gained through our case study are also utilized.

Our list of performance measures is as follows:

- Total RTI pool management cost (including the cost items in the final cost list in section 6.3)
- The average cycle time (trip duration)
- The trippage (total number of cycles completed by an RTI in its lifetime)
- The average useful lifetime of RTIs
- The average pool size (total number of RTIs in circulation in the CLSC)
- The rate of new RTI replenishment
- The service level for satisfying the empty RTI need of the filling operation
- The service level for satisfying the full RTI demand of DCs
- The average time that RTIs spend in the field (i.e. the duration between the time when an RTI leaves the manufacturer and the time when it comes back)

6.5 Optimal RTI Pool Management

It may be possible to construct a mathematical programming model which aims to minimize the total undiscounted RTI pool management cost of the manufacturer in which the decision variables are the timing and quantity of new RTI purchases and initial RTI pool size. In this optimization model, the objective function is minimizing the total expected cost of RTI pool management. It includes the terms of the purchasing cost of new RTIs, the cost of repair, and the cost of capital spent on the RTI pool, respectively. The constraints include inventory balance equations and the constraint for the target service level for satisfying the full RTI demand of DCs. It may be possible to solve this optimization model by taking average values for the stochastic parameters such as time that RTIs spend in the field, RTI losses and damages. As a result, it may be possible to estimate the total cost of RTI pool management. However, this approach does not seem satisfactory for our purposes for the following reasons and it is required to find a better method to deal with our problem:

1. There are many other performance measures to look at for the RTI pool management as mentioned in section 6.4. ‘Total RTI pool management cost’ is just one of them.
2. Solving the optimization model with the average values is expected to result in missing the effect of the variability of parameters on the optimal solution. For example, the time that an RTI is emptied and returned by an end user, i.e. the duration between the time when an RTI leaves the manufacturer as full and the time when it comes back to a DC after being emptied, may have high variability and decreasing this variability may have significant impact on the performance measures.
3. It is not possible to fully reflect all of the characteristics of the CLSC and to consider all chosen performance measures in such an optimization model. For example, the rule for giving the decision of whether or not to make an emergency shipment when the amount of empty RTIs is not enough to satisfy the need of filling operation, has many steps and some of these steps are repeated for several numbers of emergency shipments during the same week. It is almost impossible to fully model such a complex decision rule using mathematical programming.

The CLSC to be modeled is a complex and dynamic system for Lesyna (1999). Rather than only dealing with a single decision like the timing and quantity of new RTI orders, considering the whole CLSC introduces great complexity. The complexity stems from the various rules and the logic that must be followed, for example, for giving the decision of emergency shipments. Such rules can be easily modeled in a discrete event simulation (DES) model, although it is impractical to implement them in linear programming. On the other hand, the CLSC has various dynamic features, since stock levels fluctuate and RTIs cycle continuously. For such dynamic systems, working with the average values are of little value and likely to be misleading (Lesyna, 1999). We are also interested in the reduction in variances of some parameters such as the time that RTIs spend in the field.

In conclusion, it is found more suitable to construct a DES model and then try to solve the optimization problem with the help of the DES. Two simulation models (one for the situations in which emergency shipment is not allowed and one for the opposite situations) are constructed with the help of Arena. Next, the constructed simulation models are embedded into OptQuest which is Arena's simulation optimization solver engine. They include the decision rule for the timing and quantity of new RTI purchases and ensure the constraints other than the ones for the target service level. OptQuest ensures the target service level and searches for the optimal solution in terms of total cost by changing the initial pool size. It is possible to obtain the values of performance measures in the optimal solution which is found by OptQuest. The details of the simulation optimization study can be found in section 6.7.

The decision rule for the timing and quantity of new RTI purchases is inserted into the simulation models with the required parameters. In the next section, we discuss this decision rule. We conclude that the timing and quantity of new RTI purchases should be determined according to the (s, Q) inventory policy. This is added to the definition of the CLSC to be modeled.

6.6 New RTIs Purchasing Decision

Our approach is to determine the quantities of new RTI orders by netting the demand against the returns of empty RTIs. This approach is referred to as reducing the problem to a traditional setting in practice by Fleischmann et al. (1997). Kelle and Silver (1989b) have a fundamental study about optimal purchasing policy of new RTIs. In this study, they consider a purchasing policy in which the net demand (the number of RTIs to be filled minus the number of RTI returns) is taken into account.

Minner and Lindner (2004) study lot sizing decisions for reverse logistics processes where demand can be satisfied with two supply sources, namely manufacturing or remanufacturing. They discuss that a netting approach can be used when one of the setup costs associated with manufacturing or remanufacturing is negligible and the processing rates of the two supply sources are infinite. In our problem, we have also two supply sources, namely RTI returns and new RTI purchases. According to the Minner and Lindner (2004), our problem reduces to the determination of the order quantities of new RTIs with a net demand rate. In this reduced problem, RTI returns should be prepared for reuse as they are received. Actually, this is just the case in our problem.

Van der Laan et al. (2004) describe this approach as ‘naive netting’ and they argue that the return process is not taken into account explicitly in this approach. However, they indicate that when there is a high correlation between the returns and the demand, this approach works and provides fair results. In our case, a full RTI sent to satisfy demand is always returned to the manufacturer after being emptied if it is not lost in the field. As a result, the returns are a function of the full RTI demand.

Kelle and Silver (1989b) formulate the optimal purchasing problem as a stochastic problem by considering the demand and the returns as random, and using a chance constraint of the prescribed high service level. They prove that “this stochastic problem of optimal purchasing of RTIs is equivalent to the usual dynamic lot-sizing problem”.

Empty RTI stock at the manufacturer should be checked based on the periodic review policy. Since the demand of empty containers occurs only once in a week (on the day of filling operation), it is pointless to consider continuous review for this stock level. Besides, a rolling schedule should be applied because of the reason that both the demand and the returns are stochastic, which results in the forecasts different than the actual.

Since we are looking for the optimal RTI pool management, we need to use a lot-sizing algorithm that guarantees to produce fair results. In order to do this, Kelle and Silver (1989b) advise us to use the Wagner- Whitin algorithm. However, Blackburn and Millen (1980) show that the Silver Meal heuristic may perform better than Wagner-Whitin algorithm in terms of cost performance in a rolling schedule environment. On the other hand, Vargas (2008) discusses that an order-point, order-up-to or (s,S) inventory policy provides the optimal solution for the cases when one is only interested in the decision for the first period in the planning horizon. Besides, he also indicates that such a policy is more suitable for inventory stocking.

The purchasing decision in our specified problem situation has the following properties:

- Constant transportation cost for a truck shipment
- Limited capacity of trucks
- Constant inventory holding cost (the cost of capital tied in the RTI pool)
- Constant price of new RTIs
- Constant lead time for new RTI orders
- Uncertain returns of empty RTIs
- Stochastic and stationary full RTI demand

Since we consider stationary full RTI demand with a fixed ***Probability of Loss***, i.e. the probability that an RTI cannot be reused again once it is sent to the field, the forecasted net demand for future periods is the same. In the light of the above discussions and considering the properties of our purchasing decision, we have concluded that it is best to order new RTIs when on hand empty RTI stock level at the manufacturer drops below ***Reorder Point for Purchasing*** with a fixed ***Purchasing Lot Size*** which is found with the help of economic order quantity (EOQ) model.

The notation and the formulas for ***Reorder Point for Purchasing*** are given below. Kelle and Silver (1989a) provide the forecast method utilizing only information on

- the probability that an RTI is ever returned, and

- the expected value and variance of the lead time empty RTI demand at the manufacturer.

The formulas of Kelle and Silver (1989a) are adjusted to our problem by using the probability that an RTI can be reused again instead of the probability that an RTI is ever returned. The reason is that there is a positive probability that an RTI is disposed due to a non-repairable damage after it is returned. The only assumption for using these formulas is that each RTI sent to satisfy demand has a fixed probability of return. In our problem, this assumption is fulfilled because there is a fixed probability of reuse.

$E(D_L)$: Expected lead time full RTI demand.
$E(R_L)$: Expected lead time RTI reuses.
$V(D_L)$: Variance of lead time full RTI demand.
$V(R_L)$: Variance of lead time reuses.
$E(ND_L)$: Expected lead time net full RTI demand.
$V(ND_L)$: Variance of lead time net full RTI demand.
P : Probability that an RTI sent to the field can be reused again.
$p_{disposal}$: Probability that an RTI is disposed due to a non-repairable damage.
$p_{field\ loss}$: Probability that an RTI is never returned once it is sent to the field.
p_{loss}: Probability that an RTI cannot be reused again once it is sent to the field.
k_p: Safety factor for lead time net full RTI demand

Then, ***Reorder Point for Purchasing*** is determined as in equation 6.7:

$$E(R_L) = P\ E(D_L) \tag{6.1}$$

$$V(R_L) = [P^2\ V(D_L)] + [P\ (1-P)\ E(D_L)] \tag{6.2}$$

$$E(ND_L) = E(D_L) - E(R_L) = (1-P)\ E(D_L) \tag{6.3}$$

$$V(ND_L) = [(1-P)^2 V(D_L)] + [P\ (1-P)\ E(D_L)] \tag{6.4}$$

$$P = 1 - p_{loss} \tag{6.5}$$

$$p_{loss} = p_{field\ loss} + p_{disposal}\left(1 - p_{field\ loss}\right) \tag{6.6}$$

$$\boldsymbol{Reorder\ Point\ for\ Purchasing} \ = \ E(ND_L) + \left(k_p\sqrt{V(ND_L)}\right) \tag{6.7}$$

Purchasing Lot Size is found based on the EOQ model. However, the classic EOQ formula should be modified, since there is a capacity limit for the shipments and a unit transportation cost per shipment. The notation and how to find the ***Purchasing Lot Size*** are given below.

$c_{holding}$: Inventory holding cost per empty RTI per year
c_{new}: Unit price of new RTIs
$c_{transportation}$: Unit truck trip cost
FTL_e: Full truck load (the capacity of trucks) for empty RTIs
n: Number of trips needed to ship Q amount of new RTIs
ND: Annual net demand rate
Q: Number of new RTIs to be purchased in a single order
$Y_n(Q)$: The function for the unit cost of RTI purchasing when Q units of RTI are ordered

Then, ***Purchasing Lot Size*** should be found as it is explained below:

$$Unit\ inventory\ holding\ cost = \frac{c_{holding}\,Q}{2(ND)} \tag{6.8}$$

$$Unit\ transportation\ cost = \frac{n\,c_{transportation}}{Q} \quad \text{where} \quad n = \left\lceil {}^{Q}/_{FTL_e} \right\rceil \text{ and } Q > 0 \tag{6.9}$$

$$Y_n(Q) = \frac{c_{holding}\,Q}{2(ND)} + \frac{n\,c_{transportation}}{Q} + c_{new} \quad \text{for} \quad n = 1, 2, 3\ldots \text{ and } \quad Q > 0 \tag{6.10}$$

As a result, we have a set of cost formulas consisting of $Y_n(Q)$'s for each n ($n = 1, 2, 3\ldots$). Each $Y_n(Q)$ function is convex for $Q > 0$. This convexity is proved below.

$$\frac{dY_n(Q)}{dQ} = \frac{c_{holding}}{2(ND)} - \frac{n\, c_{transportation}}{Q^2} \tag{6.11}$$

$$\frac{d^2Y_n(Q)}{dQ^2} = \frac{2n\, c_{transportation}}{Q^3} \tag{6.12}$$

$$\frac{d^2Y_n(Q)}{dQ^2} > 0 \quad \text{for} \qquad Q > 0.$$

As a result, it is possible to find the Q value which gives the minimum value for $Y_n(Q)$ in the interval $(n-1)FTL_e < Q \le (n)FTL_e$ for each n. Let's denote the Q value giving the minimum $Y_n(Q)$ in interval $(n-1)FTL_e < Q \le (n)FTL_e$ with Q^{n*}.

Q^{n*}can be found as follows:

Step 1: Find $Q^{n'}$ which gives the minimum $Y_n(Q)$ for $Q > 0$. $Q^{n'}$ is the Q value which makes the first derivative of $Y_n(Q)$ equal to zero.

$$\frac{dY_n(Q^{n'})}{dQ} = 0 \tag{6.13}$$

$$\frac{c_{holding}}{2(ND)} - \frac{n\, c_{transportation}}{(Q^{n'})^2} = 0 \tag{6.14}$$

$$Q^{n'} = \sqrt{\frac{2\, n\, c_{transportation}\, ND}{c_{holding}}} \tag{6.15}$$

Step 2: Find Q^{n*} with the help of $Q^{n'}$ and the end points of the interval $(n-1)FTL_e < Q \le (n)FTL_e$ as follows:

$$Q^{n*} = \begin{cases} Q^{n'}, & \text{if } (n-1)FTL_e < Q^{n'} \leq (n)FTL_e \\ (n-1)FTL_e + 1, & \text{if } Q^{n'} \leq (n-1)FTL_e \\ Q^{n'} > (n)FTL_e, & \text{if } Q^{n*} = (n)FTL_e \end{cases} \tag{6.16}$$

In conclusion, ***Purchasing Lot Size*** is the Q value among the set of Q^{n*}s which gives the minimum $Y_n(Q)$ value.

6.7 Simulation Optimization Study

This section starts with a brief introduction to simulation optimization in section 6.7.1. In section 6.7.2, we present the main features of the software used in our simulation optimization study. Our simulation optimization study requires firstly the simulation models (one for the cases in which emergency shipment is not allowed and one for the opposite situations) of the CLSC with the decision rules of RTI pool management. Secondly, it requires the optimization model which aims to minimize total RTI pool management cost by changing initial RTI pool size. Total RTI pool management cost is a performance measure of the simulation models. Initial RTI pool size is a decision variable that RTI pool manager should determine. This is entered to the simulation models as an input. In sections 6.7.3 and 6.7.4, we present the simulation models and the optimization model, respectively.

6.7.1 Introduction to Simulation Optimization

Simulation optimization is defined by Ólafsson and Kim (2002) as the process of finding the best values of decision variables for a system according to the output of a simulation model of this system. In other words, it is an optimization where the performance measure is the output of a simulation model and the problem setting includes the common optimization elements, namely decision variables, objective function and constraints.

According to Ólafsson and Kim (2002), simulation optimization is a product of the need for a more exploratory process since a simple evaluation of performance is often insufficient. Fu (2001a) provides some examples of simulation optimization in manufacturing systems, supply chains and inventory control systems. Fu (2001b) discusses two important parts of simulation optimization, namely generating candidate solutions and estimating their objective function value. Fu (2001a) summarizes the techniques used in simulation optimization into the following main categories:

1. Statistical procedures (such as ranking and selection procedures)
2. Metaheuristics (such as simulated annealing, tabu search, genetic algorithms)
3. Stochastic optimization (such as random search, stochastic approximation)
4. Others (such as ordinal optimization, sample path optimization)

According to Law (2002), the availability of faster PCs and improved heuristic optimization search techniques lead to integration of optimization packages into simulation packages. He also indicates that “the goal of an optimization package is to orchestrate the simulation of a sequence of system configurations, so that a system configuration is eventually obtained that provides an optimal or near optimal solution”. System configurations are particular settings of the decision variables. Law and Kelton (2000) list the available software routines for performing this optimization.

There are several survey papers that discuss foundations, theoretical developments and applications of the techniques used in simulation optimization in the literature (Meketon, 1987; Jacobson and Schruben, 1989; Safizadeh, 1990; Azadivar, 1992; Fu,1994; Andradóttir, 1998; Swisher et al., 2000; Tekin and Sabuncuoglu, 2004).

6.7.2 Introduction to OptQuest

OptQuest is one of the available routines for simulation optimization. Fu (2001a) describes it as a stand-alone optimization routine that can be bundled with simulation environments such as Arena and Crystal Ball. Its optimization procedure uses a combination of strategies based on scatter search and tabu search as well as neural networks for screening out candidate solutions that are likely to be poor. More details about its algorithm can be found in Fu (2001a), Glover et al. (1999) and user's guide of OptQuest.

In OptQuest, it is possible to separate the optimization procedure from the simulation model (OptQuest for Arena User`s Guide, 2007). The optimization procedure uses the outputs of the simulation model to evaluate the results of the values of the decision variables that are entered into the simulation model as inputs. According to both this evaluation and the evaluation of past results, the optimization procedure decides on a new set of values for the decision variables as inputs to the simulation model. This relationship can be seen in Figure 6.2. The optimization procedure executes a special 'non-monotonic search' in which the successively generated values of the decision variables result in changing evaluations. Not all of these evaluations are improving; however the procedure seeks for a highly efficient path to the best solutions. This process continues until a terminating criterion is reached.

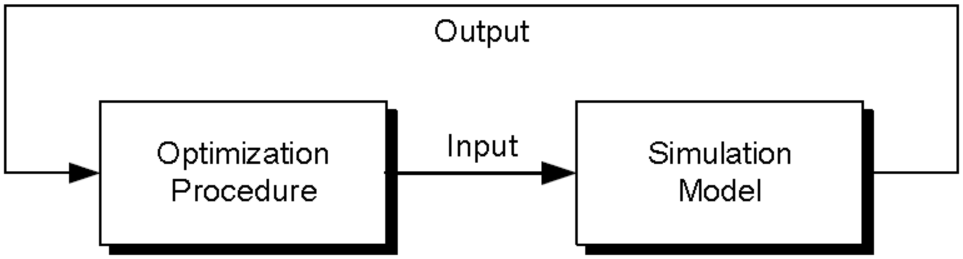

Figure 6.2: The coordination between optimization and simulation in OptQuest

6.7.3 The Simulation Models

Arena is utilized for the simulation modeling. It is the simulation package built on SIMAN which is a general purpose simulation language. Our simulation model is

- stochastic, i.e. it has inputs and outputs which are random variables,
- dynamic, i.e. there is a time dimension and the system state changes over time,
- discrete, i.e. the system state changes at discrete points in time.

The time unit in our simulation study is day. A month and a year are assumed to have 30 and 360 days, respectively. The CLSC is modeled according to the definition given in section 6.3. Two simulation models are developed for the same CLSC. In the first one, emergency shipment is not an option. In the second one, it is an option exactly like in our case study. With the help of these simulation models, the impact of the emergency shipment option on the performances of the CLSC and RTI pool management can be investigated and managerial insights can be drawn.

The elements of the simulation study are given in section 6.7.3.1. Additionally, the simulation models are explained in detail with several flow charts in section 6.7.3.2. The notation used in the simulation study is written in bold and italic letters.

6.7.3.1 The Elements of the Simulation Study

Main elements of a simulation study are entities, events, input parameters, variables, and performance measures. Entities, input parameters and variables are presented in this section. Events are not given separately, because they can be understood from the detailed explanation of the simulation models in section 6.7.3.2. The performance measures have already been given in section 6.4.

The Entities

Entities are objects of interest or components of the system which flow through the system throughout a simulation run. There are four types of entities in our simulation models. These are ***RTIs***, ***Demand***, ***Periodic Review*** and ***Report***. They are explained in the next paragraph with their attributes, if they have any. Attributes represent the characteristics of entities and they move with entities throughout a simulation run. An entity can have more attributes than the ones given here. However, only a subset of possible attributes for an entity which served to the purpose of finding out the required performance measures is used in the simulation models.

1. ***RTIs*** represent the RTIs flow through the CLSC. Their attributes are as follows:
    - ***Assigned DC*** represents the DC to which an RTI is lastly sent.
    - ***Cleanness*** indicates whether an RTI is ***Clean*** or ***Dirty***.
    - ***Condition*** indicates whether an RTI has no damage (***Undamaged***), a repairable damage (***Reparably Damaged***) or a non-repairable damage (***Non-Reparably Damaged***).
    - ***Cycle Time Attribute*** records the duration that an RTI completes its last cycle. Cycle time is taken as the duration between two consecutive times that an RTI enters empty and clean RTI stock at the manufacturer.
    - ***Emptying Duration*** indicates the duration between the time that an RTI arrives at its ***Assigned DC*** and the time that it comes back to the same DC from one of end users.
    - ***Fullness*** indicates whether an RTI is ***Empty*** or ***Full***.
    - ***Number of Rotations*** records how many times an RTI has completed a whole cycle since its entrance to the CLSC. It records the number of rotations since the end of warm up period for the RTIs in the CLSC at that time.
    - ***Time to Enter CLSC*** is the entrance time of RTIs to the CLSC in order to keep the statistics of useful lifetime of RTIs. It records the value of the simulation clock when the related RTI entity is created.

  - ***Time to Enter Empty and Clean RTI Stock*** records the last entrance time of RTIs to empty and clean RTI stock. This is required to calculate ***Cycle Time Attribute***.
  - ***Time to Enter Field*** records the last entrance time of RTIs to the field, i.e. the arrival time of RTIs at their ***Assigned DC***, in order to keep statistics of ***Time Spent in the Field*** of RTIs.

2. ***Demand*** represents the demand arrivals for full RTIs from DCs. Its attributes are as follows:
   - ***Demand Interarrival Time*** indicates the time between two consecutive orders of a DC.
   - ***Demand Owner*** indicates the DC from which the full RTI demand arrives
   - ***Demand Size*** is the size of the coming full RTI order.

3. ***Periodic Review*** executes the periodic decisions of RTI pool management. These periodic decisions are the determination of filling lot size and new RTI orders.

4. ***Report*** ensures the calculation of ***Total RTI Pool Management Cost*** just before simulation replications end. It also helps to keep the record of ***Pool Size*** just before the warm up period ends. This is required to calculate ***Total RTI Pool Management Cost*** accurately, because the value of ***Pool Size*** just before the warm up period ends is the actual initial value of ***Pool Size***.

The Input Parameters

The input parameters are listed below.

- ***Annual RFID Fee*** is the fee annually paid by the manufacturer to the supplier of RFID technology for all of its services related with RFID technology.

- ***Demand Interarrival Time Distribution*** is the distribution of ***Demand Interarrival Time*** of a DC.
- ***Demand Size Distribution*** is the distribution of ***Demand Size***.
- ***Emergency Shipment Threshold*** determines the minimum level of empty and reusable RTI shortage at the manufacturer that is worth to do an emergency shipment.
- ***Emptying Duration Distribution*** is the distribution of ***Emptying Duration***.
- ***FTL of Empty RTIs*** is the full truck load of empty RTIs, i.e. the maximum number of empty RTIs that can be loaded into a truck at the same time.
- ***FTL of Full RTIs*** is the full truck load of full RTIs, i.e. the maximum number of full RTIs that can be loaded into a truck at the same time.
- ***Initial Distribution of RTI Pool*** is the distribution of the RTI pool in the CLSC at the start of a simulation run.
- ***Initial Pool Size*** is the pool size at the start of a simulation run. This is entered into the simulation models as a parameter; however it is a decision variable that RTI pool manager should determine.
- ***Lead Time of Filling*** is the time that the filling operation takes.
- ***Lead Time of Preparing for Reuse*** is the time that the preparing for reuse operation takes.
- ***Lead Time of Purchasing*** is the duration between the time that an order of new RTIs is given and the delivery time of the same order to the manufacturer.
- ***Lead Time of Transportation*** is the time that the transportation of RTIs between the manufacturer and a DC takes.
- ***Minimum Emergency Shipment Lot Size*** determines the minimum returns stock level at a DC which is worth to do an emergency shipment.
- ***Minimum Emptying Duration*** is the assumed minimum ***Emptying Duration*** that can happen in real life.
- ***Order up to Level of Full RTI Stock*** is the order up to level of full RTI stock at the manufacturer which is required to determine ***Filling Lot Size***.
- ***Probability of Disposal*** is the probability that an RTI is disposed due to a non-repairable damage after it is returned to the manufacturer.

- ***Probability of Field Loss*** is the probability that an RTI is lost in the field, i.e. that an RTI has never been returned back to the manufacturer after it is sent to the one of DCs.
- ***Probability of Loss*** is the probability that an RTI is lost due to a non-repairable damage or never being returned after it is sent to the one of DCs.
- ***Probability of Repairable Damage*** is the probability that an RTI requires repair due to a repairable damage after it is returned to the manufacturer.
- ***Probability of Reuse*** is the probability that an RTI can be reused again once it is sent to the one of DCs. It can be calculated with the following formula:

$$\textbf{\textit{Probability of Reuse}} = 1 - \textbf{\textit{Probability of Loss}} \tag{6.17}$$

- ***Purchasing Lot Size*** is the size of a new RTI order required to determine the size of new RTI replenishments.
- ***Reorder Point for Purchasing*** is the reorder point of empty and reusable RTI inventory position required to determine the timing and the size of new RTI replenishments.
- ***Review Period for Filling*** is the length of review period for checking full RTI stock and determining ***Filling Lot Size*** accordingly.
- ***Review Period for Purchasing*** is the length of the review period for checking the need of new RTI purchases.
- ***RTI Condition Distribution*** is the distribution of the condition of RTIs (undamaged, having repairable or non-repairable damage) when they are returned to the manufacturer. This distribution takes ***Probability of Disposal*** and ***Probability of Repair*** into account.
- ***Safety Factor for Empty RTI Stock*** is the safety factor for empty and reusable RTI availability at the manufacturer which is determined according to target service level for satisfying the need of the filling operation.
- ***Safety Factor for Full RTI Stock*** is the safety factor determined for full RTI stock at the manufacturer according to target service level for satisfying the full RTI demand of DCs.

- ***Time to Action*** is the time (in months) required for the implementation of RFID technology, the accumulation of RFID data and finally taking action to reduce problems in the CLSC.
- ***Time to Activate Filling Decision*** is the duration between the time that filling lot size is determined and the starting time the filling operation. It is enough to give emergency shipment decision (if it is an option), make the emergency shipment (if it is found to be necessary and worth to do) and prepare the emergently shipped RTIs for reuse.
- ***Unit Repair Cost*** is the cost of repair (including both spare part and labor cost) of an RTI having a repairable damage.
- ***Unit RTI Holding Cost*** is the holding cost of an RTI for a year.
- ***Unit RTI Price*** is the price of a new RTI.
- ***Unit Transportation Cost*** is the transportation cost per shipment.

The simulation model includes the following demand parameters. Below, lead time refers to ***Lead Time of Purchasing***.

- ***Expected Annual Full RTI Demand***
- ***Expected Daily Full RTI Demand***
- ***Expected Lead Time Full RTI Demand***
- ***Expected Weekly Full RTI Demand***
- ***Standard Deviation of Weekly Full RTI Demand***
- ***Variance of Lead Time Full RTI Demand***

In addition to the above full RTI demand parameters, the following net RTI demand parameters are required to calculate ***Purchasing Lot Size*** and ***Reorder Point for Purchasing***:

- ***Expected Annual Full RTI Demand*** is the yearly full RTI demand.
- ***Expected Annual Net RTI Demand*** is the net yearly RTI demand (the demand for full RTIs minus the amount of reusable returns).
- ***Expected Lead Time Net RTI Demand*** is the net RTI demand (the demand for full RTIs minus the amount of reusable returns) in ***Lead Time of Purchasing***.

- ***Variance of Lead Time Net RTI Demand*** is the net RTI demand (the demand for full RTIs minus the amount of reusable returns) in ***Lead Time of Purchasing***.

It should also be noted that the simulation models have three run parameters, namely ***Replication Length***, ***Warm up Period*** and ***Number of Replications***.

The Variables

The variables of the simulation models are listed below. They are clarified in order to help the understanding of the flowcharts of the simulation models given in section 6.7.3.2. The required calculations of these variables are explained in section 6.7.3.2.

- ***Actual Starting Pool Size*** is the value of ***Pool Size*** recorded at the end of ***Warm up Period***.
- ***Cycle Time*** is the variable tallies the time of cycles completed by RTIs when they enter to empty and clean RTI stock at the manufacturer.
- ***Empty RTI Backorders*** is the number of RTIs that is failed to be sent to the filling operation in order to satisfy ***Filling Lot Size***.
- ***Empty RTI Inventory Position*** is the inventory position of empty and clean RTI stock at the manufacturer.
- ***Filling Lot Size*** is filling lot size determined according to the on hand full RTI stock at the manufacturer, ***Full RTI Backorders (All)*** and ***Order up to Level of Full RTI Stock***.
- ***Fill Rate for Empty RTIs*** is the proportion of the need of the filling operation immediately satisfied from on hand empty and clean RTI stock at the manufacturer at the start of the filling operation.
- ***Fill Rate for Full RTIs*** is the proportion of the full RTI demand of DCs immediately satisfied from on hand full RTI stock at the manufacturer.

- ***Full RTI Backorders (All)*** is the number of full RTI backorders to all DCs. It is updated when a full RTI demand of a DC is backordered and when a full RTI backorder to a DC is satisfied.
- ***Full RTI Backorders (DC i)*** is the number of full RTI backorders to DC *i*. It is updated when a full RTI demand of DC *i* is backordered and when a full RTI backorder to DC *i* is satisfied.
- ***Lack of Empty RTIs*** is the difference between the RTI need of the filling operation (***Filling Lot Size***) and ***RTIs on Hand***, exactly when the decision of ***Filling Lot Size*** is given. This is only required in the simulation model with emergency shipment option.
- ***New RTI Replenishment Rate*** is the rate of new RTI purchases with respect to time.
- ***Number of Contacts with DCs*** counts the number of times that the manufacturer contacts with DCs in order to obtain the required information for emergency shipment decision.
- ***Number of Emergency Shipments*** counts the number of emergency shipments.
- ***Number of Empty RTI Stockouts*** counts the number of empty RTI stockout situations. Such stockout situations happen when on hand empty and clean RTI stock is less than ***Filling Lot Size*** just before the start of the filling operation.
- ***Number of Full RTI Stockouts*** is the number of full RTI stockout situations. Such stockout situations happen when on hand full RTI stock at the manufacturer is not enough to completely satisfy a full RTI order of a DC.
- ***Number of New RTI Shipments*** counts the number of truck shipments required to transport ***Purchasing Lot Size***. It shows the accumulated value of ***Required Number of Shipments***.
- ***Number of Periods*** counts the number of periods passed since the end of warm up period.
- ***Number of RTI Disposals*** counts the number of RTIs disposed due to a non-repairable damage.
- ***Number of RTI Field Losses*** counts the number of RTIs lost in the field, i.e. RTIs that have never been returned back to the manufacturer.

- ***Number of RTI Repairs*** counts the number of repaired RTIs.
- ***Number of RTI Returns*** counts the number of RTIs returned from DCs.
- ***Pool Size*** is the size of the RTI pool.
- ***Quantity to Fill*** is the number of RTIs entering the filling operation.
- ***Quantity to Purchase*** is the order quantity of new RTI purchases.
- ***Quantity to Send*** is the number of full RTIs sent to the demanding DC after a demand arrival.
- ***Required Number of Shipments*** is the number of truck shipments enough to transport ***Quantity to Purchase*** amount of new RTIs.
- ***RTI Lifetime*** is the variable tallies the useful lifetime of RTIs just before they leave the CLSC.
- ***RTIs on Hand*** is the number of RTIs that can be ready to enter the filling operation just before the filling operation starts. This is only required in the simulation model with emergency shipment option.
- ***Time Spent in the Field*** is used to keep statistics of the time that RTIs spent in the field.
- ***Total Demand*** is total amount of full RTIs demanded by all DCs since the end of warm up period.
- ***Total Number of Purchased New RTIs*** counts the number of purchased RTIs since the end of warm up period.
- ***Trippage*** is the variable tallies total numbers of cycles completed by RTIs in their lifetimes before they leave the CLSC.
- ***TNOW*** shows the value of simulation clock. It is an internal variable kept by Arena.

The simulation model also finds out the following cost values:

- ***Total Cost of RFID Technology***
- ***Total Emergency Shipment Cost***
- ***Total Purchasing Cost***
- ***Total Repair Cost***
- ***Total RTI Pool Holding Cost***

- ***Total RTI Pool Management Cost***

There are two options to initialize the value of a variable, namely initializing with system (at the start of the simulation replication) and with statistics (at the end of warm up period). The variables related with recording the required statistics like ***Trippage*** and ***Fill Rate for Full RTIs*** as well as the variables that are needed to account for only the time after warm up period like ***Number of New RTI Shipments*** and ***Total Number of Purchased RTIs*** are initialized with statistics. On the other hand, the variables which are the elements of the system state like ***Empty RTI Backorders*** and ***Filling Lot Size*** are initialized with the system.

6.7.3.2 Detailed Explanation of the Simulation Models

The main structure of the simulation models is shown in Figure 6.3. A simulation replication starts with the creation of the initial RTI pool and the distribution of this initial RTI pool to the stock points in the CLSC. Among these stock points, the returns stock at the manufacturer is not included since RTIs returned back to the manufacturer from DCs directly enter the preparing for reuse operation without waiting.

After the initialization of RTI pool, the created RTIs continue their flows through the CLSC starting with the points that they are initially distributed at the start of the simulation replication. RTIs enter the filling operation with a batch size of ***Quantity to Fill*** after receiving a signal indicating that the filling operation is started. Similarly, RTIs also wait for a signal to be sent to a DC with a lot size of ***Quantity to Send*** in order to satisfy its full RTI demand. This signal indicates the demand arrivals for full RTIs from DCs. As simulation clock advances, the decision of new RTI purchases is given in each ***Review Period for Purchasing***. Accordingly, the newly purchased RTIs are created and entered the CLSC after they are delayed by ***Lead Time of Purchasing.***

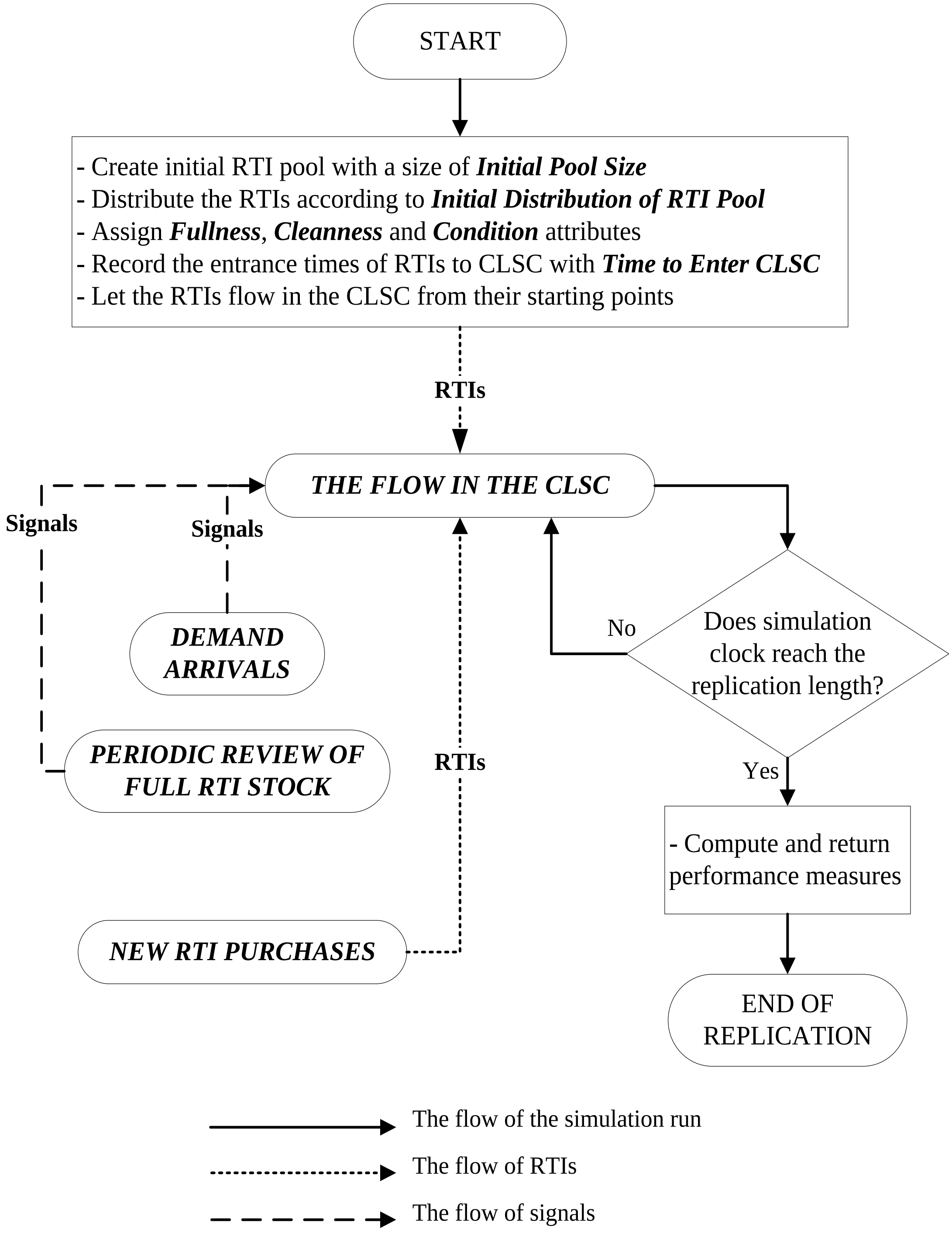

Figure 6.3: The main structure of the simulation models

A simulation replication reaches its end when the simulation clock reaches replication length. A simulation run reaches its end when it completes a desired number of replications. When the simulation run ends, Arena returns summary statistics based on the collected records and calculates desired performance measures. The outputs of the simulation models include the summary statistics of the following performance measures:

- Average cycle time (with the help of ***Cycle Time Attribute*** and ***Cycle Time***)
- Average trippage (with the help of ***Number of Rotations*** and ***Trippage***)
- Average useful lifetime of RTIs (with the help of ***Time to Enter CLSC*** and ***RTI Lifetime***)
- Pool size (with the help of ***Pool Size***)
- Type 2 (β) service level (fill rate) for satisfying the empty RTI need of the filling operation (with the help of ***Fill Rate for Empty RTIs***)
- Type 2 (β) service level (fill rate) for satisfying the full RTI demand of DCs immediately from on hand full RTI stock at the manufacturer (with the help of ***Fill Rate for Full RTIs***)
- Average time that RTIs spend in the field (with the help of ***Time Spent in the Field*** and ***Time to Enter Field***)

In addition, Arena calculates and returns the following performance measures at the end of the simulation run:

- ***Total RTI Pool Management Cost***
- The rate of new RTI replenishment with respect to time:

New RTI Replenishment Rate = ***Total Number of Purchased New RTIs*** / (***Replication Length−Warm up Period***) (6.18)

At the end of simulation replication ***Total RTI Pool Management Cost*** is calculated with the following cost formulas:

Total RTI Pool Management Cost (6.19)

= Total Cost of RFID Technology + Total Emergency Shipment Cost

+ Total Purchasing Cost + Total Repair Cost + Total RTI Pool Holding Cost

Total Cost of RFID Technology (6.20)

= ***Annual RFID Fee***

× ((***Replication Length−Warm up Period***)/360 + ***Time to Action***/12)

Total Emergency Shipment Cost (6.21)

= ***Unit Transportation Cost*** × ***Number of Emergency Shipments***

Total Purchasing Cost (6.22)

= Unit RTI Price × (***Actual Starting Pool Size*** + ***Total Number of Purchased New RTIs***) + ***Unit Transportation Cost*** × (Required number of shipments to transport ***Actual Starting Pool Size*** + ***Number of New RTI Shipments***)

Total Repair Cost = Unit Repair Cost × ***Number of RTI Repairs*** (6.23)

Throughout a simulation run, ***Total RTI Pool Holding Cost*** is updated as follows at each time that the newly purchased RTIs are delivered to the manufacturer:

Total RTI Pool Holding Cost (6.24)

= Total RTI Pool Holding Cost (the value at ***TNOW***)

+ ***Unit RTI Holding Cost*** × ***Purchasing Lot Size*** × ((***Replication Length−TNOW***)/360)

At the end of a simulation run, ***Total RTI Pool Holding Cost*** is calculated as follows by taking account the holding cost of ***Actual Starting Pool Size*** since the end of warm up period:

$$\textbf{\textit{Total RTI Pool Holding Cost}} \quad (6.25)$$

$$= \textbf{\textit{Total RTI Pool Holding Cost}}$$

$$+ \textbf{\textit{Unit RTI Holding Cost}} \times \textbf{\textit{Actual Starting Pool Size}} \times$$

$$((\textbf{\textit{Replication Length}} - \textbf{\textit{Warm up Period}})/360)$$

The part of the simulation model involving the circulation of RTIs in the CLSC (***THE FLOW IN THE CLSC***) is shown in Figure 6.4 and 6.5. The flow of RTIs is described starting with empty and clean RTI stock at the manufacturer. The variable ***Quantity to Fill*** is determined in ***PERIODIC REVIEW OF FULL RTI STOCK*** and communicated via signals to ***THE FLOW IN THE CLSC***. ***PERIODIC REVIEW OF FULL RTI STOCK*** also determines and communicates the emergency shipment(s) in each period for the cases in which the emergency shipment can be useful. Similarly, the variable ***Quantity to Send*** is determined in ***DEMAND ARRIVALS*** and communicated via signals to ***THE FLOW IN THE CLSC***.

THE FLOW IN THE CLSC calls two modules during the simulation run. The first module is ***SATISFY FULL RTI BACKORDERS***. The flowchart of this module is shown in Figure 6.6. The aim of this module is to send full RTIs firstly to satisfy full RTI backorders to DCs (without entering them to full RTI stock at the manufacturer) once they leave the filling operation, when there is any outstanding full RTI backorder to a DC. When the number of outstanding full RTI backorders (***Full RTI Backorders (All)***) or the amount of full RTIs to satisfy the outstanding full RTI backorders reaches zero, ***SATISFY FULL RTI BACKORDERS*** returns to ***THE FLOW IN THE CLSC*** to start the shipment of full RTIs to satisfy backorders. The second module is ***RTI SHRINKAGE***. The flowchart of this module is shown in Figure 6.7. This module serves the purpose of firstly keeping the statistics of the lost RTIs due to never being returned or non-repairable damages. Secondly, it removes the lost RTIs from the flow in the CLSC.

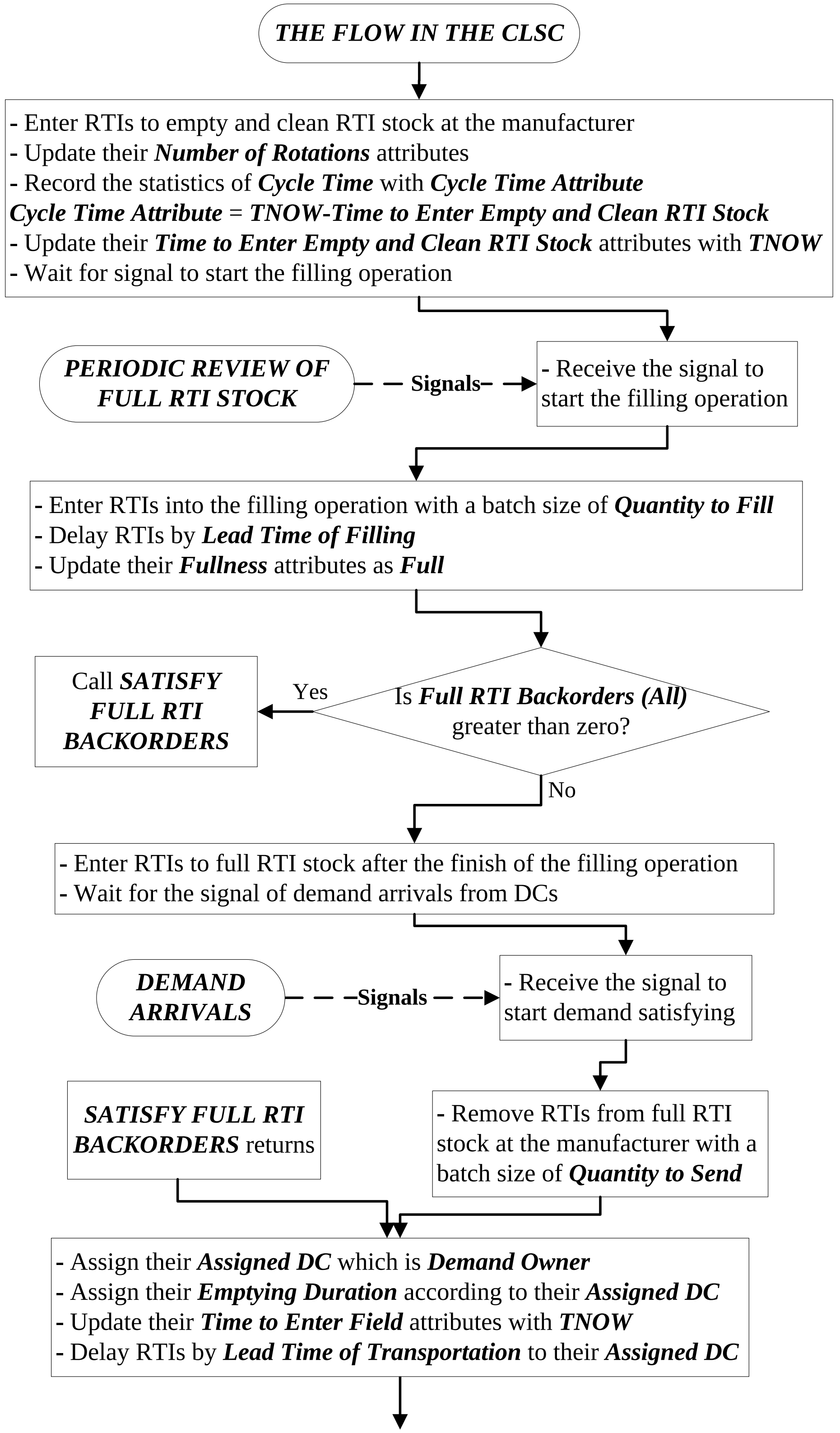

Figure 6.4: The flow in the CLSC – part 1

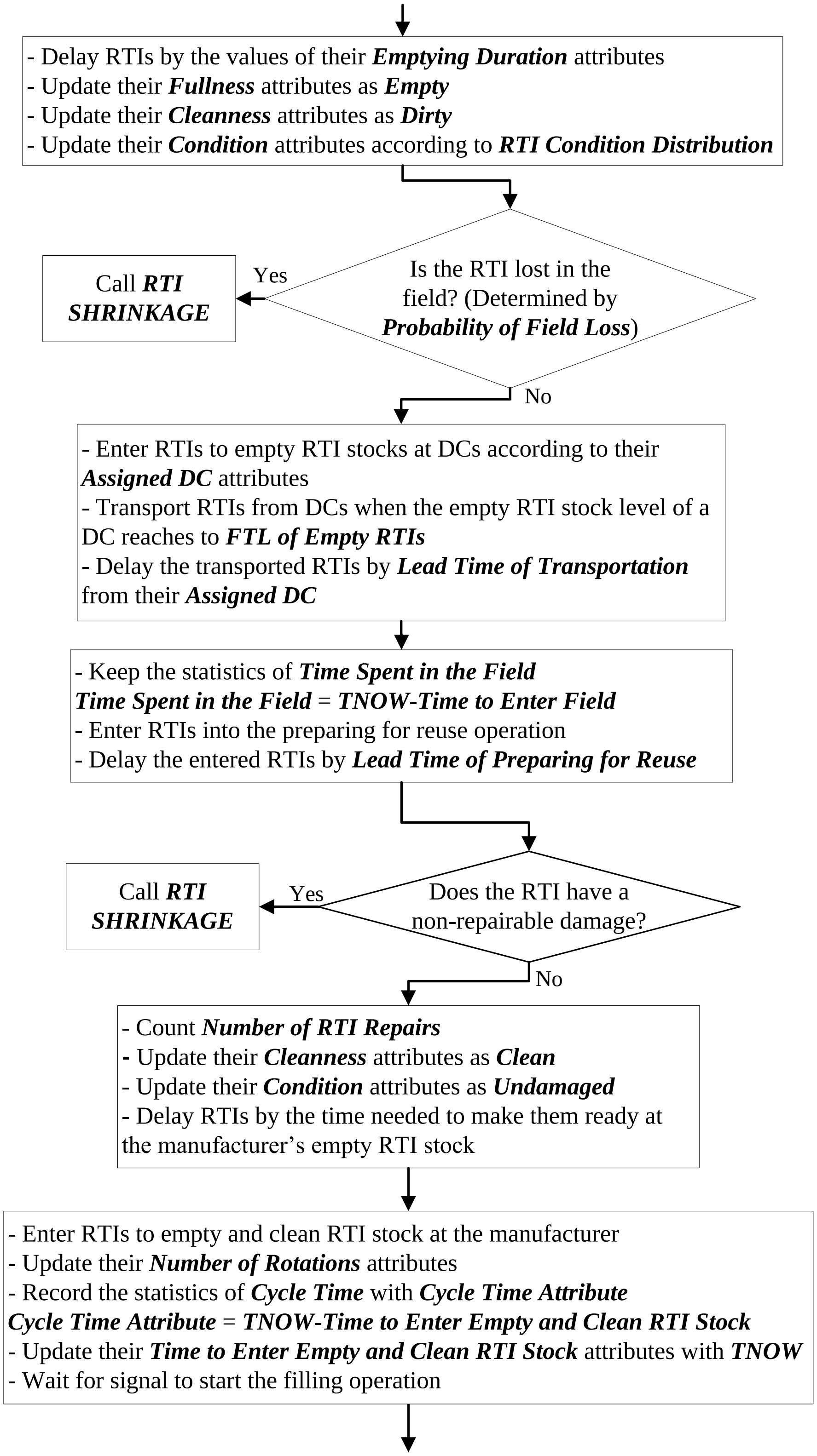

Figure 6.5: The flow in the CLSC – part 2

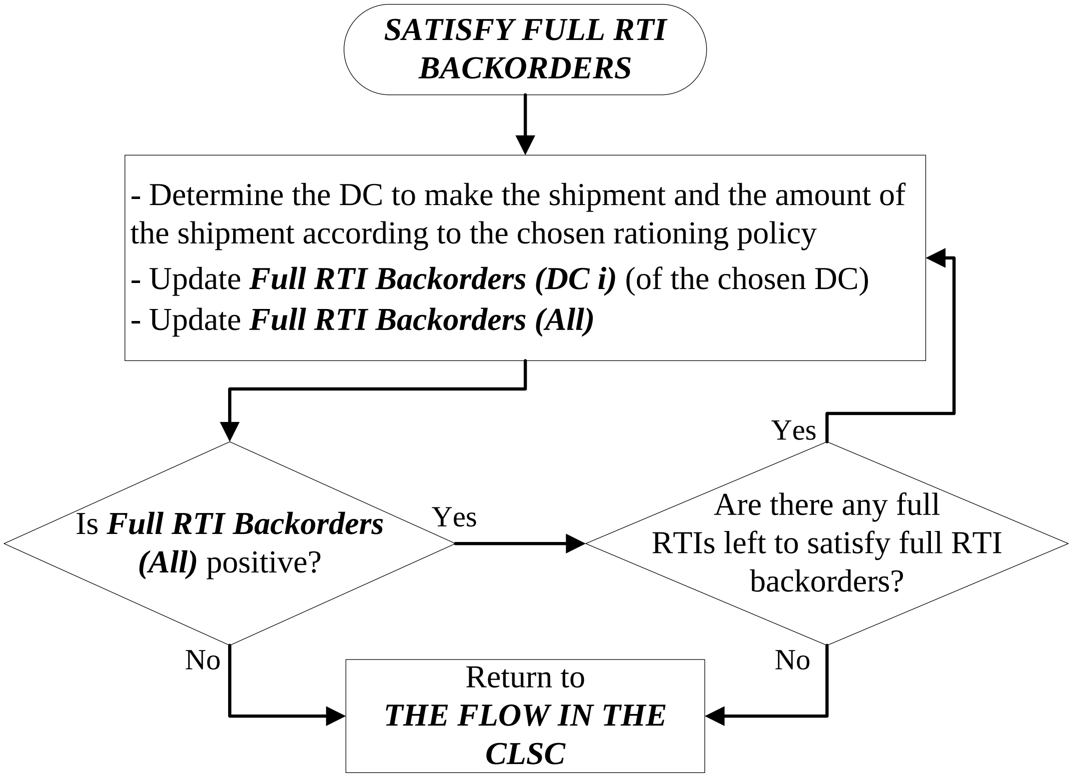

Figure 6.6: ***SATISFY FULL RTI BACKORDERS*** module of the simulation model

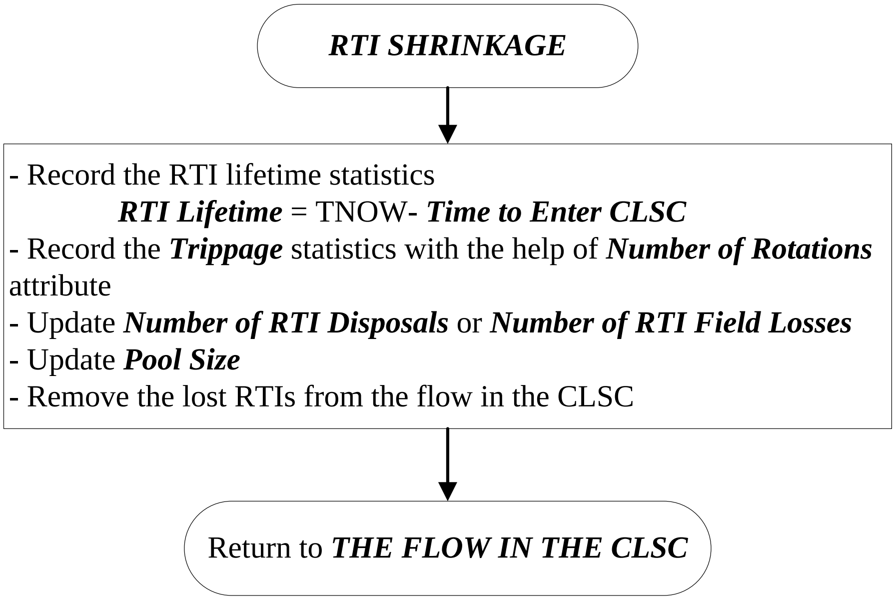

Figure 6.7: ***RTI SHRINKAGE*** module of the simulation model

DEMAND ARRIVAL part of the simulation model is demonstrated in Figure 6.8. This part determines ***Quantity to Send*** and run by the entity ***Demand***. When there are enough full RTIs on hand at the manufacturer to satisfy all of the incoming demand from a DC, ***Quantity to Send*** equals to ***Demand Size*** of the incoming demand. Otherwise, ***Quantity to Send*** equals to the level of full RTI stock at the manufacturer because this is the maximum number of full RTIs that can be sent to the demanding DC.

PERIODIC REVIEW OF FULL RTI STOCK part of the simulation model is demonstrated in the figures 6.9-6.11. This part determines ***Filling Lot Size*** and ***Quantity to Fill*** and is run by an entity whose type is ***Periodic Review***. Flowcharts are drawn for the cases when the emergency shipment is not useful (Figure 6.9) and when it can be useful (Figure 6.10 and Figure 6.11), respectively.

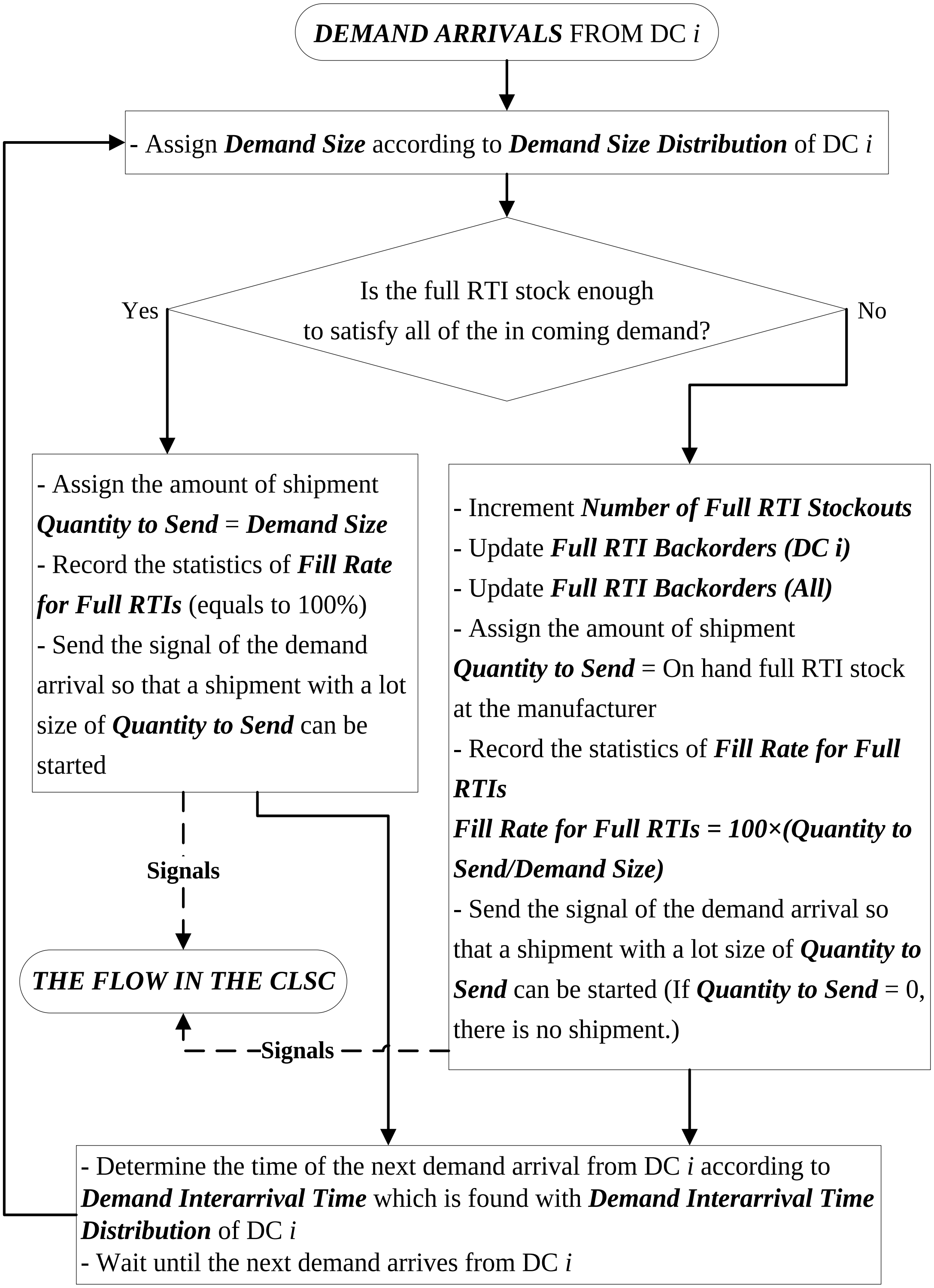

Figure 6.8: ***DEMAND ARRIVALS*** part of the simulation model

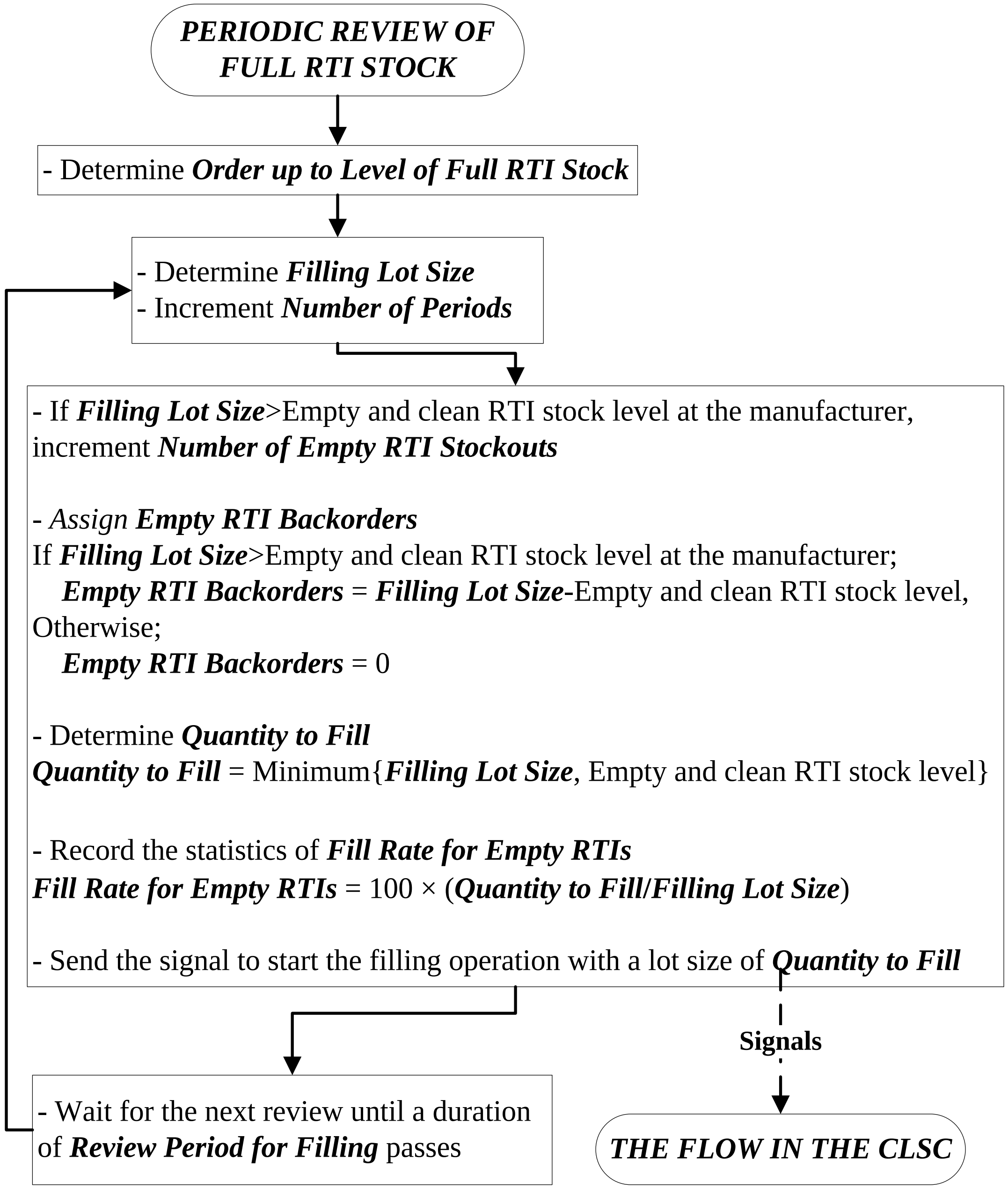

Figure 6.9: ***PERIODIC REVIEW OF FULL RTI STOCK*** part of the simulation model when emergency shipment is not useful

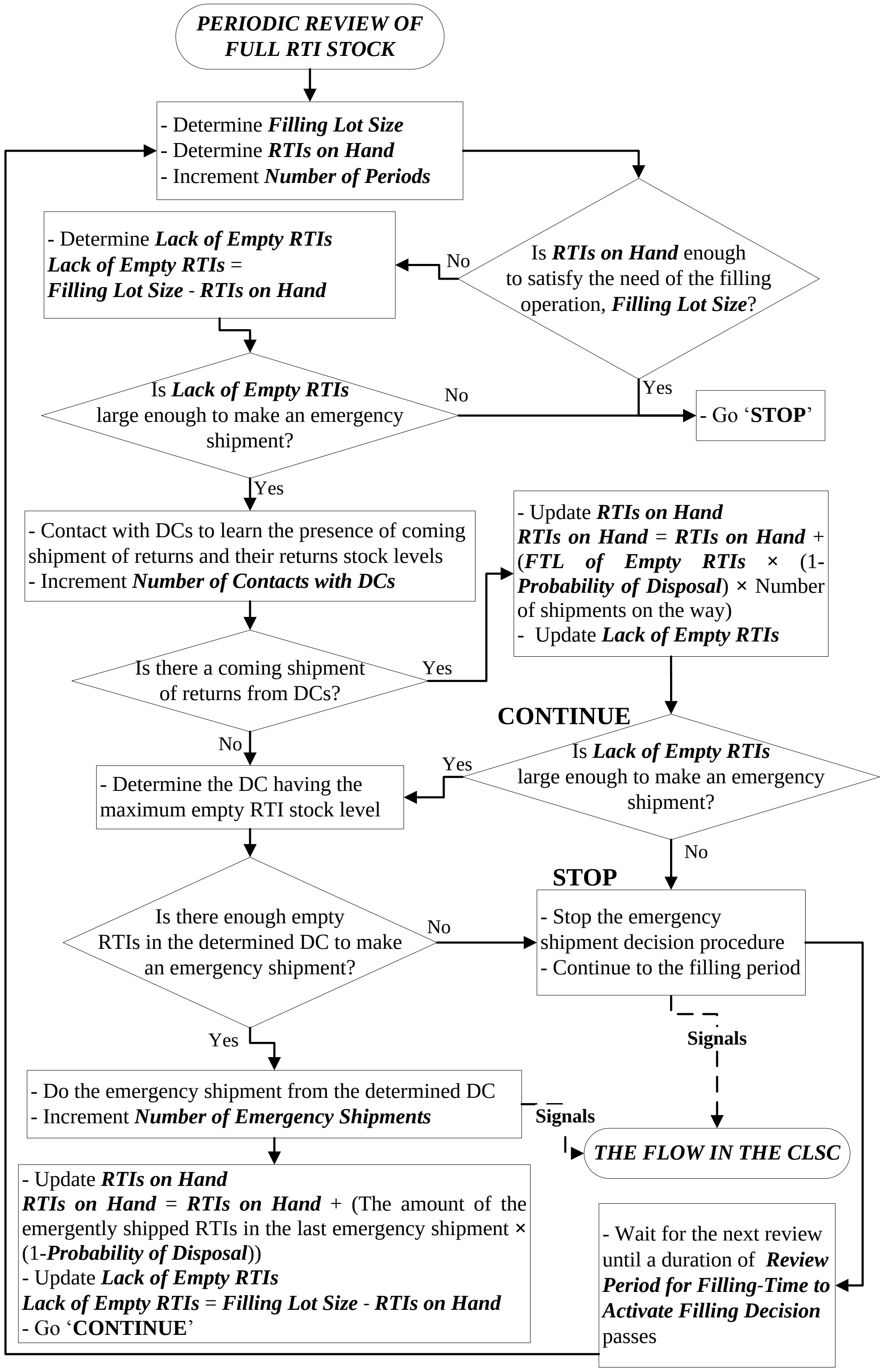

Figure 6.10: ***PERIODIC REVIEW OF FULL RTI STOCK*** part of the simulation model when emergency shipment can be useful

STOP

- Stop the emergency shipment decision procedure

- Wait for the time of the filling operation until a duration of ***Time to Activate Filling Decision*** passes

- If ***Filling Lot Size***>Empty and clean RTI stock level at the manufacturer
    Increment ***Number of Empty RTI Stockouts***:

- *Assign* ***Empty RTI Backorders***
If ***Filling Lot Size***>Empty and clean RTI stock level at the manufacturer;
    Empty RTI Backorders = ***Filling Lot Size***-Empty and clean RTI stock level,
Otherwise;
    Empty RTI Backorders = 0

- Determine ***Quantity to Fill***
Quantity to Fill = Minimum{***Filling Lot Size***, Empty and clean RTI stock level}

- Record the statistics of ***Fill Rate for Empty RTIs***
Fill Rate for Empty RTIs = 100 × (***Quantity to Fill/Filling Lot Size***)

- Send the signal to start the filling operation with a lot size of ***Quantity to Fill***

Figure 6.11: The explanation of how the filling period continues in the 'STOP' part of the ***PERIODIC REVIEW OF FULL RTI STOCK*** shown in Figure 6.10

Order up to Level of Full RTI Stock and ***Filling Lot Size*** in ***PERIODIC REVIEW OF FULL RTI STOCK*** are calculated as shown below.

For both of the simulation models:

Order up to Level of Full RTI Stock = Expected Weekly Full RTI Demand + (***Safety Factor for Full RTI Stock*** × ***Standard Deviation of Weekly Full RTI Demand***) (6.26)

For the simulation model of the case when the emergency shipment is not useful:

Filling Lot Size = Maximum {0, ***Order up to Level of Full RTI Stock***

– On hand full RTI stock level at the manufacturer

\+ ***Full RTI Backorders (All)***} (6.27)

For the simulation model of the case when the emergency shipment can be useful, ***Filling Lot Size*** is determined ***Time to Activate Filling Decision*** days before the start of the filling operation in order to do give time for the emergently shipped RTIs (if there are any) to be made ready for filling. Because of this reason, ***Filling Lot Size*** is forecasted with the following formula which considers the expected full RTI demand of DCs in ***Time to Activate Filling Decision***.

Filling Lot Size = Maximum {0, (***Order up to Level of Full RTI Stock***

– On hand full RTI stock level at the manufacturer +***Full RTI Backorders (All)***

\+ (***Time to Activate Filling Decision*** × ***Expected Daily Full RTI Demand***))}

(6.28)

For the simulation model with emergency shipment, ***RTIs on Hand*** is calculated as follows:

***RTIs on Hand* =** On hand empty and clean RTI stock level at the manufacturer

\+ (The number of RTIs in preparing for reuse × (1 –***Probability of Disposal***))

\+ The number of RTIs on their ways from the preparing for reuse operation

\+ The number of new RTIs on order and expected to arrive at the manufacturer before the filling operation starts (6.29)

NEW RTI PURCHASES part of the simulation model is demonstrated in Figure 6.12. In this part, ***Quantity to Purchase*** is determined. After, new RTIs are ordered and sent to ***THE FLOW IN THE CLSC*** after the duration of ***New RTI Purchasing Lead Time*** passes. This part is run by an entity whose type is ***Periodic Review***.

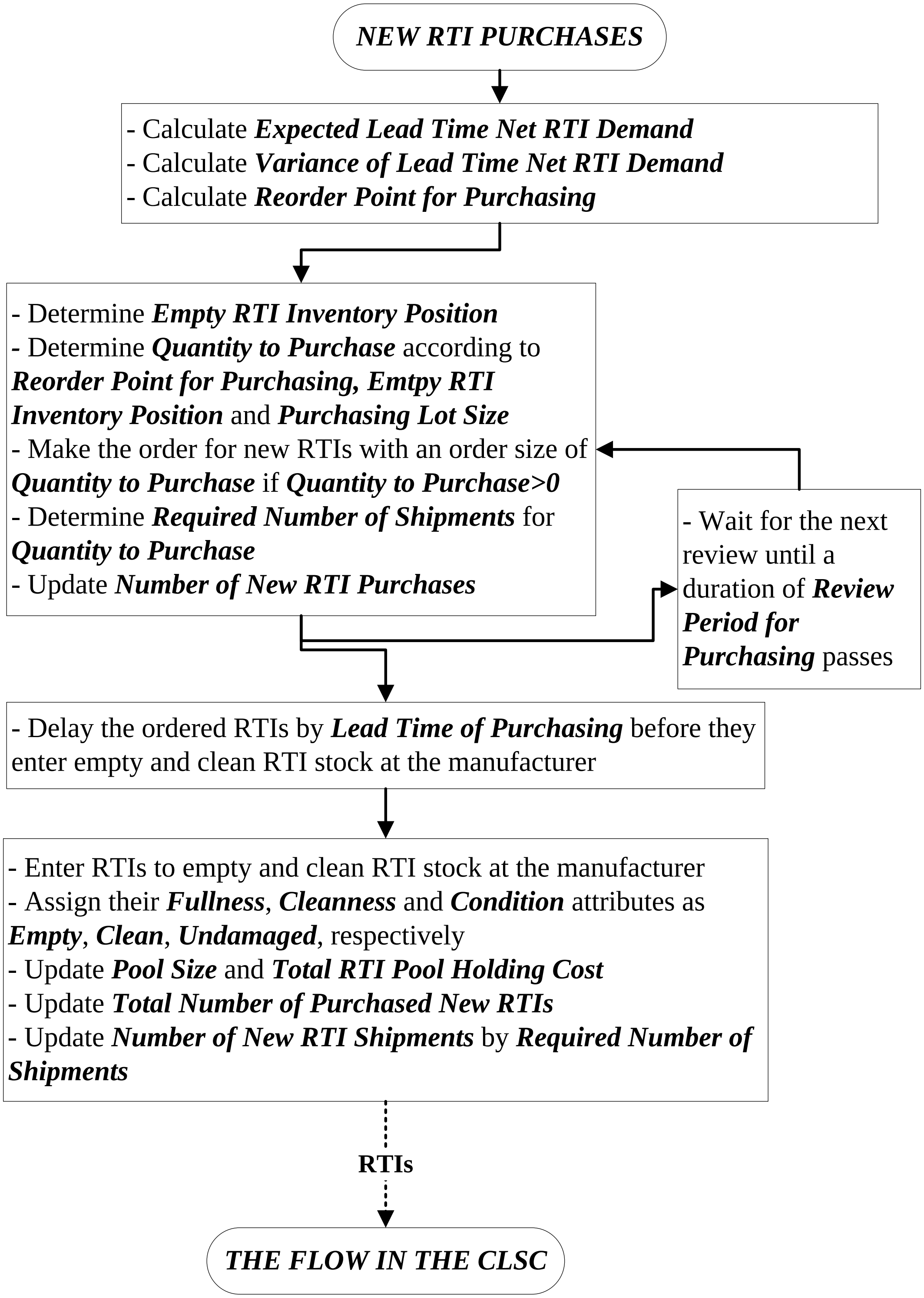

Figure 6.12: ***NEW RTI PURCHASES*** part of the simulation model

This part of the model starts with calculating ***Expected Lead Time Net RTI Demand, Variance of Lead Time Net RTI Demand*** and then ***Reorder Point for Purchasing***. The required formulas are already given in section 6.6. These parameters are calculated once in a simulation replication and the same values are used until its end. ***Purchasing Lot Size*** is also required for this part. This should be calculated with the related formulas given in section 6.6 and entered as an input to the simulation model.

In each period, ***Empty RTIs Inventory Position*** is calculated and compared with ***Reorder Point for Purchasing***. When ***Empty RTIs Inventory Position*** drops at or below ***Reorder Point for Purchasing***, a replenishment order should be given with a size enough to make ***Empty RTIs Inventory Position*** larger than ***Reorder Point for Purchasing***. If a replenishment order having a size of ***Purchasing Lot Size*** is not enough, then its size should be the minimum multiples of ***Purchasing Lot Size*** which is enough to increase ***Empty RTIs Inventory Position*** above ***Reorder Point for Purchasing. Empty RTIs Inventory Position***, ***Quantity to Purchase and Required Number of Shipments*** are found with the following formulas.

Empty RTI Inventory Position = On hand empty and clean RTI stock level
+ (The number of RTIs in preparing for reuse × (1 – ***Probability of Disposal***))
+ The number of RTIs coming from the preparing for reuse operation
+ The number of RTIs on order
− ***Empty RTI Backorders*** ` (6.30)

Let Q'' be calculated as follows:

$Q'' =$ (***Reorder Point for Purchasing− Empty RTIs Inventory Position)/Purchasing Lot Size*** (6.31)

Then, ***Quantity to Purchase*** and ***Required Number of Shipments*** are found with the following formulas in each period.

$$\textbf{\textit{Quantity to Purchase}} = \begin{cases} 0, & \text{if } Q'' < 0 \\ \textbf{\textit{Purchasing Lot Size}}, & \text{if } Q'' = 0 \\ \lceil Q'' \rceil \times \textbf{\textit{Purchasing Lot Size}}, & \text{if } Q'' > 0 \end{cases} \tag{6.32}$$

$$\textbf{\textit{Required Number of Shipments}} = \left\lceil \frac{\boldsymbol{Quantity\ to\ Purchase}}{\boldsymbol{FTL\ of\ Empty\ RTIs}} \right\rceil \tag{6.33}$$

6.7.4 The Simulation Optimization Model

OptQuest requires the determination of controls and responses from the set of variables and parameters defined in the simulation model. The controls of OptQuest are the variables that OptQuest can meaningfully manipulate to affect the performance of a simulated system. In other words, the controls are the decision variables. The responses are the outputs from the simulation model and they are required to define the objective function and the constraints. There is only one control which is ***Initial Pool Size***. On the other hand, the responses are ***Total RTI Pool Management Cost*** and ***Fill Rate for Full RTIs***. The optimization model can be written for both of the simulation models as follows:

Minimize ***Total RTI Pool Management Cost*** (6.34)

Subject to ***Fill Rate for Full RTIs*** ≥ Target fill rate (6.35)

By changing ***Initial Pool Size*** (6.36)

In formula 6.37, target fill rate is the one for satisfying the full RTI demand of DCs by the manufacturer. At the end of a run, OptQuest returns ***Initial Pool Size*** that gives the best ***Total RTI Pool Management Cost*** for a ***Fill Rate for Full RTIs*** greater than target fill rate. In order to find out the values of other performance measures, the simulation model should be run with ***Initial Pool Size*** of the best solution.

CHAPTER 7

EXPERIMENTAL ANALYSIS

This chapter starts with the presentation of the scenarios developed to compare the optimal RTI pool management without and with the use of RFID technology and gather experimental results in section 7.1. In section 7.2, we present the detailed input analysis required for the simulation optimization study. This input analysis is based on our case study. In section 7.3, we give the run parameters of both the simulation models and the simulation optimization model. In section 7.4, we present the verification and the validation of both the simulation models and the simulation optimization model. In section 7.5, we provide the experimental results. Finally, in section 7.6, we conclude this chapter with a brief discussion on software implementation issues.

7.1 Scenario Generation

It is discussed before that our aim is to compare the optimal RTI pool management without and with the use of RFID technology in order to find out to the impact of using this technology. In order to make such a comparison, we firstly need to develop scenarios for the situation of the CLSC without the use of RFID technology. A scenario is composed of the set of parameters directly changing with the use of RFID technology, namely ***Probability of Field Loss***, ***Probability of Disposal***, and ***Probability of Repairable Damage*** and ***Emptying Duration Distribution*** for all DCs. Secondly, we need to develop scenarios which present the possible improvements in the CLSC after the use of RFID technology given the situation of the CLSC before it.

The first scenario is developed for the situation of the CLSC before the use of RFID technology based on our case study. This scenario uses estimate values for ***Probability of Field Loss***, ***Probability of Disposal***, and ***Probability of Repairable Damage***. On the other hand, the distributions of ***Emptying Duration*** are found out by using the available RFID data.

The second scenario for the situation of the CLSC before the use of RFID technology is developed to reveal the impact of RFID technology for a situation of the CLSC much worse than the situation described with the first scenario in terms of the parameters changing with the use of this technology. For the second scenario, it is assumed that ***Probability of Field Loss***, ***Probability of Disposal***, ***Probability of Repairable Damage***, and the coefficient of variation (CV) of ***Emptying Duration*** are the triples of their values used in the first scenario. The first and the second scenario are named as *the less problematic case* and *the more problematic case*, respectively. The parameter values for both of these cases can be seen in Table 7.1. This table gives ***Emptying Duration Distribution*** for all DCs as normal which is denoted as $NORM(\mu, \sigma)$.

Table 7.1: The set of input values (changing directly with the use of RFID technology) for the less and the more problematic cases

	The Less Problematic Case	**The More Problematic Case**
Probability of Field Loss	0.05	0.15
Probability of Disposal	0.05	0.15
Probability of Repairable Damage	0.10	0.30
Emptying Duration Distribution of DC-1	NORM(21.5,10.5)	NORM(21.5,31.5)
Emptying Duration Distribution of DC-2	NORM(22.5,12.7)	NORM(22.5,38.1)
Emptying Duration Distribution of DC-3	NORM(25.9,16.0)	NORM(25.9,48.0)

For both the less and the more problematic cases, the situation of the CLSC after the use of RFID technology is expected to differ with respect to the extent of the improvement. Therefore, four scenarios are developed for each of the two cases, namely pessimistic, neutral, optimistic and very optimistic, which present possible extents of the improvement. The extent of the improvement presented by these four scenarios can be seen in Table 7.2. The percentage values given in the rows of ***Probability of Field Loss***, ***Probability of Disposal***, and ***Probability of Repairable Damage*** are the percentages of expected decreases in these parameters. In addition, the values given in the row of ***Emptying Duration*** show the maximum percentiles that should be taken into account for finding ***Emptying Duration Distribution*** with the use of RFID technology. The reason of presenting the improvement in ***Emptying Duration Distribution*** in such a way is the assumption that the highest realizations of ***Emptying Duration*** in the right tail of its distribution are firstly removed after finding out the excessive holding areas in the field and taking action to remove them.

Table 7.2: The extent of improvements with the use of RFID technology for both the less and the more problematic cases

	With RFID			
	Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
Probability of Field Loss	10%	30%	50%	70%
Probability of Disposal	10%	30%	50%	70%
Probability of Repairable Damage	10%	30%	50%	70%
Emptying Duration	95th Percentile	85th Percentile	75th Percentile	65th Percentile

In summary, there are $2 \times 5 \times 2 = 20$ scenarios to experiment with, because there are

- two cases, namely the less problematic case and the more problematic case;

- five scenarios for each case, one of them presents the situation without the use of RFID technology, 4 of them presents a subset of possible situations with the use of RFID technology; and
- two possible options regarding emergency shipment, namely allowed emergency shipments and not allowed emergency shipments.

7.2 Input Analysis

It is possible to divide the parameters that are needed as inputs of the simulation model into two groups. The first group of parameters does not change with respect to the use of RFID technology. These parameters are given in detail in section 7.2.1. They have values fixed in each scenario that is developed in section 7.1. On the other hand, the values of the parameters in the second group change directly or indirectly with respect to the use of RFID technology. As a result, the values of parameters in the second group are expected to change between scenarios. These parameters are given in detail in section 7.2.2.

7.2.1 The Inputs Fixed in Scenarios

The Inputs Related with the Initialization of Simulation Runs

At the start of each simulation run, the RTI pool should be distributed among the stock points of the CLSC. Once RTI pool is created, each RTI should be sent to a part of the CLSC according to a probability. The RFID data shows that on average approximately the 60% of RTI pool is held in the field and the 40% of RTI pool is held by the manufacturer. In addition to this finding, the following assumptions are made regarding the initial state of the distribution of RTI pool in order to make a valid estimation for ***Initial Distribution of RTI Pool***.

1. There are no RTIs in transportation.

2. There are no RTIs in the processes of filling and preparing for reuse.
3. There are no RTIs on order.
4. The manufacturer holds all on hand RTIs as empty.
5. The probability that an RTI is lastly sent to a DC is proportional to its average daily full RTI demand rate.

In the next filling period following to the start of the simulation run, ***Filling Lot Size*** is determined by taking into account that the full RTI stock is empty. As a result, the effect of the fourth assumption is expected to disappear as simulation clock advances. This makes the fourth assumption suitable although it seems to be unrealistic. The fifth assumption suggests that the probability that an RTI in the field is assigned to a DC is proportional to its average daily full RTI demand rate. An RTI is assigned to a DC means that this RTI is either at its assigned DC or one of the end users assigned to this DC. The cumulative distribution function (CDF) of the allocation of RTIs between the manufacturer and the field is given in Figure 7.1. Besides, the CDF of the allocation of RTIs in the field among three DCs is given in Figure 7.2. These two CDFs together determine the ***Initial Distribution of RTI Pool***.

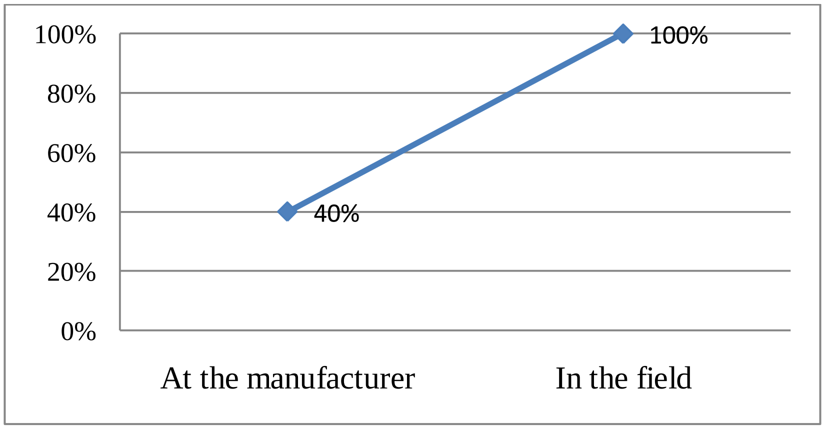

Figure 7.1: The CDF of the allocation of RTIs between the manufacturer and the field

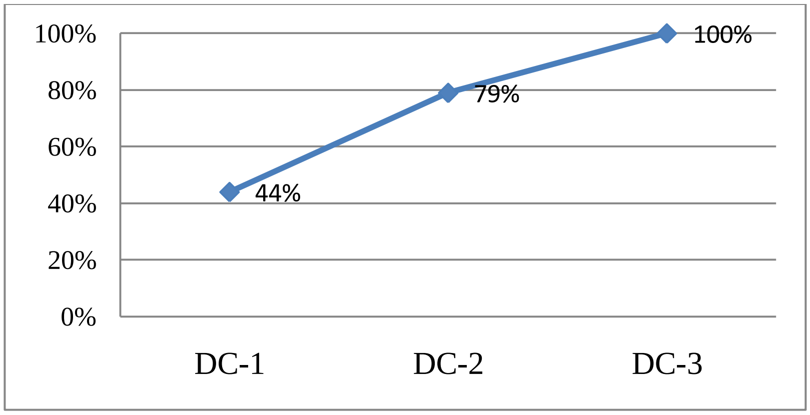

Figure 7.2: The CDF of the allocation of RTIs in the field among three DCs

The Inputs Related with Purchasing New RTIs

Review Period for Purchasing is 1 week. Besides, ***Lead Time of Purchasing*** is 8 weeks. The values of ***Purchasing Lot Size*** and ***Reorder Point for Purchasing*** depend on the size of net demand, and accordingly ***Probability of Field Loss*** and ***Probability of Disposal***. As a result, their values change between scenarios. They are given in section 7.2.2.

The Inputs Related with Filling

Review Period for Filling is 1 week. ***Lead Time of Filling*** is 1 day. ***Time to Activate Filling Decision*** is 4 days, which is the just enough time to give emergency shipment decision (if it is an option), make the emergency shipment, prepare the emergently shipped RTIs for reuse and make them ready at empty and clean RTI stock. ***Order up to Level of Full RTI Stock*** is calculated according to equation 6.26**.** Assuming that the weekly full RTI demand is normally distributed, ***Safety factor for Full RTI Stock*** is chosen as 1.65 because the desired service level for satisfying the full RTI demand of DCs at the manufacturer is 95% fill rate.

Order up to Level of Full RTI Stock* = *Expected Weekly Full RTI Demand + (***Safety Factor for Full RTI Stock*** × ***Standard Deviation of Weekly Full RTI Demand***) (6.26)

Order up to Level of Full RTI Stock $= 786 + (1.65\ \times 106) \cong 961$

The Inputs Related with Full RTI Demand

The quantity demanded in a single order can take values of 20, 40 and 60. The CDF of ***Demand Size Distribution*** for each DC can be seen in the following figures.

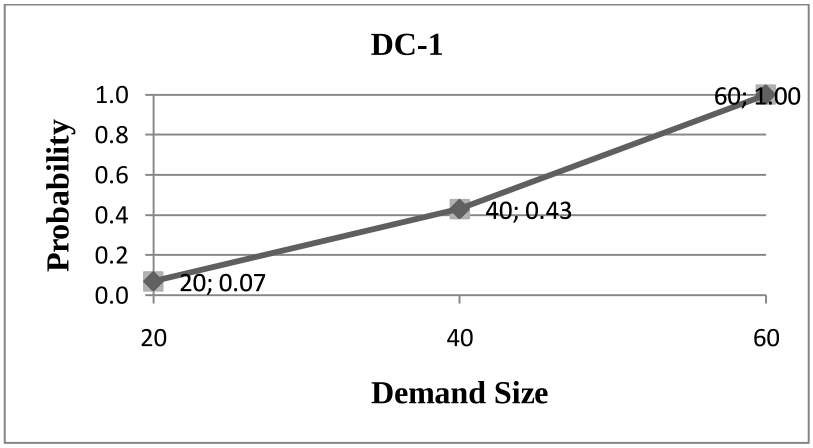

Figure 7.3: The CDF of ***Demand Size Distribution*** of DC-1

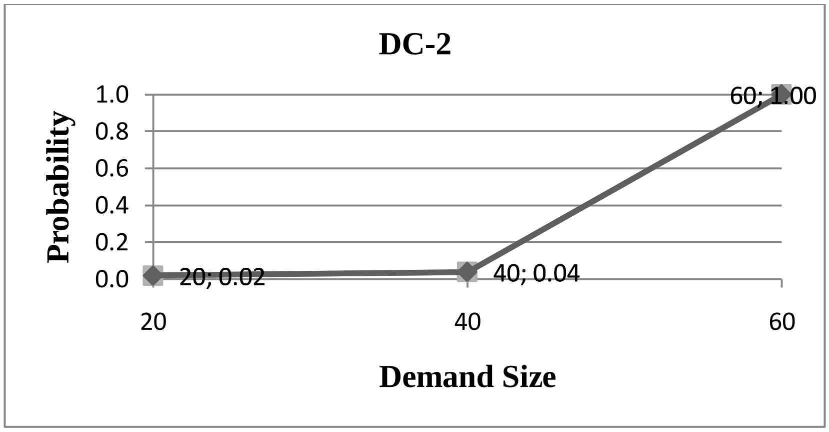

Figure 7.4: The CDF of ***Demand Size Distribution*** of DC-2

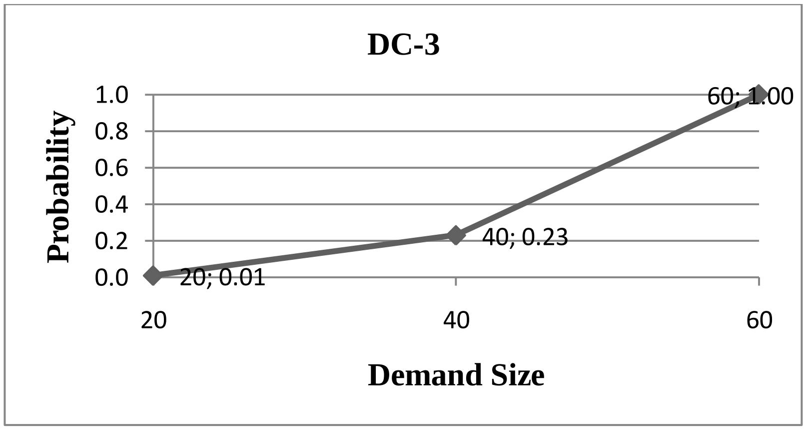

Figure 7.5: The CDF of ***Demand Size Distribution*** of DC-3

In order to find ***Demand Interarrival Time Distribution***, Arena Input Analyzer is used. All possible continuous probability distributions, namely beta, erlang, exponential, gamma, lognormal, normal, triangular, uniform and weibull distributions, are tested with this software. It gives the best fitted distribution (in days) for each DC as follows:

- For DC-1, ***Demand Interarrival Time*** $= -0.5 + 6 \times BETA(8.3, 23.5)$ where 8.3 and 23.5 are the shape parameters of the beta distribution typically denoted as α and β, respectively.

- For DC-2, ***Demand Interarrival Time*** $= -0.5 + LOGNORMAL(1.98, 1.07)$ where 1.98 and 1.07 are the mean and the standard deviation of the random variable's natural logarithm, respectively.
- For DC-3, ***Demand Interarrival Time*** $= -0.5 + ERLANG(0.396, 7)$ where 0.396 and 7 are exponential mean and erlang shape parameter, respectively.

A set of demand data is generated by utilizing the distributions of ***Demand Size*** and ***Demand Interarrival Time*** given for three DCs in order to find out the distribution of total (arriving from all DCs) full RTI demand observed by the manufacturer. A simulation model is developed to generate demand data covering a year with the help of Arena. The experiment and model frames of this simulation model can be seen in Appendix D. From the generated data, we obtain data sets of total daily and weekly full RTI demand observed by the manufacturer. These data sets are analyzed with Arena Input Analyzer in order to find the best fitted distributions. As a result, it is found that the weekly demand is normally distributed with a mean of 786 and a standard deviation of 106. In addition, the daily demand is normally distributed with a mean of 103 and a standard deviation of 59.

The Inputs Related with Transportation

Lead Time of Transportation is 1 day regardless of the DC. ***FTL of Full RTIs*** is 60 and ***FTL of Empty RTIs*** is 380.

Both ***Emergency Shipment Threshold*** and ***Minimum Emergency Shipment Lot Size*** are half of ***FTL of Empty RTIs***. They are taken as equal because the reasoning behind the determination of those levels is similar. ***Lack of Empty RTIs*** should be larger than ***Emergency Shipment Threshold***. Otherwise, it is assumed that it is not worthwhile to increase the level of empty RTI stock at the manufacturer with an emergency shipment.

The maximum level of empty RTI stock among DCs should be larger than ***Minimum Emergency Shipment***. Otherwise, it is assumed that it is not worthwhile to do an emergency shipment due to its additional cost and planning effort.

The Inputs Related with Preparing for Reuse

Lead Time of Preparing for Reuse is 1 day. In addition, it takes 1 day to make the prepared for reuse RTIs ready at empty and clean RTI stock at the manufacturer.

The Inputs Related with Cost Items

The cost related inputs are shown in Table 7.3. Unit capital cost is found by assuming that the opportunity cost of capital is 15% of its value for a year. Unit transportation cost is the same for both emergency shipments and the shipments of new RTIs.

Table 7.3: The values of the cost related inputs of the simulation model

Cost Item	**Value**
Unit RTI Holding Cost	€ 18
Unit RTI Price	€ 120
Unit Repair Cost	€ 50
Unit Transportation Cost	€ 500
Annual RFID Fee	€ 100,000

7.2.2 The Inputs Changing in Scenarios

This section gives the inputs of the simulation study whose values change with respect to the developed scenarios. It should be noted here that the values of input parameters are calculated with respect to the distinctions between

- Without and with the use of RFID technology, and
- The less and the more problematic cases.

The option of emergency shipment does not affect the value of the parameters.

The Inputs Related with Shrinkage and Repairable Damage

The values of ***Probability of Field Loss***, ***Probability of Disposal***, and ***Probability of Repairable Damage*** in the pessimistic, neutral, optimistic and very optimistic scenarios for the less and the more problematic cases are shown in Table 7.4 and Table 7.5, respectively. The values under the columns of 'with RFID' are calculated based on the improvement percentages given in Table 7.2.

Table 7.4: The values of ***Probability of Field Loss***, ***Probability of Disposal***, and ***Probability of Repairable Damage*** for the scenarios of the less problematic case

	Without RFID	**With RFID**			
		Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
Probability of Field Loss	0.05	0.045	0.035	0.025	0.015
Probability of Disposal	0.05	0.045	0.035	0.025	0.015
Probability of Repairable Damage	0.10	0.090	0.070	0.050	0.030

Table 7.5: The values of ***Probability of Field Loss***, ***Probability of Disposal***, and ***Probability of Repairable Damage*** for the scenarios of the more problematic case

	Without RFID	**With RFID**			
		Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
Probability of Field Loss	0.15	0.135	0.105	0.075	0.045
Probability of Disposal	0.15	0.135	0.105	0.075	0.045
Probability of Repairable Damage	0.30	0.270	0.210	0.150	0.090

The Inputs Related with Emptying Duration

The data gathered with RFID technology makes possible to reach the distribution of time that an RTI spends in the field. i.e. the duration between the time that an RTI leaves the manufacturer and the time it returns back. The distribution of time that RTI spends in the field is expected to change with respect to the DC that it is sent to. The main reasons for this are the facts that the demand rates of DCs are different (which especially changes the waiting times at DCs) and how DCs are operated may show differences.

With the help of available RFID data, we find out the distribution of ***Time Spent in the Field*** for each DC. Since there are missing scans of shipments and missing reads of individual RTIs during the scan of shipments, RFID data contain some inconsistent entries. Because of this reason, we have not used the raw data. Rather, we have used the data after cleaning inconsistent entries as much as possible. In Appendix E, it is explained how the data is cleaned.

The cleaned data sets of time spent in the field for all DCs are analyzed with ARENA Input Analyzer. Since the distribution of ***Time Spent in the Field*** has a long right tail, no distribution (among beta, erlang, exponential, gamma, lognormal, normal, triangular, uniform and weibull distributions) is found to be fitted well. The chi-square test gives p-values less than 0.005 for all of the mentioned distributions. We choose to fit normal distribution in order to utilize the property of this distribution stating that if X_1, X_2 are two independent random variables normally distributed with means μ_1, μ_2 and standard deviations σ_1, σ_2, then their linear combination is also be normally distributed. This property is required because what we need to find out as input to our simulation model from these analyzed data is ***Emptying Duration Distribution***. ***Emptying Duration*** is the duration between the time that an RTI enters to a DC as full and the time that it comes back to the same DC as empty from one of the end users. Finding out ***Emptying Duration Distribution*** is required in order to be able to model the shipments of RTIs from DCs in ***FTL of Empty RTIs***. Normal distribution fitting has given the mean and standard deviation values as shown in Table 7.6.

Table 7.6: The parameters of the normal distribution of ***Time Spent in the Field***

	Mean (days)	**Standard deviation (days)**
DC-1	27.3	10.3
DC-2	29.3	12.4
DC-3	35.6	15.4

In order to find out the distribution of ***Emptying Duration***, we need to make estimation for the time difference between ***Time Spent in the Field*** and ***Emptying Duration***. The details of this estimation can be found in Appendix F. The normal distribution is fitted to this time difference. As a result, we estimate that ***Emptying Duration*** is normally distributed with the parameters (changing with respect to the DC that RTI is sent to) given in Table 7.7.

Table 7.7: The parameters of the normal distribution of ***Emptying Duration***

	Mean (days)	**Standard deviation (days)**
DC-1	21.5	10.5
DC-2	22.5	12.7
DC-3	25.9	16.0

The fitted normal distributions produce random values and they are symmetric around their means. Therefore, it may happen that they give unrealistic values for ***Emptying Duration***. For example, it is possible to produce an ***Emptying Duration*** of 3 days with any normal distribution given in Table 7.7, although it is not possible to happen in real life. Therefore, it is required to truncate the fitted normal distributions with ***Minimum Emptying Duration***. ***Minimum Emptying Duration*** is assumed to be the minimum of ***Emptying Duration*** that can happen in real life. Table 7.8 shows how it is calculated.

Table 7.8: The calculation of ***Minimum Emptying Duration***

Activity	**Minimum Assumed Duration (days)**
Waiting time at DC (full)	1
Transportation to end user	1
Waiting time at end user (full)	1
Emptying at end user	1
Waiting time at end user (empty)	1
Transportation from end user	1
TOTAL	**6**

In order to find the distribution of for all developed scenarios, the following steps are conducted:

1. ***Emptying Duration*** data are generated with each normal distribution given in Table 7.8 for the less problematic case. For the more problematic case, the same normal distributions are used after their CV values are tripled, i.e. the standard deviation values are multiplied by three. ***Emptying Duration*** data are generated with the help of a simulation model build in Arena in order to obtain a data set including 5000 data points each of which greater than or equal to ***Minimum Emptying Duration***. The model and experiment frames of this Arena model can be found in Appendix G.

2. Generated data are sorted. Next, for each scenario regarding the use of RFID technology, a smaller data set is obtained by only including the data points smaller than a certain percentile (as given in Table 7.2) of the whole data set. The smaller data sets have the number of data points found according to a certain percentile value as given in Table 7.9.

Table 7.9: The number of data points used in each scenario

Scenario	**Percentile**	**The Number of Data Points**
Pessimistic	95th Percentile	4750
Neutral	85th Percentile	4250
Optimistic	75th Percentile	3750
Very Optimistic	65th Percentile	3250

3. The whole data set and the smaller data sets are analyzed with Arena Input Analyzer. It is found that they are best fitted to the beta distribution among all possible continuous probability distributions which can be tested with this software, namely beta, erlang, exponential, gamma, lognormal, normal, triangular, uniform and weibull distributions. The equations for ***Emptying Duration Distribution*** with and without the use of RFID technology for the less and the more problematic cases can be found in tables 7.10-12.

Table 7.10: ***Emptying Duration Distribution*** without the use of RFID technology for the less and the more problematic cases

	The Less Problematic Case	**The More Problematic Case**
DC-1	6 + 53 * BETA(1.98, 4.16)	6 + 128 * BETA(1.39, 4.15)
DC-2	6 + 60 * BETA(1.74, 3.83)	6 + 146 * BETA(1.18, 3.46)
DC-3	6 + 79 * BETA(1.79, 4.30)	6 + 203 * BETA(1.33, 4.34)

Table 7.11: ***Emptying Duration Distribution*** with the use of RFID technology for the less problematic case

	With RFID			
	Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
DC-1	6 + 34 * BETA(1.56, 1.75)	6 + 28 * BETA(1.49, 1.4)	6 + 24 * BETA(1.43, 1.21)	6 + 21 * BETA(1.42, 1.15)
DC-2	6 + 39 * BETA(1.45, 1.79)	6 + 31 * BETA(1.39, 1.39)	6 + 26 * BETA(1.33, 1.16)	6 + 23 * BETA(1.35, 1.17)
DC-3	6 + 48 * BETA(1.4, 1.71)	6 + 39 * BETA(1.39, 1.43)	6 + 32 * BETA(1.28, 1.1)	6 + 28 * BETA(1.28, 1.07)

Table 7.12: ***Emptying Duration Distribution*** with the use of RFID technology for the more problematic case

	With RFID			
	Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
DC-1	6 + 74 * BETA(1.17, 1.75)	6 + 56 * BETA(1.11, 1.3)	6 + 47 * BETA(1.12, 1.22)	6 + 40 * BETA(1.13, 1.2)
DC-2	6 + 86 * BETA(1.03, 1.59)	6 + 66 * BETA(1.02, 1.3)	6 + 54 * BETA(1.02, 1.2)	6 + 45 * BETA(1.05, 1.17)
DC-3	6 + 111 * BETA(1.09, 1.69)	6 + 84 * BETA(1.08, 1.34)	6 + 69 * BETA(1.09, 1.24)	6 + 57 * BETA(1.12, 1.19)

The Inputs Related with Purchasing of New RTIs

Reorder Point for Purchasing for the scenarios of the less and the more problematic cases are calculated according to the formulas given in section 6.6. The values of required parameters, namely ***Expected Lead Time Full RTI Demand*** and ***Variance of Lead Time Full RTI Demand***, for these formulas are given in section 7.2.1. Tables 7.13 and 7.14 give the values of the related parameters in the calculation of ***Reorder Point for Purchasing*** and the values of ***Reorder Point for Purchasing*** for the scenarios of the less and the more problematic cases, respectively.

Table 7.13: The calculation of ***Reorder Point for Purchasing*** without and with the use of RFID technology for the less problematic case

	Without RFID	**With RFID**			
		Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
Probability of Field Loss	0.05	0.045	0.035	0.025	0.015
Probability of Disposal	0.05	0.045	0.035	0.025	0.015
Probability of Loss	0.0975	0.0880	0.0688	0.0494	0.0298
Probability of Reuse	0.9025	0.9120	0.9312	0.9506	0.9702
Expected Lead Time Full RTI Demand	6,288	6,288	6,288	6,288	6,288
Variance of Lead Time Full RTI Demand	719,104	719,104	719,104	719,104	719,104
Expected Lead Time Reuses	5,674.9	5,734.8	5,855.5	5,977.5	6,100.8
Variance of Lead Time Reuses	586,268	598,648	623,995	650,141	677,101
Expected Lead Time Net RTI Demand	613.1	553.2	432.5	310.5	187.2
Variance of Lead Time Net RTI Demand	7,389.3	6,070.1	3,804.1	2,048.2	819.2
Reorder Point for Purchasing	**813**	**734**	**576**	**415**	**254**

Table 7.14: The calculation of ***Reorder Point for Purchasing*** without and with the use of RFID technology for the more problematic case

	Without RFID	**With RFID**			
		Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
Probability of Field Loss	0.15	0.135	0.105	0.075	0.045
Probability of Disposal	0.15	0.135	0.105	0.075	0.045
Probability of Loss	0.2775	0.2518	0.1990	0.1444	0.0880
Probability of Reuse	0.7225	0.7482	0.8010	0.8556	0.9120
Expected Lead Time Full RTI Demand	6,288	6,288	6,288	6,288	6,288
Variance of Lead Time Full RTI Demand	719,104	719,104	719,104	719,104	719,104
Expected Lead Time Reuses	4,543.1	4,704.8	5,036.8	5,380.2	5,734.8
Variance of Lead Time Reuses	376,638	403,768	462,409	527,229	598,648
Expected Lead Time Net RTI Demand	1,744.9	1,583.2	1,251.2	907.8	553.2
Variance of Lead Time Net RTI Demand	56,636.2	46,769.0	29,472.3	15,765.9	6,070.1
Reorder Point for Purchasing	**2,297**	**2,085**	**1,649**	**1,199**	**734**

Purchasing Lot Size for the scenarios of the less and the more problematic cases are found according to the modified EOQ method which is given in section 6.6. The values of the required parameters, namely ***Unit RTI Price***, ***Unit RTI Holding Cost***, ***Unit Transportation Cost***, and ***FTL of Empty RTIs*** are given in section 7.2.1. ***Expected Annual Net RTI Demand*** is calculated by multiplying ***Expected Annual Full RTI Demand*** and ***Probability of Loss***.

Empty RTI consumption in one week may be large enough so that a replenishment size of one ***Purchasing Lot Size*** is not enough to raise the inventory position above

Reorder Point for Purchasing. In such a situation, a solution can be using the minimum integer number of multiples of ***Purchasing Lot Size*** which is enough to raise ***Empty RTI Inventory Position*** above ***Reorder Point for Purchasing***. On the other hand, it is possible to find a replenishment size which is large enough and gives the smallest purchasing cost per RTI. The difference in unit purchasing cost between these two possible solutions is found to be very small for all of the developed scenarios. As a result, it is found suitable to use the first solution, i.e. using the minimum integer number of multiples of ***Purchasing Lot Size*** which is enough to raise ***Empty RTI Inventory Position*** above ***Reorder Point for Purchasing***. More detailed information regarding this conclusion and the calculation of ***Purchasing Lot Size*** can be found in Appendix H. Table 7.15 shows the values of ***Purchasing Lot Size*** for the scenarios of both the less and the more problematic cases.

Table 7.15: The values of ***Purchasing Lot Size*** for the scenarios of both the less and the more problematic cases

	Without RFID	**With RFID**			
		Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
The Less Problematic Case	380	380	380	335	260
The More Problematic Case	380	380	380	380	380

7.3 Run Parameters

7.3.1 Simulation Run Parameters

There are three run parameters for a simulation study namely ***Warm up Period, Replication Length*** and ***Number of Replications***. These parameters are studied in sections 7.3.1.1 and 7.3.1.2. They are determined by considering the capability of the simulation models to produce fair and unbiased results as well as the run time. The simulation run time is crucial in our study because the simulation models are prepared to be embedded in a simulation optimization tool which requires many simulation runs in order to find the optimal solution.

Trial runs show us that the simulation run time is large due to the high number of entities representing RTIs in the system. In order to obtain a reasonable simulation run time, a solution can be scaling the RTI pool by using entities representing more than one RTI and adjusting the input parameters accordingly. The decision of scaling is expected to affect the simulation run time like the simulation run parameters. Because of this reason, it is discussed in section 7.3.1.3 under this title.

7.3.1.1 Warm up Period and Replication Length

It is assumed that once RFID technology is set in place, it can be used for three years. When ***Time to Action*** is taken as twelve months, the usable lifetime of RFID technology remains two years. Since we want to simulate the usable lifetime of RFID technology after ***Time to Action***, ***Replication Length*** should be the total of ***Warm up Period*** and two years.

The initial conditions of the simulation mostly do not present the steady state of the system. This problem is called ‘initial transient’ or ‘initial bias’. In order to minimize this, we select the initial conditions close to steady state as much as possible. However, initial bias cannot be eliminated with the selection of initial conditions. We need to truncate some initial observations because they are the ones responsible from the most of the initial bias.

We run the simulation model in which the emergency shipment is not an option without initializing the statistics and the system state with 50 replications each having a length of 100 days. Since we choose not to initialize the statistics and the system state at the beginning of each replication, the values of performance measures in the i^{th} replication give the evaluation of the observations accumulated until the simulation clock reaches 100*i* days since the start of the simulation run. Figure 7.6-7.10 show the change of some performance measures with respect to the simulation time without truncating any initial observations. From these figures, it can be concluded that ***Cycle Time***, ***Fill Rate for Full RTIs*** and ***Pool Size*** reach the steady state very quickly compared to ***Trippage*** and ***RTI Lifetime***. ***Trippage*** and ***RTI Lifetime*** require much longer time than the others to reach the steady state.

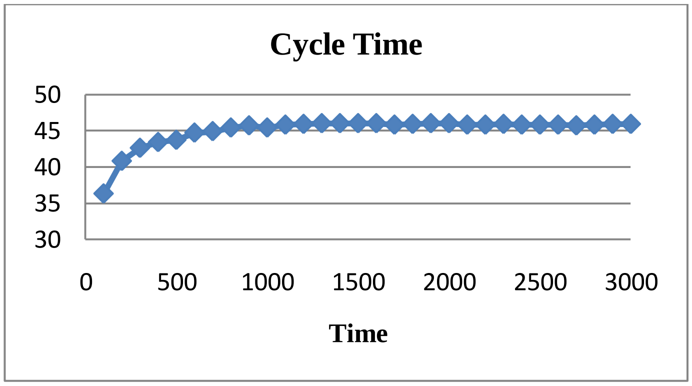

Figure 7.6: The change of average ***Cycle Time*** with respect to the simulation time

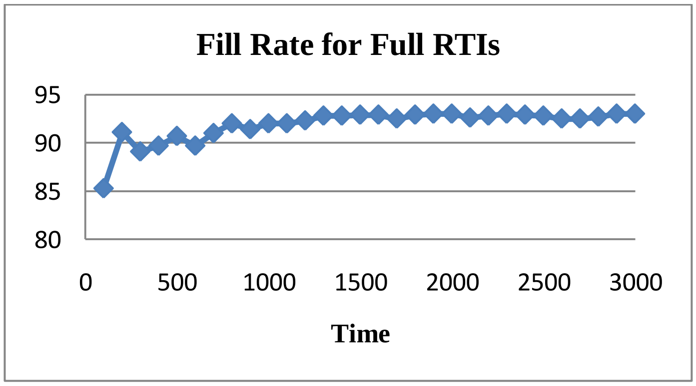

Figure 7.7: The change of average ***Fill Rate for Full RTIs*** with respect to the simulation time

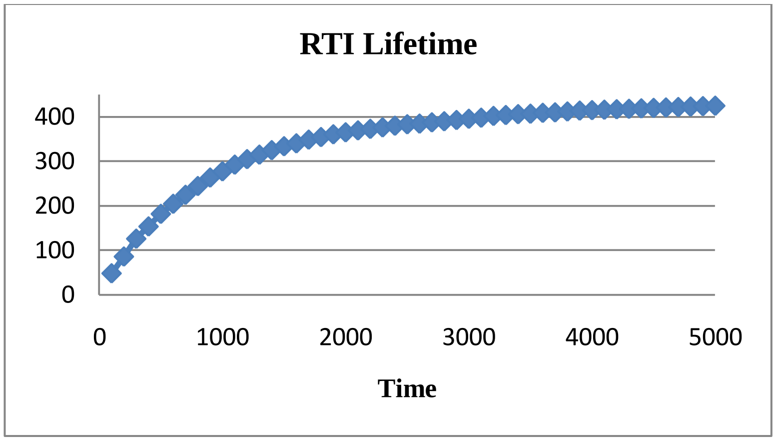

Figure 7.8: The change of average ***RTI Lifetime*** with respect to the simulation time

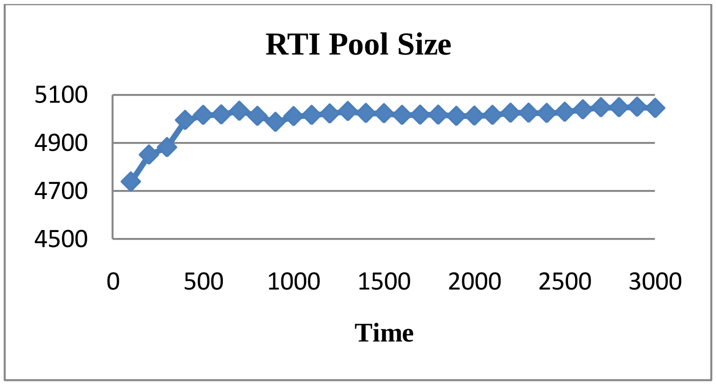

Figure 7.9: The change of average ***Pool Size*** with respect to the simulation time

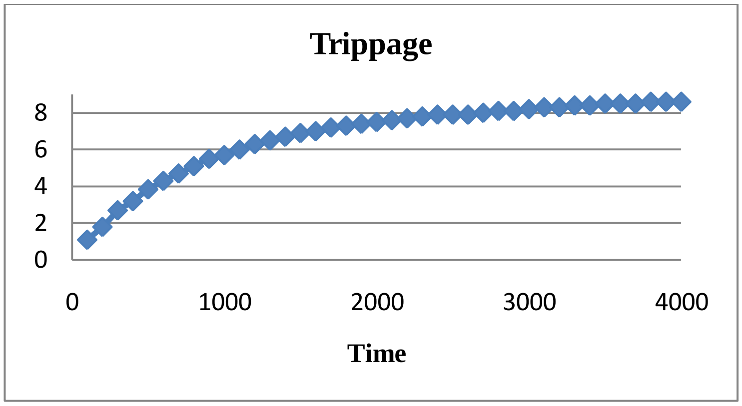

Figure 7.10: The change of average ***Trippage*** with respect to the simulation time

At this point, the following three options are considered in order to find ***Warm up Period*.**

1. Determining ***Warm up Period*** long enough so that the effect of the initial bias becomes negligible at the end of ***Warm up Period***.

2. Reducing the initial bias by assigning initial values to ***Number of Rotations*** and ***Time to Enter CLSC*** attributes of the RTIs created at the start of the simulation replication. These initial values should be equal to the expected values of these variables found with using the following distributions.

$$\textbf{\textit{Number of Rotations}} = \begin{cases} 0 & \text{with probability } p_f \\ \text{n} & \text{with probability } p_d(1-p_f)\,(1-p_f)^{\,n-1} + p_f(1-p_l)^{\,n} \end{cases} \tag{7.1}$$

$$\textbf{\textit{Time to Enter CLSC}} = \begin{cases} 0 & \text{with probability } p_f \\ -n \times CT^{ss} & \text{with probability } p_d(1-p_f)\,(1-p_f)^{\,n-1} + p_f(1-p_l)^{\,n} \end{cases} \tag{7.2}$$

where

$n = 1,2,3 \ldots$

p_d: ***Probability of Disposal***

p_f: ***Probability of Field Loss***

p_l: ***Probability of Loss*** ($p_l = p_f + p_d(1 - p_f)$)

CT^{ss}: The steady state value of average ***Cycle Time***

3. Estimating the average values of ***RTI Lifetime*** and ***Trippage*** with the following formulas and determining ***Warm up Period*** with respect to other variables which reach steady state more quickly. The idea behind the formulas belongs to Goh and Varaprasad (1983). In equation 7.3, the expected value of ***Number of Rotations*** should be found with its distribution given in equation 7.1.

Trippage = E[***Number of Rotations***] (7.3)

RTI Lifetime = ***Cycle Time*** × ***Trippage*** (7.4)

Although the simulation run times of the second and the third option are better than the run time of the first one, it is found suitable to use the first option because of the following reasons:

- Removing the initial bias of the distribution of RTIs throughout the supply chain is also important to obtain fair results. As a result, a high ***Warm up Period*** is preferable to a smaller one.
- The estimation of ***RTI Lifetime*** in the second and the third option is questionable because it should be the exact multiples of ***Trippage***. In our model, an RTI can be lost both in the field and in the preparing for reuse operation without completing its last cycle in its usable lifetime.

The RTIs created at the start of the simulation run are responsible for the initial bias because their attributes ***Number of Rotations*** and ***Time to Enter CLSC*** are equal to zero. Therefore, the minimum required ***Warm up Period*** should cover a period during which the most of the RTIs created at the start of the simulation run are disposed. It is expected to change with respect to ***Probability of Disposal*** and ***Probability of Field Loss***, and ***Emptying Duration Distribution***. Hence, the chosen ***Warm up Period*** should be valid for all developed scenarios.

Firstly, the simulation model without emergency shipments is run for all scenarios with one replication having a ***Replication Length*** of 100,000 days and a ***Warm up Period*** of 50,000 days. We run the simulation model long enough so that the impact of initial bias completely vanishes and we can find the steady state value of ***RTI Lifetime*** for this scenario. We choose the model without emergency shipment, because it is expected to reach steady state less quickly than the model with emergency shipment given the parameters ***Probability of Disposal*** and ***Probability of Field Loss***, and ***Emptying Duration Distribution***. The reason of this expectation is the fact that RTIs are expected to circulate faster due to emergency shipments. After finding the steady state values of ***RTI Lifetime***, we search for ***Warm up Period*** which gives ***RTI Lifetime*** at or very close to its steady state value. It turns out to be that a ***Warm up Period*** of 3,000 days is enough for all developed scenarios, which increases the run time significantly.

For the sake of obtaining a reasonable run time, it is decided to scale 20 RTIs to one entity. The details of this decision are given in section 7.3.1.3. In that case, it is observed that a ***Warm up Period*** of 3000 days is again enough to remove the initial bias for all scenarios.

7.3.1.2 Number of Replications

The precision of an output value can be controlled by determining ***Number of Replications***. Let,

- CT_{ij} be the observation i of ***Cycle Time*** in replication j where $i = 1,2,\ldots,m$ and $j = 1,2,\ldots,n$.

- $\overline{CT_j}$ be the replication averages of ***Cycle Time*** observations and $\overline{CT_j} = \frac{1}{m}\sum_i^m CT_{ij}$ for $j = 1,2,\ldots,n$.

CT_{ij}'s for $i = 1,2,\ldots,m$ for the same j (for the same replication) are expected to be dependent. On the other hand, $\overline{CT_j}$ for $j = 1,2,\ldots,n$ are independent, since the system state and the statistics are initialized at the start of each replication and different random numbers are used in each replication. It is also approximately normally distributed by Central Limit Theorem provided that m is not too small, because $\overline{CT_j}$ is the average of m observations. For a ***Replication Length*** of 3,720 days, m is around 3,500. We choose to make this analysis with ***Cycle Time*** due to its high number of observations because m should not be small.

We have $\overline{CT_j}$ independent and identically distributed as well as approximately normally distributed. Half length for $(1-\alpha)\%$ confidence interval can be found with the following formula:

$Half\ length = t_{n-1,1-\alpha/2}\frac{s}{\sqrt{n}}$ where s is the sample standard deviation. (7.5)

We run the simulation model without emergency shipments (for the scenario without RFID in the less problematic case) with a ***Replication Length*** of 3,720 days and a ***Warm up Period*** of 3,000 days for $n = 5$ replications. We use the scaled version as it is discussed in section 7.3.1.3. Table 7.16 shows the values of $\overline{CT_j}$ for $n = 5$ replications, $\overline{\overline{CT_j}}$ which is the average of $\overline{CT_j}$'s, and s.

Table 7.16: The sample of average ***Cycle Time*** for 5 replications and sample statistics

$\overline{CT_1}$	46.14
$\overline{CT_2}$	46.16
$\overline{CT_3}$	46.56
$\overline{CT_4}$	47.30
$\overline{CT_5}$	47.70
$\overline{\overline{\boldsymbol{CT_J}}}$	**46.77**
$\boldsymbol{s}$	**0.70**

If a relative precision of 5% is desired, $\frac{Half\ length}{\overline{\overline{CT_J}}} \leq 0.05$ should be. According to Table 7.16, $Half\ length = 2.776\frac{0.70}{\sqrt{5}} = 0.87$ and $\frac{Half\ length}{\overline{\overline{CT_J}}} \cong 0.02$ which is less than 0.05 where $t_{n-1,1-\alpha/2}$=2.776 for $n = 5$ and $\alpha = 0.05$. As a result, ***Number of Replications*** of 5 is enough to have a relative precision of 5%.

In order to be sure, we also do the same analysis for ***RTI Lifetime***. Although the number of observations for ***RTI Lifetime*** is not as much as the same for ***Cycle Time***, it is not small. It is around 400 for the same simulation run that is obtained for the analysis with ***Cycle Time***. Table 7.17 shows the values of $\overline{LT_J}$, i.e. the average value of ***RTI Lifetime*** observations in replication j, for $n = 5$ replications, and $\overline{\overline{LT_J}}$ which is the average of $\overline{LT_J}$.

Table 7.17: The sample of average ***RTI Lifetime*** for 5 replications and sample statistics

$\overline{LT_1}$	464.9
$\overline{LT_2}$	491.2
$\overline{LT_3}$	488.6
$\overline{LT_4}$	514.9
$\overline{LT_5}$	491.2
$\overline{\overline{\boldsymbol{LT_J}}}$	**490.1**
$\boldsymbol{s}$	**17.70**

According to Table 7.17, $Half\ length = 2.776\frac{17.70}{\sqrt{5}} = 21.97$ and $\frac{Half\ length}{\overline{\overline{CT}}_J} \cong 0.045$ which is less than 0.05, where $t_{n-1,1-\alpha/2}$=2.776 for $n = 5$ and $\alpha = 0.05$. As a result, ***Number of Replications*** of 5 is again found to be enough to have a relative precision of 5%.

7.3.1.3 Scaling Decision

It is possible to decrease the simulation run time by allowing ***RTI*** entities to represent more than one RTI. The decision of representing n RTIs with one entity results in RTIs circulating in the CLSC in groups of n.This decision requires the following adjustments in the input parameters:

1. The following parameters should be divided by n:
    - ***Demand Size***
    - ***Expected Daily Full RTI Demand***
    - ***Expected Lead Time Full RTI Demand***
    - ***Expected Weekly Full RTI Demand***
    - ***Emergency Shipment Threshold***
    - ***Minimum Emergency Shipment Lot Size***
    - ***FTL of Full RTIs***
    - ***Initial Pool Size***
    - ***Purchasing Lot Size***
    - ***Standard Deviation of Weekly Full RTI Demand***

Adjusting these parameters is enough because once they are adjusted, the other parameters which are calculated with a subset of these parameters like ***Reorder Point for Purchasing*** and ***Order up to Level of Full RTI Stock*** by the simulation models becomes adjusted accordingly. In addition, ***Variance of Lead Time Full RTI Demand*** should be divided by n^2. If X is an independent random variable normally distributed with mean μ, and variance σ^2, then X/n is also be normally distributed with mean μ/n, and variance σ^2/n^2 provided that n is a constant.

2. The following parameters should be multiplied by n in order to calculate ***Total RTI Pool Management Cost*** correctly:
    - ***Unit Repair Cost***
    - ***Unit RTI Holding Cost***.
    - ***Unit RTI Price***

We run the simulation models with and without emergency shipments

- For the case without the use of RFID technology in the less problematic case,
- With 10 replications (more than the decided ***Number of Replications*** to increase the precision) each having a ***Warm up Period*** of 3,000 days and a ***Replication Length*** of 3,720 days, and
- For n=1 (no scaling), n=10 and n=20,

in order to see the impact of the scaling decision on performance measures. The following two tables show the obtained results. The 'Output Values' columns show the average values of performance measures for 10 replications. The percentage values under '% Change' columns are the proportion of the difference between the results with and without scaling to the result without scaling. The values under this column are calculated after making the readjustments if necessary. For example, ***Pool Size*** value obtained by scaling with n=20 is multiplied with 20 in order to readjust the value of this performance measure.

Table 7.18: The change of performance measures with respect to the scaling decision for the simulation model without emergency shipment

	No Scaling	**Scaled with 1:10**		**Scaled with 1:20**	
	Output Values	**Output Values**	**% Change**	**Output Values**	**% Change**
Cycle Time (days)	45.9	46.6	1%	46.8	2%
Lifetime (days)	470.6	476.4	1%	482.4	2%
Trippage (days)	9.8	9.8	0%	9.9	0%
Pool Size	5,029	508.6	1%	256.7	2%
Fill Rate for Empty RTIs	96.2	96.9	1%	97.6	1%
Fill Rate for Full RTIs	93.9	94.8	1%	94.9	1%
New RTIs Replenishment Rate (RTIs/day)	10.9	1.1	-2%	0.5	0%
Time Spent in the Field (days)	32.4	32.3	0%	32.0	-1%
Total Cost of RTI Pool Management (€)	2,230,900	2,236,600	0%	2,262,000	1%
Run Time (minutes)	9.68	1.48	-85%	0.95	-90%

Table 7.19: The change of performance measures with respect to the scaling decision for the simulation model with emergency shipment

	No Scaling	**Scaled with 1:10**		**Scaled with 1:20**	
	Output Values	**Output Values**	**% Change**	**Output Values**	**% Change**
Cycle Time (days)	45.6	46.7	2%	46.8	3%
Lifetime (days)	465.8	476.4	2%	463.5	0%
Trippage (days)	9.7	9.8	1%	9.5	-2%
Pool Size	5,046.8	513.6	2%	256.68	2%
Fill Rate for Empty RTIs	98.2	98.8	1%	98.9	1%
Fill Rate for Full RTIs	94.3	95.0	1%	94.6	0%
New RTIs Replenishment Rate (RTIs/day)	11.0	1.06	-4%	0.54	-2%
Time Spent in the Field (days)	32.3	32.3	0%	32.1	-1%
Total Cost of RTI Pool Management (€)	2,269,000	2,241,700	-1%	2,249,400	-1%
Run Time (minutes)	11.4	1.5	-87%	0.97	-91%

From the results in these two tables, it can be concluded that scaling does not affect performance measures significantly while reducing the run time significantly. As a result, it is decided to adapt scaling with n=20 in our experimental analysis.

7.3.2 Simulation Optimization Run Parameters

OptQuest requires the followings for a simulation optimization run:

- Lower and upper bounds of ***Initial Pool Size*** to search its optimal vale within the specified interval
- The suggested value of ***Initial Pool Size*** to start the search
- A discrete step size to change ***Initial Pool Size*** and to continue the search
- A termination criterion to stop the search

As suggested by Lange and Semal (2010), the lower bound for the pool size of RTIs can be found with the assumption of 'perfect coordination'. That is, a DC sends its RTIs to the manufacturer when it has reached its lot size ***FTL of Empty RTIs***. On the other side, the manufacturer receives this shipment exactly when needed, at the time when its inventory has just dropped to zero. Since Lange and Semal (2010) consider a network including only customers and factories, their assumption of perfect coordination only includes the relationship between these parties. We need to broaden their 'perfect coordination' assumption in order to include the relationship between DCs and end users. It is assumed that DCs do not hold full RTI inventory because they immediately distribute what they receive from the manufacturer to end users. In addition, it is also assumed that an end user receive a full RTI exactly when needed, at the time its only RTI has just emptied. In the notion of perfect coordination, it is also assumed that there are no RTI losses. As a result, the lower bound of the pool size should be found as follows:

Notation

PS_{LB}: The lower bound of the pool size
FTL_e: The full truck load (capacity of a truck) for empty RTIs
d_i: The average demand rate of DC-i

Formulas

$$PS_{LB} = \text{The average number of RTIs in DCs} \\ +\text{The average number of RTIs at the manufacturer} \\ +\text{The average number of RTIs at end users} \tag{7.6}$$

$$PS_{LB} = 3\frac{FTL_e}{2} + \sum_i \left(\frac{FTL_e}{2} \times \frac{d_i}{\sum_i d_i}\right) + \text{Number of end users} \tag{7.7}$$

The inventory varies at DCs from 0 to FTL_e. As a result, average inventory at each DC is $FTL_e/2$. In order to calculate the number of RTIs at the manufacturer, let us assume the manufacturer has no RTIs left and just receives the lot size FTL_e sent by DC-i. It will consume the received RTIs at the speed of $\sum_i d_i$, i.e. total demand of DCs for full RTIs. During this time, its average inventory will be $FTL_e/2$. Since the $d_i/\sum_i d_i$ represents the portion of time the manufacturer consumes the RTIs sent by DC-i, the average inventory at the manufacturer is given by the second term in equation 7.7. Since the lot sizes of all DCs equal to FTL_e, this term reduces to $FTL_e/2$. In conclusion, PS_{LB}=2,260 given that FTL_e=380 and the assumed number of end users is 1,500.

The upper bound for pool size of RTIs can be found by summing up the maximum levels of all stock points in the CLSC. The maximum levels are found with the following assumptions. These assumptions may not be found realistic. However, the important point here is to find an upper bound for pool size which is better than taking infinity and at the same time certainly greater than the optimal pool size.

- The maximum level of empty RTI stock at the manufacturer is assumed to be the total of ***Reorder Point for Purchasing*** and ***Purchasing Lot Size.*** It is assumed that this stock level hit ***Reorder Point for Purchasing***, so that an order of new RTIs having a lot size of ***Purchasing Lot Size*** is given and the level of this stock is at ***Reorder Point for Purchasing*** when the order arrives.

- The maximum possible level of full RTI stock at the manufacturer is ***Order up to Level of Full RTI Stock***.
- The maximum level of full RTI stock at DCs is assumed to be enough to satisfy one week's full RTI demand.
- The maximum number of RTIs per end user is assumed to be two. One of them is assumed be half-full and the other one is assumed to be empty or full.
- The maximum level of empty RTI stock level of DCs is FTL_e.

Reorder Point for Purchasing and ***Purchasing Lot Size*** change with respect to ***Probability of Loss***. ***Probability of Loss*** changes with respect to the use of RFID technology and the extent of improvement that it brings. As a result, the upper bound of pool size is expected to change between scenarios developed in section 7.1. Table 7.20 shows the upper bounds of pool size for developed scenarios.

Table 7.20. The upper bound of pool size in different scenarios

	Without RFID	**With RFID**			
		Pessimistic	**Neutral**	**Optimistic**	**Very Optimistic**
The less problematic case	7085	7006	6848	6642	6406
The more problematic case	8569	8357	7921	7471	7006

The suggested value must be within the interval specified by these bounds. The average of these bounds can be taken as the suggested value. Step size, upper and lower bounds determine the number of candidate solutions. As a result, they affect the run time required to search the solution set. Step size should be determined considering the length of specified interval and run time. Besides, it must be positive multiples of 20, since we decided to use scaling 20 RTIs to one entity. Considering the observations of run time in trial runs, step size is taken as one which corresponds to 20 RTIs. The terminating criterion is chosen to be reaching a number of simulation runs. The number of simulation runs in one simulation optimization run is selected to be the half of the difference between the lower and upper bounds of pool size divided by the chosen step size so that one of the two solutions in the solution space can be checked. The bounds (scaled by 20), the suggested value (scaled by 20) and the number of simulations are provided in the following two tables.

Table 7.21: Simulation optimization run parameters for the scenarios in the less problematic case

Scenario	Lower Bound	Suggested Value	Upper Bound	Number of Simulations
Without RFID	113	234	354	120
Pessimistic	113	232	350	120
Neutral	113	228	342	110
Optimistic	113	223	332	110
Very Optimistic	113	217	320	100

Table 7.22: Simulation optimization run parameters for the scenarios in the more problematic case

Scenario	Lower Bound	Suggested Value	Upper Bound	Number of Simulations
Without RFID	113	271	428	160
Pessimistic	113	266	418	150
Neutral	113	255	396	140
Optimistic	113	244	374	130
Very Optimistic	113	232	350	120

7.4 Verification and Validation

Verification is about answering the question “Did we do the things right?”. Verification of a model is questioning whether or not the conceptual model is correctly translated into computer codes as intended. On the other hand, validation is about answering the question “Did we do the right thing?”. It is the process of resolving whether or not the conceptual model is a correct representation of the system by taking the objectives of the study into account. According to Irobi et al. (2001), the validation of conceptual models is questioning that the assumptions underlying the conceptual models are correct and they reasonably represent the problem for a given purpose.

7.4.1 Verification of the Simulation Models

Our simulation models are verified by

- tracing the operation in the simulation models,
- checking consistency of the outputs of the simulation models, and
- various extreme value checks.

This section presents these steps of the verification of the simulation models

7.4.1.1 Tracing the Operation in the Simulation Models

We have firstly started with a simple model, and then added the details until we reach the final simulation model of the whole CLSC. At each time that simulation models are modified, they are debugged with Arena’s run controller. ‘Set Trace’ commands are mostly used in order to trace the flows of entities in the system. Debugging is repeated with a small number of RTI pool size in order to not to be distracted by the enormous number of entities while tracing. The errors are found out and immediately corrected. After each correction, debugging is restarted. It has been made certain that the flow of entities in the system is modeled as intended and the formulas are correct. In the end, it is ensured that the conceptual simulation model is correctly translated into Arena simulation software.

7.4.1.2 The Consistency Check of the Outputs

In this section, we present an example to the consistency check that is performed for the final version of the simulation models. In this example, we run both of the models with the run parameters determined in section 7.3.1. The scenario without the use of RFID technology in the less problematic case is used in this example.

The consistency check is started with balancing the number of ***RTIs*** at the end of simulation run. The number of ***RTIs*** in the system should be equal to the number of ***RTIs*** that have entered to the system after the number of ***RTIs*** that have left the system is deducted from this number.

Pool Size = ***Actual Starting Pool Size*** (7.8)
+ ***Total Number of Purchased RTIs***
−***Number of RTI Disposals***
−***Number of RTI Field Losses***

The final value of ***Pool Size*** should equal to the total amount of RTIs distributed among the parts of the CLSC.

Pool Size = The empty and clean RTI stock level at the manufacturer (7.9)
+ The number of RTIs in the filling operation
+ The full RTI stock level at the manufacturer
+ The RTIs in transportation (including emergency shipment if it is an option) between the manufacturer and DCs
+ The RTIs that are sent to DCs and have not been returned to DCs
+ The empty RTI stock levels at DCs

+ The number of RTIs in the preparing for reuse operation
+ The number of RTIs in carrying from the preparing for reuse operation

At the start of each replication, RTI pool created with ***Initial Pool Size*** should be distributed according to ***Initial Distribution of RTI Pool.*** As a result, the following equations should hold:

Initial Pool Size = Initial number of RTIs that are sent to the empty and clean RTI stock + Initial number of RTIs that are sent to the field (7.10)

Initial number of RTIs that are sent to the empty and clean RTI stock (7.11)
≈ The probability that an RTI is sent to this stock point × ***Initial Pool Size***

Initial number of RTIs that are sent to the field (7.12)
≈ The probability that an RTI is sent to this part of the CLSC × ***Initial Pool Size***

The final (and also average) value of ***Full RTI Backorders (All)*** should be the total of final (and also average) values of ***Full RTI Backorders (DC i)*** variables. In other words, the following equation should hold:

Full RTI Backorders (All) = ***Full RTI Backorders (DC-1)*** (7.13)
+ ***Full RTI Backorders (DC-2)***
+***Full RTI Backorders (DC-3)***

In addition, the following equations and inequalities are also checked. They are presented to give the idea of how the simulation models are verified by checking if there are any inconsistencies in the outputs. This is not the exhaustive list.

- The maximum empty RTI stock levels at DCs should be equal to ***FTL of Empty RTIs***.

- The number of emergency shipments at one week cannot be greater than three, since there are three DCs.
- Once the returns arrive at the manufacturer, they are immediately entered to the preparing for reuse operation without waiting. Therefore, the waiting time at the returns stock and the maximum level of returns stock at the manufacturer should be zero.
- If there is a backorder, the full RTIs leaving the filling operation are directly sent to satisfy outstanding backorders without waiting at the manufacturer. If the final value of ***Full RTI Backorders (All)*** is greater than zero, then the minimum value of waiting time in full RTI stock should not be zero because the full RTIs that are send to satisfy backorders do not enter the full RTI stock.
- Total number of demand arrivals from DCs should be equal to the number of observations for the statistics variable ***Fill Rate for Full RTIs***.
- ***Number of Periods*** should be equal to the number of observations of for the statistics variable ***Fill Rate for Empty RTIs***.
- The daily rate of new RTI replenishment should be close to the daily RTI loss rate:

  $$\textbf{\textit{Total Number of Purchased New RTIs}} / (\textbf{\textit{Replication Length}} - \textbf{\textit{Warm up Period}}) \approx \textbf{\textit{Expected Daily Full RTI Demand}} \times (\textbf{\textit{Probability of Loss}}) \quad (7.14)$$

Besides, the following equalities should hold if the simulation models give consistent outputs. In formula 7.20, the expected ***Number of Rotations*** can be found with formula 7.1.

$$\textbf{\textit{Total Demand}} / ((\textbf{\textit{Replication Length}} - \textbf{\textit{Warm up Period}}) \approx \textbf{\textit{Expected Daily Full RTI Demand}} \quad (7.15)$$

$$\textbf{\textit{Number of RTI Disposals}} \approx (1 - \textbf{\textit{Probability of Field Loss}}) \times \textbf{\textit{Probability of Disposal}} \times \textbf{\textit{Total Demand}} \quad (7.16)$$

$$\textbf{\textit{Number of RTI Field Losses}} \approx \textbf{\textit{Probability of Field Loss}} \times \textbf{\textit{Total Demand}} \tag{7.17}$$

$$\begin{aligned}&\textbf{\textit{Number of RTI Repairs}}\\ &\quad\approx (1 - \textbf{\textit{Probability of Field Loss}}) \times \textbf{\textit{Probability of Repairable Damage}} \times\\ &\quad\textbf{\textit{Total Demand}}\end{aligned} \tag{7.18}$$

$$\textbf{\textit{Number of RTI Returns}} \approx (1 - \textbf{\textit{Probability of Field Loss}}) \times \textbf{\textit{Total Demand}} \tag{7.19}$$

$$\text{Average value of } \textbf{\textit{Trippage}} \approx \mathrm{E}[\textbf{\textit{Number of Rotations}}] \tag{7.20}$$

$$\begin{aligned}&\text{Average value of } \textbf{\textit{RTI Lifetime}}\\ &\quad\approx \text{Average value of } \textbf{\textit{Trippage}} \times \text{Average value of } \textbf{\textit{Cycle Time}}\end{aligned} \tag{7.21}$$

$$\begin{aligned}&\text{Average number of RTIs in the preparing for reuse operation}\\ &\quad\approx (\textbf{\textit{Number of RTI Returns}} \times \textbf{\textit{Lead Time of Preparing For}}\\ &\quad\textbf{\textit{Reuse}})/(\textbf{\textit{Replication Length}} - \textbf{\textit{Warm up Period}})\end{aligned} \tag{7.22}$$

7.4.1.3 Extreme Value Checks

This check is performed in order to see whether or not the simulation models provide plausible outputs to extreme and unlikely combination of levels of parameters. The simulation runs are conducted with the input parameters given in section 7.2. The scenario without the use of RFID technology in the less problematic case is used for the runs. The results of 15 extreme cases are checked and compared with the results of the original scenario. In all of the checks, the simulation models have provided expected results. As a result, we could conclude that the simulation models seem to be working and providing correct results.

1. Zero Demand Rate

Since there is zero demand, no RTIs are sent to the field after the end of warm up period. The outputs of the simulation models give no values for ***Cycle Time***, ***Lifetime***, ***Trippage***, ***Time Spent in the Field*** and ***Fill Rate for Full RTIs*** because the number of observations of these variables are zero. ***Fill Rate for Empty RTIs*** is 100% because the empty and clean RTI stock does not fail to satisfy the complete need of the filling operation which is always zero. Most of the RTIs initally sent to the field return to the manufacturer. However, some of them stuck in the DCs because the empty RTI stock levels at DCs stay at a level less than ***FTL of Empty RTIs***. Since a small part of the initial RTI pool is lost or disposed, ***Actual Starting Pool Size*** is less than ***Initial Pool Size***. After the completion of warm up period, there are no losses because there are no RTIs sent to the field. As expected, ***New RTI Replenishment Rate*** and ***Number of Emergency Shipments*** (of the model with emergency shipments) is zero. ***Total RTI Pool Management Cost*** only includes ***Total Purchasing Cost*** and ***Total RTI Pool Holding Cost*** of the ***Actual Starting Pool Size***.

2. Very High Demand Rate

For this check, ***Demand Size*** for each demand arrival is taken as 600. ***Order up to Level of Full RTI Stock*** and ***Reorder Point for Purchasing*** are not adjusted according to the high demand rate. If we have adjusted, this check would look like reversing the scaling without updating cost parameters. In this check, average ***Cycle Time*** decreases approximately 25% due to decreases in the waiting times at stock points, especially at empty RTI stocks of DCs and at full RTI stock at the manufacturer. Average ***Cycle Time*** also decreases due to the high level of full RTI backorders because RTIs sent to satisfy backorders do not enter and wait at full RTI stock at the manufacturer. Since empty RTIs wait less at DCs for FTL shipments, average ***Time Spent in the Field*** also decreases. Average ***Pool Size*** and ***Total RTI Pool Management Cost*** increase greately due to high ***New RTI Replenishment Rate*** (around 120 RTIs per day). ***Fill Rate for Full RTIs*** is less than 0.5% despite of high ***New RTI Replenishment Rate*** because

Order up to Level of Full RTI Stock is not adjusted. Average ***Trippage*** stays at the same level given the same ***Probability of Disposal*** and ***Probability of Field Loss***. On the other hand, average ***RTI Lifetime*** decreases due to the decrease in average ***Cycle Time***. According to the output of the model with emergency shipments, ***Number of Emergency Shipments*** increases approximately 800%.

3. No Purchasing

For this check, it is assumed that giving orders for new RTIs is not allowed after the end of warm up period. The final value of ***Pool Size*** is much more smaller than ***Actual Starting Pool Size***. Average ***Fill Rate for Full RTIs*** is around 25% and 22% for the models with and without emergengency shipments, respectively. For both of the models, the maximum ***Fill Rate for Full RTIs*** is 100%. On the other hand, the minimum of the same is 0% since ***Pool Size*** decreases greately towards to end of simulation replication. ***Full RTI Backorders (All)*** increases greatly and has a very large final value. ***Total Number of Purchased New RTIs*** is a positive small number because RTIs on order at the end of warm up period arrive later. ***Total RTI Pool Management Cost*** decreases 50% because our total cost formula does not contain penalty cost and, ***Total Purchasing Cost*** and ***Total RTI Pool Holding Cost*** decrease greately. For the simulation model with emergency shipments, ***Number of Emergency Shipments*** is 750% higher.

4. Very Large *Purchasing Lot Size*

For this check, it is assumed that new RTIs can only be purchased with a lot size of 10 times ***Purchasing Lot Size*** after the end of warm up period. Two of the prominent changes in the outputs are the increases in average empty RTI stock level and waiting time of RTIs at that stock point. ***Cycle Time*** also increases due to the increase in waiting time at empty and clean RTI stock. Average ***Pool Size*** increases by 32% and 35% for the models with and without emergency shipments. Although ***Total Purchasing Cost*** does not increase significantly, ***Total RTI Pool Holding Cost*** increases in both models. For the model with emergency shipments, average ***Number of Emergency Shipments*** is close to zero, as expected.

5. Breakdown at the Filling Operation

For this check, it is assumed that a breakdown at the filling line occurs at the end of warm up period and it takes three months to repair it. Until repair, it is not possible to fill any RTIs. The outputs show that the maximum level of ***Full RTI Backorders (All)*** increases enormously to a level close to the expected full RTI demand of three months. As expected, the minimum level of ***Fill Rate for Full RTIs*** is zero and the average level of ***Fill Rate for Full RTIs*** decreases for both of the models. In addition, average ***Cycle Time*** more than doubles for both of the models due to high waiting time before the filling operation.

6. Zero *Emptying Duration*

In this check, it is assumed that RTIs arrived at DCs immediately are emptied and entered to the empty RTI stock of DCs. In order to do this check, both ***Minimum Emptying Duration*** and ***Emptying Duration*** for all DCs are taken as zero. The outputs of the simulation models show that average ***Cycle Time*** decreases greately (approximately %50) due to the huge decrease in average ***Time Spent in the Field***. As a result, average ***RTI Lifetime*** also decreases given the same level of average ***Trippage***. The most prominent change is in average ***Pool Size*** with an approximately 55% decrease for both of the models.

7. Very Large *Emptying Duration*

In this check, it is assumed that ***Emptying Duration*** takes a very high and fixed number, 150 days, at the end of warm up period. The outputs of the simulation models shows that average ***Cycle Time*** increases approximately 60%. Since the return of RTIs takes more time than usual, both ***Fill Rate for Empty RTIs*** and ***Fill Rate for Full RTIs*** decrease. Average ***Time Spent in the Field*** approximately triples. In addition, ***New RTI Replenishment Rate*** more than doubles in order to increase ***Pool Size*** and to cope with the new level of ***Emptying Duration***.

Although it is expected that average ***Trippage*** stays approximately the same and average ***RTI Lifetime*** increases (due to the increase in average ***Cycle Time***), both of them decrease. The reason is that the determined ***Replication Length*** is not enough for these performance measures to reach their new steady state values after the change in ***Emptying Duration*** at the end of warm up period.

8. No Waiting for *FTL of Empty RTIs*

In this check, empty RTIs arriving at DCs from end users are assumed to be transported one by one without waiting at DCs. It is expected that the empty RTI stock levels of DCs and the waiting times at these stock points become zero. According to the outputs, the average values of ***Cycle Time***, ***RTI Lifetime*** and ***Time Spent in the Field*** decrease as expected. At the end of warm up period, ***Pool Size*** is less than ***Initial Pool Size*** due to the decrease in ***Cycle Time***. Besides, average ***Pool Size*** is less than the one of original scenario. On the other hand, ***New RTI Replenishment Rate*** (which is measured after the end of warm up period until the end of run) is close to the one of original scenario as expected since ***Probability of Disposal*** and ***Probability of Field Loss*** stays the same. It should be also noted that ***Number of Emergency Shipments*** is zero as expected for the model with emergency shipment, because there is no empty RTI stock at DCs.

9. Very Large *Emergency Shipment Threshold* and *Minimum Emergency Shipment*

This check is firstly performed with a ***Emergency Shipment Threshold*** which is three times of the original one without changing ***Minimum Emergency Shipment***. ***Number of Contacts with DCs*** greatly decreases as expected. As a result, ***Number of***

Emergency Shipments also greatly decreases. Indeed, only one emergency shipment in 5 replications is observed.

This check is secondly performed with a ***Minimum Emergency Shipment*** which is larger than ***FTL of Empty RTIs*** and the same level of ***Emergency Shipment Threshold***. As expected, the output shows no significant difference in ***Number of Contacts with DCs***, since ***Emergency Shipment Threshold*** stays the same. However, ***Number of Emergency Shipments*** is given as zero for all replications due to larger ***Minimum Emergency Shipment***.

10. Zero *Emergency Shipment Threshold* and *Minimum Emergency Shipment*

This check is firstly performed with zero ***Emergency Shipment Threshold***. The output shows that ***Number of Contacts with DCs*** approximately doubles. In addition, ***Number of Emergency Shipments*** more than quadruples compared to the original scenario. The increase in both inputs are expected.

This check is secondly performed with a ***Minimum Emergency Shipment*** equal to 1. The average of ***Number of Contacts with DCs*** turns out to be very close to the same of the original scenario. The same conclusion can be made for ***Number of Emergency Shipments***. Although sounds unlikely, this result is expected because ***Number of Contacts with DCs*** limits ***Number of Emergency Shipments***. It is not possible to make an emergency shipment without contacting. Besides, after contacting with DCs, the manufacturer may learn that there is a shipment of empty RTIs on the way and decide not to make any emergency shipments.

11. Zero *Probability of Field Loss*

In this check, ***Probability of Field Loss*** is taken as zero. According to the outputs of the simulation models, ***Number of RTI Field Losses*** equals to zero. In addition ***New***

RTI Replenishment Rate and ***Total Purchasing Cost*** decrease. On the other hand, the average values of ***RTI Lifetime*** and ***Trippage*** increases, as expected.

12. Zero *Probability of Disposal*

In this check, ***Probability of Disposal*** is taken as zero. The results similar to the check with zero ***Probability of Field Loss***. ***Number of RTI Disposals*** equals to zero. In addition ***New RTI Replenishment Rate*** and ***Total Purchasing Cost*** decrease. On the other hand, the average values of ***RTI Lifetime*** and ***Trippage*** increases, as expected.

13. Zero *Probability of Repairable Damge*

In this check, ***Probability of Repairable Damage*** is taken as zero. The outputs give zero ***Number of Repairs*** and ***Total Repair Cost***. As a result, ***Total RTI Pool Management Cost*** decreases. There is no other significant change in the outputs, mainly because it is assumed that repairing does not affect ***Lead Time of Preparing for Reuse***.

14. Zero *Initial Pool Size*

Initial Pool Size is taken as zero in this check. The results seem to be almost the same with the results of the original scenario. This is an expected outcome, because until the end of warm up period new RTIs are purchased as well as both the distribution and the size of the pool reach their steady states. Indeed, ***Actual Starting Pool Size*** is at a level close to average ***Pool Size*** for the period after warm up.

15. Very Large *Initial Pool Size*

Initial Pool Size is taken as 20 times as the same of original scenario. The most prominent changes are zero ***New RTIs Replenishment Rate*** and great increase in ***Total RTI Pool Holding Cost***.

7.4.2 Validation of the Simulation Models

The simulation models are validated by using the methods face validity, internal validity and degenerate tests. These methods are explained in detail in sections 7.4.2.1-7.4.2.3.

7.4.2.1 Face Validity

Face validity is described by Irobi et al. (2001) by asking people familiar with the system if the logic used in the conceptual model is correct and whether or not input-output relationship is reasonable. The correctness of the conceptual model of the CLSC is discussed in detail in several meetings. These discussions are made in the light of the observations provided by our case study, the knowledge of similar cases and theoretical knowledge. In addition, input-output relationship is found reasonable when the outputs of the simulation models are compared with the ones of the CLSC of our case study.

7.4.2.2 Internal Validity

According to Sargent (2003), a large amount of stochastic variability may be a sign of lack of consistency and may result in questionable results. He suggests that several replications (or runs) of the simulation model should be performed to determine the extent of internal stochastic variability of the simulation model.

The internal validity of both of the simulation models is checked by running them with 50 replications with a ***Replication Length*** of 3000 days, a ***Warm up Period*** of 3720 days, and scaling 20 RTIs to one entity of ***RTIs*** type. The used set of inputs belongs to the scenario without the use of RFID technology in the less problematic case.

The results of the simulation runs can be found in Tables 7.23 and Table 7.24. The column named 'Average' shows the average of 50 replication averages for each performance measure. The columns named ‘Minimum’ and ‘Maximum’ show the minimum and the maximum of the average values of each performance measure in 50 replications. From these tables, it can be concluded that there is not a large amount of stochastic variability in each of the performance measures. The maximum ratio of half-width to average is less than 5%.

Table 7.23: The values of the performance measures provided by the simulation model without emergency shipments

	Average	**Half-width**	**Minimum**	**Maximum**	**Half-width/ Average**
Cycle Time (days)	46.9	0.2	45.8	48.6	0.4%
Lifetime (days)	479.8	6.6	432.2	534.5	1.4%
Trippage (days)	9.8	0.1	8.8	10.8	1.3%
Pool Size	5155.6	217.6	4962.2	5377.0	4.2%
Fill Rate for Empty RTIs	97.6	0.3	94.9	99.4	0.3%
Fill Rate for Full RTIs	94.9	0.4	90.9	97.0	0.4%
New RTIs Replenishment Rate (RTIs/day)	10.7	0.2	9.0	12.7	2.0%
Time Spent in the Field (days)	32.1	0.1	31.7	32.5	0.2%
Total Cost of RTI Pool Management (€)	2,243,600	17,415	2,109,600	2,354,900	0.8%

Table 7.24: The values of the performance measures provided by the simulation model with emergency shipments

	Average	Half-width	Minimum	Maximum	Half-width /Average
Cycle Time (days)	46.8	0.2	45.5	48.1	0.4%
Lifetime (days)	478.9	7.7	429.6	542.3	1.6%
Trippage (days)	9.8	0.2	8.8	11.1	1.5%
Pool Size	5153.0	18.0	5026.4	5324.8	0.3%
Fill Rate for Empty RTIs	98.9	0.1	97.5	99.6	0.1%
Fill Rate for Full RTIs	94.4	0.3	90.9	96.3	0.4%
New RTIs Replenishment Rate (RTIs/day)	10.8	0.2	9.5	12.1	1.5%
Time Spent in the Field (days)	32.1	0.1	31.6	32.5	0.2%
Total Cost of RTI Pool Management (€)	2,256,000	17,671	2,112,200	2,379,300	0.8%

7.4.2.3 Degenerate Tests

The degeneracy of the simulation model's behaviors is also tested by suitable choice of input parameters in order to answer whether or not the results change reasonable. An example to degeneracy tests is given by Irobi et al. (2001) as testing whether or not the average number in the queue of a single server continues to increase with respect to time when the arrival rate is larger than the service rate.

Several degenerate tests are designed and it is observed that the simulation models give expected results. Some examples to these tests include increasing and decreasing ***Demand Size***, ***Emptying Duration***, and ***FTL of Empty RTIs***.

7.4.3 Verification and Validation of the Simulation Optimization Model

The simulation optimization model is verified with several extreme value checks. The results of extreme value checks are given in section 7.4.3.1. On the other hand, the model is validated with degenerate tests. The results of degenerate tests are given in 7.4.3.2.

7.4.3.1 Extreme Value Checks

This check is performed in order to see whether or not the optimization simulation model provides plausible outputs to extreme and unlikely combination of parameter values. The scenario without the use of RFID technology in the less problematic case is used in the simulation runs. Only two extreme cases can be developed with the target level of ***Fill Rate for Full RTIs***, which is the only constraint in the optimization procedure of the simulation optimization model. In addition, it is observed that ***Total RTI Pool Management Cost***, the only variable in the objective function, is largely affected by ***Pool Size***. Pool Size is expected to change with respect to ***Probability of Field Loss***, ***Probability of Disposal***, and ***Emptying Duration Distribution***. As a result, four additional extreme cases are developed with these parameters.

The results of the extreme cases are checked and compared with the results of the original scenario giving best ***Total RTI Pool Management Cost*** as €2,205,460 and average ***Pool Size*** of 5150. The simulation optimization model provides the expected results in all extreme value checks. As a result, it can be concluded that the simulation optimization model is working and providing correct results.

1. Target *Fill Rate for Full RTIs* of 1%

The constraint of the simulation optimization model given with formula 6.35 is updated as follows:

$$\textbf{\textit{Fill Rate for Full RTIs}} \geq 1\% \qquad (7.23)$$

As expected, all tested solutions of ***Initial Pool Size*** within the bounds of pool size given in section 7.3.2 are found to be feasible. The best found solution gives an ***Initial Pool Size*** of 3800. We run the simulation model with this input and found that ***Fill Rate for Full RTIs*** is 94%. It is not close to 1% because the decision rules for the timing and quantity of replenishments of the full and empty RTI stocks at the manufacturer are modeled according to the target service levels.

2. Target *Fill Rate for Full RTIs* of 99%

The constraint of the simulation optimization model given with formula 6.35 is updated as follows:

$$\textbf{\textit{Fill Rate for Full RTIs}} \geq 99\% \qquad (7.24)$$

As expected, all tested solutions of ***Initial Pool Size*** within the bounds of pool size given in section 7.3.2 are found to be infeasible. This is expected because the decision rule for the timing and quantity of replenishments of the full RTI stock at the manufacturer is modeled according to the target service level of 95%.

3. No Losses

The simulation optimization model is solved with zero ***Probability of Disposal*** and zero ***Probability of Field Loss***. The best found solution gives average ***Total RTI Pool Management Cost*** about € 1,460,000. We run the simulation model with the ***Initial***

Pool Size of the best found solution and find out that average ***Pool Size*** is about 5,500. As RTIs are lost in the CLSC, it is required to sustain RTI losses by new RTI replenishments. When RTI loss is zero, this does not mean that average ***Pool Size*** should extensively decrease. Rather, this means that new RTI replenishments should decrease and as a result ***Total RTI Pool Management Cost*** should decrease as well.

4. Very High Losses

The simulation optimization model is solved with taking both ***Probability of Disposal*** and ***Probability of Field Loss*** as 0.5. The best found solution gives average ***Total RTI Pool Management Cost*** about € 9,000,000. We run the simulation model with the ***Initial Pool Size*** of the best found solution and find out that average ***Pool Size*** is about 6,000.

5. Zero *Emptying Duration*

The simulation optimization model is solved with zero ***Emptying Duration*** and zero ***Minimum Emptying Duration*** by assuming that RTIs are immediately emptied when they reach DCs. The best found solution gives average ***Total RTI Pool Management Cost*** about € 1,700,000 over 5 replications. We run the simulation model with the ***Initial Pool Size*** of the best found solution and find out that average ***Pool Size*** is about 2,300. The decrease in average ***Pool Size*** is expected due to the decrease in average ***Cycle Time***. In addition, smaller average ***Pool Size*** brings less cost, as expected.

6. Very Large *Emptying Duration*

The simulation optimization model is solved with a very large ***Emptying Duration***, which is 150 days for all DCs. The best found solution gives average ***Total RTI Pool Management Cost*** about € 4,500,000. We run the simulation model with the ***Initial Pool Size*** of the best found solution and find out that average ***Pool Size*** is about 19,000. The high increase in average ***Pool Size*** is expected due to the high increase in average ***Cycle Time***. In addition, larger average ***Pool Size*** brings higher cost, as expected.

7.4.3.2 Degenerate Tests

The degeneracy of the simulation optimization model's behavior is also tested by suitable choice of input parameters in order to answer whether or not the results change in a reasonable way. The parameters changing with the use of RFID technology and the extent of improvement that it brings, namely ***Probability of Disposal***, ***Probability of Field Loss*** and ***Emptying Duration Distribution*** are used in these tests. The reason of this parameter choice is to ensure the validity of the simulation optimization model in providing fair results in experimental analysis with the developed scenarios. It is observed that the changes in ***Total RTI Pool Management Cost*** with respect to these parameters are expected. The experimental results given in section 7.5 represent examples for such tests. Because of this reason, it is found unnecessary to give any results here.

7. 5 Experimental Results

In experimental analysis, the scenarios developed in section 7.1 are analyzed. The simulation optimization model is used to find the optimal solutions for all scenarios of the cases in which emergency shipments cannot be useful and emergency shipments can be useful. In total, the optimal solutions are sought for 20 scenarios.

The optimal solutions are ***Initial Pool Size*** values giving the minimum ***Total RTI Pool Management Cost*** with the condition of the minimum fill rate of 95% for satisfying the full RTI demand of DCs at the manufacturer. The optimal values of ***Initial Pool Size*** are inputted into the simulation models in order to find out the values of other performance measures of the optimal solutions. In this analysis, the following performance measures are considered:

- Total RTI pool management cost
- Average Cycle Time
- Average pool size
- Average trippage
- Average RTI lifetime
- Average time spent in the field
- Average rate of new RTI replenishment

The performance measures ***Fill Rate for Full RTIs*** and ***Fill Rate for Empty RTIs*** are exluded from this list, because it is already ensured that they are at a desired level with the constraint of target fill rate for the full RTI demand. It should be noted here that the ultimate reason of ensuring target fill rate of 99% for the empty RTI stock is to obtain the target fill rate for the full RTI stock. The values of these performance measures can be found in Appendix I.

The outputs presented in this section are the average values of 5 replications. Figure 7.11 shows the optimal values of total RTI pool management cost for all scenarios. In the following figures, ‘No ES’ and ‘With ES’ refer to the case in which the emergency shipment is not allowed and to the case in which emergency shipment can be useful, respectively. In addition, ‘Case 1’ and ‘Case 2’ refer to the less problematic case and the more problematic cases, respectively.

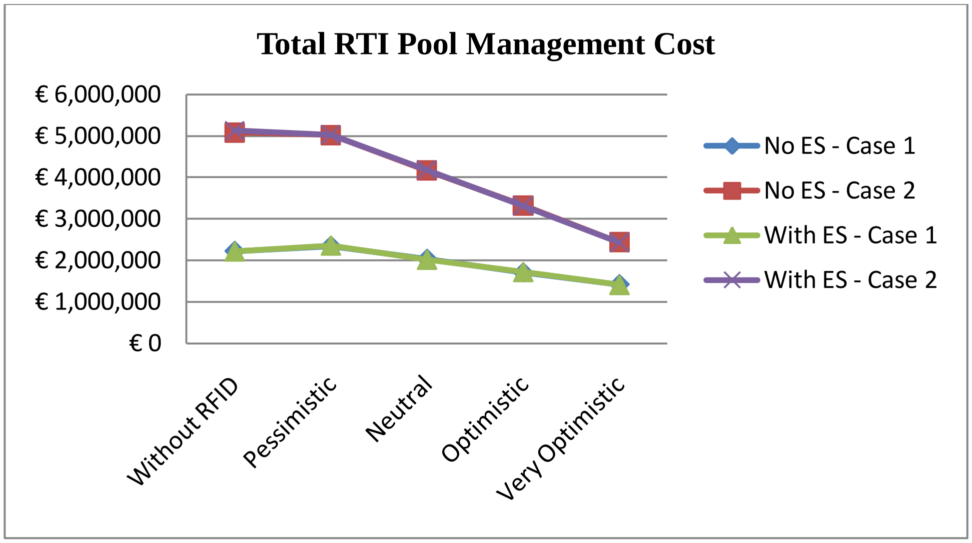

Figure 7.11: Optimal total RTI pool management cost values for all scenarios

Although it is hard to recognize at the first sight, Figure 7.1 shows four lines. The lines for the case in which emergency shipment is not allowed and for the case in which emergency shipments can be useful, collide for the cases having the same degree of problems. The reason is that the optimal level of total RTI pool management cost is approximately same regardless of the option of emergency shipments, with all other things being the same. In fact, the same issue is valid for the other performance measures as it can be seen from figures 7.12-7.17. In the optimal solutions, the number of emergency shipments made in the time horizon of simulation runs is very small. As a result, the option of emergency shipment does not significantly affect the results.

The lower and the upper lines in Figure 7.11 show the change of optimal total RTI pool management cost with respect to the use of RFID technology and the extent of the improvement that it brings from the pessimistic level to the very optimistic level in the less and in the more problematic cases, respectively. In the less problematic case, total cost with the use of RFID technology is less than the same without it, if the extent of the improvement is neutral, optimistic or very optimistic. On the other hand, in the more problematic case total cost can be decreased with the use of RFID technology if the extent of improvement is not smaller than the pessimistic level.

Figure 7.12 shows the average pool size in optimal solutions of all scenarios. In this figure, the upper (lower) line belongs to the more (less) problematic case. In addition, Figure 7.13 shows the average rate of new RTI replenishment to maintain the RTI pool in optimal solutions. In this figure, the upper (lower) line also belongs to the more (less) problematic case due to higher (lower) RTI losses. The rate of decreases in pool size and in the rate of new RTI replenishment as the level of improvement increases are larger in the more problematic case than in the less problematic case.

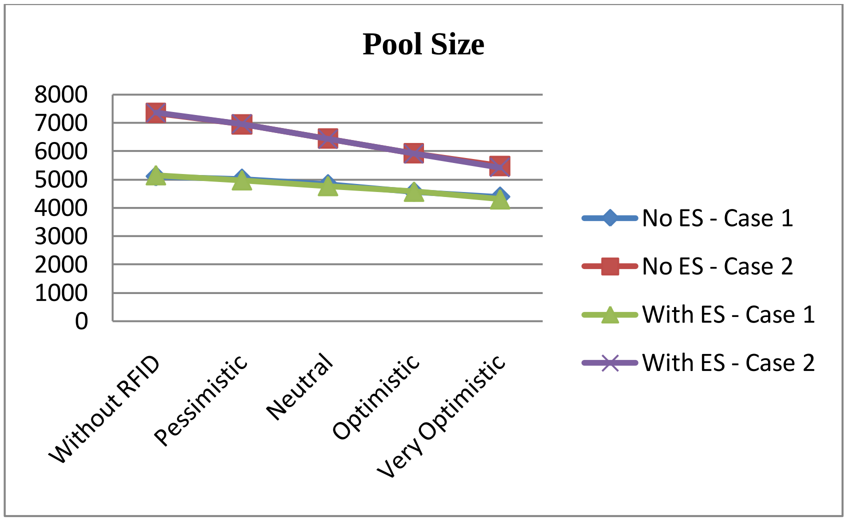

Figure 7.12: Average pool size in optimal solutions of all scenarios

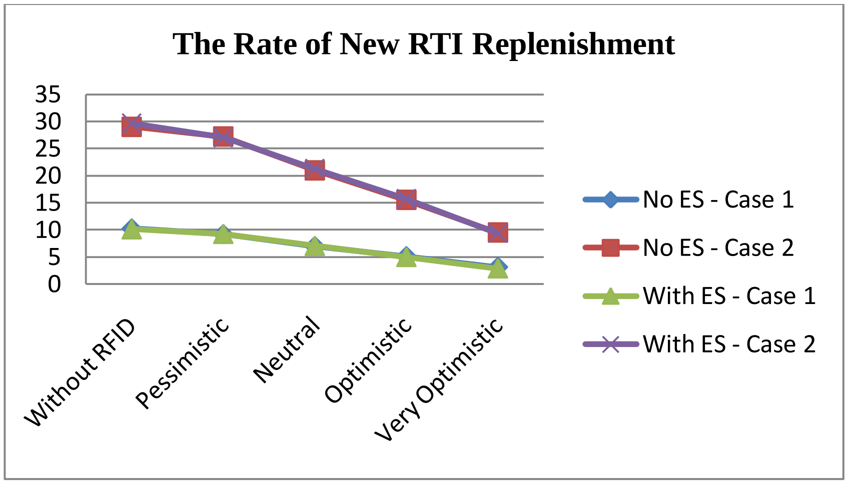

Figure 7.13: Average rate of new RTI replenishment in optimal solutions of all scenarios

Figure 7.14 shows the average cycle time in optimal solutions of all scenarios. In this figure, the upper (lower) line belongs to the more (less) problematic case. In addition, Figure 7.15 shows the average time spent in the field which is a part of the cycle time. As the extent of improvement increases, both cycle time and time spent in the field decrease less in the less problematic case compared to the more problematic case.

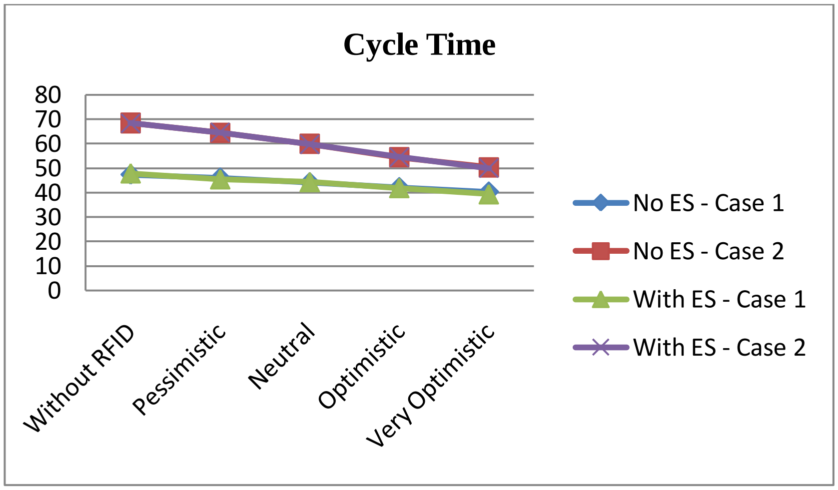

Figure 7.14: Average cycle time in optimal solutions of all scenarios

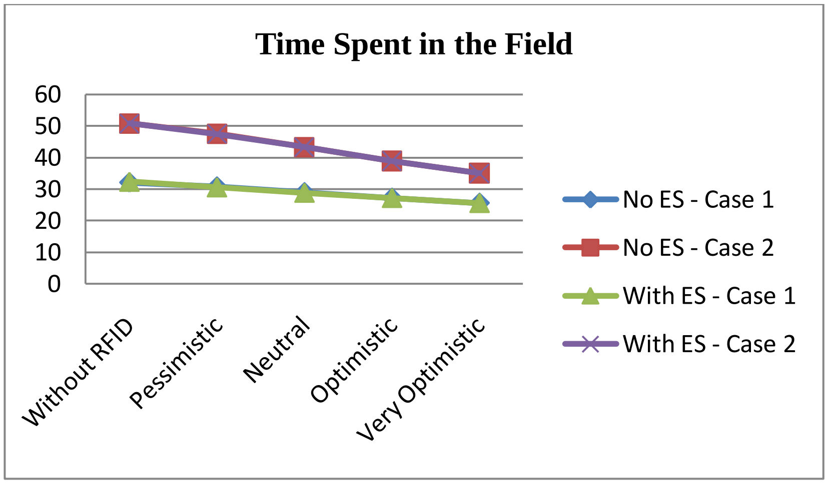

Figure 7.15: Average time spent in the field in optimal solutions of all scenarios

Figures 7.16 and 7.17 show the average trippage and the average useful lifetime of RTIs in optimal solutions of all scenarios. In these figures, the lower (upper) lines belong to the more (less) problematic case. The rates of increases in both of these performance measures rise as the level of improvement increases both in the more and in the less problematic cases.

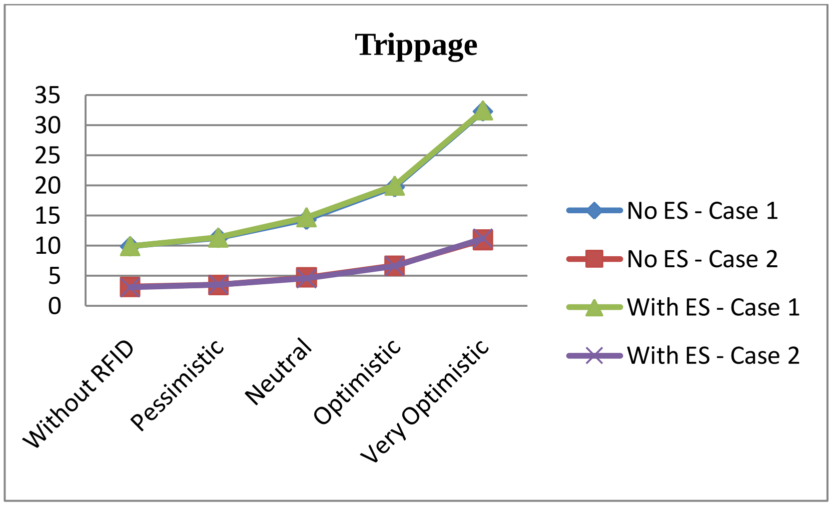

Figure 7.16: Average trippage in optimal solutions of all scenarios

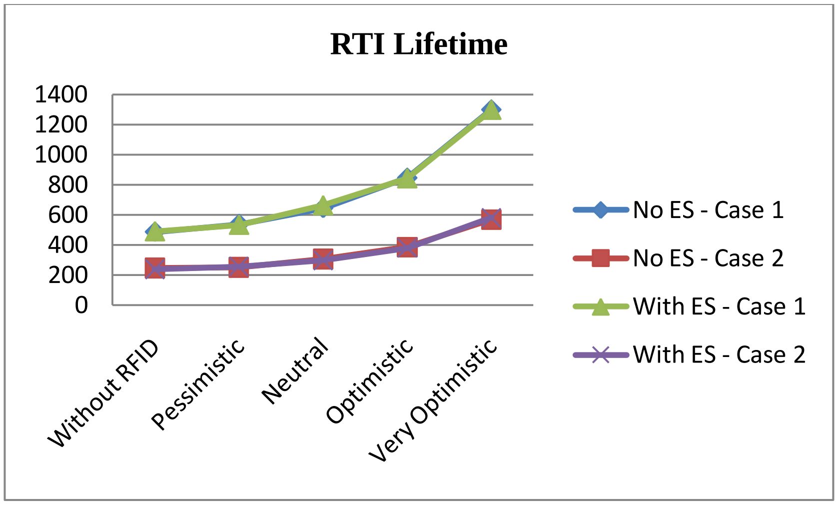

Figure 7.17: Average useful RTI lifetime in optimal solutions of all scenarios

7.6 Software Implementation

The software packages used in this study together with the purpose of using them are as follows:

1. Arena simulation software is used to develop the simulation models. This software together with Excel spreadsheets are used to generate data, for example ***Emptying Duration*** data.
2. Arena Input Analyzer is used to analyze both available and the generated data in order to find out the distribution of parameters required for the simulation models.
3. OptQuest for Arena optimization routine is used for the application of simulation optimization method.

The implementation issues related with the above software packages are explained in sections 7.6.1-7.6.3.

7.6.1 Arena Simulation Software

The simulation models are developed in parallel to the development of the problem definition. As some assumptions in the problem definition are modified and new ones are added to the problem definition, the simulation models are updated by adding the new decision rules or modifying the existing ones. The simulation models are updated conveniently with Arena since the models are composed of small units named as blocks. Each block has its own purpose. When a simulation model is needed to be modified, it is enough to change only the related blocks and elements. In the same way, the simulation models can be utilized after changing the related blocks and input parameters for similar problems and for different set of input parameters. As a result, they can be used to measure the effect of some policy changes on performance measures of RTI pool management. In brief, the main reasons for choosing Arena as simulation software can be summarized as the ease of modeling and updating the simulation models.

The simulation models are verified by debugging the process of the simulation runs with Arena’s run controller. This run controller has various commands to trace the flow of entities from the selected block, the flow of the selected entity through the blocks, the change of the selected variable, the change of the selected attribute value of active entities. It is also possible to trace the flow of all entities through all blocks at the same time. Using this run controller is a convenient and reliable way to verify the simulation models due to available trace options and the ease of use.

In addition to the development of the simulation models, Arena is also used to generate data. It is possible to read input from and write output to Excel spreadsheets with Arena. The required data are successfully generated with Arena and the generated data are written by Arena to Excel spreadsheets. In the Excel spreadsheets, the necessary operations to the generated data are completed and the required data sets are obtained. For instance, ***Emptying Duration*** data sets are obtained by firstly generating data with respect to ***Minimum Emptying Duration*** and ***Emptying Duration Distribution*** and secondly performing the required operations in Excel spreadsheets like sorting in order to find out ***Emptying Duration Distribution*** for different scenarios depicting the extent of the improvement that RFID technology provides. Using Arena for data generation is more convenient than using Arena Input Analyzer since the data is generated considering a minimum value and the generated data are needed in Excel spreadsheets for the operations necessary for obtaining ***Emptying Duration Distribution***'s for different scenarios.

7.6.2 Arena Input Analyzer

Arena Input Analyzer is used for

- Fitting distributions to the available data, for example to the data of ***Demand Interarrival Time***;
- Generating data from a given distribution, for example the data for the waiting time at empty RTI stock of DCs with uniform distribution.

It is an easy to use input analyzer. It has an option named 'Fit All', which checks every possible defined distribution and returns the best fitted one. In addition, it gives the formula of the fitted distribution in the format of Arena. So, its result can be directly copy-pasted to Arena without any change of format.

7.6.3 OptQuest for Arena

OptQuest is easy to use software only if the user has basic knowledge of optimization models. It tries to find the best value for the selected objective function by changing the value of the selected controls within their range in the simulation model. Its run time depends on several factors including

- the run time of a single replication of the simulation model,
- the number of replications per simulation (can be fixed and varying), and

- the number of simulations which depends on the size of the solution space determined by the controls (decision variables) and their ranges.

In our study, the run times of single replications of the simulation models are very large due to the high number of entities without the use of scaling. Because of this reason, scaling is used in order to reduce the run time. If our study was just a simulation study without the consideration of optimization, the run time would be acceptable. However, it is required to run the simulation models for each developed scenario for a high number of simulations each having five replications. With the help of scaling, the reasonable run times are obtained for finding the best solution for a scenario.

CHAPTER 8

CONCLUSIONS

In this study, we quantify the value of RFID technology for the management of RTI pools in a CLSC setting. We consider both the benefits and the costs of using RFID technology. We start our study with the literature review in order to discover all potential benefits of using RFID technology for RTI pool management in the CLSC of RTIs. We then provide a general quantification formula for all these potential benefits and costs.

We conduct a case study within an RFID pilot project in a company that sells its product in a single type of RTI. The aim of the case study is to identify and understand how an existing RTI pool is managed, as well as the impact of using RFID technology on the management of such an RTI pool. We define our problem environment in which we seek for the added value of using RFID technology based on the problem environment in the case study but with some simplifying assumptions. Based on the defined problem environment, the simulation models of the CLSC are developed and embedded into a simulation optimization tool in order to find out the difference between the optimal ways of RTI management with the use of RFID technology and without the use of RFID technology. The comparisons are made based on the developed scenarios portraying the severity of problems related with the use of RTIs (the less and the more problematic cases) and the extent of improvement that RFID technology brings about (pessimistic, neutral, optimistic and very optimistic).

In the less problematic case, the use of RFID technology is only profitable if the extent of improvement is neutral, optimistic or very optimistic. If the expected extent of improvement cannot exceed the pessimistic level, it is better not to use RFID technology. The threshold value for the extent of improvement is less in the more problematic case. The total cost of RTI pool management can be decreased with the use of RFID technology even if the extent of improvement stays at the pessimistic level.

The results have shown that the added value of RFID technology increases as the severity of the problems before the use of RFID technology and the extent of improvement provided by RFID technology increases, as expected. Besides, the added value is mostly positive in the less problematic case and always positive in the more problematic case for the investigated scenarios. As the extent of improvement provided by RFID increases, we observe the following outcomes:

- Total cost of RTI pool management decreases.
- Pool size and cycle time decrease.
- Trippage and RTI lifetime increase.

It is also observed that the option of emergency shipment is useless. Its effect both on the total cost of RTI pool management and on the other performance measures is insignificant. The reason behind this is the fact that the decisions regarding new RTI purchases are assumed to be made such that there will be no need for the emergency shipments of empty returns from DCs even when emergency shipment is allowed.

The percentage increases in trippage and RTI lifetime are driven by the extent of improvement that RFID provides, regardless of the severity of problems. As the extent of improvement provided by RFID increases, trippage and RTI lifetime increases with an increasing rate. The decrease in cycle time is mostly due to the decrease in time spent in the field. The rates of decreases in cycle time and pool size are larger in the more problematic case. Similar to RTI lifetime and trippage, the percentage decrease in the rate of new RTI replenishment is driven by the extent of improvement that RFID provides, regardless of the severity of problems.

In this study, we quantify the added value of using RFID technology for managing RTI pools by considering both costs and benefits, as well as the CLSC as a whole. Our conclusions only pertain to the defined problem environment and the chosen RFID configuration in our study. The potential benefits of RFID technology is expected to differ with respect to the characteristics of the problem environment and the configuration of RFID application. In addition, total cost values and the profitability of RFID technology are expected to change with respect to the cost parameters like unit RTI price and the length of planning horizon taken into account. It should also be noted that optimality is not guaranteed with the simulation optimization method since it includes stochasticity.

To the best of our knowledge, this study is the most comprehensive one on the value quantification of RFID technology for managing RTI pools. All aspects of the CLSC that can be known by the owner of the pool and every decision under her responsibility are taken into account. Although the results seem to be specific for the particular problem under study, they can be used for benchmarking to have an early impression about the added value of using RFID technology before carrying out a detailed study for initiating an RFID pilot project. The methodology developed for finding the optimal RTI pool management can be utilized even when using the RFID technology is not the issue. Our study is also a sample application of the simulation optimization method for a real life problem.

The area of this study requires further research in different modes of RTI pool management and in different types of CLSCs, especially to perceive the impact of using RFID technology in different cases. The true credibility of the positive value of RFID technology in RTI pool management can only be established with additional studies on different cases.

All in all, we suggest repeating a similar study on the cases having the following characteristics:

- Full RTI demand is non-stationary.
- RTI pool is shared (used) and owned by more than one manufacturer.
- The product can be supplied in several different substitutable RTIs.
- Additional RFID scan points are set at DCs and/or at the sites of end users.

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APPENDIX A

RFID Technology

Fosso Wamba et al. (2008) classify RFID technology as a wireless automatic identification and data capture (AIDC) technology. According to Hassan and Chatterjee (2006) "RFID technology characteristics differ along intended uses, physical dimensions, radio frequencies, and data storage". A growing literature explains technical aspects of RFID (Hedgepeth, 2007; Myerson, 2007; Sheng, Li, and Zeadally, 2008).

The RFID is essentially composed of three components as it can be seen from Figure A.1. The tags and the readers are the hardware components. The middleware is "the software that acts as a bridge between the data that the readers read from tags and a database" (Langer et al., 2007). A more complete description of the RFID technology, its emerging standards and potential uses can be found in Bhuptani and Moradpour (2005). Langer et al. (2007) describes the basic components as follows:

1. Tags: An RFID tag is a small transponder attached to the object to be tracked. The tag holds data that are transmitted to a reader when interrogated.

2. Readers: Readers are the interrogators and they track the tags. They collect and process the information that is embedded in the tags.

3. Middleware: Middleware translates signals into usable data and facilitates the actual data operations. These software applications help in monitoring and managing the data that RFID tags transmit and readers read. The data are then aggregated and standardized according to the specific application functionality. They can then be fed into the existing IT databases for reporting or other purposes.

Figure A.1: The basic elements of RFID technology are tags, readers, and middleware (Langer et al., 2007)

APPENDIX B

Barcode vs. RFID Tags

As stated by Ngai et al. (2008b), “the capability of RFID technology has been criticized as being too similar to that of the barcode”. Burnell (1999) infers that most of the functionality needed had already been achieved by barcode technology. On the other hand, Jones et al. (2005) discuss that a main reason for RFID diffusion is the capability of RFID tags to supply more information about products than traditional barcodes. Karkkainen (2003) points out the limitations of barcode data collection, including the necessity to read barcodes manually and poor barcode readability in some environments.

Manufacturing site, production lot, expiry date and components type are among information that can be stored into the tag chip. Moreover, tags do not need line-of-sight scanning to be read, since they act as passive tracking devices, broadcasting a radio frequency when they pass within yards of a reader (Karkkainen, 2003). On the other hand, adding barcodes requires manual operations on packages, that is either the packages with barcodes or the reading devices should be manually handled to read the codes (Boxall, 2000; Bylinsky, 2000; Jones, 1999). This may result in time consumption and difficult data capture if large amounts of goods have to be handled, such as in distribution centres or retail stores. In some cases, readability of barcodes can also be problematic, due to dirt and bending, bringing about reduced accuracy and low reading rate (Ollivier, 1995; Moore, 1999).

In conclusion, RFID is an emerging technology intended to replace traditional barcodes in many ways (Asif and Mandviwalla, 2005; Chuang, 2005; DoIT, 2004a–c, Wang et al., 2005). According to De Kok et al. (2008), more and more, RFID technology is expected to take the place of bar codes in the supply chain allowing manufacturers and retailers to know the exact location and quantity of their inventory without conducting time consuming audits at several points along the chain.

APPENDIX C

The Advantages and the Disadvantages of RFID Technology

As illustrated by Ngai et al. (2007a), RFID is an enabling technology that a company can adopt to enhance asset visibility and improve operations, like improving receiving and picking accuracies, and reducing human errors in handling repairable items by automation. Singer (2003) defines the four benefit factors of RFID technology as operational efficiency, accuracy, visibility, and security. Although RFID begins as a tool to attain operational efficiency, some practitioners believe that RFID could become the next major weapon for organizations to obtain strategic competitive advantage (Tzeng et al., 2008).

According to Green at al. (2005), RFID has all the ingredients to deliver benefits for a range of reasons:

- RFID is maturing and successful RFID projects in logistics have been implemented since the early 90’s.
- RFID greatly facilitates and automates labor-intensive work.
- RFID is non-intrusive. The flow of assets is not being disrupted and, as a result, the number of reads is not a limiting factor.

On the other hand, RFID has limitations that can challenge its wide adoption. The adoption of RFID requires a large investment with significant risk and careful planning (Kulwiec 2005). Several studies agree on that the main limit to a wide use of RFID technology is its cost (Prater et al., 2005; Karkkainen and Holmstrom, 2002; Burnell, 1999; Riso, 2001). In addition to the fixed costs of the purchase and the implementation of the necessary infrastructure, especially the substantial cost of RFID tags seems to prohibit extensive use at the item level (Heese, 2007).

Tzeng et al. (2008) indicate that the implementation of RFID is not just buying hardware and software. It requires the organization to undertake business process re-engineering. Langer et al. (2007) point out that a key determinant of the success of a firm's RFID implementation is the extent that firm can change its business processes to leverage the technology most effectively. In order to gain benefit from any technology, a firm is required to redesign its business processes or distinguish innovative uses for that technology (Bresnahan and Greenstein 1996).

A survey by the Computing Technology Industry Association uncovers that 80% of the responding companies said that there were not sufficient numbers of skilled RFID professionals. As indicated by two-thirds of them that training their employees in RFID technology was one of the biggest challenges in order to succeed in the RFID market (Morrison, 2005).

In the early phase of RFID technology, its limitations are related to its high cost and the improbability of an investment pay-off (Burnell, 1999; Riso, 2001). However, according to Jones et al. (2005), the price of an RFID tag was about $1 in 2000, had fallen to $0.25–0.35 by early 2004, and is expected to drop to around $0.05 as RFID technology becomes more widely adopted. Langer et al. (2007) indicate that retail giants, such as Wal-Mart and Gillette, have reported optimistic news detailing real and anticipated savings because of their pioneering RFID efforts (Faber 2005). Such reports suggest that RFID is being adopted extensively and that it is beginning to deliver value according to Langer et al. (2007). On the other hand, Tzeng et al. (2008) asserts that RFID applications are still in their infancy and their contributions to enterprises are still unproven.

Langer et al. (2007) agree with Katz (2005) and state that “Industry Week reported that manufacturers have been finding it difficult to financially justify its implementation because they have been unable to make a good business case”. Katz (2005) suggests that manufacturers and suppliers may be adopting RFID only to comply with demands from key customers like Wal- Mart. Many of them seem to be limiting their RFID projects to meet the minimum requirements of these customer demands.

APPENDIX D

The Simulation Model for Generating Demand Data

The simulation model is built in Arena. Its model and experimental frames are given below.

Model Frame

```
0$          CREATE,      1:,1:NEXT(16$);

16$          ASSIGN:      DC_ID=1;
2$          ASSIGN:      Demand_Arriving_Time_DC1=TNOW:
                      Demand_Size_DC_1=DISC(0.07,20,0.43,40,1.0,60):NEXT(1$);


;
;
;    Model statements for module:  AdvancedProcess.ReadWrite 1 (Demand Arriving
Time DC1)
;
1$          WRITE,       Demand,RECORDSET(AT_All),Record_Number:
                      Demand_Arriving_Time_DC1:NEXT(21$);


;
;
;    Model statements for module:  AdvancedProcess.ReadWrite 8 (DC ID 1)
;
21$          WRITE,       Demand,RECORDSET(IDs),Record_Number:
                      DC_ID:NEXT(4$);


;
```

```
;
;    Model statements for module:  AdvancedProcess.ReadWrite 3 (Demand Size DC1)
;
4$          WRITE,        Demand,RECORDSET(DS_All),Record_Number:
                          Demand_Size_DC_1:NEXT(13$);

13$         ASSIGN:       Record_Number=Record_Number+1;
3$          DELAY:        MAX(0,-0.5 + 6 * BETA(8.3, 23.5)),,Other:NEXT(2$);


17$         CREATE,       1:,1:NEXT(18$);

18$         ASSIGN:       DC_ID=2;
6$          ASSIGN:       Demand_Arriving_Time_DC2=TNOW:
                          Demand_Size_DC_2=DISC(0.02,20,0.04,40,1.0,60):NEXT(5$);



;
;
;    Model statements for module:  AdvancedProcess.ReadWrite 4 (Demand Arriving
Time DC2)
;
5$          WRITE,        Demand,RECORDSET(AT_All),Record_Number:
                          Demand_Arriving_Time_DC2:NEXT(22$);



;
;
;    Model statements for module:  AdvancedProcess.ReadWrite 9 (DC ID 2)
;
22$         WRITE,        Demand,RECORDSET(IDs),Record_Number:
                          DC_ID:NEXT(8$);



;
;
;    Model statements for module:  AdvancedProcess.ReadWrite 5 (Demand Size DC2)
;
8$          WRITE,        Demand,RECORDSET(DS_All),Record_Number:
                          Demand_Size_DC_2:NEXT(14$);

14$         ASSIGN:       Record_Number=Record_Number+1;
7$          DELAY:        MAX(0,-0.5 + LOGN(1.98, 1.07)),,Other:NEXT(6$);


19$         CREATE,       1:,1:NEXT(20$);
```

```
20$         ASSIGN:      DC_ID=3;
10$         ASSIGN:      Demand_Arriving_Time_DC3=TNOW:
                    Demand_Size_DC_3=DISC(0.01,20,0.23,40,1.0,60):NEXT(9$);


;
;
;     Model statements for module:  AdvancedProcess.ReadWrite 6 (Demand Arriving Time DC3)
;
9$          WRITE,       Demand,RECORDSET(AT_All),Record_Number:
                    Demand_Arriving_Time_DC3:NEXT(23$);


;
;
;     Model statements for module:  AdvancedProcess.ReadWrite 10 (DC ID 3)
;
23$         WRITE,       Demand,RECORDSET(IDs),Record_Number:
                    DC_ID:NEXT(12$);


;
;
;     Model statements for module:  AdvancedProcess.ReadWrite 7 (Demand Size DC3)
;
12$         WRITE,       Demand,RECORDSET(DS_All),Record_Number:
                    Demand_Size_DC_3:NEXT(15$);

15$         ASSIGN:      Record_Number=Record_Number+1;
11$         DELAY:       MAX(0,-0.5 + ERLA(0.396, 7)),,Other:NEXT(10$);
```

Experiment Frame

```
PROJECT,      "Demand Data
Generation","test",29/07/2010,No,No,No,No,No,No,No,No,No,No,No;

ATTRIBUTES:   DC_ID,DATATYPE(Real);

FILES:       Demand,"C:\Users\S099377\Desktop\Input Data Analysis\Demand Data
Generation\GeneratedDemandData.xls",MSExcel,,

Error,,Hold,RECORDSET(AT_All,"Arrival_Time_All",512),RECORDSET(DS_All,"
Demand_Size_All",512),RECORDSET(IDs,"DC_ID",512);

VARIABLES:    Demand_Size_DC_1,CLEAR(System),CATEGORY("User
Specified-User Specified"),DATATYPE(Real):
            Demand_Size_DC_2,CLEAR(System),CATEGORY("User Specified-User
Specified"),DATATYPE(Real):
            Demand_Size_DC_3,CLEAR(System),CATEGORY("User Specified-User
Specified"),DATATYPE(Real):
            Demand_Arriving_Time_DC1,CLEAR(System),CATEGORY("User
Specified-User Specified"),DATATYPE(Real):
            Demand_Arriving_Time_DC2,CLEAR(System),CATEGORY("User
Specified-User Specified"),DATATYPE(Real):
            Demand_Arriving_Time_DC3,CLEAR(System),CATEGORY("User
Specified-User Specified"),DATATYPE(Real):
            Record_Number,CLEAR(System),CATEGORY("None-
None"),DATATYPE(Real),1;

REPLICATE,    1,0.0,380,Yes,Yes,0.0,,,24.0,Days,No,No,,,No,No;
```

APPENDIX E

RFID Data Cleaning

It is realized that RFID data regarding ***Time Spent in the Field*** had inconsistent entries. There are data points stating unrealistically small and large values for ***Time Spent in the Field.*** Because of this reason, we have removed unrealistic data points which are either

- Smaller than the minimum realistic value, or
- Larger than the maximum realistic value of ***Time Spent in the Field***.

The minimum realistic value of ***Time Spent in the Field*** is calculated for all of DCs according to Table E.1.

Table E.1: The calculation of the minimum realistic value of ***Time Spent in the Field*** for all DCs

Activity	**Minimum Assumed Duration (days)**
Transportation to DC	1
Waiting time at DC (full)	1
Transportation to end user	1
Waiting time at end user (full)	1
Emptying at end user	1
Waiting time at end user (empty)	1
Transportation from end user	1
Waiting time at DC (empty)	1
Transportation from DC	1
TOTAL	**9**

The maximum realistic value of ***Time Spent in the Field*** is calculated for DC-1 as shown in Table E.2. The maximum duration between the time that a full RTI leaves the manufacturer and the time it enters the empty RTI stock of the end user is at most 75 days, which is the shelf life of the product. When the shelf life ends, the end user is expected to move the RTI to its empty RTI stock even it is half-empty at that time. Considering the average full RTI demand of DC-1, it is expected to make empty RTI shipments to the manufacturer 1 in 8 days on average. As a result, this value is taken as the maximum assumed value for the waiting time at the empty RTI stock of DC-1.

Table E.2: The calculation of the maximum realistic value of ***Time Spent in the Field*** for DC-1

Activity	**Maximum Assumed Duration (days)**
Waiting at the manufacturer	75
Transportation to DC	
Waiting time at DC (full)	
Transportation to end user	
Waiting time at end user (full)	
Emptying at end user	
Waiting time at end user (empty)	1
Transportation from end user	1
Waiting time at DC (empty)	8
Transportation from DC	1
TOTAL	**86**

The same values for the other two DCs are calculated in a similar way. Table E.3 shows maximum realistic values of ***Time Spent in the Field*** for all DCs.

Table E.3: The maximum realistic values of ***Time Spent in the Field*** for all DCs

DC	**Maximum Assumed Value (days)**
1	86
2	87
3	93

APPENDIX F

The Estimation of Emptying Duration

DCs make shipments of returns once they have a ***FTL of Empty RTIs***. As a result, we can conclude that the stock level of RTI returns at DCs fluctuate between 0 and ***FTL of Empty RTIs***. Assuming that empty RTIs return to DCs at a constant rate, average WIP level of empty RTIs at DCs should be $(\boldsymbol{FTL\ of\ Empty\ RTIs} + 0)/2$. We also know the average demand rate of DCs and the average demand rate can be seen as the RTI throughput (TH) of DCs. ***Probability Of Field Loss*** is ignored because its effect is insignificant in such an estimation having days as time unit. With the information regarding WIP and throughput, Little's formula $(CT = WIP/TH)$ give us average cycle time (CT) that RTIs spent in DCs. With the assumption that empty RTIs return to DCs at a constant rate, we can conclude that the waiting time at DCs uniformly distributed between 0 and 2CT. With the addition of the transportation time between DCs and the manufacturer, the time difference between ***Time Spent in the Field*** and ***Emptying Duration*** is estimated to be uniformly distributed between 0 and 2CT days. Since we need to fit normal distribution to this time difference, we generated data (5000 data points) with U(0, 2CT) and then fit a normal distribution to the generated data. The fitted normal distribution has the following parameters shown in Table F.1.

Table F.1: The parameters of the fitted normal distribution of the waiting time at the empty RTI stock of DCs

	Mean (days)	**Standard deviation (days)**
DC-1	3.81	2.21
DC-2	4.77	2.80
DC-3	7.75	4.51

The time difference between ***Time Spent in the Field*** and ***Emptying Duration*** is the total of waiting time at the empty RTI stock of DCs, the transportation times from the DC to the manufacturer and from the manufacturer to the DC. The total transportation time is constant and it is 2 days. If X is a random variable normally distributed with mean μ and standard deviation σ, then $X + a$ is also be normally distributed with mean $\mu + a$ and standard deviation σ. As a result, the time difference ***Time Spent in the Field*** and ***Emptying Duration*** is expected to be normally distributed with the parameters given in Table F.2

Table F.2: The parameters of the fitted normal distribution to the difference between ***Time Spent in the Field*** and ***Emptying Duration***

	Mean (days)	**Standard deviation (days)**
DC-1	5.81	2.21
DC-2	6.77	2.80
DC-3	9.75	4.51

APPENDIX G

The Simulation Model for Generating Emptying Duration Data

The simulation model is built in ARENA. Its model and experimental frames are as follows:

Model Frame

```
$         CREATE,      1:,1:NEXT(2$);

2$                                                                ASSIGN:
Emptying_Duration_DC1=Emptying_Duration_Distribution_DC1:NEXT(1$);

;
;
;    Model statements for module:  AdvancedProcess.ReadWrite 1 (Emptying Duration
DC1)
;
1$                WRITE,              EmptyingDuration,RECORDSET(Recordset
1),Record_Number_DC1:
                  Emptying_Duration_DC1:NEXT(15$);

15$        BRANCH,      1:
                  If,Emptying_Duration_DC1>=Minimum_Emptying_Time,10$,Yes:
                  If,Emptying_Duration_DC1<Minimum_Emptying_Time,3$,Yes;
10$        ASSIGN:       Record_Number_DC1=Record_Number_DC1+1;
3$         DELAY:        1,,Other:NEXT(2$);


13$        CREATE,      1:,1:NEXT(5$);

5$                                                                ASSIGN:
Emptying_Duration_DC2=Emptying_Duration_Distribution_DC2:NEXT(4$);
```

```
;
;
;     Model statements for module:  AdvancedProcess.ReadWrite 4 (Emptying Duration
DC2)
;
4$                    WRITE,               EmptyingDuration,RECORDSET(Recordset
2),Record_Number_DC2:
                      Emptying_Duration_DC2:NEXT(16$);

16$          BRANCH,       1:
                      If,Emptying_Duration_DC2>=Minimum_Emptying_Time,11$,Yes:
                      If,Emptying_Duration_DC2<Minimum_Emptying_Time,6$,Yes;
11$          ASSIGN:       Record_Number_DC2=Record_Number_DC2+1;
6$          DELAY:        1,,Other:NEXT(5$);


14$          CREATE,       1:,1:NEXT(8$);

8$                                                                          ASSIGN:
Emptying_Duration_DC3=Emptying_Duration_Distribution_DC3:NEXT(7$);


;
;
;     Model statements for module:  AdvancedProcess.ReadWrite 6 (Emptying Duration
DC3)
;
7$                    WRITE,               EmptyingDuration,RECORDSET(Recordset
3),Record_Number_DC3:
                      Emptying_Duration_DC3:NEXT(17$);

17$          BRANCH,       1:
                      If,Emptying_Duration_DC3>=Minimum_Emptying_Time,12$,Yes:
                      If,Emptying_Duration_DC3<Minimum_Emptying_Time,9$,Yes;
12$          ASSIGN:       Record_Number_DC3=Record_Number_DC3+1;
9$          DELAY:        1,,Other:NEXT(8$);
```

Experiment Frame

```
PROJECT, "Emptying Duration Data
Generation","test",29/07/2010,No,No,No,No,No,No,No,No,No,No,No;

FILES:	EmptyingDuration,
	"C:\Users\S099377\Desktop\Input Data Analysis\Emptying Duration Data
Generation\EmptyingDurationGeneration.xls",
	MSExcel,,Error,,Hold,RECORDSET(Recordset
1,"DC_1",512),RECORDSET(Recordset 2,"DC_2",512),RECORDSET(Recordset
3,"DC_3",512);

VARIABLES:	Record_Number_DC1,CLEAR(System),CATEGORY("None-
None"),DATATYPE(Real),1:
	Record_Number_DC2,CLEAR(System),CATEGORY("None-
None"),DATATYPE(Real),1:
	Record_Number_DC3,CLEAR(System),CATEGORY("None-
None"),DATATYPE(Real),1:
	Emptying_Duration_DC1,CLEAR(System),CATEGORY("User Specified-
User Specified"),DATATYPE(Real):
	Emptying_Duration_DC2,CLEAR(System),CATEGORY("User Specified-
User Specified"),DATATYPE(Real):
	Emptying_Duration_DC3,CLEAR(System),CATEGORY("User Specified-
User Specified"),DATATYPE(Real):
	Minimum_Emptying_Time,CLEAR(System),CATEGORY("None-
None"),DATATYPE(Real),6;

REPLICATE,
1,0.0,10000,Yes,Yes,0.0,(Record_Number_DC1>=5001)&&(Record_Number_DC2>=
5001)&&(Record_Number_DC3>=5001),,24.0,Days,
	No,No,,,No,No;


EXPRESSIONS:

Emptying_Duration_Distribution_DC1,DATATYPE(Native),NORM(21.5,10.5):


Emptying_Duration_Distribution_DC2,DATATYPE(Native),NORM(22.5,12.7):


Emptying_Duration_Distribution_DC3,DATATYPE(Native),NORM(25.9,16.0);
```

APPENDIX H

The Calculation of Purchasing Lot Size

Purchasing Lot Size for the scenarios of the less and the more problematic cases are found separately according to modified EOQ method. Tables H.1-H.5 show the calculation of ***Purchasing Lot Size*** for the scenarios in the less problematic case. On the other hand, Tables H.6-H.10 show the calculation of ***Purchasing Lot Size*** for the scenarios in the more problematic case. The first columns in these tables show the number of shipments required to transport a replenishment size whose minimum and maximum values can be found in the next two columns. The columns named with "EOQ", "Best Value" and "Unit Purchasing Cost" show the values of $Q^{n\prime}$, Q^{n*} and $Y(Q)$ for each n, respectively. The difference between the values of unit purchasing costs provided by the best values for ***Purchasing Lot Size*** of n and $n+1$ is found to be at most 2% (and in most of the cases less than 1%). Because of this reason, for the times when a replenishment having a size of ***Purchasing Lot Size*** is not enough to raise the inventory position above ***Reorder Point for Purchasing***, it is found suitable to use the minimum integer number of multiples of ***Purchasing Lot Size*** which is enough to raise the inventory position above ***Reorder Point for Purchasing***.

Table H.1: The calculation of ***Purchasing Lot Size*** for the situation without the use of RFID technology in the less problematic case

The Less Problematic Case - Without RFID					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**469.4**	**380**	**122.18**
2	381	760	663.8	664	123.01
3	761	1140	813.0	813	123.69
4	1141	1520	938.8	1141	124.34
5	1521	1900	1049.6	1521	125.10
6	1901	2280	1149.8	1901	125.89
7	2281	2660	1241.9	2281	126.71
8	2661	3040	1327.7	2661	127.54
Minimum Cost Value					122.18

Table H.2: The calculation of Purchasing Lot Size for the situation with the use of RFID technology (the extent of improvement: pessimistic) in the less problematic case

The Less Problematic Case - With RFID (Pessimistic)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**445.9**	**380**	**122.27**
2	381	760	630.6	631	123.17
3	761	1140	772.3	772	123.88
4	1141	1520	891.8	1141	124.62
5	1521	1900	997.1	1521	125.47
6	1901	2280	1092.2	1901	126.36
7	2281	2660	1179.8	2281	127.27
8	2661	3040	1261.2	2661	128.19
Minimum Cost Value					122.27

Table H.3: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: neutral) in the less problematic case

The Less Problematic Case - With RFID (Neutral)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**394.3**	**380**	**122.54**
2	381	760	557.6	558	123.59
3	761	1140	682.9	761	124.42
4	1141	1520	788.5	1141	125.42
5	1521	1900	881.6	1521	126.54
6	1901	2280	965.7	1901	127.69
7	2281	2660	1043.1	2281	128.87
8	2661	3040	1115.1	2661	130.06
Minimum Cost Value					122.54

Table H.4: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: optimistic) in the less problematic case

The Less Problematic Case - With RFID (Optimistic)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**334.1**	**335**	**122.99**
2	381	760	472.5	472	124.23
3	761	1140	578.6	761	125.38
4	1141	1520	668.2	1141	126.86
5	1521	1900	747.0	1521	128.46
6	1901	2280	818.3	1901	130.09
7	2281	2660	883.9	2281	131.75
8	2661	3040	944.9	2661	133.42
Minimum Cost Value					122.99

Table H.5: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: very optimistic) in the less problematic case

The Less Problematic Case - With RFID (Very Optimistic)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**259.4**	**260**	**123.86**
2	381	760	366.8	381	125.46
3	761	1140	449.3	761	127.63
4	1141	1520	518.8	1141	130.23
5	1521	1900	580.0	1521	132.95
6	1901	2280	635.3	1901	135.71
7	2281	2660	686.3	2281	138.49
8	2661	3040	733.6	2661	141.28
Minimum Cost Value					123.86

Table H.6: The calculation of ***Purchasing Lot Size*** for the situation without the use of RFID technology in the more problematic case

The More Problematic Case - Without RFID					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**791.9**	**380**	**121.62**
2	381	760	1120.0	760	121.92
3	761	1140	1371.7	1140	122.22
4	1141	1520	1583.9	1520	122.53
5	1521	1900	1770.8	1771	122.82
6	1901	2280	1939.8	1940	123.09
7	2281	2660	2095.3	2281	123.35
8	2661	3040	2239.9	2661	123.62
Minimum Cost Value					121.62

Table H.7: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: pessimistic) in the more problematic case

The More Problematic Case - With RFID (Pessimistic)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**754.3**	**380**	**121.65**
2	381	760	1066.8	760	121.98
3	761	1140	1306.5	1140	122.32
4	1141	1520	1508.6	1509	122.65
5	1521	1900	1686.7	1687	122.96
6	1901	2280	1847.7	1901	123.25
7	2281	2660	1995.7	2281	123.54
8	2661	3040	2133.5	2661	123.84
Minimum Cost Value					121.65

Table H.8: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: neutral) in the more problematic case

The More Problematic Case - With RFID (Neutral)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**670.6**	**380**	**121.74**
2	381	760	948.3	760	122.16
3	761	1140	1161.5	1140	122.58
4	1141	1520	1341.1	1341	122.98
5	1521	1900	1499.4	1521	123.33
6	1901	2280	1642.6	1901	123.69
7	2281	2660	1774.2	2281	124.07
8	2661	3040	1896.7	2661	124.46
Minimum Cost Value					121.74

Table H.9: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: optimistic) in the more problematic case

The Less Problematic Case - With RFID (Optimistic)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**571.2**	**380**	**121.90**
2	381	760	807.8	760	122.48
3	761	1140	989.4	989	123.03
4	1141	1520	1142.4	1142	123.50
5	1521	1900	1277.3	1521	123.97
6	1901	2280	1399.2	1901	124.49
7	2281	2660	1511.3	2281	125.03
8	2661	3040	1615.6	2661	125.58
Minimum Cost Value					121.90

Table H.10: The calculation of ***Purchasing Lot Size*** for the situation with the use of RFID technology (the extent of improvement: very optimistic) in the more problematic case

The More Problematic Case - With RFID (Very Optimistic)					
n	**Min**	**Max**	**EOQ**	**Best Value**	**Unit Purchasing Cost**
1	**0**	**380**	**445.9**	**380**	**122.27**
2	381	760	630.6	631	123.17
3	761	1140	772.3	772	123.88
4	1141	1520	891.8	1141	124.62
5	1521	1900	997.1	1521	125.47
6	1901	2280	1092.2	1901	126.36
7	2281	2660	1179.8	2281	127.27
8	2661	3040	1261.2	2661	128.19
Minimum Cost Value					122.27

APPENDIX I

The Fill Rates of the Optimal Solutions

The following figures show the change of fill rates with respect to optimal solutions of scenarios. In all optimal solutions, the target service level of 95% fill rate for satisfying the full RTI demand is fulfilled.

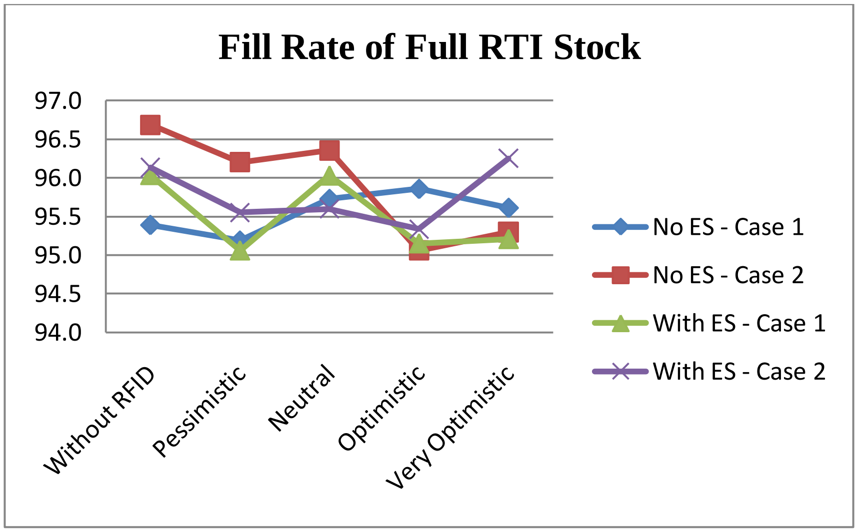

Figure I.1: The values of the fill rate of the full RTI stock at the manufacturer in optimal solutions of scenarios

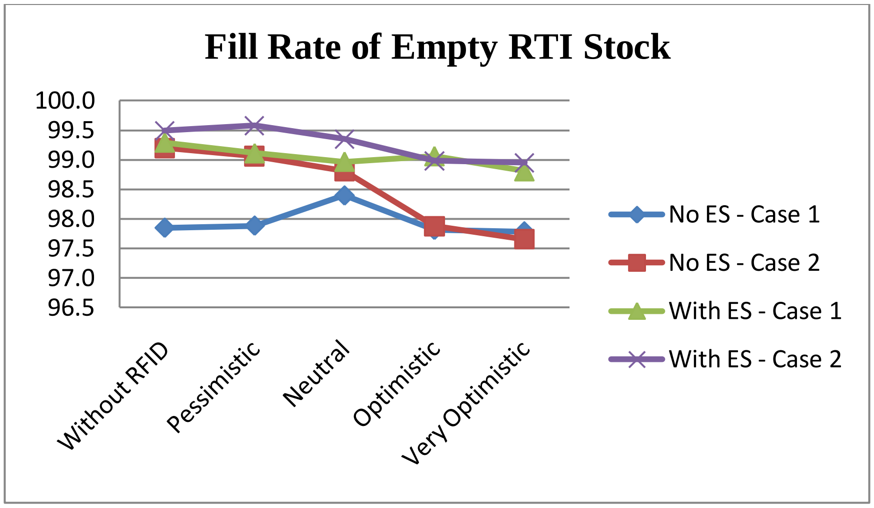

Figure I.2: The values of the fill rate for satisfying the demand of the filling operation in optimal solutions of scenarios