INTEGRATION AND OPERATION OF PROGNOSTICS IN LOGISTICS SYSTEMS

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INTEGRATION AND OPERATION OF PROGNOSTICS IN LOGISTICS SYSTEMS

Proefschrift

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To my parents

Preface

The work presented in this thesis has been supported by the prognostics integrated logistics project (PILOT) of the TRANSUMO research program, and has been developed at the Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology.

I would like to thank my promotor, Prof. dr. ir. Gabriel Lodewijks for all the support he gave me, even in his busiest hours he would always find time to listen to my ideas and support me in my decisions. I am very grateful to Dr. ir Hans Veeke, with whom I had the privilege to work almost on a daily basis, and who thought me not to just solve the *problems correctly* but to identify the *correct problems*.

To all my colleagues in the group of Transport Engineering and Logistics a huge thanks for making this experience a very positive one. I could not have asked for better colleagues and a better environment to pursue my PhD research, I will definitely miss Friday's ”Koffietijd”.

Finally, my deepest gratitude goes to my family. My parents, Edgar and Amelia, who always supported me and encouraged to exceed my expectations, even if this was from 8500km away from home. My sister Juliana and her husband Theodore, who helped me through troubled moments and gave me confidence in the hardest times. Lastly, but most certainly, not least, my best friend and my partner, Hugh, whose love and support always reminded me of the important things in life, and with whom I look forward to starting the next stage of my life.

Contents

CHAPTER 1

Introduction

Logistics plays a vital role in today's modern life. From the worldwide express operations of parcels to the maintenance, repair and overhaul operations of aircrafts, the number of elements involved in logistics and/or their value can be very high. No matter the context in which applied, logistics deals with all the activities necessary to optimize resources, maximize performance and minimize costs (Martin, 2005).

Early definitions of logistics refer mainly to military applications (Simpson and Weiner, 1989). In (Luttwak, 1971) logistics is described as:

All the activities and methods connected with the supply of armed force organizations, including storage requirements, transport and distribution.

Over the years, the interest in logistics moved to the business area. In the business context, logistics is defined as (Cavinato, 1982):

The management of all inbound and outbound materials, parts, supplies, and finished goods. Logistics consists of the integrated management and purchasing, transportation, and storage in a functional basis.

The above definitions focus mainly on the flow of physical goods. The flow of information was not included in the definition of logistics until 1988 when the Council of Logistics Management integrated the flow of information with the flow of materials, work in process and finished goods. The Council of Logistics

Management (CLM) defines logistics as (CLM, 1998):

The process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements.

The integration of the information flow in the CLM definition of logistics supports the idea of information being a logistic resource to gain competitive advantage (Closs et al., 1997). In (Langley, 1985), Ballou's definition of logistics, having the right product, at the right place at the right time (Ballou, 1992), was shown to be equally relevant in the management of information. Logistics systems are designed to add place value and time value to products according to customer needs (Introna, 1993). On-time delivery, order status, completeness of the order, are only some of areas that logistics systems try to prioritize as being conceived highly important for customer requirements. These activities not only represent the proper management of logistics systems but heavily depend upon a timely and accurate flow of meaningful information (Langley, 1985). Having the right information, at the right place at the right time is crucial to coordinate logistics systems and fulfill customer demands.

Information systems transform data into information that is useful for the end user (Introna, 1993). Information technology (IT) is used to realize information systems and to add value to logistic processes. Effective IT has become necessary to support logistics systems (LaLonde and Masters, 1994). In (Bhatnagar et al., 1999), (Closs et al., 1997), and (Daugherty et al., 1995) , IT is seen as a mean that can improve logistical efficiency, effectiveness, productivity, flexibility, costs, and service quality. The Global Logistics Research Team (GLR, 1995), defines information technology capabilities as *"the application of hardware, software and networks to enhance information flow and facilitate decisions"*. Adoption and successful implementation of IT is seen as a prerequisite for logistics success.

IT helps to automate routine logistic activities, and to facilitate the flow and sharing of information among different members in logistic systems (Lai et al., 2006). Sharing meaningful information may lead to high visibility (Barrat and Oke, 2007). Logistics visibility can be defined as the extent to which the position or location of an object, service, or information and its status are known in a logistic system (Lodewijks et al., 2006). Some of the benefits of improved visibility are suggested to be: Improved responsiveness ((Berry et al., 1994), (Patterson et al., 2004)) , improved decision making ((Kent and Mentzer, 2003), (Mentzer et al., 2000)), improved quality of products (Armistead and Mapes, 1993). Visibility in logistics systems is limited. This may partly depend on the lack of willingness to share information among members of the logistics system, and also, on the lack of quality, timely and accuracy of the information shared.

Logistics visibility can be improved by using automatic identification technologies (Auto- ID). Auto-ID is a broad term given to a host of technologies that are used to help machines to identify objects. These include bar codes, smart cards, voice recognition, some biometric technologies (e.g. retinal scans), optical character recognition, and radio frequency identification (RFID). The logistic visibility of objects can be further improved by automatic data capture. Automatic data capture enables the automated transfer of data attached to an object to a data storage environment like an enterprise resource planning system (ERP). This reduces data entry errors and frees up staff to perform more valued added functions. Where the application of, for example bar codes, may still require human involvement, the application of RFID in theory enables automated data capture.

Radio Frequency IDentification or RFID is an automatic identification technology that enables data capture and identification without contact or direct line of sight (Finkenzeller, 2003). RFID not only increases the amount of data captured at different locations in a logistics system, but also, enables tracking and tracing of (valuable) items as they move from one subsystem to another; making logistics systems more responsive and effective to possible disturbances and uncertainties. RFID is a technology that can provide data fast, accurately, and continuously and in real time. The large amounts of data that can be generated by such a technology need to be handled precisely so meaningful information can be derived and shared through the logistics system.

The visibility gained by constant monitoring processes and subsystems, such as the product flow from the point of origin to the point of consumption, creates knowledge on the true cause and effect relationship that exists within logistics systems. The knowledge gained, enables the ability to effect and control change in the system (Introna, 1993). This will create logistics systems capable of adapting to generate the desired state required at any point in time, and with the ability to control and reduce the variability, randomness or risk by introducing prognostics capabilities.

Integrating prognostics into today's logistics systems involves the combination of high quality data in decision making processes, and more responsive logistics systems to timely react to disturbances. By using prognostics, different members of a logistics system can be prepared and react (adapt) to situations that in previous cases could have severely disrupted the normal functioning of the overall system. The anticipated benefits of using prognostics integrated logistics are substantial improvements in e.g. logistic services, safety, reliability and flexibility. Furthermore, it is expected that prognostics integrated logistics will reduce, for example: the number of transport movement and CO_2 emissions, maintenance costs and operational costs.

1.1 Aim of the Thesis

The aim of the thesis is to introduce the concept of prognostics logistics. Prognostics integrated logistics or prognostics logistics is the combination of using timely and accurate information into a decision making system to generate prognoses of possible disturbances in order to improve the performance of logistics systems. By applying prognostics logistics, the planning, implementing and controlling functions, in charge to enhance responsiveness and efficiency in logistics systems, are expected to be improved.

The two main research questions in this thesis are:

- What is necessary to integrate prognostics into logistics systems?
- What are the benefits (if any) of using prognostics integrated logistics?

The first question can be answered by identifying two main elements in prognostics logistics: an information system and a decision making system. The information system basically includes sensors, data acquisition systems, communication technologies, and microprocessor-based software in order to fully analyze the collected data, and transform it into useful information. Data capture is the main process in the information system. The confidence of the future predictions in prognostics logistics depends on the quality of the information that can be derived from the acquired data. The data acquisition is expected to be done fast, in real time or nearly real time, and almost without human involvement in order to reduce errors and automate the logistics support system.

The required level of data capture depends on the desired prognostics capability. Logistic systems are composed of subsystems in charge of fulfilling a specific function within the whole system. With the knowledge gained by monitoring logistics systems, it is possible to determine in what subsystem(s) visibility should be increased by acquiring more specific data. This will create an infrastructure capable of adjusting to logistics demands and able to function as an adaptable network based on accurate anticipation of logistics requirements.

The decision making system uses the derived information to perform prognoses about the future condition of a system. The prognoses are based on a model of the logistic system and are designed to provide fast situation awareness in order to detect future possible problems early. With accurate prognoses, the logistic system is expected to timely allocate resources where needed, continuously reduce operation and labor costs, and optimize the planning, scheduling and control of activities.

The accuracy of the predictions in prognostic logistics relies on the timely and accuracy of the data. These characteristics depend on the data capture system. Logistic managers constantly recur to technological tools to improve everyday practice ((Kerr, 1990), (Lai et al., 2006), (Introna, 1993), (Closs et al., 1997)). Recently, RFID has received a lot of attention in industry. Although applications of RFID in logistics systems emerged in the 1980's, the popularity of RFID grew significantly when Wal-Mart and the United States Department of Defense (DoD) mandated all their suppliers to comply with their RFID programs. In (Cooke, 2004b), a survey indicates adoption rates of 60% among larger companies, with leading industries being automotive (59% implementation rate for 2007), consumer goods (58%), and transportation logistics (58%). Although it seems to be a high enthusiasm for RFID implementation, a closer look to this percentages show that most of them derive from the Walt-mart mandates (Morton, 2004). Besides, most of the companies implementing RFID are focusing on minimal compliance to meet Wal-Mart and DoD requirements (Cooke, 2004a). In (Cooke, 2004c), it is predicted that widespread RFID implementation will not occur until 2010. One of the reasons for such an assertion is the lack of understanding of RFID technology due to misguiding and inaccurate information available ((Johnson, 2005), (Murphy-Hoye et al., 2005)).

Prognostics logistics is a technology independent concept, but, because of the large attention that RFID technology has received in the past years and the lack of understanding on RFID, this technology is further investigated as a possible tool to support data capture for the information system in prognostics logistics. In order to have a comprehensive view on the capabilities and limitations of RFID technology, as well as possible application requirements, a testing methodology for implementing RFID will be developed and applied in several case studies.

The testing methodology will be developed following a bottom-up approach. It will investigate RFID in a fundamental level, semi-fundamental level and in an operational level. The fundamental tests aim to determine the technical characteristics and the RF air interface performance of the RFID equipment. These tests are carried out in a laboratory in order to minimize external interference and have a throughout understanding on the basic functioning principles of RFID. The fundamental test is only done once for every equipment under investigation. This information is stored in a data base in order to facilitate, in the future, the selection of a specific RFID provider that fulfills the requirements of the application at a fundamental level.

The semi-fundamental tests aim to determine the influence of specific item characteristics in the reliability of RFID systems. These are usually packaging materials, and multiple items in pallets or containers. These tests are also performed in the laboratory and give a good indication on what the performance would be once it is introduced to the operational environment. With the semi-fundamental tests, it is also possible to determine if processes in the logistics system need to be altered in order to enhance RFID performance.

The operational tests take place in the application environment. These tests study the overall performance of the system and can finally determine the level of RFID integration. With these final results, the overall integration of RFID is analyzed and the reliability level is determined. Whether of not this reliability is sufficient for that specific application depends on the sensitivity of the logistic system to a disruption in objects visibility.

The second research question will be answered by using a simulation model to investigate the effect of timely and accurate information in the logistics control of an automated wireless maintenance system for belt conveyors systems.

The model will show the benefits of using a radio frequency based monitoring system to check the health of different components in belt conveyor systems. Belt conveyors are an important component of logistic systems where large quantities of goods, people or bulk materials need to be transported overland without interruptions (Nuttall, 2007). In bulk commodity logistic systems, belt conveyors usually transport bulk solid materials over distances up to 100km. These belt conveyors are usually exposed to difficult operational conditions. Dust contamination and continuous high loading can strain the system components leading to early failures, belt damage or total shut down of the system (Lodewijks, 2004). Monitoring large belt conveyor systems is considerably labor intensive, and therefore expensive. The amount of data retrieved from large belt conveyor systems is extremely high to ensure correct interpretation of human inspectors. Furthermore, the final result of the inspection will be subject to the inspectors experience and training. The bearings are the most critical mechanical components of the support system of the belt conveyor. Bearing failure can be hastened by common operation factors like lubricant contamination, shaft misalignment or improper loading. It has been estimated that only 90% of the bearings fulfill their lifetime expectancy (Lodewijks, 2004). Hence, a condition radio frequency based monitoring system might be a feasible solution for monitoring idler bearings in order to reduce downtime of the system. Furthermore, the use of radio frequency based sensors to monitor the bearing health is expected to optimize maintenance and reduce the risk of failure due to inaccurate data.

1.2 Outline of the Thesis

In Chapter 2 a literature review on logistics systems is presented. Emerging logistics strategies will be discussed. Special attention will be given to the information system and the visibility concept. This will provide the framework for the concept of prognostics integrated logistics. In Chapter 3 the information system and the decision making system in prognostics logistics will be further explained. Special attention will be paid to the data capture system in prognostics logistics.

In Chapter 4 an overview of Radio Frequency IDentification including RFID components and operation principles is presented. In Chapter 5 the applicability of RFID will be analyzed in more detail. A testing methodology is developed to determine the applicability of RFID. Using this methodology, several application cases will be described. Successful and unsuccessful implementations of RFID will be presented. Finally, conclusions on the real possibilities and limitations of the technology will be drawn.

In Chapter 6, a concept for the prognostics logistics control of an automated wireless maintenance system for belt conveyors is presented. First the feasibility of using RF based condition monitoring system in belt conveyors is assessed by means of the testing methodology presented in chapter 5. Then, a simulation model is used to determine the effect of prognostics logistics (accurate and timely information) on the system performance of belt conveyors.

Finally Chapter 7 summarizes conclusions and recommendations for further research.

1.3 References

Armistead, C. G. and Mapes, J. (1993). The impact of supply chain integration on operating performance. *Logistics Information Management*, 6(4):9–14.

Ballou, R. H. (1992). *Business Logistics Management*. Prentice Hall, New York.

Barrat, M. and Oke, A. (2007). Antencedents of supply chain visibility in retail supply chains: a resource-based theory perpective. *Journal of Operations Management*, 25:1217–1233.

Berry, D., Towill, D. R., and Wadsley, N. (1994). Supply chain management in the electronics products industry. *International Journal of Physical Distribution and Logistics Management*, 24(10):20–32.

Bhatnagar, R., Sohal, A. S., and Millen, R. (1999). Third party logistics services: a Singapore perpective. *International Journal of Physical Distribution and Logistics Management*, 29(9):569–587.

Cavinato, J. L. (1982). The traffic service coorporation. The Traffic Service Coorporation, Washington D.C.

CLM (1998). What it's all about. Council of Logistic Management, Oak Brook IL.

Closs, D. J., Goldsby, T. J., and Clinton, S. R. (1997). Information technology influences on world class logistics capability. *International Journal of Physical Distribution and Logistics Management*, 27(1):4–17.

Cooke, J. A. (2004a). Companies focusing on minimal RFID compliance. *Logistics Management*, 43(5):24.

Cooke, J. A. (2004b). RFID based investment planning underway. *Logistics Management*, 43(9):21.

Cooke, J. A. (2004c). Technology advocate says RFID boom is still years away. *Logistics Management*, 43(10):20.

Daugherty, P. J., Ellinger, A. E., and Rogers, D. S. (1995). Information accesibility: Customer responsiveness and enhanced performance. *International Journal of Physical Distribution and Logistics Management*, 25(1):4–17.

Finkenzeller, K. (2003). *RFID Handbook*. John Wiley and Sons, West Sussex, England, second edition.

GLR (1995). World class logistics: The challenge of managing logistics change. The Global Logistics Research Team at Michigan State University, Council of Logistic Management, Oak Brook IL.

Introna, L. D. (1993). The impact of information technology in logistics. *Logistics Information Management*, 6(2):37–42.

Johnson, E. (2005). RFID: Taking the next step. *American Shipper*, 47(11):26–32.

Kent, J. L. and Mentzer, J. T. (2003). The effect of investment in interorganizational information technology in a retail supply chain. *Journal of Business logistics*, 24(2):155–176.

Kerr, A. (1990). Information technology creating strategic opportunities for logistics. *Logistics Information Management*, 3(3):18–20.

Lai, F., Zhao, Z., and Wang, Q. (2006). The impact of information technology on the competitive advantage of logistics firms in China. *Industrial Management and Data Systems*, 106(9):1249–1271.

LaLonde, B. J. and Masters, J. M. (1994). Emerging logistics strategies: blueprints for the next century. *International Journal of Physical Distribution and Logistics Management*, 24(7):35–47.

Langley, C. J. J. (1985). Information-based decision making in logistics management. *International Journal of Physical Distribution and Logistics Management*, 15(7):41–55.

Lodewijks, G. (2004). Strategies for automated maintenance of belt conveyor systems. *Bulk Solids Handling*, 24:16–22.

Lodewijks, G., Veeke, H. P. M., and López de la Cruz, A. M. (2006). Reliability of RFID in logistic systems. In *Proceedings of the 2006 IEEE Conference on Service Operations and Logistics, and Informatics*, Shanghai, China.

Luttwak, E. (1971). *A Dictionary of Modern War*. Harper and Row, New York.

Martin, C. (2005). *Logistics and supply chain management: creating value adding networks*. Pearson Education, third edition.

Mentzer, J. T., Min, S., and Zacharia, Z. G. (2000). The nature of inter-firm partnering in supply chain management. *Journal of Retailing*, 76(4):549–568.

Morton, R. (2004). Cultural problems solving RFID momentum overseas. *Logistics Today*, 45(6):15.

Murphy-Hoye, M., Lee, H., and Bice, J. B. (2005). A real world look at RFID. *Supply Chain management review*, 9(5):18–24.

Nuttall, A. (2007). *Design Aspects of Multiple Driven Belt Conveyors*. PhD thesis, Delft University of Technology.

Patterson, K. A., Grimm, C. M., and Corsi, T. M. (2004). Difussion supply chain technologies. *Transportation Journal*, 43(3):5–23.

Simpson, J. and Weiner, E. (1989). *The Oxford English Dictionary 3*. Clarendon Press, Oxford, second edition.

CHAPTER 2

Logistics Systems

This thesis investigates the influence of timely, and accurate information in the performance of logistics systems. The use of high timely and accurate information to support decisions and generate prognoses about possible disturbances is expected to improve the control of logistics systems.

The aim of this chapter is to provide an insight into the integration of logistics systems. With the integration of logistics activities information becomes vital to coordinate, among different member of the logistics system, the efficient and effective flow of goods. In section 2.1, the different phases of logistics integration are presented. With the increased complexity of logistics systems due to market globalization, the demand for having real time or nearly real time visibility has increased considerably. In section 2.2, it is determined that visibility is the result of sharing timely, accurate and quality information. The importance of increased visibility is the possible knowledge that can be generated on the true cause and effect relationship that exists within logistics systems. Real knowledge will create logistics systems capable of adapting to generate the desired state required at any point in time, and with the ability to control and reduce the variability, randomness or risk by introducing prognostics capabilities.

2.1 Literature Review on Logistics

Logistics has gained much attention in recent years as being recognized as a critical factor of competitive advantage to organizations ((Bowersox and Closs, 1996), (Bowersox and Daugherty, 1995), (Christopher, 1988)). In (Christopher, 1988), it was stated that to achieve competitive advantage, logistics should reduce costs while improving customer service. It was mentioned that one of the best features of logistics is that it emphasizes the integration of activities that traditionally have been identified as different functions of the organization.This integration motivates a systematic thinking of logistics.

Example 2.1 In Figure 2.1 a systematic representation of logistics systems is shown. A logistic system is a subsystem of an organization. It *controls* the flow of goods and information so it happens in an efficient and effective way. The inputs of the logistic system are transformed into outputs according to the system requirements. The control function coordinates the transformation by the vertical flow of information. The horizontal flow of information contains relevant data for the transformation itself (Veeke, 2003).

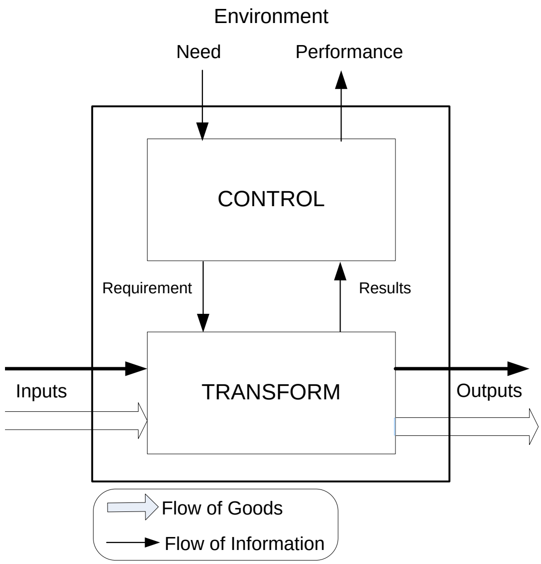


Figure 2.1: Logistics System. Adapted from (Veeke, 2003).

Before integration, organizations were divided into functional units, departments, each one within their own area of expertise. In the 1950s, the vast majority of organizations were fragmented. The distribution function was not coordinated and divided into multiple departments, each one with its own set of priorities. This fragmentation of functions led to both cost inefficiencies and departmental conflicts (LaLonde, 1969). The need for a more scientific approach to business management and the recognized importance of distribution in improving customer service were key factors in the interest for integrating logistics activities. The process of logistics integration was recognized to take place in four stages in (McKinnon, 2001).

The first stage can be traced back to the USA in the 1960s with the integration of the activities associated with the outbound and distribution of finished goods. Previously, these logistics functions where assigned to different areas within the organization, each one with its own set of priorities sometimes disassociated with the rest of the system (Lambert and Stock, 1993). The creation of distribution departments where all the fragmented activities of transport management, warehousing, inventory management and order processing were integrated, permitted a better control and coordination of the finished goods flow in the organization. Figure 2.2 shows the systematic decomposition of the logistics activities in the 1950s.

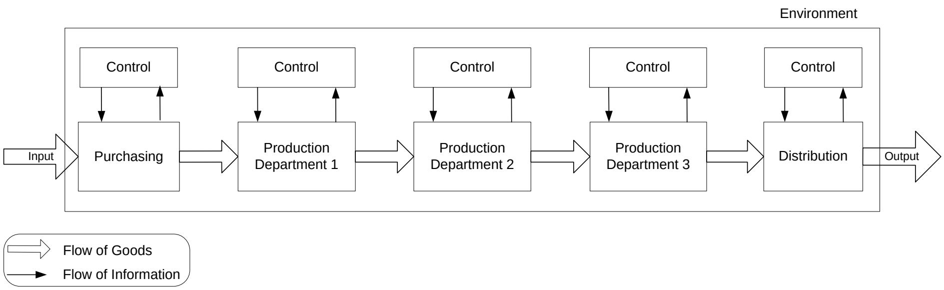


Figure 2.2: Functional organization of logistics. Adapted from (Visser and van Goor, 2006) and (LaLonde, 1969)

The integration of the distribution functions had three beneficial effects:

- The distribution system was able to achieve an optimal trade off between the costs of the combined activities. The integration showed that the finished goods were being delivered in small quantities at high delivery costs.

This prompted the organizations to raise the minimum quantity per order, stopping delivery to small outlets and effectively rationalizing the delivery network(McKinnon, 1989).

- It gave distribution a stronger customer focus. In (Stewart, 1965) was recognized that the quality of service could have significant impact on sales, market share, and long term customer loyalty. The new distribution systems started to develop more service strategies focused on customer service.

- Distribution gained function status, and was seen as important as production, sales and marketing. A new generation of managers were in charge of overseen distribution activities and designing new distribution strategies.

The second stage in logistics integration included, besides the physical distribution of finished goods, the whole movement of materials, components and subassemblies along the entire production system. This enabled a more consistent inbound and outbound flow and a better application of logistical principles (McKinnon, 2001). Figure 2.3 shows the functional organization with the integration of material managers in charge of controlling the flow of material between the different departments (Visser and van Goor, 2006).

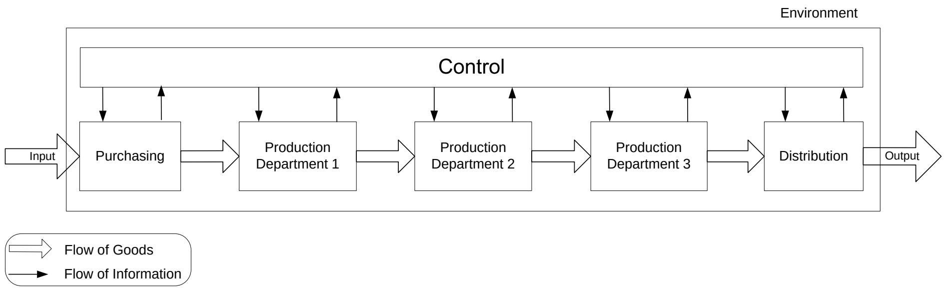


Figure 2.3: Functional organization of logistics with integral logistics. Adapted from (Visser and van Goor, 2006).

The third stage of logistics integration was a closer coordination among different functions within the organization. Logistics is seen as a tool for cross functional integration, a way to coordinate and communicate within the organization to achieve better system performance (Morash et al., 1996). Figure 2.4 shows the functional integration of logistics focused on internal integration.

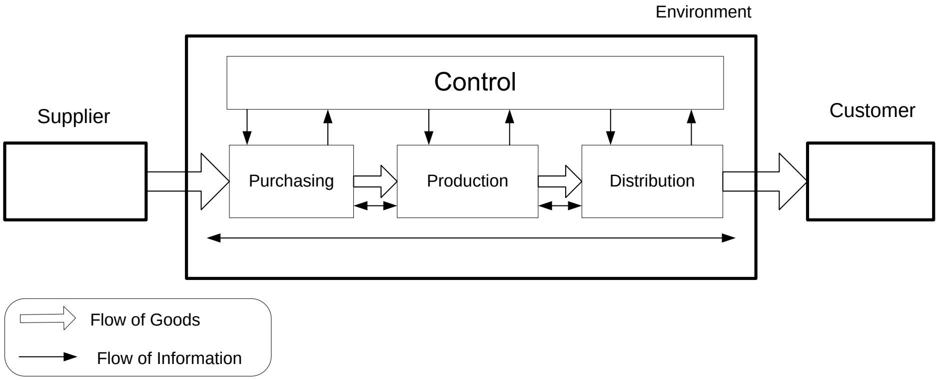


Figure 2.4: Logistics focus on internal integration.

The forth stage of logistics integration was integration among different members of the logistics system. By optimizing internally a member of a logistics system, it is unlikely to achieve an overall optimization of the system. It is possible to increase the efficiency and effectiveness of the entire logistics system by applying integrated logistics in the entire flow of materials and information throughout the system (LaLonde and Masters, 1994). For wider optimization it is necessary for all the members to coordinate their operations. This external integration of activities is referred to as supply chain management. Figure 2.5 shows the logistics chain integration.

Supply Chain Management, abbreviated as SCM, is defined in (Boorsma and van Noord, 1992) as: ”*Supply Chain management is the tuning of the logistics activities to each other between and within separate logistics links so that the logistics processes can be all controlled as an integrated whole. The logistics activities should be supported by an integrated information system which aims to optimize the logistics performance of the entire chain.*”. The SCM strategy generally involves four elements (LaLonde and Masters, 1994):

- Two or more organizations enter into a long term understanding to cooperate with closely integrated logistics processes. Independently, each organization is a logistics system, when they agree to coordinate their activities they become members or subsystems of a larger logistics system.
- High levels of trust need to be developed.
- The integration of the logistics activities involves the share of high sensitive

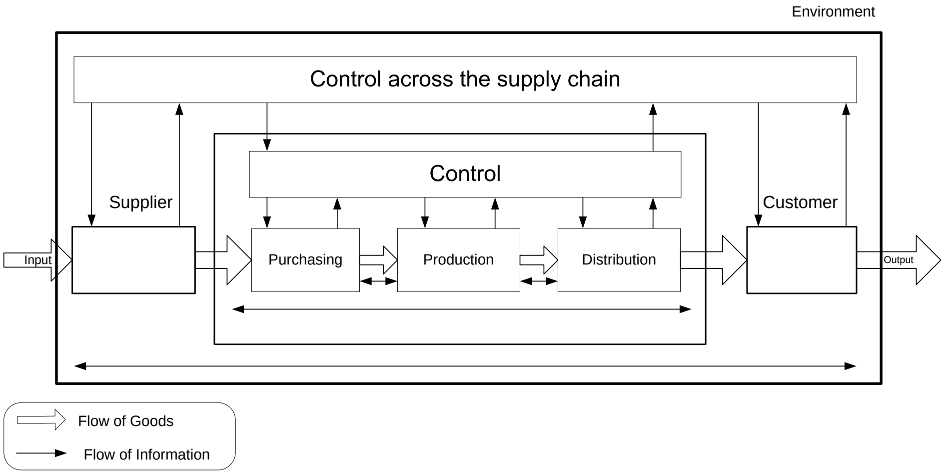


Figure 2.5: Supply Chain Integration.

data. Data sharing involves giving the rights to access the internal database of the system.

- Visibility and flexibility are required to improve the control system of the logistics processes.

The introduction of supply chain management aims to improve customer service by focusing on the performance of the entire logistics system and not the internal performance of the individual logistics processes. The purpose is to improve the quality of the product such as improving delivery reliability by using information that is shared from every link in the chain (Visser and van Goor, 2006).

With the globalization of the markets, organizations have new opportunities to search for new sources of basic materials and components, as well as new manufacturing sites (Hugos, 2006). An increasing number of companies have expanded their operations to international sites, taking advantage of lower manufacturing costs and cheap raw materials (Ghiani et al., 2004). As a result, more emphasis has been place in the design of global logistics strategies. In (Christopher, 1988), two important challenges in a increasing globalizing market for logistics systems are discussed. The first one is cutting short the pipeline by implementation of ”just in time” principles in deliver and manufacture. The second challenge is to improve pipeline visibility by removing organizational barriers, sharing information and introducing more information systems and information technologies.

The first challenge described in (Christopher, 1988), involves the introduction of just in time strategies and reduction of the cycle times. The first part of the first challenge is the introduction of just in time strategies. Just in Time (JIT) refers to the delivery of components to the production process only when needed (Taylor, 2001). If components, parts or products are been supplied, produced and distributed, only when needed, the communication with customers and suppliers is expected to be effective, transport is expected to be reliable and responsive, order processing time is expected to be minimized, quality should be high and so on. The successful implementation of JIT depends on the level of communication in the logistics systems (Jackson, 1983). When logistics systems are designed in such a way that information sharing exists between different members, inventory levels and production flows are transparent and manufacturing, transportation and distribution is coordinated, JIT can efficiently and effectively be implemented (Taylor, 2001). The challenges for JIT are therefore:

- assure on-time deliveries
- define and develop the buyer supplier relationship
- limit loss and damage
- maintain quality standards
- share relevant information

Example 2.2 The Toyota Production System (TPS) has been recognized to be a successful implementation of the JIT principle. The Toyota production system combines two concepts, the Jidoka concept that translates ”as automation with a human touch”, and the JIT concept. The Jidoka concept highlights the visualization of problems. Once a machine has finished doing a job or has detected a defect it automatically stops, preventing defective products to be manufactured and ensuring quality. With JIT the idea is to improve productivity by making only ”what is needed, when it is needed, and in the amount needed”. (TPS, 2008)

The second part of the first challenge is reduction of the cycle times. Cycle time can be analyzed in two different forms. The first one is the order cycle time

(LaLonde and Masters, 1994). This is the time that passes between the moment a customer places an order and the moment the goods are received. Traditionally, the order cycle time has been controlled by increasing the stock availability and deliveries (Ghiani et al., 2004). Large inventories make the logistics system more responsive to possible disturbances in the demand (Hugos, 2006). However, having large inventories can also be highly expensive.

The second form of the cycle time is the length of the time material remains in the system as it flows from raw material to production to finish goods and on to delivery to the customer (LaLonde and Masters, 1994). This type of cycle time has been reduced with the use of Manufacture resource planning systems(MRP) and Distribution resource planning systems (DRP) (Langley, 1985).

Example 2.3 In traditional material inventory control systems, raw materials were stocked to support the manufacture of a wide range of products periodically produced. The stockpiles were kept according to the aggregate demand and without regard of the production schedule. This led to large quantities of materials being held for prolong periods of time. With the MRP just the necessary amount of materials are ordered and scheduled to arrive when needed. In the same way, the DRP system schedules distribution of products based on the expected demand. Reducing this cycle time made systems more responsive since the production and the distribution can be done quicker. (LaLonde and Masters, 1994).

The second challenge presented in (Christopher, 1988) for logistics in an increasing globalization of the markets is visibility. In (Moberg et al., 2002) six variables as potential antecedents of information sharing were identified: information technology commitment, information quality, SCM commitment, organizational size, relationship commitment and trust. Two main problems were found to be significantly related to information exchange: relationship commitment an information quality. The first is the unwillingness of different members in a logistics network to share what might be considered sensitive information. The second problem is the lack of shared information that can actually be used to increased visibility. Sharing information and visibility can not be treated as the same. If the information shared is not of quality, timely, or accurate, the resulted visibility will still be limited.

2.2 Information and Visibility in Logistics

Logistics visibility can be defined as the extend to which the position or location of an object, service, or information and its status are known in a logistic system (Lodewijks et al., 2006). In (Barrat and Oke, 2007), the link between shared information and visibility is studied. It is stated that improved performance due to sharing information is a two stage process. First, it needs to be determined whether or not the information shared is timely, accurate and useful (Closs et al., 1997). If this is determined, the information needs to be incorporated in the decision making processes of the recipient, who now may be able to do a more informed decision due to the better visibility on the current situation of the sender. In (Barrat and Oke, 2007) the information shared within the logistics system leads to improve visibility and improve performance if the information actually provides distinctive visibility. Information sharing is an activity and visibility is an outcome.

The range of visibility depends on the amount of information shared and the extend in which the information is timely, accurate, trusted, useful (Closs et al., 1997). It has been suggested the need to gain visibility of several aspects of the logistics system, some of these are: being able to see the real demand (Barrat and Oliveira, 2001) , inventory holdings (Petersen et al., 2005), process visibility (van der Zee and der Vorst, 2005), visibility of goods as they move through the system (Karkkainen, 2003). Also, some of the benefits of enhanced visibility have been documented: Improved responsiveness ((Berry et al., 1994), (Patterson et al., 2004)) ,improved planning and replenishment capabilities (Karkkainen, 2003), improved decision making ((Kent and Mentzer, 2003), (Mentzer et al., 2000)), improved quality of products (Armistead and Mapes, 1993). With high visibility it is expected that the uncertainty resulting from demand volatility could be alleviated with the sharing of true demand data with all the members of the logistics system in a real or near real time basis.

Example 2.4 The bullwhip effect suggests that the variability in demand increases as one moves up the logistics chain. This means that the orders to the supplier tend to have larger variance than sales to buyer. This variability is mainly attributed to the lack of information sharing. In (Lee et al., 1997), it is suggested that the effects of the bullwhip effect can be mitigated if information about demand, inventory status, and order status is shared in each stage of the logistics system.

The advances in information and communication technologies have made it possible to have powerful and inexpensive information technology to operate and control logistics system (LaLonde and Masters, 1994). Logistics visibility can be improved by using automatic identification technologies (Auto- ID). Auto-ID is a broad term given to a host of technologies that are used to help machines to identify objects. These include bar codes, smart cards, voice recognition, some biometric technologies (e.g. retinal scans), optical character recognition, and radio frequency identification (RFID). The logistics visibility of objects can be further improved by automatic data capture. Automatic identification technologies and automatic data capture systems had made it possible to have large amounts of information with reduced errors and in real or near real time. With the electronic data interchange (EDI) the access of updated information in a standardized format allows the organization to automate transactions. These capabilities give the organization the ability to automate logistics information and control systems and to determine an appropriate logistics strategy (LaLonde and Masters, 1994).

The integration of logistics activities enabled by technology (e.g. point of sale data POS, inventory levels, vendor managed inventory VMI, collaborative planning, forecasting and replenishment CPFR, the internet) has been a growing trend in organizations to increase visibility of processes and operations in order to improve internal decision making and performance ((Rungtusanathan et al., 2003), (Kulp et al., 2004)). The adoption of information technologies and the importance of such technologies in the improvement of logistics operations have been recognized in (Walton and Miller, 1995). In (Bowersox et al., 1989), it is mentioned that one of the differentiators between leading edge logistics organizations and average organizations is the ability and willingness to invest in state of the art information technologies. Adoption and successful implementation of IT is said to be a prerequisite for logistics success (GLR, 1995). While importance of adopting IT technology has been studied and supported, in (Dawe, 1994), the reasons for organizations to hesitate in adopting IT are discussed. Some of these reasons are: the expected obsolescence of hardware and software, application redundancy, irrelevance of the application to the particular industry and information needs. In (Kerr, 1990), it is stated that, in general, there is a large number of organizations that do not understand on how to use their existing information systems, and are quite reluctant of investing in new systems without fully understanding the overall benefits.

In (Langley, 1985), it is discussed the need and benefits of implementing logistics information systems. Three topics were covered: the quality of information, the logistics system concept, and the share of information and personal computers. The quality is said to be characterized by three important issues. Firstly, managers usually do not have the information they truly need to make effective decisions. This is due to uncertainty on their information needs and due to lack of accessability to what can be considered confidential information. Secondly, available information is very poor due to lack of innovation systems and standardized data. Thirdly, information is not communicated effectively. There is a need for standardization of the communication language that is shared. Also, there should be a common agreement on what is actually important to communicate and what is not. The second topic discussed in (Langley, 1985) is the logistics information system concept. The author stressed the importance of having a information structure and a decision support system to help managers make decisions based on the available information. The third topic discussed in (Langley, 1985) is sharing information. The use of Electronic data interchange EDI to share information among two or more members in the logistics system is highly encouraged. The use of techniques like Just in time, or MRP and DRP, are highly dependent on timely and high quality information.

Advances in IT and IS have had a innovative impact in logistics systems (Langley, 1985). Effective management of information can be seen as a key to provide high quality costumer service. Logistics activities like on time delivery, stock out levels, order status, shipping, among others, heavily depend on timely and accurate flow of information. IT is a great opportunity to improve logistical efficiency, effectiveness and flexibility (Sum et al., 2001). In (Daugherty et al., 1995) information systems were found to enhance productivity, flexibility, operations and competitiveness. Effective IT becomes necessary to support logistics processes (LaLonde and Masters, 1994), and to coordinate worldwide distribution, product design, production, procurement and inventory (Lai et al., 2006).

2.3 Conclusions

With the integration of logistics activities, the coordination among different members of the logistics systems became a necessity if customer demands and cost reductions are to be achieved. The coordination of processes and activities depend on the amount of the information shared and the possible increased visibility. Visibility can be improved if the shared information is derived from timely, accurate and quality data.

Auto identification technologies (Auto- ID) have been used to improve the quality of the data capture in logistics systems. With the use of software platforms, designed to share information among different members in the logistics systems, information sharing has improved. However, visibility is still limited. Information about goods in transit, or status of the goods and equipment used for transport, or information about production processes is either not available, inaccurate or not timely shared among different members of the logistics system. With limited visibility comes limited knowledge. Without comprehensive knowledge of logistics systems, trying to implement control strategies to improve performance is rather difficult.

Information technologies, in particularly for data capture like Auto-ID technologies, are still necessary for improving visibility and creating comprehensive knowledge of logistics systems. The created knowledge is expected to support logistics control systems by, not only, doing diagnostics and prognostics of future problems, but also, developing a plan of action to prevent or correct particular causes of disturbances in the system.

In Chapter 3 the integration of prognostics for logistics systems is presented. The use of information and communication technologies to support data capture in order to increase visibility will be investigated. With the available information and the possible level of control that can be achieved, the prognostics capabilities of the logistics system can be determined.

2.4 References

Armistead, C. G. and Mapes, J. (1993). The impact of supply chain integration on operating performance. *Logistics Information Management*, 6(4):9–14.

Barrat, M. and Oke, A. (2007). Antencedents of supply chain visibility in retail supply chains: a resource-based theory perspective. *Journal of Operations Management*, 25:1217–1233.

Barrat, M. A. and Oliveira, A. (2001). Exploring the experiences of collaborative planning initiatives. *International Journal of Physical Distribution and Logistics Management*, 31(4):266–289.

Berry, D., Towill, D. R., and Wadsley, N. (1994). Supply chain management in the electronics products industry. *International Journal of Physical Distribution and Logistics Management*, 24(10):20–32.

Boorsma, M. J. and van Noord, J. (1992). Ketenintegratie. *Tijdschrijft voor inkoop en logistiek*, 8(6):40–48.

Bowersox, D. J., adn C. L. Droge, P. J. D., Rogers, D. S., and Wardlow, D. L. (1989). Leading edge logistics: Competitive positioning for the 1990s. Council of Logistic Management, Oak Brook IL.

Bowersox, D. J. and Closs, D. J. (1996). *Logistics Management: The integrated supply chain process*. New York: Macmillan.

Bowersox, D. J. and Daugherty, P. J. (1995). Logistics paradigms: the impact of information technology. *Journal of Business Logistics*, 16(1):65–80.

Christopher, M. (1988). Logistics and competitive strategy. *Logistics information management*, 1(4):204–206.

Closs, D. J., Goldsby, T. J., and Clinton, S. R. (1997). Information technology influences on world class logistics capability. *International Journal of Physical Distribution and Logistics Management*, 27(1):4–17.

Daugherty, P. J., Germain, R., and Droge, C. (1995). Predicting EDI technology adoption in logistics management: the influence of context and structure. *Logistics and transportation review*, 31(4):309–324.

Dawe, R. L. (1994). An investigation of the pace and determination of information tehcnology use in manufacturing materials logistics systems. *Journal of Business Logistics*, 15(1):229–259.

Ghiani, G., Laporte, G., and Musmanno, R. (2004). *Introduction to logistics systems planning and control*. John Wiley and Sons.

GLR (1995). World class logistics: The challenge of managing logistics change. The Global Logistics Research Team at Michigan State University, Council of Logistic Management, Oak Brook IL.

Hugos, M. (2006). *Essentials of supply chain management*. John Wiley and Sons.

Jackson, G. C. (1983). Just in time production: Implications for logistics managers. *Journal Bussiness Management*, 4(2):1–19.

Karkkainen, M. (2003). Increasing efficiency in the supply chain for short shelf life goods using RFID tagging. *International Journal of Retail and Distribution Management*, 31(10):529–537.

Kent, J. L. and Mentzer, J. T. (2003). The effect of investment in inter-organizational information technology in a retail supply chain. *Journal of Business logistics*, 24(2):155–176.

Kerr, A. (1990). Information technology creating strategic opportunities for logistics. *Logistics Information Management*, 3(3):18–20.

Kulp, S. C., Lee, H. L., and Ofek, E. (2004). Manufacturer benefits from information integration with retail customers. *Management Science*, 50(4):431–444.

Lai, F., Zhao, Z., and Wang, Q. (2006). The impact of information technology on the competitive advantage of logistics firms in China. *Industrial Management and Data Systems*, 106(9):1249–1271.

LaLonde, B. J. (1969). Integrated distribution management - the american perspective. *Long Range Planning*, 2(2):61–71.

LaLonde, B. J. and Masters, J. M. (1994). Emerging logistics strategies: blueprints for the next century. *International Journal of Physical Distribution and Logistics Management*, 24(7):35–47.

Lambert, D. and Stock, J. R. (1993). *Strategic Logistics management*. Irwin Homewood, third edition.

Langley, C. J. J. (1985). Information-based decision making in logistics management. *International Journal of Physical Distribution and Logistics Management*, 15(7):41–55.

Lee, H. L., Padmanabhan, V., and Whang, S. (1997). Information distortion in a supply chain. *Management Science*, 43(4):546–558.

Lodewijks, G., Veeke, H. P. M., and López de la Cruz, A. M. (2006). Reliability of RFID in logistic systems. In *Proceedings of the 2006 IEEE Conference on Service Operations and Logistics, and Informatics*, Shanghai, China.

McKinnon, A. (1989). *Physical distribution systems*. London: Routledge.

McKinnon, A. (2001). Integrated logistics strategies. In *Handbook of Logistics and supply chain management*, chapter 10. Pergamon.

Mentzer, J. T., Min, S., and Zacharia, Z. G. (2000). The nature of inter-firm partnering in supply chain management. *Journal of Retailing*, 76(4):549–568.

Moberg, C. R., Cutler, B. D., Gross, A., and Speh, T. W. (2002). Identifying antecedents of information within supply chains. *International Journal of Physical Distribution and Logistics Management*, 32(9):755–770.

Morash, E. A., Droge, C., and Vickery, S. (1996). Boundary spanning interfaces between logistics, production, marketing, and new product development. *International Journal of Physical Distribution and Logistics Management*, 26:43–62.

Patterson, K. A., Grimm, C. M., and Corsi, T. M. (2004). Difussion supply chain technologies. *Transportation Journal*, 43(3):5–23.

Petersen, K. J., Ragatz, G. L., and Monczka, R. M. (2005). An examination of collaborative planning effectiveness and supply chain performance. *Journal of Supply Chain Management*, 41(2):14–25.

Rungtusanathan, M., Salvador, F., Forza, C., and Choi, T. Y. (2003). Supply chain linkages and operational performance: a resource based perspective. *International journal of operations and production management*, 23:1084–1099.

Stewart, W. (1965). Physical distribution: key to improved volume and profits. *Journal of Marketing*, 29:65–70.

Sum, C. C., Teo, C. B., and Ng, K. K. (2001). Strategic logistics management in Singapore. *International Journal of Operations and Production Management*, 21(9):1239–1260.

Taylor, S. Y. (2001). Just in time. In *Handbook of Logistics and supply chain management*, chapter 13. Pergamon.

TPS (2008). Toyota production system. http://www.toyota.co.jp.

van der Zee, D. J. and der Vorst, J. G. A. J. V. (2005). A modelling framework for supply chain simulation: opportunities for improve decision making. *Decision Science*, 36(1):65–95.

Veeke, H. P. M. (2003). *Simulation Integrated Design for Logistics*. PhD thesis, Delft University of Technology.

Visser, H. M. and van Goor, A. R. (2006). *Logistics: Principles and Practice*. Stenfert Kroese, first edition.

Walton, L. W. and Miller, L. G. (1995). Moving toward LIS theory development: a framework of technology adoption within channels. *Journal of Business logistics*, 16(2):117–136.

CHAPTER 3

Prognostics Integrated Logistics

In the previous chapter, the integration of logistics systems was presented. With integration, information sharing among all the members of the logistics systems was recognized to be vital to coordinate the efficient and effective flow of goods. Information technologies were recognized to have an innovative impact in logistics systems. Furthermore, the need for timely and accurate information to support the control of logistics systems was established.

Logistics control systems use the available information to structure and design decision making strategies. Decisions like maintenance activities, ordering of raw materials, delivery of goods so that they arrive on-time, among many others, are taken based on the information at hand. Most of the time, the information that is available does not reflect the current status of the system. It is outdated information, usually gathered days, weeks or even months in advance, and it is subject to human errors. With this type of information, it is only possible to determine that a disturbance occurred once the effects of such a disturbance are noticed, i.e. breakdown of the system, late deliveries due to out of stock products and so on. Moreover, with such information, the cause of the disturbance in the system is difficult to track because of the time lag between the time data is collected and the time data is actually reported and used for decision making. Without knowing, precisely, what the cause of the low performance in the system was, very little control can be implemented. Besides, without understanding the relationship between cause and effect in logistics systems due to the lack of information or information delays, any corrective measure will probably be inefficient or be implemented too late to have an effect. Thus, in order to improve the control of logistics systems, the information that is collected from different processes and activities should be timely and accurate.

The performance of logistics systems is highly sensitive to the accuracy of the control system (Pyle, 1993). If timely and accurate information is made available, the decision support system can detect changes in the normal functioning of the systems and, with the gained knowledge, prognoses of possible disturbances can be generated, and corrective actions can be taken, to prevent any impact in the overall performance of the system. Thus, the combination of using timely and accurate information into decision making systems to generate prognoses of possible disturbances in order to improve the performance of logistics systems is defined in this thesis as prognostics integrated logistics or prognostics logistics.

It is possible to recognize two important elements in the concept of prognostics logistics. The first one is an information system where acquisition and processing of timely and accurate information is the main function. The second one is a decision support system where prognoses of possible disturbances based on the available information are generated. In this chapter these two elements of prognostics logistics will be investigated [1] . In section 3.1, the information system will be presented in more detail. The information system is in charge of transforming data into information. The features and available technological tools to support the information system will be presented. In section 3.2, decision support systems for prognostics logistics will be presented. In section 3.3 application scenarios for prognostics logistics are developed. Possible implementations for the information system and the decision support system for the applications are presented. In Section 3.4 conclusions are drawn.

3.1 Information system

In prognostics logistics, timely and accurate information are crucial to support the decision making system. Timely information implies that the information should be available when needed, where needed, with no delays. Also, the information

[1] This chapter is based on the published paper (López de la Cruz et al., 2006)

provided should be sufficient and accurate, without errors, to successfully control the logistics system. The reliability of the predictions made in prognostics logistics highly depends on the quality of the information acquired. Information systems transform data into information that is useful for the end user (Introna, 1993). The information system is in charge of acquiring, communicating and processing the data so that it can be used in the decision making system. In order to have the right information when needed, where needed, it is important to have an information system monitoring objects, processes and equipments. The monitoring frequency depends on the change rate of the aspects of the system, this condition requires a system that can capture and transmit information in real or near real time. Furthermore, the information system should be capable of automatic data capture in order to limit human involvement and reduce errors.

The level of data capture of the information system is application dependant. However, no matter the application, it is desirable for the information system to support a large flow of information and be pervasive, so information about products, equipments, environmental conditions, location, among many others, can be made available to support the decision making system.

There are four important features of the information system. The first one is to have identification information about the objects. The type of data capture system should be reliable and limit human involvement in order to reduce possible data entry errors. The second one is to have location information to implement track and trace capabilities in the system in order to provide information about object presence and movement. The third one is to collect all kinds of relevant information to have a good insight into the physical environmental conditions of the objects. The fourth one is to be able to communicate all the acquired data to the system in order to be analyzed and then used to improve control strategies. These four features require the combination of different technological tools. As mentioned before, every application have different requirements, for this reason, prognostics logistics is a technology independent concept. However, the mentioned features of the information system impose a series of characteristics for technologies to be considered. In this section a review of relevant technological tools that can support each of the mentioned features will be provided.

Table 3.1: Features and technological tools for the information system

Features	Technological Tool
Object Identification and Limited Human Involvement	Automatic Identification Technologies
Track and Trace	Location Sensing
Operation Conditions	Physical Environmental Sensing
Communication	Communication Systems

3.1.1 Automatic Identification Technologies

Automatic Identification and data capture systems have been used for years to automate and reduce the number of data errors in the flow of information in logistics systems. Automatic Identification (Auto-ID) systems refer, in a broad scope, to the methods used to automatically identify objects, collect data and register it without human involvement (Wyld, 2006). Figure 3.1 shows the technologies usually referred to as part of the Auto-ID group. In Table 3.2, the pros and cons of the mentioned Auto-ID technologies will be presented.

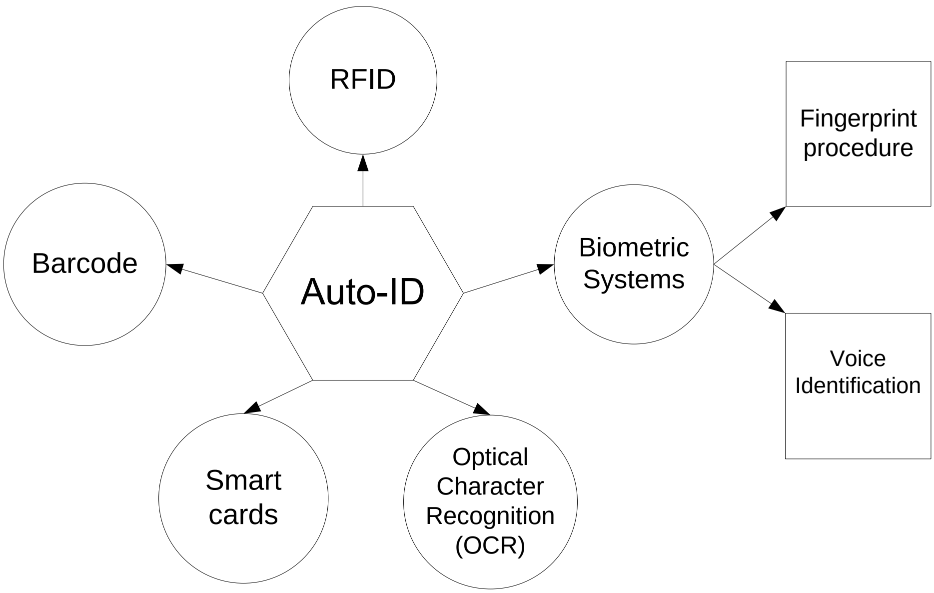


Figure 3.1: The group of Auto-ID Technologies. (Finkenzeller, 2003)

Barcode

The most well known Auto-ID technology is the barcode. For the past 20 years, the barcodes have been the primary means to identify objects. The black and white stripes contain fixed information about the object and its manufacturer (Haller and Hodges, 2002). The information is communicated through the use of an optical scanner. The barcode needs to be in the line of sight of the scanner so the code can be read, this implies that objects can only be seen one at a time (SUN, 2005). In theory, barcodes can be of any size, in practice, they are limited in size and contain no serial number (Haller and Hodges, 2002). This means that the system can only track product categories, it can not distinguish one bottle of water from another of the same brand and make.

Smart Cards

These systems are composed of an integrated circuit embedded into a plastic body (SCF, 2005). This is a secure system with relatively high storage capability. Smart cards are very common nowadays, they can be found in credit cards, debit cards, phone cards and so on. In order to retrieve the information contained in a smart card, it is necessary to make use of a special reader where the card needs to be introduced and the information decoded. This protects the information of undesired access and manipulation (Finkenzeller, 2003).

Biometrics

Biometrics refers to the automatic identification of people based on their physiological characteristics (Angle et al., 2005). A biometric system is basically a pattern recognition system which makes a personal identification by determining the authenticity of a user based on a physical characteristic. The used of biometrics is related to the pattern recognition made by a machine where personal characteristics are validated, i.e. fingerprints, iris, voice, among others (Finkenzeller, 2003). These characteristics are first taught to the identification system using a pattern recognition method, like for example neural networks. After the system has the information of the user, it is possible to later automatically identify the user by scanning its physical characteristics into the system.

Optical Character Recognition (OCR)

Optical character recognition intends to re-create the human function of reading into machines (Mantas, 1986). The main motivation for the development of OCR was the need to improve the management of the flood of paper such as bank cheques, commercial forms, government records, mail sorting among many others. An OCR system enables to scan a book, put it into a computer file, and edit the text with the use of a simple word processor (Govindan and Shivaprasad, 1990). All OCR systems include an optical scanner for reading text, and sophisticated software for analyzing images. OCR has failed to become a universally applicable technique because of the high price of the readings involved and the high level of complexity when compared with other identification systems (Finkenzeller, 2003).

Radio Frequency Identification (RFID)

RFID is a generic term for systems that read the unique identity of an RF tag (ISO/IEC, 2005). An RFID tag combines a medium storage capacity with the means to communicate the stored data wirelessly to an RFID reader (Haller and Hodges, 2002). There are several methods of identifying objects using RFID. The most common is to store a serial number that identifies the object and some additional data on a microchip that is attached to an antenna. The antenna enables the microchip to transmit the information to an interrogator. In passive RFID systems the data transmission is triggered and powered by the interrogator, which implies that the transmission is off-line. In active RFID systems the microchip is equipped with a battery that powers it which allows on-line continuous data transmission. The combination of microchip, antenna, and battery (for active RFID) combined into a single package is called a tag. Superficially, RFID appears to be an automated form of bar-code tracking. However, while both are used for tracking objects, RFID can provide much more information on what the object is, since it can store additional data together with its serial number (Lodewijks et al., 2006). This technology can be combined with sensors and other wireless systems, in order to make it a more powerful tool for capturing and transmitting specific data (López de la Cruz et al., 2007).

Table 3.2: Summary of Pros and Cons of different Auto-Id technologies in Prognostic Logistics

Auto-Id Technology	Pros	Cons
Bar Code	Widely used, low prices, 2-D Barcodes can store more information	The bar code must be in the line of sight of the reader, read only one code at a time, required human intervention, it can be easily compromised or damaged, seldom cases provide real time information, one way communication
Smart Cards	Secure system, high Storage capability	Requires human intervention, the information is decoded using a special reader that requires contact with the chips' card
Biometrics	Very secure system, not human intervention necessary after programmed	Highly expensive, products do not have unique characteristics
OCR	Reads high density of information	Highly expensive, complicated infrastructure, needs line of sight
RFID	Tags are getting cheaper, standards are being created, provides real time information flow and constant monitoring, data acquisition without human intervention, high storage capability, multiple tags can be read at once, promotes the creation of intelligent products (A.Zaharudin et al., 2002), possible sensor integration	Security issues, costs need to go even lower, readability problems with metals and liquids

3.1.2 Location Sensing

Location sensing is a very important characteristic of the information system. In order to improve planning and control of objects, specially moving objects, timely and accurate information about current locations needs to be provided in real time or near real time. In order to determine the characteristics of a location system, it is important to understand not only the environment in which the location system will be implemented, but also, the inherent properties of different location systems. In this section an overview of location sensing properties will be presented. In Table 3.3[2] a comparison of different location sensing technologies is shown.

Location Sensing Techniques

Location sensing techniques can be classified into three procedures (Hightower and Boriello, 2001a): triangulation, proximity and scene analysis.

Triangulation: Triangulation can be done via lateration (distance measurements) or angulation (angle measurements).

Lateration computes the position of an object's distance from multiple reference positions (Roussos, 2002). With lateration there are three main means in which distance from the object to the reference point can be estimated, these are:

- Direct: Direct measurements by using a device to get specific information, probing. For example a robot with a step motor can be used to investigate how many steps are required to the desired target. However, this information can be difficult to obtain due to the complexities involved in coordinating autonomous movement.

- Time of Flight: This method calculates the time that a signal (with known velocity) takes to arrive at a known reference point from a particular location. With this approach it is very important time synchronization. In GPS systems, satellites need to be precisely synchronized with each other, otherwise it is not possible to precisely measure the time of flight and determine the location (Roussos, 2002).

[2] A complete overview of current location sensing technologies is available in (Hightower and Boriello, 2001a)

- Attenuation: With this method the decrease of the signal strength relative to its original intensity is measured. In free space, a radio signal emitted by an object will be attenuated by a factor proportional to $1/r^2$ when it reaches a reference point at distance r from the object (Hightower and Boriello, 2001b). In close environments, attenuation measurements can be less accurate than in open spaces. This is due to the amount of reflections, refractions and multiple paths caused by the objects indoors.

Angulation is similar to lateration only that it uses angle measurements to determine the position of an object. Two dimensional angulation requires two angle measurement and one distance measurement (Hightower and Boriello, 2001b). The distance can be the distance between two reference points.

Proximity: Proximity location sensing determines when an object is near a known reference point. Two main approaches are used (Roussos, 2002):

- Detecting physical contact: This is the most basic sort of proximity sensing. Touch sensors are used to determine physical contact (Patridge et al., 2002).

- Wireless monitoring: Monitoring the proximity of a mobile device when it is in range of one or more access points in a cellular network, or when an automatic identification system, RFID, records the ID number of a particular object are types of location sensing using proximity. If the location of the reader in the case of automatic identification systems is known, the location of the mobile object can be inferred as being contained within the area of the reference point (Roussos, 2002).

Scene Analysis: With this methodology features of a scene observed from a particular point are used to draw conclusions about the location of the observer or of objects in the scene (Hightower and Boriello, 2001b). Geometric representations of the space under observation are employed to simplify the imagines and create features that are easy to compare (Roussos, 2002).

Physical Information and Symbolic Information

The provided information in location sensing system can be either physical information or symbolic information (Hightower and Boriello, 2001a). Physical information provides the position of a location in a coordinate system (longitude, latitude, altitute). Symbolic information provides textual descriptions of locations (in the park, on the first floor of the library).

Absolute or Relative Location

Whether physical information or symbolic information is used the information provided may be either absolute or relative. Absolute location uses a location system that employs a shared reference grid for all located objects, i.e. longitude, latitude, altitude, (Roussos, 2002). In a relative location system each object can have its own frame of reference (Hightower and Boriello, 2001a). For example, a warehouse with multiple RFID readers will report the position of a specific RFID relative to its own known location.

Localize location calculation or external location calculation

There are systems that provide location capability and demand for the object to calculate its current location and broadcast it if necessary. These systems ensure privacy of the users since no one but the object itself knows its location (Roussos, 2002). In contrast, there are systems that requires a signal from the object to calculate its current location. In this case, the object is liberated of the computational and power demands involved in determining its location. Once the object transmits a signal, or is sensed to be in proximity of a know reference point, the system infrastructure calculates the object's location (Hightower and Boriello, 2001a).

Accuracy and Precision

The property of the smaller distance that a system can differentiate between two positions is called the accuracy of the system. Some GPS systems have an accuracy of 10 meters for approximately 95% of the measurements. The percentage is the times the mentioned accuracy is achieved, this is called the precision of the system (Hightower and Boriello, 2001a). Less accuracy may be trade off for more precision. Although accuracy and precision are suitable measures of the effectiveness of location sensing systems, they should not be considered in isolation of the overall system (Roussos, 2002). If information about the working environment is at hand, this can be used to calibrate the location system and increase accuracy. There is also the possibility to invest more in infrastructure in order to increase accuracy as well. For example, in cellular mobile systems, the location sensing accuracy based on the cell ID can be increased by reducing the size of the cell.

Scale

To assess the scale of a location system, it is important to consider the coverage area per unit of infrastructure and the number of objects the system can locate per unit of infrastructure per time interval (Hightower and Boriello, 2001a). In RFID systems, only a limited numbers of objects can be tolerated before the communication channels become congested. When this occurs, delays in determining the location of the objects will occur or a loss in accuracy will occur due to the less frequent calculations on the objects' locations.

Recognition

In applications where recognition or classification of located objects is necessary, an automatic identification system is needed (Hightower and Boriello, 2001b). In this case, it is important to evaluate what are the necessary characteristics that need to be recognized in order to choose the proper Auto-ID system. There are cases in which only some features like color or shape are necessary, in these cases a biometric auto-ID system is the best option.

Costs

It is possible to asses the costs for location systems in different ways. Time costs usually refer to the installation process and the system's administration needs. Space costs involve the amount of installed infrastructure. Capital costs refer to the price per mobile unit, the infrastructure and support personnel (Hightower and Boriello, 2001a).

Limitations

There are systems that will not function under certain environmental conditions. GPS systems, for example, do not function indoors. Tagging systems like RFID, may have limitations when multiple tags are in the reading field (Roussos, 2002). Technical limitations together with environmental conditions need to be analyzed before choosing a specific location sensing system.

Table 3.3: Location Sensing Technologies.(Hightower and Boriello, 2001a)

Technology	Technique	Phy.(P) Sym.(S)	Abs.(A) Rel(R)	LLC	Recognition	Accuracy Precision	Scale	Costs	Limitations
GPS	Time of flight, lateration	P	A	Yes	No	1-5meters (95-99%)	Global	Receiver US$100	Not indoors
Active Badge	Infrared proximity	S	A	No	Yes	Room size	1 base per room	Admin. costs cheap tags and bases	Sunlight
MotionStar	Ultasound time of flight lateration	P	A	No	Yes	9cm (95%)	1 base per 10 square meters	Admin. costs cheap tags and sensors	Required ceiling sensor grid
Pinpoint 3D-iD	RF lateration	P	A	No	Yes	1-3m	Several bases per building	Expensive hardware	Propietaty, 802.11 interference
Avalanche Transceivers	Radio Signal strength proximity	P	R	No	No	Variable 60-80m range	1 transceiver per person	aprox. US$200 transceiver	Short radio wave, signal attenuation
Auto-ID systems	proximity	S	A/R	No	Yes	Range of sensing, RFID ¡1m	Sensor per location	Hardware costs	Must know sensor locations
SpotON	Ad-hoc lateration	P	R	No	Yes	Depends on cluster size	Cluster at least 2 tags	Tag US$30, no infrastructure	Attenuation less accurate than time of light

3.1.3 Physical Environment Sensing

Nowadays a large variety of sensors are available in the market. Different characteristics of the physical environment can be measured and transformed into useful information about the operation conditions an object is exposed to, some examples are:

- temperature
- pressure
- humidity
- vibration
- acceleration.

In (White, 1987), a complete sensor classification scheme is presented. Sensor characteristics, as well as the primary phenomena used to convert the measurement into a form suitable for producing a sensor output are shown. Sensors characteristics like size, power consumption, processing requirements and, especially cost, are determinant when integration into a certain application is considered.

3.1.4 Communication

The communication capability of the information system is probably one of the most important characteristics. How to transmit the data obtained so that it is available when needed, where needed, finally determines the timely and accuracy of the acquired information. In this section some relevant communication technologies are reviewed.

Light

Infrared data port (irDA) is a common form of data communication using light. Wireless infrared communication refers to the use of free space propagation of light waves in the near infrared band as a transmission medium for communication (Carruthers, 2002). Wireless infrared communications can be characterized by the application for which they are designed:

- Short term cable-less connectivity for information exchange between two users. IrDA is the primary example for this type of application. IrDA provides high data rates over short distances, and its components are relative short powered (Williams, 2000).
- Wireless local area networks (WLAN) provide network connectivity inside buildings. The primary example of this type of application is the IEEE 802.11 standard. The IEEE 802.11 standard supports the use of both radio and infrared connectivity to facilitate mobility, or to establish ad-hoc networks where there is no LAN (Carruthers, 2002).
- Building to building connections for high speed network access or campus area networks. This type of infrared links must have a clear Line of Sight (LOS) to reduce path loss. The emerging products to support this technology are typically placed in rooftops to increase the change of establishing line of sight paths in urban environments (Kahn and Barry, 1997).
- Wireless input and control devices as wireless mouse, remote controls, wireless game controllers and remote electronic keys (Carruthers, 2002).

Short range - Active radio communication

Active radio communication implies the need of a power source on each side of the communication link. The transmitter and the receiver in short range radio communication systems can communicate over distances of up to 100 meters (Haller and Hodges, 2002). Radio communication works without line of sight, so even if there are a number of obstacles between the transmitter and the receiver communication is still feasible. One of the most well known standard for short range radio communication is Bluetooth. Bluetooth was designed as a short range connectivity solution for personal, portable and handheld electronic devices (Bisdikian, 2001). Bluetooth supports ad-hoc connectivity with a number of wireless devices. The bluetooth network is established when two or more devices that want to exchange information form what is called a piconet. Within a piconet, a bluetooth device can serve either as a master or a slave. A piconet can have only one master and up to seven slaves. Communication is only possible when a master polls each slave according to a polling scheme. A slave can only transmit after it has been polled by a master. Transmission between the master and a slave is only possible after the master polls the slave (Johansson et al., 2001).

Cellular communication

When communication over distances longer than 100 meters is required, two possible approaches can be used. The first approach is to increase the transmission power under the disadvantage of needing more powerful energy sources which may increase the size and value of portable devices. The second approach is the one used in mobile telephony and WiFi wireless networking (Haller and Hodges, 2002). In these cases, an infrastructure of radio base stations is created in such a way that communication only occurs with the nearest base station. A number of standards exits nowadays, including GSM, GPRS, UMTS, WiFi.

Passive radio communication

Contrary to active radio communication where both sides of the communication link are required to have a power source, in passive radio communication usually only one member of the communication link has a power source which is used to power the entire communication. This is how the communication link is established in passive RFID systems. The reader generates an RF field that power the tags within its read range, and the tags use the harvest energy from the RF field to communicate with the reader (Finkenzeller, 2003).

Wire-based communication

Wire based communication can be very convenient in situations where wire power is available and higher performance, robustness and longevity of sensing devices is required. For this applications, the concept of network-direct appliances can be applied. This approach investigates the possibility to incorporate an ethernet interface into small electronic devices to have full connectivity to any other device in the network (Haller and Hodges, 2002).

3.2 Decision Making system

In the previous section, an overview of possible technological tools to support the information system in prognostics logistics were reviewed. The availability of possible object level information, including unique identification, location, status and operational condition can fundamentally enhance control approaches for logistics systems. Prognostics logistics intends to influence decision making systems or control systems by using timely and accurate information to generate prognoses, and create a suitable time window to react and, either prevent or correct, the possible effects of a disturbance. This implies that control strategies in prognostics logistics should be based on a close loop approach where decisions are made based on the available prognoses generated using accurate and timely information acquired from objects, processes and operational conditions, Figure 3.2 shows a close loop control system with prognostics. In this case, the available information at a given time is compared with the reference point. The change of the object status or condition is feed into the prognostics model. With this information, the prognostics model generate prognosis on the future expected status or condition of the object. Using this prognosis, the decision making system generates instructions and takes actions to prevent or correct possible disturbances in the system.

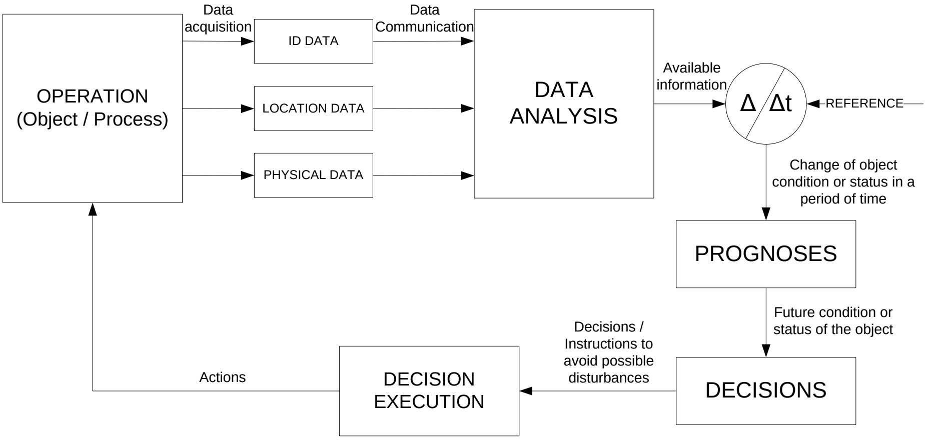


Figure 3.2: Closed loop control in prognostics logistics.

Figure 3.3 shows another possible configuration for the closed loop control in prognostics logistics. In this case, the prognoses of the future state or condition of the objects are compared with the reference point. The outcome of this comparison is used to make decisions and take actions to avoid disturbances in the system.

The four features of the information system should provide a physical and information based representation of an object or process in which:

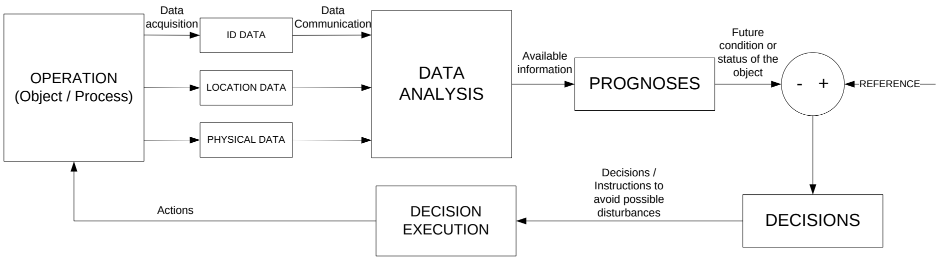


Figure 3.3: Alternative closed loop control in prognostics logistics.

- a unique identification is available
- communication with its environment is possible and effective
- contains physical data about the operational conditions
- it is capable of actively influencing decision making on a continuous basis.

Having a virtual representation of numerous objects involved in a process, makes it possible to have high quantities of information that was not available before (McFarlane, 2002). Changing the role of the objects from passive to active should influence the way decisions are made. The available information will generate knowledge on the cause and effect relationship that exists within logistics systems. With the available knowledge, once minor changes in the operational conditions are detected, prognoses about possible disturbances will be used in decision making systems to prevent or correct the disturbance and minimize its effects. There is a wide variety of decision making systems. Table 3.4 summarizes the pros and cons of three well known decision making systems.

3.3 Application examples for prognostics logistics

Activities are planned, scheduled and controlled based on the available information at different stages of the logistics process. The information mainly depends in the tools used to capture and process data, this influences the level of visibility of objects and processes. Timely and accurate information is the core of prognostics logistics. With this type of information is expected that prognoses can be generated to improve decision making systems. With this characteristic, it is

Table 3.4: Decision making systems

Decision Making System	Pros	Cons
Expert Systems	Ability to solve complex problems, Improve decision making process, improved decision quality, decreased decision making time.	Difficulty in capturing the deep knowledge of the problem domain, lack of robustness and flexibility, difficulties in solution verification, little learning from experience. Difficulty to work in real-time (Beemer and Gregg, 2008)
Agent Systems	Automating the retrieval of information and improving quality of information with real time, on-line data capabilities. Continuously monitoring whether the parameters used for decision making are up to date, relieving the user from having to monitor this themselves.	Determining appropriate decision making rules and decision making strategies for distributed decision making (Hess et al., 2008).
Arificial Neural Netwoks	ANN has been proven to produce better results as compared to more traditional statistical modeling techniques. It is a suitable technique for complex problems where there is not an optimal solution option (Delen and Sharda, 2008).	Development can be quite complex. Neural networks need to be retrained if major changes in the environment happened in order to maintained the accuracy of the predictions.

possible to think feasible applications where prognostic logistics will improve the way the logistics systems are managed. Five applications of prognostics logistics in the supply chain are developed. The implementation of prognostics in the cases mentioned below improves the activity planning and the control of production and optimizes the transportation network.

3.3.1 Tracking and Tracing

Tracking and tracing is an added functionality of prognostic logistics. With tracking and tracing, it is possible to know the location of products, materials and company assets. Furthermore, it is possible to know current status and even environmental conditions. Constantly tracking and tracing every product in the logistics systems enables the possibility to know where the product is, what the next location is, when it was shipped, and so on. With this type of information, it is easy to detect theft and counterfeiting fast enough to take proper action in order to reduce costs and to improve safety. Another application of this functionality is in inventory management. Goodyear is using RFID technology for tracking and tracing the leased tires in the NASCAR race car (Swedberg, 2005). The company expects that RFID will simplify inventory and ensure the return of the leased tires. Another company, Michelin, is using transponders for tracking and tracing the tires along the supply chain (Michelin, 2003). They are testing the transponders with temperature and pressure sensors that will inform the driver about the tires' condition. The tracking and tracing functionality combined with technological health of equipment will allow having better transport coordination between different locations. For example, in Figure 3.4, a truck is continually being monitored along the route. Using RFID tags equipped with sensors (for example temperature), the products inside the truck are also monitored. Using wireless cellular communication, the position of the truck can be determined through proximity analysis to one of the base stations. The gathered information can be used to analyze not only the trucks condition but also the products status. According to the truck condition, it is possible to determine how many kilometers it has left before scheduling maintenance. This will give enough time to the central system to allocate a new resource to fulfill the routes of the truck while it is being served. Monitoring the products inside the truck increase the visibility of the logistics system, so it is possible to know exactly when and where deliveries can be expected.

3.3.2 Condition monitoring and technological health

Equipment and its components have a certain amount of functioning hours before they have to be replaced. The number of hours of a piece is given by a confidence interval. Confidence intervals are the result of tests and reliability models. Reliability models use historical data about the behaviour of the equipment to predict the amount of functioning hours a piece has. It is really important for

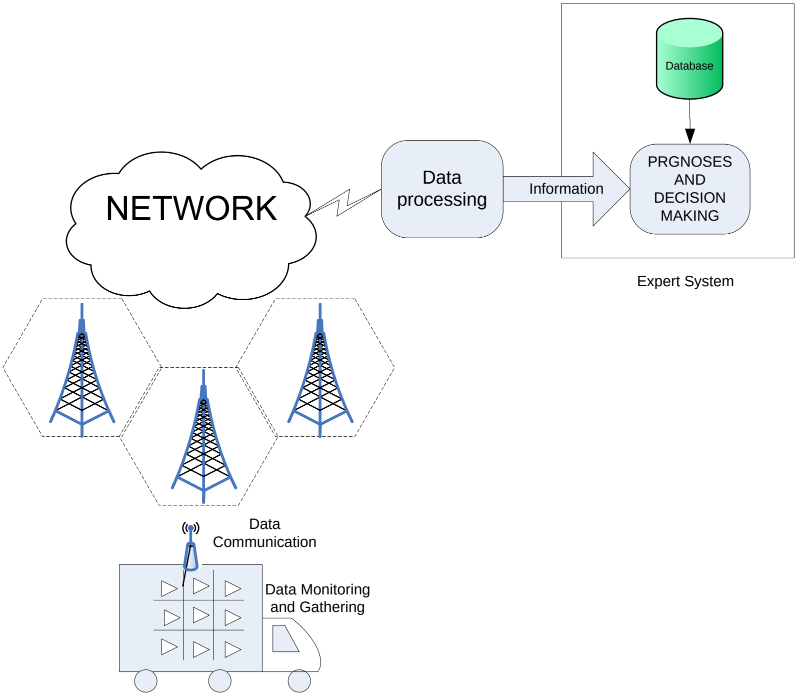


Figure 3.4: Track and Trace in prognostics logistics

this model to have up to date information. If these models are actualized with real information about the behaviour of the piece while functioning, they can be used to accurately determine whether the piece is presenting an early failure or if there is another factor affecting the right functioning of the equipment. When a third party handles the predictive maintenance, they base their decisions about the functioning of a piece on what it is available at sight and the confidence interval. However, using this extra information, catastrophic failure can be avoided, and corrective maintenance can be scheduled without delaying the production. According to reliability surveys, three phase induction motors broke down because of 4 main factors (Durocher and Feldmeier, 2004): bearing failure (lubrication, misalignment, and unbalance), stator turn faults, rotor bar failure, and other. The misalignment can be detected by monitoring the amplitude variances in the motor current spectrum. Using prognostic logistics, the technological health of such an equipment can be measured and controlled in real time by means of sensors that reply alarms when the current levels are above the allowed value; helping to prolong the expected life of the motor. Oil pipe inspection can be determined by probability analysis (Kumar, 2004). The mathematical model optimizes the costs of the pipeline operations and identifies the right segment for inspection. This model does not eliminate the subjectivity of the results. The weight given to each failure factor is based upon experience and historical data. Using prognostic logistics, the subjectivity will be eliminated. Acquiring real information from inside the pipeline will notify what factors are affecting the pipeline and the type of influence they have on certain strips of the oil pipeline. With this data, the inspections will be directed to the cases where assistance is needed; resources are relocated efficiently and without delay. For example, in Figure 3.5 maintenance activities for belt conveyor systems can be automatically schedule using, in this example, agent systems. Agents, together with sensors to capture physical information about the different parts of the belt conveyor, monitor and analyze the data. Agents have the ability to access directly a database that contains information about the normal functioning of the parts in the belt conveyor. With this data, agents can be used to autonomously make prognoses and decide when the next schedule needs to be performed. In the same way, the agents automatically can access the central system and schedule the maintenance. Users are only informed of the decisions made by the agents.

Another application for condition monitoring is in manufacturing. Intelligent equipment in manufacturing involves self identification of unique parts, communication between parts and equipment, automation in manufacturing, quality control and more (Zhekun et al., 2004). Integrating these smart parts in the production and assembling of an airplane, can facilitate tracking and tracing of missing components and maintenance (Lampe et al., 2004). Security is the main factor in the airplane industry. Using technologies like RFID, it is possible to tag all the replaceable items with its corresponding life cycles embedded in the information of the tag. Using handheld readers, it is possible to verify whether all the lifejackets are under the seats or if a certain oxygen tank needs to be changed.

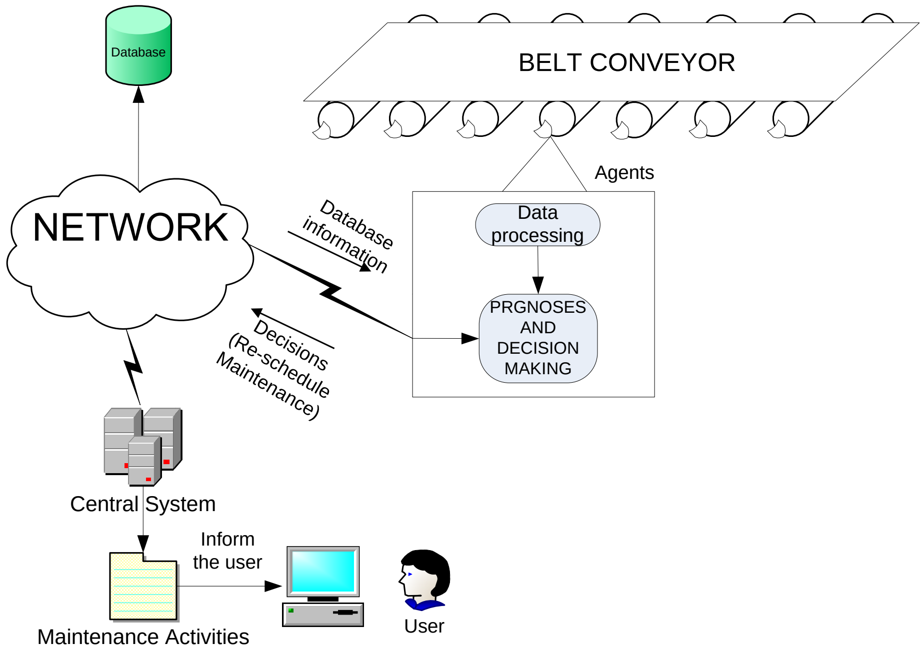


Figure 3.5: Condition monitoring of a belt conveyor.

3.3.3 Product status and situation assessment

Transport of perishable goods

Almost 10% of all perishable goods are wasted before purchase (Roberti, 2005). A concept called quality oriented tracking and tracing is being developed to follow the total amount of time it takes perishable goods to move from one point to another. At the same time, environmental data is collected (temperature and humidity) to determine what goods were exposed to the toughest conditions for longer time. With this information, replenishment strategies can be scheduled for specific products; first replenished with the products exposed the longest to hard conditions. Perishable goods, like tomatoes, are usually scheduled to delivery according its colour. When a pallet of tomatoes is sent to the retailer, it is usually because the tomatoes have a colour between red and green. For this delivery to be scheduled, it is necessary to have people constantly examining and inspecting the colour status of the tomatoes. Using a prognostic logistics tool like RFID combined with a colour sensor (Siemens, 2005), it is possible to tag around 10% of the tomatoes in a pallet. The sensor will determine when the colour of the tomatoes reaches the desired one, and an alarm is sent through the logistic network to inform that the pallet is ready to be delivered. The conditions of perishable goods are mostly related to temperature and humidity. Using technological tools available, it is possible to accommodate the environmental conditions. If a certain amount of tomatoes is needed, it is possible to place the tomatoes in a container, increase temperature and humidity conditions, and make the goods available at minimum time. Also, by reducing temperature and humidity, the products can be kept on stock for a longer period. Handling the conditions of perishable goods in store and in transport will reduce the costs related to spoilage and will increase the productivity and efficiency of this supply chain.

Potatoes starch production process

The AVEBE group, Suikerunie, and CSM company yearly convert 1.5 million ton potatoes and 5.5 million ton sugar beets into respectively potato starch and sugar. Potatoes and sugar beets are harvested and supplied to the factories in a relatively short period, also called the campaign. Potatoes are stored in heaps, covered pits or climate controlled warehouses after being harvested. Sugar beets are just stored in heaps awaiting transport to the processing factory. Normally, the transport of the potatoes and sugar beets from the farmers to the factories is outsourced to specialized transportation companies that have long term contracts with the AVEBE and the sugar manufacturers. These companies also pre-clean the potatoes and sometimes the sugar beets. Since the factories have a specific capacity and do not want a stockyard of potatoes or sugar beets, the production of potato starch and sugar needs to be planned. The campaign production planning consists of the determination of the harvesting moment and the logistic planning of the transport from the farmer to the factory. The production planning is fixed long before the campaign starts. Typically the supply of sugar beets or potatoes to the factory is based on a lottery system. This system allocates a specific ”supply slot” to a specific farm. A farm can only supply its products to the factory during this slot (JIT supply system). The production planning is therefore not influenced by actual grow process details or the way the potatoes or sugar beets are stored after harvest. Both the moment of harvesting and the way and time the products are stored affect the quality. For example the longer potatoes are stored the lower the starch content and thus the quality. The current production process does not take quality into account. If the quality of the products is taken into account then the volume or quantity of the production of potato starch and sugar can be maximized. For example the quality of potatoes is quantified by the starch content of the potatoes. Accounting for the quality of the potatoes during the campaign means accounting for the potato starch content. This can be achieved by using a distributed sensor system that can measure the quality of the potatoes and sugar beets on the farm before harvesting and during storage after harvesting. In case of potatoes the sensors for example continuously measure the starch content and wirelessly report that to the factory by using a distributed agent based communication system. In the factory the production planning of a specify day can then be based on the information of the average potato starch content of the potatoes of all the farmers that supply the factory of the previous day. By doing this the logistics of the production process can be optimized and reduction of the overall quality of the products can be minimized.

Flower Supply

The Netherlands are well known for their production of a wide range of flowers. The fast majority of the flowers is grown in greenhouses. After the harvest of the flowers the flowers are bundled and put in buckets on unit load devices (ULD). These ULD are then loaded into trucks and transported to auction. Since the auction starts early in the morning, the flowers have to be packet and transported at night. All trucks with flowers arrive at the auction in a relatively small time window leading to serious congestion on the road. The idea is to develop ULD in which the temperature can be controlled. If the temperature can be controlled then the blossoming process can be controlled as well. At a low temperature this process develops much slower then at a high temperature. The climate control unit can be controlled by sensors that are put on the flowers measuring colour or extension of the flowers. This first of all allows the farmers to pack the ULD earlier so that their business can take place at regular business hours. Secondly, the climate controlled ULD can be placed on a pick up station next to the road. Specialised trucking companies can then collect them at any time during the night. With climate control the ULD can also be delivered at the auction at any time and temporarily stored there. This means that the logistics become much more flexible. In addition, if the ULD are equipped with a camera system and communication tools then it is possible for the flowers to be auctioned on-line. On-line auction is already possible but means today that the flowers are physically present at the auction. The buyer may be somewhere else following and participating in the auction on-line. If a camera system is available in the ULD and the volume of a specific batch of flowers that a buyer wants to buy is large enough then it becomes possible to completely by-pass the auction and transport the flowers straight from the farmer to the buyer's premises

3.4 Conclusions

The prognostic logistics concept was discussed in this chapter. It is possible to recognize two important elements in the concept of prognostics logistics. The first element in prognostics logistics is an information system where acquisition and processing of timely and accurate information is the main function. The second element in prognostics logistics is a decision making system where prognoses of possible disturbances based on the available information are generated. With prognostic logistics it is expected that uncertain situations can be reduced, giving the possibility to logistics systems to early detect possible equipment failures, and hazardous situations fast enough to take prompted actions. However, how far prognoses can be generated and how good the prognoses are, ultimately depends on acquiring timely and accurate information.

The quality of the information acquired has a direct influence in the reliability of the prognoses in prognostics logistics. Four important features of the information systems were presented, these are: unique identification of objects and processes, location information, physical environmental information and communication . Characteristics and possible technological tools to support each of the four features of the information system were presented. Radio frequency identification (RFID) is a technology that stands out against the other technologies presented. This technology alone, offers unique identification of objects and processes, with proximity analysis location sensing can be realized (this enables track and tracing capabilities), it can be used in combination with sensors to capture physical environment information, and it can communicate, passively or actively, information about objects or processes. There are different sources investigating what RFID can do, and how to implement RFID in the organization. In (Lodewijks et al., 2006), it was suggested that in order to determine the applicability of RFID in a certain application scenario, a testing methodology composed of three main testing procedures should be implemented. In (López de la Cruz et al., 2008), a testing methodology composed of fundamental tests, semi-fundamental tests and operational tests was presented. The use of a testing methodology, to study the applicability of RFID, has the objective of understanding the technical characteristics of RFID and the effects of certain environments in the overall performance of RFID systems.

In order to develop a testing methodology for RFID, it is necessary to understand the operating principles of RFID systems. In Chapter 4 an introduction to RFID systems will be presented. Technical characteristics, RFID standardization issues, opportunities of RFID systems and the factors that made RFID one of the most popular technological tools to support logistics operations will be presented and discussed.

3.5 References

Angle, S., Bhagtani, R., and Chheda, H. (2005). Biometrics: A further echelon of security. In UAE International Conference of Biological and Medical Physics.

A.Zaharudin, Wong, C., Garwal, V., McFarlane, D., Koh, R., and Kang, Y. (2002). The intelligent product driven supply chain. White Paper, Auto-ID Center. Available On-line, http://www.ifm.eng.cam.ac.uk.

Beemer, B. A. and Gregg, D. G. (2008). Advisory systems to support decision making. In *Handbook on decision support systems 1*, chapter 24. Berlin: Springer.

Bisdikian, C. (2001). An overview of the bluetooth wireless technology. *IEEE Communications Magazine*, 39(12):86–94.

Carruthers, J. B. (2002). Wireless infrared communications. *Wiley encyclopedia of telecommunications*.

Delen, D. and Sharda, R. (2008). Artificial neural networks in decision support systems. In *Handbook on decision support systems 1*, chapter 26. Berlin: Springer.

Durocher, D. and Feldmeier, G. (2004). Predictive versus preventive maintenance. *IEEE industrial applications magazine*.

Finkenzeller, K. (2003). *RFID Handbook*. John Wiley and Sons, West Sussex, England, second edition.

Govindan, V. K. and Shivaprasad, A. P. (1990). Character recognition - a review. *Pattern Recognition*, 23(7):671–683.

Haller, S. and Hodges, S. (2002). The need for a universal smart sensor network. White Paper, Auto-ID Center. Available On-line, http://www.autoidlabs.org/single-view/dir/article/6/107/page.html.

Hess, T., Rees, L., and Rakes, T. (2008). Using autonomous software agents in decision support systems. In *Handbook on decision support systems 1*, chapter 25. Berlin: Springer.

Hightower, J. and Boriello, G. (2001a). Location sensing techniques. Technical Report UW CSE 01-07-01, University of Washington, Department of Computer Science and Engineering. Available On-line, http://www.cs.washington.edu/research/portolano/papers/UW-CSE-01-07-01.pdf.

Hightower, J. and Boriello, G. (2001b). Location systems for ubiquitous computing. *IEEE Computer*, 34(8):57–66.

Introna, L. D. (1993). The impact of information technology in logistics. *Logistics Information Management*, 6(2):37–42.

ISO/IEC (2005). Information technology - automatic identification and data capture (aidc) techniques - harmonized vocabulary (part 3: Radio frequency identification (rfid)). Technical Report ISO/IEC 19762-3, The International Organization for Standarization and the International Electrotechnical Comission.

Johansson, P., Kazantzidis, M., Kapoor, R., and Gerla, M. (2001). Bluetooth: an enabler for personal area networking. *IEEE Network*, 15(5):28–37.

Kahn, J. and Barry, J. (1997). Wireless infrared communications. *Proceeding of the IEEE*, 85(2):265–298.

Kumar, P. (2004). Decision support system for inspection and maintenance: A case study of oil pipelines. *IEEE transactions on engineering management*, 51(1):47–56.

Lampe, M., Strassner, M., and Fleisch, E. (2004). A ubiquitous computing environment for aircraft maintenance. In *SAC '04: Proceedings of the 2004 ACM symposium on Applied computing*, pages 1586–1592, Nicosia, Cyprus. ACM.

Lodewijks, G., Veeke, H. P. M., and López de la Cruz, A. M. (2006). Reliability of RFID in logistic systems. In *Proceedings of the 2006 IEEE Conference on Service Operations and Logistics, and Informatics*, Shanghai, China.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2006). Prognostics in the control of logistic systems. In *Proceedings of the 2006 IEEE*

Conference on Service Operations and Logistics, and Informatics, Shanghai, China.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2007). Applicability of RFID in prognostic logistics. In *Proceedings of the 2007 IEEE Conference on Service Operations and Logistics, and Informatics*, Philadelphia, USA.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2008). Performance measuremet of RFID. In *Proceedings of the International Simulation Conference 2008*, Lyon, France. EUROSIS.

Mantas, J. (1986). An overview of character recognition methodologies. *Pattern Recognition*, 19(6):425–430.

McFarlane, D. (2002). Auto-id based control. White Paper, Auto-ID Center. Available On-line, http://www.autoidlabs.org/uploads/media/CAM-AUTOID-WH-004.pdf.

Michelin (2003). Michelin embeds rfid tags in tires. Internet, RFID Journal. Available On-line, http://www.rfidjournal.com/article/articleview/269/1/26/.

Patridge, K., Arnstein, L., Boriello, G., and Whitted, T. (2002). Fast intra-body signaling. Demostration at Wireless and Mobile Computer Systems and Applications (WMCSA).

Pyle, I. C. (1993). *Real Time Systems: Investigating Industrial Practice*. John Wiley and Sons.

Roussos, C. (2002). Location sensing technologies and applications. Technical Report TSW 02-08, Join Information Systems Comitee. Available On-line, http://www.jisc.ac.uk.

SCF (2005). What is so smart about a smart card. Internet, Smart Card Forum. Available On-line, http://www.gemplus.com/smart/cards/basics/download/smartcardforum.pdf.

SUN (2005). The Auto-ID center. Internet, Auto-ID Center. Available On-line, http://www.sun.com/solutions/documents/solution-sheets.html.

Swedberg, C. (2005). Rfid tracks tires at nascar. Internet, RFID Journal. Available On-line, http://www.rfidjournal.com/article/view/2006/1/1.

White, R. M. (1987). A sensor classification scheme. *IEEE Transactions on ultrasonics, ferroelectrics, and frequency control*, UFFC-34(2):124–126.

Williams, S. (2000). Irda: past, present amd future. *IEEE Personal communications*, 7(1):11–19.

Wyld, D. C. (2006). RFID 101: the next big thing for management. *Management research news*, 29(4):154–173.

Zhekun, P., R.Gadh, and Prabhu, B. (2004). Applications of rfid technology and smart parts in manufacturing. In *Proceeding of DECTC'04: ASME 2004 design engineering tehcnical conferences and computers and information engineering conference*, Salt Lake City, Utah USA.

CHAPTER 4

Radio Frequency Identification

The quality of the information acquired on the performance of a logistics system has a direct influence in the reliability of the prognoses in prognostics logistics. Four important features of the information systems were presented in the previous chapter: unique identification of objects and processes, location information, physical environmental information and communication. Radio frequency identification (RFID) is a technology that offers unique identification of objects and processes. It can actively or passively communicate this information and, in combination with sensors, it can capture more detailed physical information. There are different sources investigating what RFID can do, and how to implement RFID in an organization. In (Lodewijks et al., 2006), it was suggested that in order to determine the applicability of RFID in a certain application scenario, a testing methodology composed of three main testing procedures should be implemented. In Chapter 5 a testing methodology to implement RFID in different applications will be presented. However, in order to develop a testing methodology to apply RFID in different application environments, it is necessary to understand the operating principles of RFID systems. In this chapter an introduction to RFID systems will be presented. Technical characteristics, RFID standardization issues, opportunities of RFID systems and the factors that made RFID one of the most popular technological tools to support logistics operations will be presented and discussed.

Radio Frequency Identification technology has been integrated into our daily life. Gaining access to a building, paying road tolls without stoping, managing traffic, preventing theft of vehicles and merchandize, tracking library books, controlling the access of vehicles to gated communities, are some examples of successful RFID implementations. RFID is a short range radio communication technology used to communicate data between a stationary location and movable objects or between movable objects (Landt, 2005). There are different radio frequencies and techniques used in RFID systems. RFID is usually characterized by simple devices called tags or transponders at one end of the communication link, and more complex devices called readers at the other end of the link. Tags are usually small and inexpensive, can be economically deployed and are attached to the objects to be managed. Readers are in charge of acquiring the information from the tags, are bigger in size and more expensive, and are usually connected to a host computer or a network. RFID systems have been used in frequencies varying from 100kHz to 1GHz (Landt, 2005).

In this chapter, RFID technology will be presented. In section 4.1 history and development of RFID will be introduced. In section 4.2, the different components of RFID technology will be presented. The frequency ranges of RFID will be discussed in section 4.3. Operation principles will be presented in section 4.4. Data integrity and security and regulations and standardization of RFID systems will be discussed in section 4.5 and section 4.6 respectively. Conclusions will be drawn in section 4.7.

4.1 History and development of RFID

In 1948, Harry Stockman published the paper entitled ”Communication by means of reflected power”. This is considered to be the first work exploring RFID technology. For Stockman’s vision to become a reality, other developments were needed: transistors, integrated circuit, communication networks, among others. In the 1950s, following the technical development of the radar in the 1930s, technologies related to RFID like the long range transponder system or ”identification, friend or foe” (IFF) for aircraft were explored. In the 1960s Sensormatic and Checkpoint were created. These companies together with Knogo developed electronic surveillance equipment (EAS) to counter the theft of merchandize. This system is used in 1-bit tags where only the presence or absence of the tag is detected. EAS is the first and most widely commercial application of RFID technology (Landt, 2005). The 1970s were mainly characterized for developmental work. Applications in animal tracking, vehicle tracking and factory automation were investigated. Tags were improved with reduction in size and functionality. These advances were possible because of the use of CMOS[1] logic circuits. In 1975, the work of Alfred Koelle, Steven Depp and Robert Freyman, ”Short range radio telemetry for electronic identification using modulated backscatter” marked the beginning of completely passive RFID systems that can have a communication range of tens of meters. In the 1980s, implementations of RFID technology were growing. In the United States the greatest interests were for transportation, personnel access, and animal tracking. In Europe, the interest were for short range systems for animals and industrial and business applications. Toll roads applications were implemented in Norway, France, Spain and Portugal. In the 1990s, large scale implementations of RFID for electronic toll collection in the United States and Europe were realized. With the success of electronic toll collections, and the development of the first multiple use of tags across different business segments application, the interest on RFID was growing. In the Dallas-ft Worth metroplex, was the first time a vehicle using a single TollTag could not only pay for the tolls on the North Dallas Tollway, but also was able to access and pay for parking at the Dallas-ft Worth International Airport, and several other parking places nearby, as well as access gated communities and business campuses. In the 1990s, the research for smaller and more functional tags had an interest development. It was the first time that Schottky diodes were fabricated in a regular CMOS integrated circuit. This permitted the construction of microwave RFID tags that contained only a single integrated circuit and an antenna. This continued to improve, and nowadays, tags are being built as sticky labels easily attached to the objects to be managed. The size of the tag is now mainly determined by the constrains of the antenna.

Applications in supply chain management grew rapidly at the end of the 1990s due to the tag size reduction, cost reduction and increased functionality an reliability. The increased interest on RFID brought together institutions, manufactures, researchers and users and the AutoID center was organized at the Massachusetts Institute of Technology. The AutoID center’s main focus was to develop standards, perform research and share information for supply chain applications

[1]Complementary metal-oxide semiconductor is a low power, low voltage type of integrated circuits

of RFID. The concept of RFID main seem very straight forward, however, RFID is a technology that involves several research areas like electronics, antenna theory, software development, material technology, mechanical design, and more. The full potential of RFID still requires advancements not only in the areas mentioned, but also careful consideration and development of privacy policies, and the supporting infrastructure involved in installing and maintaining RFID systems.

4.2 Components of an RFID system

RFID fundamentally consists of three elements: tags, readers, and the host and software system necessary to link the hardware elements to the application system (Wyld, 2006). Figure 4.1 shows the functional blocks of RFID systems.

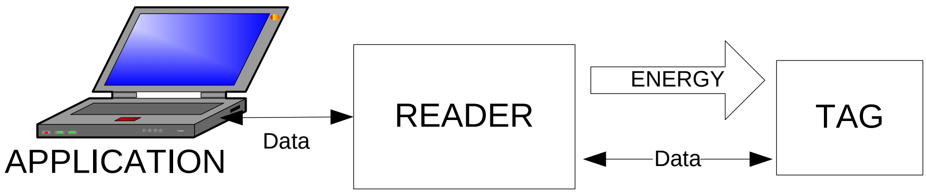


Figure 4.1: Passive RFID system.

4.2.1 Tags

An RFID tag is mainly composed of three elements: the chip, the antenna and the package that contains them. The silicon chip is an integrated circuit containing a radio receiver, a radio modulator to send the response back to the reader, a control logic, a memory to store, among others, an item unique identification and a power system. The silicon chip is attached to a small antenna and everything is protected using different packaging formats. The different packaging formats of RFID tags allows RFID systems to meet the requirements of a specific application. Figure 4.2 shows different packaging formats for RFID tags. Tag's packaging formats include (Finkenzeller, 2003):

- Disks and coins: this is the most common construction format. The tag is mounted in a round casing with diameter ranging from a few millimeters to 10cm.

- Glass housing: this type of casing is very suitable for animal tracking and identification purposes. The glass tube can be injected under the skin of the animal. The size of the tag varies between 12-32mm.
- Plastic housing: this tag was developed for applications involving high mechanical demands. It can be easily integrated into, for example, car keys for automotive industry applications, and it has greater tolerance to mechanical vibrations.
- Tool and gas bottle identification: special construction formats have been developed to integrate tags into metal structures. The external dimensions of the tags and their fitting area has been standardized into ISO69873.
- Keys and key fobs: this is a very popular system for access control to office and working areas. A tag already mounted into a plastic housing is injected into the key fob. This type of tags are also used in access applications with high security requirements.
- Clocks: this format was developed by Ski-Data. This Austrian company mainly developed this type of tag as a ski pass.
- Contactless smart cards: this type of format has the size of a standard credit card. In this case, the read range is increased due to the large area available for the antenna.
- Smart label: this is a paper thin tag. In this case, the antenna of the tag is applied to a plastic foil of 0.1mm thickness. This foil is laminated with a layer of paper and its back coated with adhesive. This tags are very versatile due to its flexibility and thinness, they can be applied to luggage, packages and goods of all types.
- Coil on chip: this type of tag is constructed using extreme miniaturization techniques that integrate the antenna onto the chip. The size of these tags is just 3mm x 3mm, and are among the smallest RFID tags in the market.

It is possible to classify RFID tags into two categories based on its power source. If the tag harvest the energy from the RF signal transmitted by the reader to power the system, then the tag is considered a passive tag. Alternatively, if the tag is equipped with its own power supply, for example a battery, then the tag is considered an active tag (Garfinkel and Rosenberg, 2006).

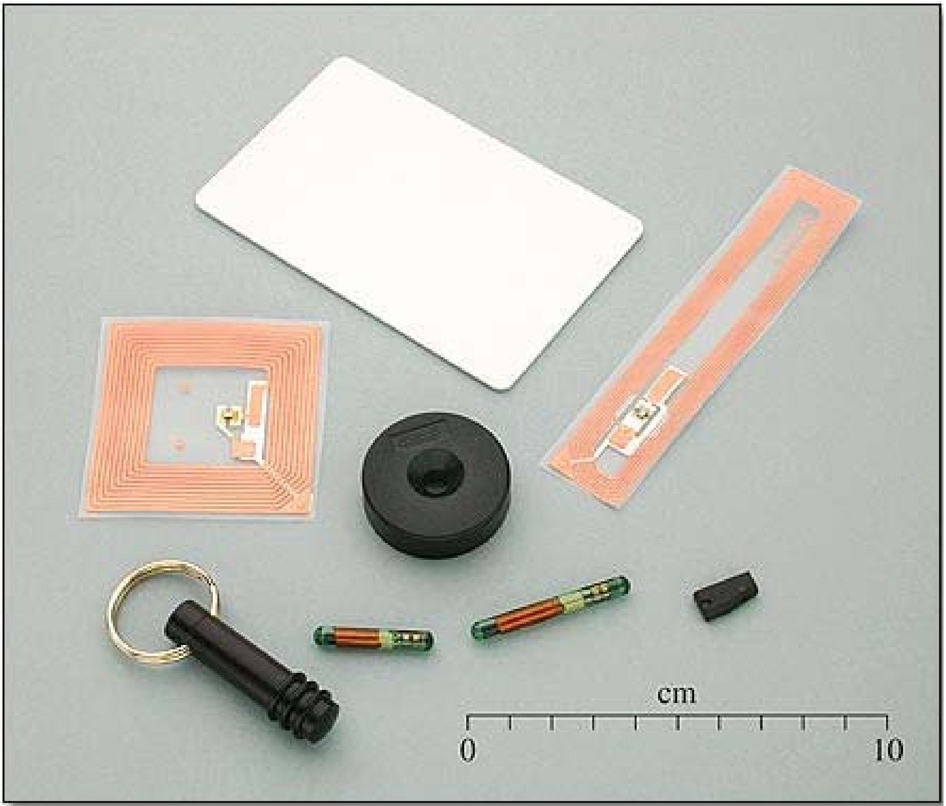


Figure 4.2: Different packaging formats for RFID tags.

Passive RFID tags collects the energy of the RF signal emitted by the reader to power the system and communicate the stored information. There are two main operation principles used in passive RFID systems, these are: inductive coupling and electromagnetic backscattering. With inductive coupling, an RFID tag collects the energy to power the silicon chip from the magnetic field of the RF wave transmitted by the reader. The tag sends back a modulated data stream to the reader (Wyld, 2006). The reader converts the tag's response into a digital form and communicates this data to the application system. In electromagnetic backscattering, the electric field of the RF signal provides the necessary operating voltage for the tag's circuits (Finkenzeller, 2003). The tag reflects back part of the incident power of the reader with a modulated data stream containing the tag's information. These two concepts will be further discussed in section 4.4.

The most popular packaging for passive RFID tags is in the form of smart labels. Smart labels combine the functionality of the passive tag with the flexibility and convenience of pre-printed and pre-coded tags ready for use or printed and coded tags on demand (Wyld, 2006).

Active tags contain a power supply, usually a battery, that provides the necessary energy to operate the circuit (Finkenzeller, 2003). The active tag changes from an active transmitting mode to a power saving mode if it is not activated to communicate with the reader. In case the tag is programmed to transmit only when interrogated by the reader, the necessary power to activate the active tag is much lower than in the case of a passive tag, and because of the internal power supply of the tag, communication ranges are typically over 10m. However, the useful life of an active tag can be limited by the life of the internal power source. Currently, active tags power with batteries have a life span of about 5 years.

There is a third category of tags, usually referred to as semi-passive tags or battery assisted passive tags. This type of tag has the same operation principles of a passive tag, but because of the internal battery the range and accuracy of the tag's response is enhanced (Garfinkel and Rosenberg, 2006). In Table 4.1 a comparison between active tags and passive tags is presented.

One of the most important functionalities of RFID tags is the possibility to store unique data about the object or process the tag is attached to, and make this data available to all the members of the logistic system when needed where needed. The data is stored insides the tag's memory. The memory characteristics of the tag can be classified in three forms:

- Read only tags: the data is programmed/printed during the production process, and can not be changed. This is the typical tag used in electronic surveillance equipment (EAS). The maximum data capacity is 96 bits.

- Write once/Read many tags: the data is programmed in the tag after purchase. Data can not be changed, it can only be retrieved as many times as needed. The maximum data capacity is 4Kbits.

- Read/Write tags: the stored data can be altered as many times (up to 1000 times) as needed. These tags can store more data and have higher security settings by using passwords and encryption methods to codify the data. The maximum data capacity is 512Kbits.

RFID tags are expected to fulfill a more active role in automatic identification systems. RFID tags can provide unique item level identification and, if possible,

Table 4.1: Comparison between passive RFID tags and active RFID tags

Passive Tags	Active Tags
Operate without a battery	Powered by an internal energy source
Low cost (25 cents per tag)	High cost (up to US$100 per tag)
Indefinitely life span	3- 5 years, according to the battery life
Read range between 3 to 5 meters (usually less)	Read range up to 100m (Free space)
Tags can only transmit data if they are with in the readers range, they can not initiate communication	Tags can initiate communication with the reader or other active tags
Sensitive to noise in the application environment	Better noise immunity
Data is transmitted at lower transmission rates	Higher transmission rates can be achieved
Greater orientation sensitivity	Almost no orientation sensitivity
Lower population of tags can be read simultaneously with high reliability	Larger population of tags can be read simultaneously

complete descriptive data about the object or process attached to. The electronic product code (EPC) was designed to be the unique, item level identifier coding system for RFID tags. EPC tags follow the EPC standard developed by the MIT Auto-ID center, now managed by EPCglobal. The EPC is comprise by 4 elements (Wyld, 2006):

- Header or version: this section identifies the length of the EPC number including the code type and version in use (up to 8 bits).
- EPC manufacturer: this section identifies the company responsible of managing the next two EPC elements (up to 28bits).
- Object class or product: this section identifies the class of the object, for example a stock keeping unit or a consumer unit (up to 24bits).

- Serial number: this section identifies a unique serial number for all items in a unique serial class (up to 36bits).

With the EPC data structure, there are 33 trillion different unique identification numbers (Comitee of RFID, 2004).This can be contrasted with 12 bit structure of the unique product code (UPC) for barcode systems. With UPC, it is only possible to identify 100,000 products for 100,000 manufacturers. Figure 4.3 shows a comparison of the UPC and the EPC data structure.

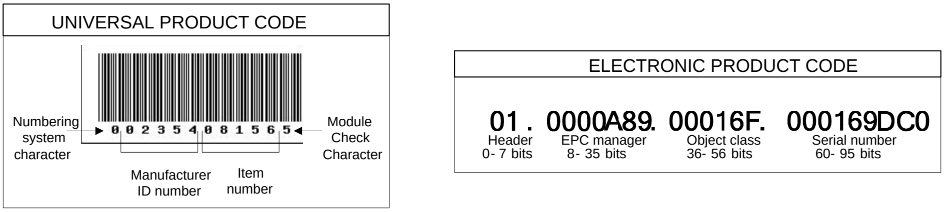


Figure 4.3: Comparison of the UPC and EPC data structure.

EPCglobal has defined a series of RFID tag classes. Most of the RFID tag providers follow the EPCglobal tag classification. Table 4.2 summarizes the EPC tag classes.

4.2.2 Reader

Readers are normally divided into two fundamental blocks (Finkenzeller, 2003): a control system and a HF interface. In this thesis, the antenna used by the RFID reader will be considered a third block of the reader. The HF interface is in charge of: generating the high frequency transmission power to activate the tags, modulating the transmission signal to send data to the tag, and receiving and demodulation of the signal transmitted by a tag. The control unit performs the following functions: communication with the application software, control of the communication with a tag, signal coding and decoding, execution of the anti-collision protocol, and encryption and decryption of data to be transferred. Antennas are the coupling element between the readers and the tags. An antenna is a component that has been optimized for radiation or reception of electromagnetic waves for certain frequency ranges (Finkenzeller, 2003). Antennas broadcast the RF signal from the reader and capture the signals send by the RFID tags. As with most radio communication systems, the size of the antenna in the reader and the tag has a direct influence in the performance and reliability of the communication link.

Table 4.2: EPC RFID tag classification.

EPC tag class	Tag class functionality
Class 0	Read only passive identity tags. EPC number is programmed by the manufacturer.
Class 1	Write once/ read many passive tags. Tags are manufactured without the EPC number. Tags are programmed by the user. Data can not be changed.
Class 2	Read/Write passive tags. Tags have larger memory with additional functionality like encryption and authenticated access control.
Class 3	Semi-passive tags. Tags have increased communication range and advanced functionality like sensing capabilities.
Class 4	Active tags. Tags are capable of broad-band communication with other active tags and with readers. Tags can be integrated with sensors with or without data logging.
Class 5	Essentially readers. They can power other Class 0, 1, and 2 tags, and communicate with class 4 and with other readers wirelessly.

The frequency used in RFID system determines the type of the antenna and the communication principle between readers and tags. This will be further discussed in section 4.3.

Readers can differ in their complexity, form and price, depending upon the type of tags being supported and the functions fulfilled (Wyld, 2006). Readers can be large and fixed or small hand held devices. Fixed readers have a larger read range because they can support larger antennas and have a more powerful power source than hand held readers(hand held devices usually run on batteries). Fixed readers can have multiple antennas (generally up to 4 antennas) arranged in such a way that the operating range and area coverage can be optimized.

RFID readers are continually transmitting radio energy and awaiting any tags entering their field of operation. For some applications where the energy supply is limited, it is possible to configure the reader so that it only sends a radio pulse in response to a external event. For example, a movement or light sensor can act as a trigger to activate the reader and start the communication process.

4.2.3 Host and Software Systems

The host and software system is composed by different software and hardware elements that link the basic RFID components to the application environment. This is referred to as the host system. The host system can be divided in: edge interface, middleware, enterprise back-end interface and enterprise back end (Lahiri, 2005).

The edge interface system integrates the RFID hardware with the entire host and software system. This system communicates with and controls the RFID reader. The main task of this component is to obtain data from the reader, and control the readers behaviour. The edge interface can also have individual control of different triggers used to activate the reader, extending the functionality of the trigger to more than a reader activation system. The edge interface can perform several different tasks, such as the following (Lahiri, 2005):

- Filter out duplicate reads from different readers
- Setting of different triggers to automate processes and data collection systems.
- Remote reading management
- Provide intelligent functions such as selectively sending tag data to host and software systems.

The middleware is the most important piece of software in the system. It can be broadly defined as every component that lies between the edge interface and the enterprise back end interface. It provides core functionalities of the system, including (Lahiri, 2005):

- Data sharing inside and outside of the enterprise.
- Efficient management of data produced by the RFID system.
- Open standard based so it can be compatible with a wide range of software systems.
- Coupling system between the interface and the back end interface, should function as a firewall in case of negative events.

The enterprise back end interface couples the middelware with the enterprise back end. In this part of the host and software system, the integration of business processes is realized. The amount of processes that need to be integrated determines the complexity and effort needed to implement this component (Lahiri, 2005).

Finally, the enterprise back end encompasses the complete suit of applications and IT systems of an enterprise. This is the business processes engine for the entire enterprise. This component is already built and the RFID integration should not disrupt or involve mayor changes in the system.

4.3 Frequency Ranges

RFID systems are classified as radio systems. The operation of RFID systems must not interfere with the normal functioning of other radio services. In order to protect other radio services, the number of suitable operating frequencies for RFID is significantly restricted. RFID systems usually operate in frequency ranges specifically reserved for industrial, scientific and medical applications (ISM frequency ranges). RFID systems can also operate in the entire frequency range below 13kHz (in North and South America and Japan below the 400kHz). The frequency ranges used in RFID systems are classified in four groups: low frequency, high frequency, ultra high frequency and microwave frequency. Table 4.3 provides a summary of the international RFID frequency regulations (AIM, 2006).

4.3.1 Low Frequency

RFID systems operating at low frequencies usually use the 125kHz to 134kHz frequency range (frequencies between 30kHz and 300kHz are considered low). A low frequency (LF) RFID system generally use passive RFID tags. The read range of LF RFID readers is very short, usually just 10cm. Also, the data transfer between tags and readers is particularly low. LF RFID systems perform very well in operating environments containing metals, liquids, dirt or mud. Tags are relatively inexpensive and it has the advantage that the operational frequency is the same worldwide.

4.3.2 High Frequency

RFID systems operating at high frequencies usually use the 13.56MHz frequency (frequencies between 3MHz and 30MHz are considered high). High frequency (HF) RFID systems use passive tags. The read range varies from 15cm to 40cm approximately. HF RFID systems have a slow data transfer, they perform well near liquids and metal. They are widely used in medical applications, especially in hospital because they do not interfere with existing equipment. The frequency used in HF RFID systems is the same worldwide.

4.3.3 Ultra High Frequency

Passive Ultra High Frequency (UHF) RFID systems operates at 915MHz in the United States and at 868MHz in Europe (frequencies between 300MHz and 1GHz are considered UHF). Active UHF RFID operates at 315MHz and 433MHz. Passive UHF RFID tags have a read range of up to 3meters. The data transfer between tags and readers is fast and multiple access protocols allows to read multiple tags almost simultaneously. However, passive UHF RFID tags perform quite poorly near metals and liquids. The frequency used for UHF RFID systems is not same worldwide.

4.3.4 Microwave Frequency

Microwave RFID systems usually operate at 2.45GHz or 5.8GHz (frequencies over 1GHz are regarded as microwave frequencies). Microwave RFID systems usually employs semi-passive and passive tags. They have the fastest data transfer rate among other RFID systems, however, they perform very poorly near water and metal. The frequency used in microwave RFID systems is the same worldwide.

4.4 Operating Principles of RFID

The operating frequency of the reader, the physical coupling method between readers and tags, and the read range of the system are the most important differentiation parameters of RFID systems (Finkenzeller, 2003). As it was mentioned in the previous section, the different frequency ranges of RFID systems varies between 135kHz to 5.8GHz. The range of RFID systems can vary from 1cm up to

Table 4.3: International RFID frequency regulations (AIM, 2006). ERP stands for Effective Radiated Power, and LBT stands for Listen Before Talk.

Country Region	LF	HF	UHF	Microwave
USA	125-134KHz	13.56MHz 10watts ERP	902-928MHz, 4 watts ERP	2.4-2.4835GHz, 4 watts ERP
Europe	125-134KHz	13.56MHz	865-865.5MHz, 0.1 watt ERP, LBT. 865.6-867.6MHZ, 2watts ERP, LBT. 867.6-868MHz, 0.5watts ERP, LBT.	2.45GHz
Japan	125-134KHz	13.56MHz	952-955MHz	2.45GHz
Singapore	125-134KHz	13.56MHz	866.1-869MHz, 0.5watts ERP 924-925MHz, 2watts ERP	2.45GHz
China	125-134KHz	13.56MHz	860-960MHz	2.446-2.454GHz, 0.5watts ERP.

15m. RFID systems with ranges up to 1cm are know as close coupling systems. Close coupling systems can operate at any frequency between DC[2] and 30MHz. In this systems, the tag must either be inserted into the reader or positioned upon a specific surface. Close coupling systems are mainly used in security systems like electronic door locking.

RFID systems with read and write ranges of up to 1m are known as remote coupling systems. This is the most popular RFID system in the market (Finkenzeller, 2003). Remote coupling systems operate based on the inductive coupling principle. The frequencies used for transmission are 135kHz and 13.56MHz. A lot of standards have been developed to specify the technical parameters of the tags and the readers for various applications, like animal identification, contactless smart cards and industrial automation.

RFID systems with ranges above 1m are known as long range systems. Long range systems operate using electromagnetic waves in the UHF or microwave

[2]DC is also know as zero frequency

frequency ranges. Ranges of up to 3 meters using passive tags and up to 15 meters with battery supported tags has been achieved. For passive long range RFID tags, the power of the electromagnetic field received from the reader is the only power used for data transmission between tag and reader.

The majority of RFID systems operate according to two physical coupling methods: Inductive coupling or electromagnetic backscattering. These two concepts are the core to understandind the procedures of power and data transfer between tags and readers, and therefore, understanding the limitations and possibilities of RFID technology.

4.4.1 Inductive Coupling

When a conductor carries current, a magnetic field and thus a magnetic flux, is produced around it. The magnitude of the magnetic field is described by the magnetic field strength H. For short cylindrical coils or conductor loops, the magnetic field and the magnetic flux (ϕ) is particularly intense. Conductor loops are used as magnetic antennas to generate the magnetic alternating field in inductively coupled RFID systems. Figure 4.4 shows the path of the lines of magnetic flux around a conductor loop.

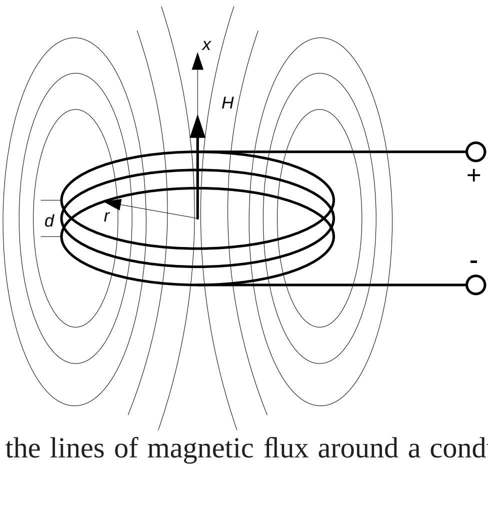


Figure 4.4: Path of the lines of magnetic flux around a conductor coil. (Finkenzeller, 2003).

The following equation can be used to calculate the path field strength H

along the coil axis (x axis) of a conductor loop:

$$H = \frac{I \cdot N \cdot r^2}{2\sqrt{(r^2 + x^2)^3}} \tag{4.1}$$

where I is electric current flowing in the conductor loop, N is the number of windings, r is the loop radius, and x is the distance from the center of the coil in the x direction. This has the following boundary condition: $d << r$ and $x < \lambda^3/2\pi$(transition into the electromagnetic far field). Figure 4.5 shows the calculated field strength path $H(x)$ for three different antennas at a distance from 0-10 m. The number of windings N is kept constant, the antennas only differ in radius. The figure shows that the field strength remains constant up to distances $(x < r)$, and then falls rapidly in proportion to x^3.

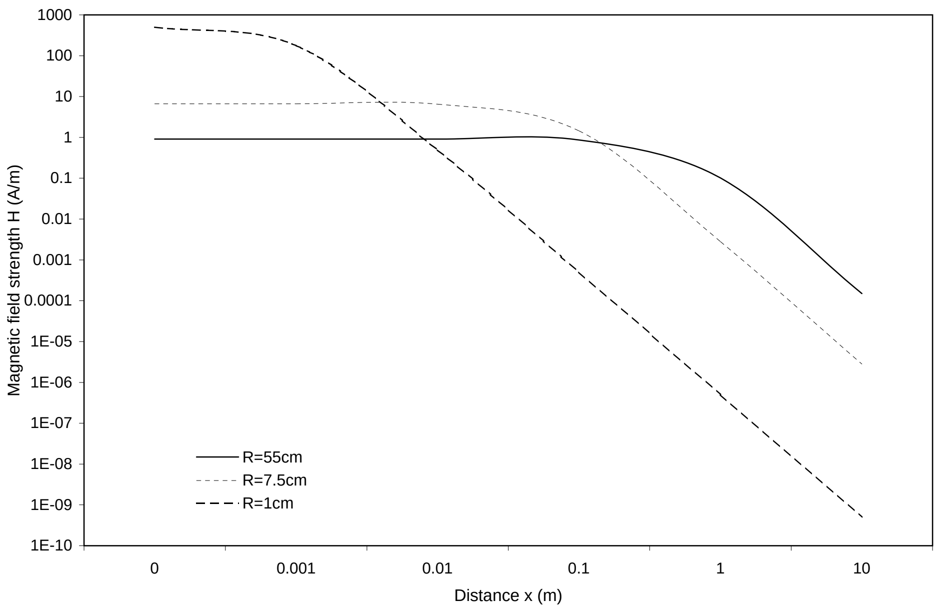


Figure 4.5: Path of magnetic field strength H in the near field of conductor coils, as the distance in the x direction is increased.

Figure 4.5 also shows that for every read range of an RFID system there is an optimal antenna radius. If the selected antenna is too big, the field strength H will

[3] λ is the wavelength of the electromagnetic wave

be too low even at distance $x = 0$. If the selected antenna is too small, then the field strength will decrease too fast in proportion to x^3.

The flux density B is defined as the amount of magnetic field flux concentrated in a given area. The relationship between flux density B and field strength H is given by:

$$B = \mu H \tag{4.2}$$

where μ is the permeability of the medium. The permeability is a specific measure of a material's acceptance of magnetic flux, greater permeability means easier passage of magnetic flux. The magnetic flux is expressed as:

$$\phi = B \cdot A \tag{4.3}$$

where A is the area of the conductor loop.

Inductance is a property of conductor loops. The inductance of a conductor loop is defined as the ratio of the total flux Φ that arises in an area enclosed by current I, to the current in the conductor loop:

$$L = \frac{\Phi}{I} = \frac{N \cdot \phi}{I} = \frac{N \cdot \mu \cdot H \cdot A}{I} \tag{4.4}$$

where N is the number of loops enclosing the same area and contributing the same proportion of magnetic flux ϕ to the total flux Φ.

When two conductor loops are placed close together, and a current is flowing through conductor loop 1, conductor 2 will be subjected to a proportion of the total magnetic flux flowing through the area of conductor 1. The mutual inductance M_{21} of conductor loop 2 in relation to conductor loop 1 describes the coupling of two circuits via the medium of a magnetic field. The magnitude of the magnetic flux depends on the geometric dimensions of the conductor loops, the position of the loops in relation to one another, and the magnetic properties of the medium (permeability). Furthermore, if a time variant current ($i_1(t)$) is flowing in conduction loop L_1, a time variant magnetic flux $d\phi(i_1)/d(t)$is generated. According to Faraday's Law [4] a voltage is induced in conduction loop L_1 and L_2 through which some magnetic flux is flowing. Both circuits are coupled by mutual inductance. Figure 4.6 shows the magnetically coupled conductor loops. In an inductive coupled RFID system L_1 would be the transmitter antenna of the reader and L_2 would be the antenna of the tag.

[4]Faraday's law establishes that any change in the magnetic flux of a coil will generate or induce a voltage in the coil.

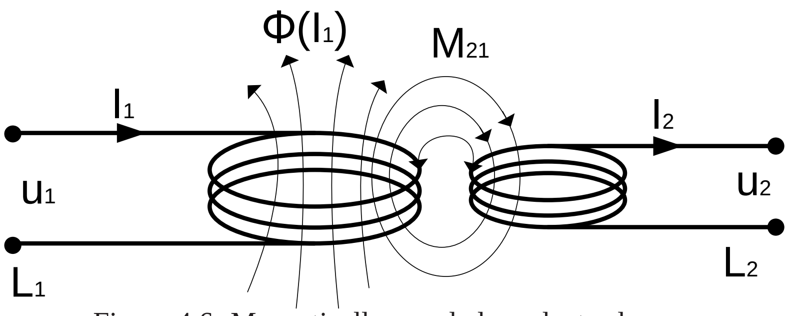


Figure 4.6: Magnetically coupled conductor loops.

The voltage u_2 induced in the antenna of the tag is used to power the microchip. A parallel resonant circuit tuned to the transmission frequency of the RFID reader is used to maximize the induced voltage u_2. The efficiency of the power transfer between the antenna coil of the reader and the tag is proportional to the operating frequency f, the number of windings N, the area enclosed by the transponder coil A, and the angle and the distance between the two coils. As frequency increases, the required inductance of the tag's antenna decreases, thus the number of windings also decreases (for low frequencies, 135kHz the typical number of windings is between 100-1000, for high frequencies, 13.56MhZ, the number of windings is between 3-10).

4.4.2 Electromagnetic Backscattering

The space surrounding an antenna is usually subdivided in three regions: the reactive near field, the radiating near field and the far field (Balanis, 1997). The boundaries of these regions are not fixed in the space, they move closer to or farther from an antenna depending on , among others, the radiation frequency.

The reactive near field is the region immediately surrounding the antenna. The energy is stored in the electric and magnetic fields very closed to the antenna but not radiated from it (Nikitin et al., 2007). Inductively coupled RFID systems harvest the energy necessary to power the tag from the near field of the antenna. The outer boundary of the reactive near field is commonly taken to exist at a distance of $r < 0.62\sqrt{D^3/\lambda}$ from the antenna surface, where λ is the wavelength and D is the largest dimension of the antenna. For electrically small antennas, the outer boundary is commonly taken to exists at $r = \lambda/2\pi$.

The radiating near field is the transition region between the reactive near field and the far field wherein the angular field distribution is dependent upon the distance from the antenna. If the antenna has a maximum overall dimension which is small compared to the wavelength, this region may not exist. The inner boundary of this region is taken to be at a distance of $r \geq 0.62\sqrt{D^3/\lambda}$ and the outer boundary at a distance $r < 2D^2/\lambda$ (Balanis, 1997).

The far field is the region where the angular field distribution is independent of the distance from the antenna. At this point the electromagnetic wave has fully formed and separated from the antenna. If the antenna has a maximum overall dimension D so that $D > \lambda$, the far field is commonly taken to exist at distances greater than $2D^2/\lambda$ from the antenna (Balanis, 1997).

Electromagnetic waves are used to transport information through a wireless medium from one point to another (Balanis, 1997). Electromagnetic waves transport energy in the electric and magnetic field of the wave. The electric field $\mathbf{E}$ is at right angles to the magnetic field $\mathbf{H}$, and both fields are at right angles to the direction of propagation, Figure 4.7shows the direction of propagation and the electric and magnetic fields.

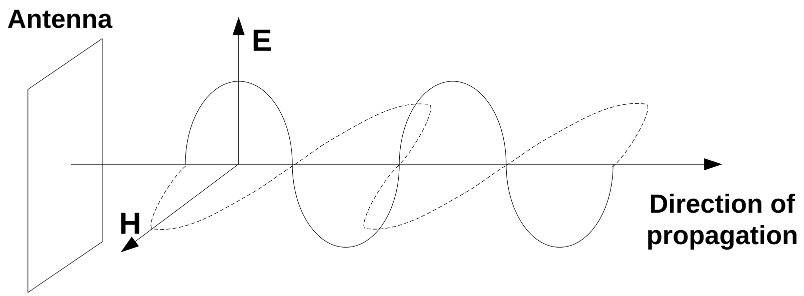


Figure 4.7: Direction of propagation and electric $\mathbf{E}$ and magnetic $\mathbf{H}$ fields.

When the distance from the radiation source increases, the energy is divided over an increasing sphere surface area (Finkenzeller, 2003). For an isotropic and lossless[5] emitter, the radiation density W at a distance r can be calculated with the following equation:

$$W = \frac{P_{EIRP}}{4\pi r^2} \tag{4.5}$$

[5] An isotropic emitter radiates equally in all directions. A lossless emitter has a radiation efficiency of 1. (Balanis, 1997)

where P_{EIRP} is the effective isotropic radiated power.

Polarization of radiated waves

The polarization of a radiated wave is defined as the time varying direction and relative magnitude of the electric field (Balanis, 1997). Polarization may be classified as linear, circular and elliptical. In linear polarization, if the direction of the field lines of the electric field propagates parallel to the surface of the earth, then the radiated wave is horizontally polarized. If the field lines of the electric field propagates at right angles of the surface of the earth, then the radiated wave is vertically polarized (Finkenzeller, 2003). For a wave to have linear polarization, the two components of the electric field vector[6] should be in time phase (Balanis, 1997).

Circular polarized waves are achieved only when the two components of the electric field have the same amplitude and the time phase difference is odd multiples of $\pi/2$ (Balanis, 1997). It is possible to distinguish between right-hand circular polarization and left-hand circular polarization depending on which way the electric field rotates. The rotation of the electric field depends on which of its two components is the leading phase. Elliptical polarized waves are attained when the electric field components have different amplitude and the time phase difference is odd multiples of $\pi/2$ or when the time phase difference is not equal to multiples of $\pi/2$, no matter their amplitudes.

Passive RFID tags extract the energy of the incoming wave to power the internal system. If the polarization of the tags' antenna is not the same as the polarization of the incoming wave, then the amount of energy that can be extracted from the incoming signal will not be maximised because of polarization loss (Balanis, 1997). The polarization loss factor can be calculated using the following formula:

$$PLF = cos^2\psi \tag{4.6}$$

where ψ is the angle between the polarization vector of the incoming wave and the polarization vector of the receiving antenna. Figure 4.8 shows the polarization loss factor (PLF) for linear wire antennas.

[6] The electric field of a plane wave can be divided into two different components. So if the electric field propagates in the negative z direction, the electric field can be written as: $\mathbf{E}(z;t) = \hat{\mathbf{a}}_x E_x(z;t) + \hat{\mathbf{a}}_y E_y(z;t)$

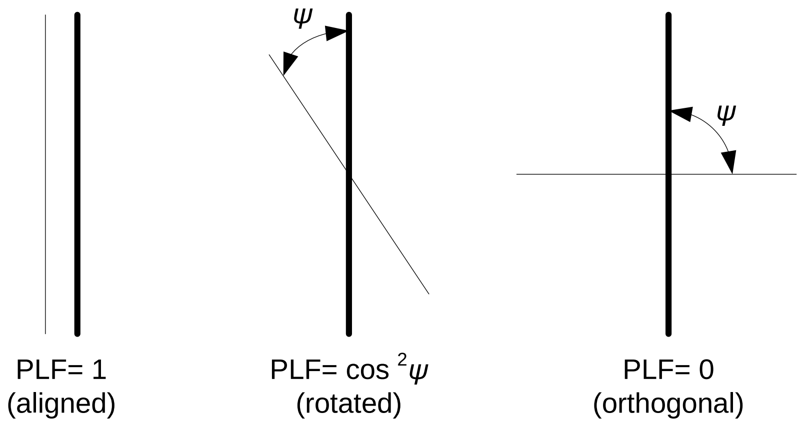


Figure 4.8: Polarization loss factor for linear wire antennas (Balanis, 1997).

If the receiver's antenna and the transmitter's antenna have the same polarization, the PLF will be unity and the receiver's antenna will extract maximum power from the incoming wave. Passive RFID systems usually employ linear polarized antennas or circular polarized antennas for the readers, and linear polarized antennas for the tags. Circular polarized tags are also available but at a higher cost. The advantage of using circular polarized antennas for the readers is the reduced dependency of the tags position in the object. Because the circular polarized antenna have two orthogonal linear components with a difference time phase of $\pi/2$, the linear polarized antenna of the tag is able to extract energy from the in-phase component of the circular polarized wave. However, a polarization loss of 3dB between a circular polarized antenna and a linear polarized antenna should be taken into account.

Transmission and Reflection of electromagnetic waves

Passive RFID systems that operate in the UHF and microwave frequencies use the reflection of electromagnetic waves to transmit data from the tag to the reader. This is similar to radar technology where the small reflected energy is used to measure the distance and position of distant objects. In order to asses the energy available for the operation of the tag, the relation between the transmitted power and received power needs to be calculated. Figure 4.9 shows the power flow of passive UHF RFID systems.

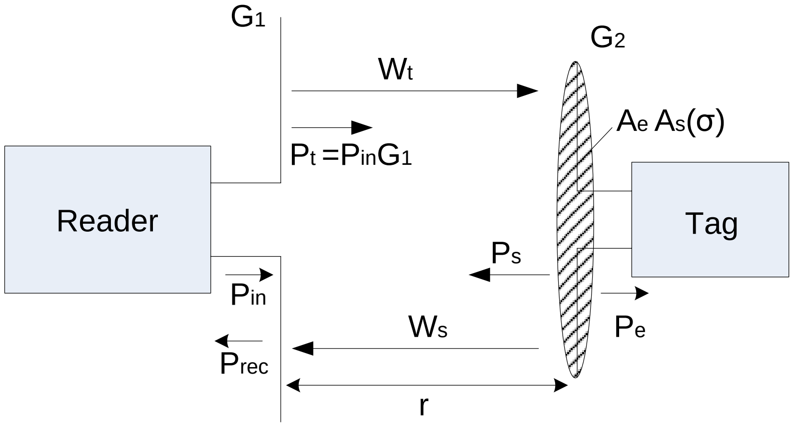


Figure 4.9: Power flow throughout the entire RFID system (Finkenzeller, 2003).

To relate the power received to the power transmitted between two antennas in the far field the Friss transmission equation is used (Balanis, 1997). If the input power at the terminals of the transmitting antenna is P_{in} then its power density W_t at a distance r from the antenna is:

$$W_t = \frac{P_{in}G_t}{4\pi r^2} \tag{4.7}$$

where G_t is the gain [7] of the transmitter's antenna. The amount of power that can be drawn from the incoming wave is proportional to the power density and the effective area (aperture) of the receiving antenna. The effective aperture is the area which, when multiplied by the incident power density, gives the power delivered to the load. However, all the power that is collected by the antenna is not delivered to the load. In power matched antennas, half of the power is delivered to the load, the other half is scattered. The effective aperture (A_e) of any antenna is related to its gain(G) by:

$$A_e = \frac{\lambda^2}{4\pi}G \tag{4.8}$$

[7]The gain of an antenna is the ratio of the radiation intensity in a given direction to the radiation intensity that would be obtained if the power produced by the antenna were radiated isotropically (Balanis, 1989). The antenna gain is a measure that takes into account the efficiency of the antenna as well as its directional capabilities.

Thus the amount of collected power P_e can be written as:

$$P_e = A_e W_t \tag{4.9}$$

$$P_e = \frac{\lambda^2 G_t G_r P_{in}}{(4\pi r)^2} \tag{4.10}$$

and the ratio of collected power and transmitted power for reflection and polarization matched antennas aligned for maximum directional radiation and reception can be written as :

$$\frac{P_e}{P_{in}} = (\frac{\lambda}{4\pi r})^2 G_t G_r \tag{4.11}$$

The above equation is known as the Friss transmission formula and it relates the power delivered to the receiver, the tags, to the input power of the transmitter antenna, the readers. The term $(\frac{\lambda}{(4\pi r)})^2$ is called the free space loss factor and takes into account the losses due to spherical spreading of energy by the antenna.

In RFID systems, the readers antenna transmits an electromagnetic wave in all directions with a transmission power of P_t. The tag collects some of the energy to power the system P_e and reflects a power P_s that is proportional to the power density W_t at the location of the tag and the tag's radar cross section σ. The radar cross section σ is a far field parameter and is defined as "the area intercepting that amount of power which, when scattered isotropically, produces at the receiver a density which is equal to that scattered by the actual target" (Balanis, 1989). For power matched antennas, $\sigma = A_e = A_s$. The tag's reflected power can be calculated using the following formula (Finkenzeller, 2003):

$$P_s = \sigma W_t = \sigma \frac{P_{in} G_t}{4\pi r^2} \tag{4.12}$$

The electromagnetic wave reflected by the tag also propagates spherically from the point of reflection. The reflected wave decreases in proportion to r^2. Thus, it is possible to calculate the power density that returns to the reader's antenna due to tag's reflection of the incoming wave:

$$W_s = \frac{P_s}{4\pi r^2} = \sigma \frac{P_{in} G_t}{(4\pi)^2 r^4} \tag{4.13}$$

The ratio of the power returning from the transponder to the reader and the power transmitted by the reader can be calculated using the radar equation:

$$\frac{P_{rec}}{P_{in}} = \sigma(\frac{\lambda}{4\pi r^2})^2 G_t G_r \tag{4.14}$$

From equation 4.13 it follows that the power reflected back from the tag is proportional to the fourth root of the transmitted power (Finkenzeller, 2003). The reflection characteristics of the tag antenna can be influenced by altering the load connected to the antenna. In order to transmit data from the tag to the reader a load connected parallel with the tags antenna is switched on and off in time with the data stream to be transmitted, the amplitude of the power reflected by the tag can thus be modulated. This procedure is known as modulated backscattering.

4.5 Data Integrity and Security

Data integrity in RFID system refers to the ability of the system to detect transmission errors and successfully read/write the information of the tags, specifically in dense environments. In RFID systems the detection of transmission errors is recognized using the cyclic redundancy check (CRC) procedure. This is a highly reliable method for detection of transmission errors but it can not be used for correction of errors (Finkenzeller, 2003).

There is an increasing demand of RFID systems for dense environments and also, high security applications. Reading multiple tags requires more complex protocols, and security environments demand for authentication systems to protect against unauthorized access to the information of the RFID tags. In this section the most relevant anti collision protocols and privacy and authentication strategies will be further explained.

4.5.1 Anti collision protocols

One of the most important application characteristics of RFID systems is the possibility to read multiple tags simultaneously. In RFID systems the procedures that facilitate the reading of multiple tags without any interference are called anticollision systems. Anti collision systems are also known in radio communication as multiple access protocols. Multiple access protocols have been developed in order to differentiate and separate the incoming signals of different devices. There are four basic multiple access protocols: space division multiple access (SDMA), frequency division multiple access (FDMA), code division multiple access (CDMA) and time division multiple access (TDMA). In RFID systems, TDMA procedures are mostly used.

TDMA divides the entire channel capacity between the tags in the field and allocates a unique time slot to each tag so they can transmit information without interference. In RFID systems, TDMA procedures can be divided into two major groups: Asynchronous tag driven procedures and Synchronous reader driven procedures.

In asynchronous tag driven procedures the data transfer is not controlled by the reader. The most known procedure in this class is the ALOHA protocol. In the ALOHA protocol, the tag begins transmitting information as soon as it is in the interrogation zone. The tag continuously retransmit their identifier at random intervals until the reader acknowledges their transmission (Shih et al., 2006). These procedures are very slow and inflexible (Finkenzeller, 2003), specially in high tag density environments. Therefore, most RFID systems use synchronous reader driven procedures since all the tags are controlled and checked by the reader simultaneously. When a tag is selected from a group of tags in the interrogation zone of a reader, communication takes place between the reader and tag, i.e. authentication, reading and/or writing. Only after the communication with the selected tag is terminated, another tag is selected. Synchronous reader driven procedures can be divided into polling and binary search procedures.

There is a growing number of anti collision protocols for RFID systems, however in this thesis only the aloha protocol and the binary search protocol will be further elaborated. For more details on different anti-collision procedures for RFID systems referred to (Shih et al., 2006), (Namboodiri and Gao, 2007), (Cha and Kim, 2005).

ALOHA Protocol

The ALOHA protocol is mainly used in read only tags which, generally, only have to transfer small amounts of data. In the ALOHA protocol, tags send information as soon as they are ready and have information to transmit (Shih et al., 2006), as shown in Figure 4.10. After sending the data, the tag waits a certain repetition time before trying to send the data again. The transmission time is only a fraction of the repetition time, so there are relatively long pauses between transmissions (Finkenzeller, 2003).

The ALOHA protocol is very attractive due to its simple implementation. For

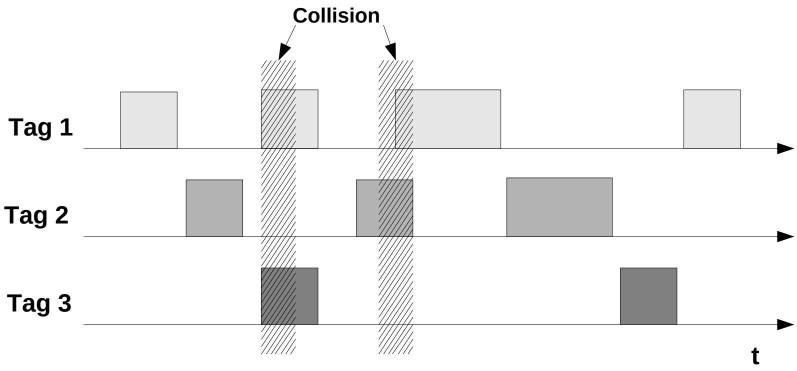


Figure 4.10: ALOHA protocol.

low transmission loads, i.e. small number of tags in the field, the ALOHA protocol works just fine. However, if the transmission load is increased, the number of collisions will increase considerably. In order to optimize the low throughput of the ALOHA protocol in dense environments, the slotted ALOHA procedure was dev eloped.

Slotted ALOHA In this procedure the tags are only able to transmit data at defined, synchronous points in time, i.e. slots. The synchronization is controlled by the reader. Usually, the reader transmits a REQUEST command at cyclical intervals (Finkenzeller, 2003). When the tags recognize the REQUEST command, each tag randomly select a time slot in which to send its serial number to the reader. The number of available time slots in a round is determined by the reader. If two tags select the same serial number, collisions occur and data is lost as shown in Figure 4.11.

If the serial number of the tag is read without errors, then communication between the reader and the tag is established and read and write procedures can be performed without interference. The rest of the tags in the field will only react to the next REQUEST command.

The throughput in the slotted ALOHA protocol is maximized when there are the same number of slots available as there are tags in the interrogation field of the reader. If the number of tags in the interrogation field increases, the throughput will be severely reduced since after several rounds there will be not enough time slots available for every tag to successfully transmit its information. Furthermore, if the number to time slots is increased, the performance of the anti collision pro-

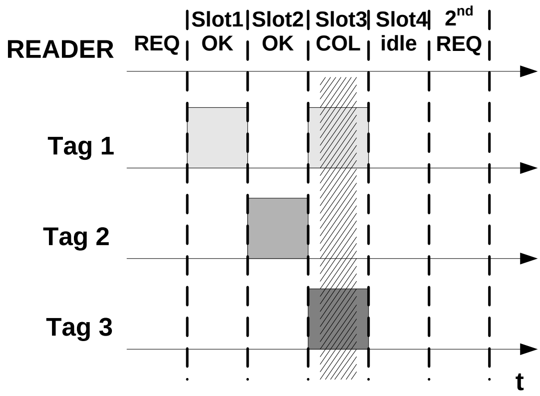


Figure 4.11: slotted ALOHA protocol.

tocol will be reduced since the reader will have to listen for possible tags for the duration of every time slot, even if a minimum amount of tags is in the interrogation field of the reader. To overcome this difficulty, *Dynamic* Slotted ALOHA procedures can be implemented. Dynamic slotted ALOHA procedures increases or decreases the number of available time slots in every round. For example, in the first REQUEST command, the reader will transmit the number of available slots. If during the first round, collisions occurred, then in the second REQUEST command the reader will increase the number of available slots until all the individual tags are detected. One of the difficulty when implementing this protocol is the initial selection of available time slots. More information about dynamic slotted ALOHA procedures for RFID systems can be found in (Cha and Kim, 2005).

Binary Search

The binary search algorithm consists of rounds of queries and responses between the reader and the tags in the interrogation field. The reader begins by transmitting a REQUEST command with a serial number as a parameter. If the serial number of the tag in the field is equal or less than the serial number received, then the tag sends its own serial number back to the reader. If more than one tag answers, then the received serial number will have collisions and the reader will know that there are more tags in the field. In the second iteration, the reader needs to limit the search range using the acquired information. In Table 4.4 the general rules for forming the address parameter in a binary search three are shown. These rules are applied in every round until a tags ID matches the serial number. After a tag has been segregated, the reader can now read and write information in the tag without interference of the other tags in the field. Only the tag whose ID matches the serial number transmitted by the reader will respond. Once the read/write operations with the selected tag has been completed, the reader will quiet the tag so that it will not respond in the next selection round. This will gradually reduce the number of necessary iterations for the selection of an individual tag. Figure 4.12 shows an example of the binary search algorithm. Optimized formats of this algorithm are the dynamic search algorithm and the Query tree short-long protocols, refer to (Finkenzeller, 2003) and (Shih et al., 2006) for a detail description of these protocols.

Table 4.4: Rules for forming the address parameter in the binary search algorithm. $Bit(c)$ corresponds to the highest value bit of the received binary sequence in which a collision occurred in the previous iteration (Finkenzeller, 2003)

Search command	1^{st} iteration	n^{th} iteration
REQUEST $\geq$ Range	0	$Bit(c) = 1$
		$Bit(0 \text{ to } c-1) = 0$
REQUEST $\leq$ Range	Max. Serial number	$Bit(c) = 0$
		$Bit(0 \text{ to } c-1) = 1$

4.5.2 Privacy and Security

RFID tags respond to the interrogation of readers without notifying their owners or bearers, posing security and privacy risks for both individuals and organizations. Most of the tags carry a fixed serial number, if unauthorized reading of the tag is performed, then the serial number can be used to link the information with the person carrying the tag, and thus, enabling physical tracking (Garfinkel and Rosenberg, 2006). If this information is further linked to the personal data of the costumer, for example payment with a credit card, then a link between the identity of the owner and the serial numbers of the products purchased can be made, allowing profiling of the costumers. These type of privacy issues are further enhanced with the use of the EPC tags (particularly EPC class 1 tags, only read tags). These

READER	REQUEST Serial Number <111	1^{st} Iteration	REQUEST Serial Number <011	2^{st} Iteration	Read/ Write	REQUEST Serial Number <111	3^{st} Iteration
		ccc		010			1cc
Tag 1 ID: 101		101					101
Tag 2 ID: 010		010		010	010		
Tag 3 ID: 110		110					110

READER	REQUEST Serial Number <101	4^{st} Iteration	Read/ Write	REQUEST Serial Number <111	5^{st} Iteration	Read/ Write	
					110		
Tag 1 ID: 101		101	101				
Tag 2 ID: 010							
Tag 3 ID: 110					110	110	

Figure 4.12: Binary search algorithm. The different serial numbers that are send back to the reader leads to collisions (c) in parts of the binary sequence. Using Table 4.4 the search area is reduced.

type of tags carry specific information about the products, like manufacturer and object class, and can be used to acquire sensitive and personal information about a person. For example, when a person purchases medicines, the EPC tag has information about the type of medicine, and if this information is linked with the person who bought it, information about possible diseases and life habits can be inferred (Juels, 2006). RFID privacy issues are becoming more apparent, some examples include (Juels, 2006):

- Toll payment transponders: This is a common worldwide application. In (Stern, 2001) was documented that the data gathered from the tag attached to the windscreen of the car was used in a divorce court case to damage the case of the defendant.

- Libraries: RFID tags are used in libraries to facilitate the inventory control of books as well as facilitate book check out. However, monitoring the book selection of individuals have increased privacy concerns on the use of RFID technology (Molnar and Wagner, 2004).

- Public transport cards (OV-Chipkaart): The OV-chipkaart aims to become the unique means of payment for public transport in the Netherlands. There has been a lot criticism about the introduction of such a system, especially the personal type of OV-Chipkaart. This personal card will contain sensitive information about the user. This information can be used to link the user to specific locations and track and trace passengers all around the Netherlands (Siekerman and van der Schee, 2008).

Privacy issues with RFID systems also extends to logistics environments. Monitoring products at an item level is seen is one of the best features of RFID (Garfinkel and Rosenberg, 2006). Although item level tagging will prevent out of stock situations, it will also make it easy for competitors to learn about stock turnover rates and reduce competitive advantage.Privacy in RFID systems has received the most attention. However, authentication is another significant problem in RFID systems. RFID tags are expected to serve as a trustworthy label for the objects they are attached to (Juels, 2006). However, RFID tags, specially basic ones, i.e. read only tags, are vulnerable to counterfeiting attacks. Scanning and reproducing these tags is inexpensive and requires little expertise. Active RFID tags and more security RFID tags can perform cryptographic operations. Security and privacy techniques can then be discussed, for tags that do not support cryptographic operations, i.e. low cost, low power, read only tags, and tags that support cryptographic operations.

Tags without cryptographic support

For the first group of tags a number of proposed approaches is surveyed in (Juels, 2006). In this thesis only killing and sleeping, minimalist cryptography and guardian approach will be briefly discussed.

Killing and sleeping The killing approach is part of the EPC protocol. Once the tag receives the ”kill” command, it makes itself permanently inoperative. The ”kill” command is protected by a PIN to avoid ruthless deactivation of tags by unauthorized readers. Although killing the tags at the point of sale is a permanent solution to the privacy issue, it also eliminates all the possible after sale benefits that RFID tags can provide. For example, RFID tags attached to garments are envisioned to provide further functionalities in smart washing machines. The RFID will contain information about the garment and this will be transmitted to the washing machine which automatically selects the proper washing cycle. In some other cases, killing the tag is not an option. In library applications and rental shops the tags need to survive the lending period of the objects they track. In this case, instead of killing the tag, making them temporarily inactive, put them to ”sleep”, could be an option. To wake up the tag another PIN will be necessary. With this approach the wake command will need to be handled by the owner of the products, i.e. consumers. However, handling individual codes for every purchased tagged object is not a very realistic scenario in applications where multiple objects, and relatively low cost objects are bought all at once. Furthermore, with luxury products remembering another code, besides the already memorized ones, to have post purchase benefits could be seen as a burden and not as a possible added value.

Minimalist cryptography Minimalist cryptography is a technique in which all the tags contain a small selection of pseudonyms. The tag rotates the pseudonyms and release a different one on every query of the reader. This technique requires previous storage of all the pseudonyms of the tags in the authorized readers. In order to avoid unauthorized readers using rapid interrogation to acquire all the pseudonyms, it is proposed in (Juels, 2004) that tags slow their responses when queried too quickly.

Guardian approach The RFID guardian acts as personal firewall for RFID systems. The RFID Guardian is meant for personal use; it manages the RFID tags within physical proximity of a person (Rieback et al., 2005). The RFID Guardian performs security protocols, such as authentication and access control. The RFID guardian acts as an intermediary between tags and readers, it is a powered device that could be integrated into mobile phones or PDAs. Details of the RFID guardian can be found in (Rieback et al., 2005).

Tags with cryptographic support

Cryptography procedures are used to protect passive attacks like eavesdropping into a transmission to obtain private information, and active attacks like actively manipulating the transmitting data to fulfill certain benefit (Finkenzeller, 2003). In order to protect the data in the tag, the data is encrypted using an encryption key and an encryption algorithm. To transform the data back to its original form, the receiver uses a decryption key and a decryption algorithm. In RFID systems, the encryption and decryption keys used are either the same or are in direct relation to each other, this is known as a symmetrical key procedure (Juels, 2006). A fundamental problem of the cryptographic procedures is the distribution of the secret key. The secret key needs to be know by all the participants prior to communication. In (Juels, 2006), different approaches to the problem of key management are explored.

4.6 Regulation and Standardization

There is no global public body that governs the frequencies used for RFID. In principle, every country can set its own rules for this. The main bodies governing frequency allocation for RFID are:

- USA: FCC (Federal Communications Commission).
- Canada: DOC (Department of Communication).
- Europe: ERO(European Radiocommunications Office), CEPT (European Conference of Postal and Telecommunications Administrations), ETSI(European Telecommunications Standards Institute), and national organizations. National organizations must approve the use of a specific frequency before it can be applied in the country.
- Japan: MPHPT (Ministry of Public Management, Home Affairs, Post and Telecommunication).
- China: Ministry of Information Industry.
- Australia: Australian Communication Authority.
- New Zealand: Ministry of Economic Development.

Low-frequency (LF) and high-frequency (HF) RFID tags can be used globally without a license. Ultra-high-frequency (UHF) cannot be used globally as there is no single global standard. In North America, UHF can be used unlicensed for 908 - 928 MHz, but restrictions exist for transmission power. In Europe, UHF is under consideration for 865.6 - 867.6 MHz. Its usage is currently unlicensed for 869.40 - 869.65 MHz only, but restrictions exist for transmission power. The North American UHF standard is not accepted in France as it interferes with its military bands. For China and Japan, there is no regulation for the use of UHF. Each application for UHF in these countries needs a site license, which needs to be applied for at the local authorities, and can be revoked. For Australia and New Zealand, 918 - 926 MHz are unlicensed, but restrictions exist for transmission power.

4.6.1 European regulations

The CEPT document entitle ”ERC Recommendation 70-03 relating to the use of short range devices (SRD)” (”ERC”, 2009) serves as a basis for national regulations in all the member states of the European Union. This document also includes notes on national restrictions for the specified applications and frequency ranges. The ERC document, (”ERC”, 2009), defines frequency bands, power levels, channel capacity and duty cycle for short range devices. It also refers to the ETSI standards that contain measurements and testing guidelines for licensing radio devices (Finkenzeller, 2003).

The standards created by ETSI serve to provide the national telecommunication authorities with a basis for the creation of national regulations for radio and telecommunications operations. In The Netherlands it is the Independent Post and Telecommunication Authority (OPTA) the national regulatory commission. The ETSI harmonized standards for SRD and RFID are:

- EN 300 330: SRD between 9kHz - 25 MHz and inductive loop systems between 9kHz - 30MHz.
- EN 300 220: SRD between 25MHz - 1GHz with power up to 500mW.
- EN 300 440 : SRD between 1GHz - 40GHz

Because the EN 300 220 did not meet the requirements for UHF RFID, the EN 302 208 (RFID in the band 865 to 868 MHz with power levels up to 2W) was developed. There are three technical parameters of the EN 302 208 that are of special interest due to its influence on the performance of RFID systems (”EPC-global”, 2005):

- Power level: This is one of the main factors defining the reading range of RFID systems. The maximum emmission power is limited to 2 Watts equivalent radiated power (ERP). This is four times more than stipulated in the EN 300 220. In the USA the maximum radiated power is 4 Watts.
- Bandwidth/Number of channels: The frequency band allocated in Europe for UHF RFID is 865 - 868 MHz. Figure 4.13 shows the channel power distribution for the RFID band. Fifteen channel with a bandwidth of 200kHz are available. The channel bandwidth limits the data rate between readers and tags. Meanwhile, the number of channels limits the number of readers that can transmit simultaneously. In the USA the allocated frequency band is 902-928MHz with channel width of 500kHz.
- Listen Before Talk (LBT) principle: This standard requires that readers listen before talking, if another reader is transmitting they do not transmit or find a different channel to transmit. The level of detected signal above which no transmission can be made determines the distance at which another user of the RFID band will inhibit an RFID reader from accessing the channel. Currently, the level at which this has been set will allow a reader to listen to another reader up to approximately 2.5 km away. This will seriously limit the number of readers that can operate in a dense environment.

4.6.2 Standardization

The international organization for standardization (ISO)has developed a series of RFID standards for the operation of RFID systems. Figure 4.14 shows the most relevant RFID technology standards, i.e. standards describing the physical and data link layers (air interface protocol, anti-collision, communication and security functions).

Animal Tagging

ISO 11785, ISO 11784 and ISO 14223 deal with the identification of animals using RFID systems in the LF frequency band. The ISO 11784 is the standard

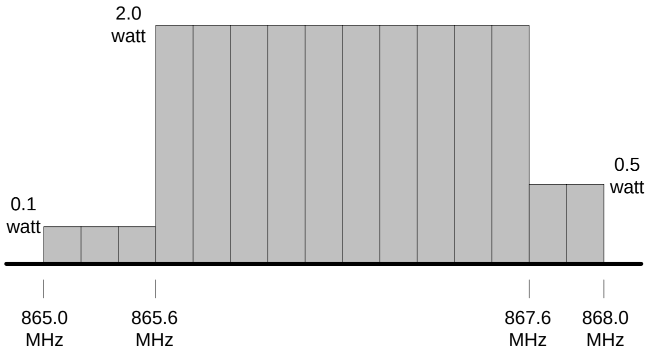


Figure 4.13: RFID standards in different frequency bands (Knospe, 2004).

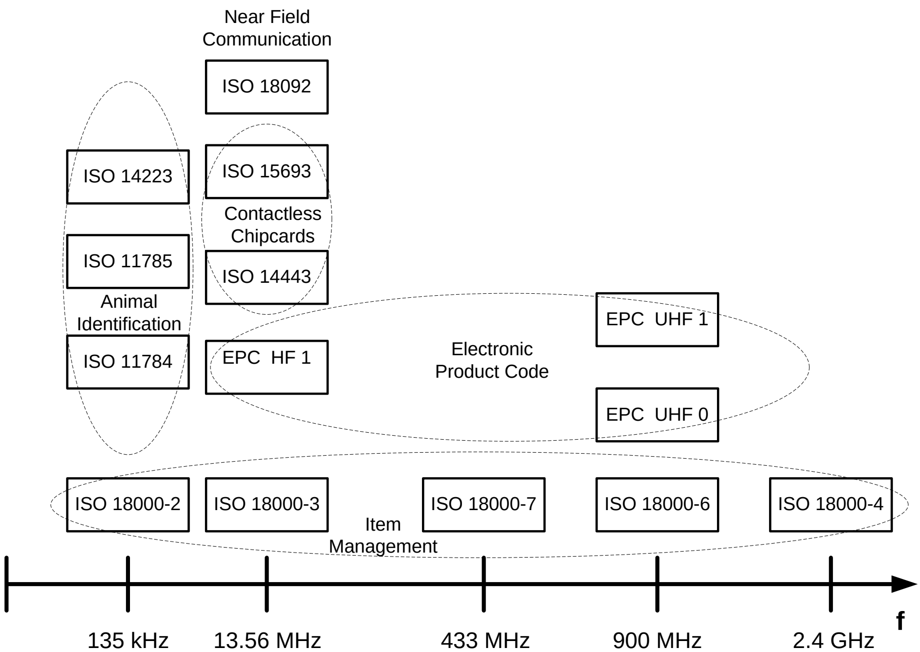


Figure 4.14: RFID standards in different frequency bands (Knospe, 2004).

for the code structure. The identification code for animals is a total of 64 bits and it is managed individually in every country. ISO 11785 defines the transmission method for the tag's data and the reader. ISO 14223 defines the interface and data structure of advanced tags. It can be seen as a further development of the ISO

11785 and ISO 11784 standards. In advanced tags data can be read, written and protected against overwriting (Finkenzeller, 2003).

Contactless Smart Cards

There are three different standards for contactless smart cards. ISO 10536 describes the structure and operating parameters of close coupling smart cards (approximate range is less than 1cm). ISO 14443 describes the operating method and parameters of proximity coupling smart cards (approximate range is 10cm). These are mostly used in the field of ticketing (Knospe, 2004). ISO 15693 describes the method of functioning and operating parameters of vicinity coupling smart cards (approximate range is up to 1 meter). These type of cards are mostly used for identification and simple access control (Finkenzeller, 2003).

Near Field Communication

The near field communication evolve from RFID technology and is designed for interactions between tags and electronic devices i.e. computer peripherals for configuration purposes. The ISO 18092 defines the near field communication range and protocol.

Item Management

The ISO 18000 series defines the air interface, collision detection mechanisms and the communication protocol for item tags in different frequency bands as shown in Figure 4.14 (Knospe, 2004). The ISO 18000 part 6 published in 2005 an amendment to include the EPC UHF Gen 2 Class 1 air interface protocol as part of the ISO 18000 series. The EPC protocol was included in the ISO 18000-6C. The recognition of the EPC Gen 2 standard is very important for companies all over world that prefer to work with, and produce RFID systems that comply with international standards.

Electronic Product Code

The Electronic product code was developed by the Auto-ID center of MIT. EPC technology was license to the Uniform Code Council, which created EPC global together with EAN international, to commercialize EPC technology. EPC deals more than just tags and readers communicating. The goal of EPC global is to create network standards to determine how the EPC data is shared among companies and other organizations (”EPCglobal”, 2008).

4.7 Conclusions

In order to develop a testing methodology for RFID, is necessary to understand the operating principles of RFID systems. In this Chapter technical characteristics of RFID systems were presented. RFID systems use radio transmission to recognize, categorize, locate and track objects. RFID consists of readers, tags and a back end application for storage and management of the collected data.

The operation frequency of the reader, the physical coupling method between readers and tags and the read range of the system are the most important differentiation parameters of RFID systems. Passive low frequency (LF) and high frequency (HF) RFID are respectively close range and remote range RFID systems. In the LF and HF frequency band, tags operate under the principle of inductive coupling. In inductive coupling, the tags harvest energy from the magnetic field of the reader. It uses this energy to power the internal system and transmit information to the reader. Passive ultra high frequency (UHF) and microwave RFID systems operate with the principle of electromagnetic backscattering. In this case, passive tags collects the necessary energy to power the system from the electromagnetic wave transmitted by the reader. It transmits information back to the reader by modulating the reflected wave. One of the biggest difficulties in both inductive coupling systems and electromagnetic backscattering systems is maximizing the collected energy. Tags are small by nature, so maximizing the collected energy is definitely a difficult task, specially when the tags are attached to objects that significantly affect the operation of the tag, i.e. metal and liquids.

One of the most important characteristics of RFID is the possibility to acquire information of multiple tags simultaneously. Anti collision protocols based on time division multiple access techniques are being developed to optimize the reading of multiple tags, specially in dense environments. Most of the developed protocols are based either on the Aloha principle or the binary search algorithm.

Depending on their requirements RFID systems need to satisfy certain security measures. Applying security measures in low cost tags is more difficult due to the lack of cryptographic support. Techniques like killing and sleeping, minimalist cryptography and the guardian approach were discussed. Although in some cases the security issues are solved with the aforementioned techniques, the privacy issue has been proven to be more challenging. Linking sensitive information, especially about people, with the serial numbers of tags in their possession can lead to unauthorized profiling of users. Furthermore, the tracking and tracing of people is becoming more of a threat with the grow of ubiquitous applications like the OV-chipkaart.

The future of RFID is not only determined by its technical characteristics but also by standardization, development of market and prices, information security and social acceptance (Juels, 2004). With the integration of the EPC Gen 2 protocol into the ISO 18000 standard manufacturers of RFID equipment will be more confident to design hardware based on the Gen 2 standard now that it is recognized. This will increase the competition in the passive UHF RFID market which could lead to lower costs.

While discussing the technical characteristics of RFID, it was evident that the performance of the system is closely related to the application environment. Applying RFID systems does not only depend on the technical characteristics of the technology. It depends on several factors of the application as well. In order to implement RFID systems, a testing procedure needs to be developed to evaluate the suitability of RFID in the application. In (López de la Cruz et al., 2008), a testing methodology composed of fundamental tests, semi-fundamental tests and operational tests was presented. In chapter 5, this methodology will be presented and used for several application scenarios.

4.8 References

AIM (2006). What is the right frequency for RFID. Internet, Association for automatic identification and mobility. Available On-line: http://www.aim-d.de/getasset.php?asid=265.

Balanis, C. (1989). *Advanced engineering electromagnetics*. Jhon Wiley and Sons, New York.

Balanis, C. (1997). *Antenna Theory: Analysis and Design*. Jhon Wiley and Sons, second edition.

Cha, J. and Kim, J. (2005). Novel anti collision algorithms for fast object identification in RFID systems. In *Proceedings of the 2005, 11th IEEE International conference on parallel and distributed systems.*, pages 63–67.

Comitee of RFID (2004). Radio frequency identification technologies: a workshop summary. Internet, National Academy of Science, National Academy press. Available On-line: http://www.nap.edu/catalog/11189.html.

”EPCglobal” (2005). User requirements for european RFID regulations at UHF. Internet, EPC global. Available On-line, http://www.epcglobal.org.

”EPCglobal” (2008). About EPCglobal. Internet, EPC global. Available On-line, http://www.epcglobal.org.

”ERC” (2009). Erc recommendation 70-03 (troms 1997 and subsequent amendments) relating to the use of short range devices (srd) recommendation adopted by the frequency management, regulatory affairs and spectrum engineering working groups. Internet, European Radiocommunications Office. Available On-line, http://www.erodocdb.dk/Docs/doc98/official/pdf/REC7003E.PDF.

Finkenzeller, K. (2003). *RFID Handbook*. John Wiley and Sons, West Sussex, England, second edition.

Garfinkel, S. and Rosenberg, B. (2006). *RFID applications, security and privacy*. Addison Wesley, Upper Saddle River, NJ.

Juels, A. (2004). Minimalist cryptography for low-cost RFID tags. In Blundo, C. and Cimato, S., editors, *Lecture Notes in Computer Science*, volume 3352, pages 149–164. Springer-Verlag, New York.

Juels, A. (2006). RFID security and privacy: a research survey. *IEEE Journal on selected areas in Communications*, 24(2):381–394.

Knospe, H. (2004). RFID security. *Information security technical report*, 9(4):39–50.

Lahiri, S. (2005). *RFID: A technology overview*. Prentice Hall Professional.

Landt, J. (2005). The history of RFID. *IEEE Potentials*, 24(4):8–11.

Lodewijks, G., Veeke, H. P. M., and López de la Cruz, A. M. (2006). Reliability of RFID in logistic systems. In *Proceedings of the 2006 IEEE Conference on Service Operations and Logistics, and Informatics*, Shanghai, China.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2008). Performance measuremet of RFID. In *Proceedings of the International Simulation Conference 2008*, Lyon, France. EUROSIS.

Molnar, D. and Wagner, D. (2004). Privacy and security in library RFID: issues, practices, and architectures. In *CCS '04: Proceedings of the 11th ACM conference on Computer and communications security*, pages 210–219, New York, NY, USA. ACM.

Namboodiri, V. and Gao, L. (2007). Energy aware tag anti collision protocols for RFID systems. In *Proceedings of the fifth IEEE International Conference on pervasive computing and communications.*, pages 23–36.

Nikitin, P., Rao, K. V. S., and Lazar, S. (2007). An overview of near field UHF RFID. In *Proceedings of the IEEE International Conference on RFID, 2007.*, pages 167–174.

Rieback, M., Crispo, B., and Tanenbaum, A. S. (2005). Rfid guardian: A battery-powered mobile device for RFID privacy management. In Boyd, C. and Gonzalez, J. M., editors, *Lecture Notes in Computer Science*, volume 3574, pages 184–194. Springer-Verlag, New York.

Shih, D., Sun, P., Yen, D., and Huang, S. (2006). Taxonomy and survey of RFID anti-collicion protocols. *Computer communications*, 29(11):2150–2166.

Siekerman, P. and van der Schee, M. (2008). Security evaluation of the disposable ov-chipkaart. Internet, University of Amsterdam. Available On-line, http://staff.science.uva.nl/ delaat/sne-2006-2007/p41/Report.pdf.

Stern, S. (2001). Security trumps privacy. Internet, Christian science monitor. Available On-line, http://www.csmonitor.com/2001/1220/p11s1-stct.html.

Wyld, D. C. (2006). RFID 101: the next big thing for management. *Management research news*, 29(4):154–173.

CHAPTER 5

Applicability of RFID in Logistics Systems

Radio Frequency IDentification (RFID) is a technology that offers unique identification of objects. It can actively or passively communicate this information and, in combination with sensors, it can capture more detailed physical information. In the previous chapter the technical characteristics of RFID were discussed, and it became evident that the performance of an RFID system is closely related to the application environment. Applying RFID systems not only depends on the technical characteristics of the technology, it also depends on the application as well. In order to implement RFID systems, a testing procedure needs to be developed to evaluate the suitability of RFID in an application. In (Lodewijks et al., 2006), it was suggested that in order to determine the applicability of RFID in a certain application scenario, a testing methodology composed of three main testing stages should be implemented. In (López de la Cruz et al., 2008), a testing methodology composed of fundamental tests, semi-fundamental tests and operational tests was presented. In this chapter, this methodology will be presented and used for several application scenarios. In each of the application cases, the experimental procedures were performed with the support of master students in the section of Transport Engineering and Logistics, at Delft University of Technology.

In section 5.1 an overview of different RFID implementations will be provided. In section 5.2 the proposed testing methodology to implement RFID systems will be presented. In section 5.3 different application cases will be summarized and in section 5.4 conclusions will be drawn.

5.1 Implementation of RFID Technology

In recent years, the interest in the application of UHF RFID systems in logistic systems has increased considerably. There are three main reasons for this. The first reason is the enormous drop in the cost of UHF RFID technology. Readers and facilitating computers dropped in price and the price of the tags went down to approximately 0.20 euros per tag. It is expected that the tag price will go down to 0.05 euros in a few years. The second reason is that the tags serial number and the working protocols are coded via the rules of the electronic product code (EPC). This enables the development of a world-wide standard that enlarges the use of this technology. The third reason is the ability of the technology to acquire a large amount of data in real time.

To increase the quality, productivity, and agility of complex logistic systems companies experiment with UHF RFID technology as an Auto-ID tool to increase the visibility of the objects, services, and information involved in their processes. The main goals to use these systems are to (Lodewijks et al., 2006):

- Serialize data; inventory control, reduction of loss, reduced carrying costs.
- Reduce human intervention; reduced errors which produce reduced costs, faster throughput and reduced damage and returns.
- Increase throughput in logistic systems; with RFID it is possible to read hundreds of objects almost simultaneously.
- Allow real time information flow; deliver on promises, reduce errors, increase customer loyalty, optimize material use.
- Increase item security; improve delivery and control, decrease counterfeiting and shrinkage.

On June 2003 Wal-Mart announced that they will be using RFID tags for pallets and cases in conducting business with selected top suppliers by the year

2005, and with all their suppliers by the year 2006 (Bhuptani and S.Moradpour, 2005). The expected benefits of RFID like increasing visibility, improved order and warehouse management, traceability of products, decrease scanning times, among others, made the organization decide to apply the technology and mandate their suppliers to follow their initiative. Some of the main requirements in the Wal-Mart mandate were:

- All suppliers were to tag cases and pallets by end of 2006.
- Ultra high frequency (UHF) tags would be used.
- Class 0 and class 1 tags were to be used (later updated with generation 2 tags); which are passive Read-Only tags.
- Data would be communicated to and from Wal-Mart via 'RetailLink' and Electronic Data Interchange (EDI).
- The EPC tag with embedded Global Trade Inventory Number (GTIN) and serial number was to be used, and the EPC number would be GTIN based.
- A mandatory 100% read accuracy was specified for tagged goods within 10 feet of the reader.

The introduction of the technology would start relatively small and scale up in order to accomplish test phases and a gradual introduction of suppliers. However, the successes of Wal-Mart were not what they hoped for. By 2006 the company expected to have 12 (out of the roughly 130) distribution centers fully equipped with RFID technology. Eventually this number was reduced to five, and the focus was directed towards implementing RFID systems in the stores that were supplied by those five distribution centers (Duvall, 2007). Furthermore, the introduction of suppliers into Wal-Mart's RFID project was not as successful as was initially hoped for; after four years only 600 out of the 60.000 suppliers were involved into Wal-Mart's RFID initiative.

Example 5.1 Schuitema Revolutionizes Food Quality Control Through RFID.

Schuitema N.V. is the second largest Dutch retailer and food distributor and wanted to pilot the use of Radio Frequency Identification (RFID). The project is designed to get fresher products to the consumer by using RFID to track crates and temperature in the supply chain. Fresh Link is the first European project to test RFID throughout the entire chain of fresh products using EPC-global Network architecture to share data between trading partners. Through the Fresh Link project, batch information and temperature registration in the chain can now be linked to RFID location information. As a result, for the first time, it is possible for Schuitema to see exactly where certain batches of products are in the chain at any given point.
(R.Bakker, 2008).

Example 5.2 Heathrow Launches RFID Trial to Track Luggage.
The U.K.'s busiest airport is starting to affix radio chips to the luggage of passengers as part of an experiment aimed at reducing lost bags. The six-month trial will involve tagging around 50,000 bags a month with RFID tags for passengers traveling or transferring on Emirates Airline between Dubai and Heathrow, said BAA, the company that runs the airport. Barcode tags are currently used, but the barcodes can be misread by scanners, especially if the tags are wet or creased. Those problems increase costs for BAA and the airlines, as well aggravating passengers with slower baggage handling. The RFID tags, which will be attached by staff at nine specially-equipped Emirates check-in desks, will be encoded the passenger's name and route. Higher-capacity chips could contain more data but won't be used for this trial, BAA said. Barcodes will still be used with the RFID tags. The RFID chips can be read by scanning equipment from a short distance away as the luggage passes through Heathrow's baggage system. Once at their destination, some passengers will receive a text message on their mobile phone informing of the baggage reclaim belt, BAA said.
New York Times, February 14, 2008.

Example 5.3 Metro Group outlines RFID strategy.
The world's fourth largest retailer will soon require that all pallets shipped to 180 locations in Germany be equipped with RFID tags using EPCglobal's second-generation Electronic Product Code standard. Christian Maas, a Metro spokesperson, told that the company's RFID plans were communicated to about 650 suppliers at a recent meeting in Düsseldorf. The RFID roll-out of the Metro Group will remain concentrated on Germany. In 2007 all Metro Cash and Carry stores as well as about 100 real hypermarkets will be equipped with RFID portals in the goods entrance section. Earlier this year Metro said RFID tests at one of its distribution centers in Germany has achieved read rates of close to 99 percent.
RFID Journal, 01-06-2007

Other companies applying RFID technology like the U.S. Department of Defense (DoD), Boeing, and Hewlett-Packard were experiencing the same developments of Wal-Mart, i.e. from the 50.000 suppliers of the DoD only 4.000 were using RFID tags (Roberti, 2007). Also, other big retailers like Best Buy, Albertson's and Target, who initially planned following aggressive RFID strategies have hold back and currently follow more cautious approaches towards RFID adoption (Duvall, 2007). One of the reasons for this slow down is that the price of tags, readers and software has not decreased as much as it was initially predicted. The other important reason for the slow down in RFID adoption is the lack of clarity in how to apply the technology (Duvall, 2007).

5.1.1 Technical Challenges

The reliability of RFID systems depends on the quality of the logistic visibility of objects, which depends on the readability of the tags attached to those objects. In order to maximize the reliability of RFID systems, the readability of the tags should be maximized. The application of RFID as an Auto-ID technology however still has some technological challenges to face before close to 100% readability can be achieved. These challenges are discussed in this section.

Maximizing collected energy

The receiving antenna of an RFID passive tag collects power from the local electromagnetic field as if they have a collecting aperture with an area that is much larger than the geometric area of the antenna. Energy collected by a passive RFID tag antenna powers the tag's circuit. Therefore maximizing collected energy is a key aspect of increasing the range and robustness of an RFID system.

Tag antenna size and shape

Because antenna dimensions are typically of the same order of magnitude as the wavelength of the radio waves, they seek to receive a direction where antenna currents constructively add at the antenna port. However, this is always accompanied by a direction where currents destructively cancel each other. The dead area in the radiation pattern of an antenna is referred to as a ”null”. Antenna directivity is extremely important for RFID tags because if the tag is oriented such that the null is pointed at the interrogator then the tag receives no power and can not function. Reading from several angles can recover missed tags caused by antenna nulls, but interrogator antenna diversity is not always possible or sufficient. While it can be a reasonable solution for a static collection of tags, moving tags are often not in the read field long enough to be interrogated by multiple reader antennas.

The difference between gain at best and worst tag orientations can be minimized by making the antenna small with respect to operating wavelength. Small antennas however, typically collect less total energy and therefore have a narrower range of operating frequencies.

Anti-collision protocols

RFID uses anti-collision protocols to read several tags at the same time to ensure that every tag is read only once. These protocols need to be improved to ensure that also the weakest tag can be read in a very short period of time.

Reading rate

Another important issue is the simultaneous readability of a large quantity of tags ($<$ 500 tags/s). Tags of Generation 1, Class 0 (US tags) can be read with approximately 300 tags/s. Tags of Generation 1 Class 1 (EU tags) can be read with approximately 50 tags/s. These numbers are far too low for many applications. The reading rate is determined by:

- The amounts of data to be sent; the more data transmitted per tag, the lower the reading rate.

- The translation of protocols; the longer and more complex the protocols are, the lower the reading rate.
- The software; the interrogator sends its data to a computer where it is filtered and translated. The longer it takes to filter and translate the lower the reading rate.
- Listen-before-talk principle; the ETSI rules now prescribe that a tag listens before it talks. This takes approximately 5 ms. If this rule is waved then the reading rate increases.
- The bandwidth and the number of sub-bands; an increase in bandwidth yields an increase in number of sub-bands and therefore an increase in channels to send data. Therefore the reading rate increases.

Tag performance

Tag performance depends on many factors, besides frequency and environment, including:

- Tag sensitivity; the ability of the chip to be energized and to maximize the signal strength to send its identifier back to the interrogator.
- Tag size; larger generally means longer read range.
- Tag shape; different antenna shapes provide remarkably different performance levels.
- Number of tag antennas attached to the chip; two dipole antennas attached to a single chip result in a tag performance that is less sensitive to orientation.
- Reading rate; the rate at which the interrogator collects identifiers. Rapid read rates increase the readability of tags.
- Tight tag stacking; when tags are densely stacked they may interfere with one another.
- Interference; well-designed tags and readers perform effectively in noisy environments.

Materials the tag is attached to; metal and liquid based materials are generally hostile to RFID systems and negatively affect the read range.

5.2 Testing methodology

The reliability of an RFID system depends on the quality of the logistic visibility of an object, which is partly determined by the readability of the tags attached to them (Lodewijks et al., 2006). In order to determine the readability of RFID tags in certain application, a series of tests was designed taking into account the characteristics of radio frequency communication systems and the desired solution's requirements. The tests investigate the reliability of the application conditions to determine the relevance of RFID in a given situation. The readability of an RFID system is influenced by the radio frequency RF air interface and the application. The first part of the tests is focused on evaluating the RF air interface performance by determining functioning conditions like the read field of the tags, the effect of tag orientation and read rate, among others. The second part of the tests introduces application parameters that can have a disturbing influence in the performance of the system. These tests are set up to check the change in readability with for example different packaging materials and can be used to design the optimum packaging with respect to readability. These tests can also be done in a laboratory environment. The third part of the test assesses the influence of the application's environment in the readability of the tags. In this part, test conditions like the packaging of the products, impact of the operational equipment, total number of boxes that can be segregated and identified, accuracy of the system, interaction with the physical environment, and more is analyzed.

Figure 5.1 shows the testing methodology. The proposed methodology is a way of identifying key parameters and finding their individual influence on readability performance. The outcome of the performance test can affect on which level tagging is applied: freight containers, returnable transport items (RTI), transport units, product packaging, the product itself. After these three series of tests the reliability of an RFID system in a certain application can be evaluated. Whether or not this reliability is sufficient for that specific application depends on the sensitivity of the logistic system to a disruption in objects visibility.

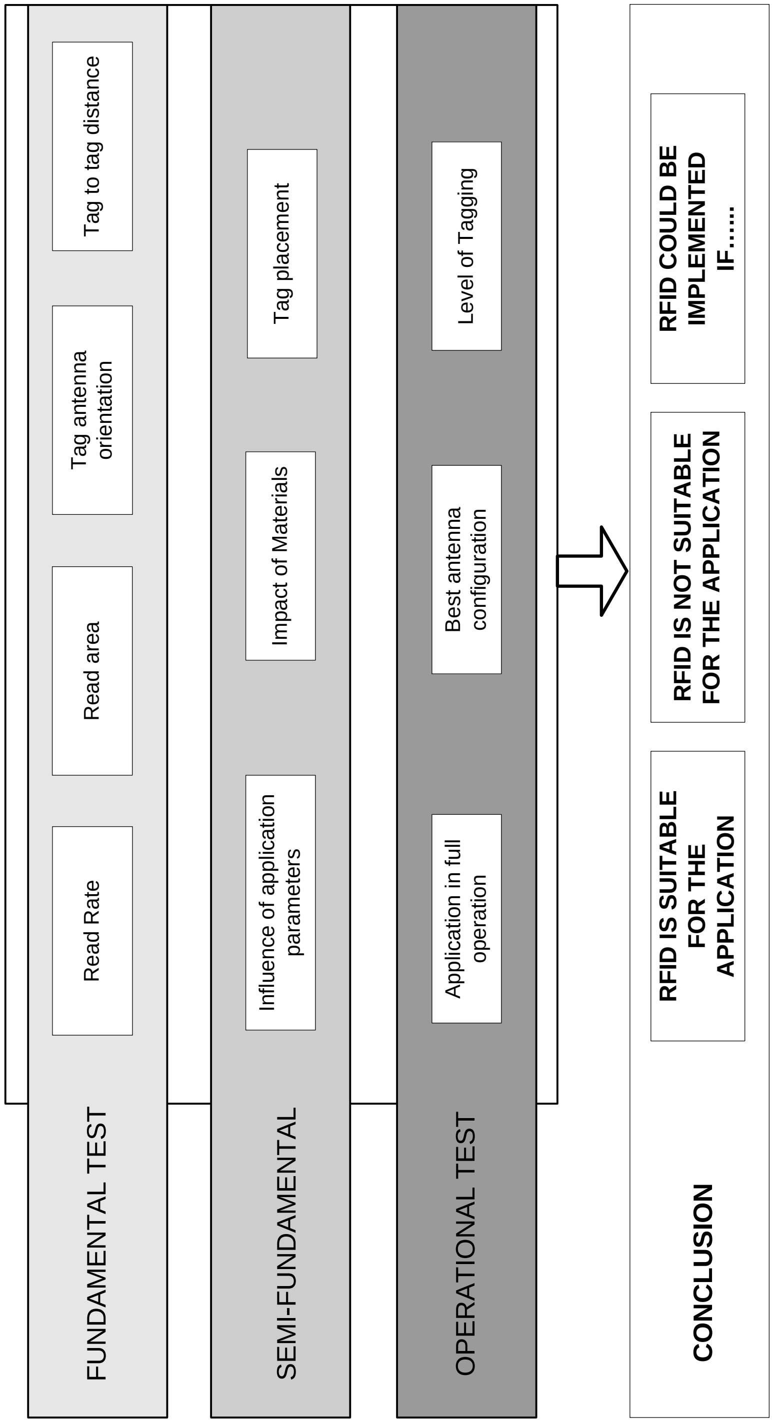


Figure 5.1: Testing methodology to evaluate readability of RFID systems.

5.2.1 Fundamental Test

The performance characteristics of RFID systems (tags and interrogating equipment) depend on the application factors and the particular RF air interface (frequency, modulation, protocol, etc.). Relevant application factors concern the tag application surface and the application environment. Relevant RF air interface factors concern the interrogator and the tag itself. Examples of these factors include:

- Tag application surface: paper, wood, glass, plastic, metal.
- Application environment: RF reflective and absorptive surfaces, moisture, chemicals, radio frequency, electrical.
- Interrogator: frequency, power of field strength, antenna directivity and polarization, receiver sensitivity, modulation characteristic.
- Tag: activation sensitivity, antenna directivity, modulation characteristic.

The fundamental test aims to research the technology, the limitations and the performance in a controlled environment. This part of the readability test is done in a RFID laboratory, where precautions have been taken to restrict possible causes of interference. This part of the assessment is made by testing the RFID equipment in different conditions. Table 5.1 specifies the test conditions for short range applications. For long range applications the distance mentioned in Table 5.1 increases from 0-10 m to 10-100 m. This assessment is only done once for every type of equipment under test, after having characterized the RFID equipments, the results can be used to compare which one gives better performance for a given application.

Performance Indicators

The functionality of RFID systems includes the identification, the read, and the write processes. The performance characteristics can be quantified by performance indicators. Given the functionality of RFID systems these include the read range, read rate, write range, and write rate.

To determine the range related performance indicators the following distances need to be determined:

Table 5.1: Short Range Test Conditions. (ISO/IEC, 2005)

conditions	Range	Comment
Distance	0- 10 meters	3-D(x,y,z)
Tag population	1,10,20,50,100	
Tag geometry	Linear, Array, Volume	
Tag orientation	0, 30, 60, 90 deg, random	3-D(ψ, θ, φ)
Tag volume	0.016, 0.125, 1 m^3	
Tag speed	0, 1, 2, 5, 10 m/s	
Tag mounting material	Paper, wood, glass, plastic, metal	
RF environment	Benign, moderate, congested	WLAN, machinery, etc.
Data transaction	1, 8, 16, 32 bytes	Read and write
Interrogator antenna height	0.5, 1, 2, 3 meters	Distance above ground plane (propagative)

- minimum and maximum distances in z-direction, which are the minimum respectively maximum distance between the center of the interrogator antenna and the centroid of the tag population under test, where 100% visibility is obtained. The measured values are symbolized as R(z) min and R(z) max, also see Figure 5.2.

- horizontal (x-direction) and vertical (y-direction) distances, which are the maximum distance across respectively through the communication zone for the centroid of the tag population under test, where 100% visibility is obtained. The measured values are symbolized as R(x) extend and R(y) extend. See Figure 5.2 for the R(x) extend. The R(y) extend can be visualized in a side view of the communication zone.

The rate related performance indicators consist of a number representing the

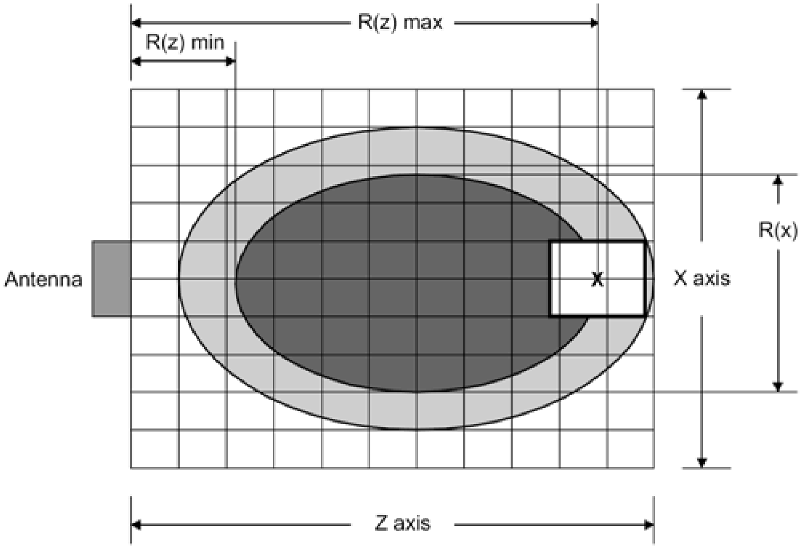


Figure 5.2: Top down view of the communication zone (ISO/IEC, 2005).

tag segregation (anti-collision) performance of the RFID system. This number is stated in ”tags per second”, or ”tags/s”. The read rate can be severely affected in dense environments. This is closely related to the type of anti-collision protocol used in the RFID reader.

Number of Samples

The reliability of an RFID system can be expressed in terms of the statistical likelihood that the functionality is operational and with a certain confidence level. However, the confidence level that can be obtained depends on the number of samples, or repetitions of a test, used. The applicable ISO/IEC standard prescribes that each performance indicator has to be collected for each test condition under evaluation with a minimum of 10 samples (ISO/IEC, 2005). It should be realized that the accuracy obtained in the determination of the performance indicators can vary if a fixed number of samples is used. When a confidence level of for example 95% is required then the number of samples to be used can vary.

5.2.2 Semi-fundamental Test

After establishing the fundamental performance of the selected RFID equipment, the effect of certain application parameters in the overall performance of RFID need to be investigated. The semi-fundamental test is designed to determine the influence of application parameters or application requirements in the overall performance of RFID, i.e. packaging materials, restrictions on possible places to tag the objects, among many others. The semi-fundamental tests are devised according to the application restrictions. In this part of the testing methodology, it is important to identify the characteristics of the application that will have the biggest disturbance effect in the performance of RFID.

The semi-fundamental tests are probably the most important series of tests that can be performed. With the results of the semi-fundamental tests it is possible to determine whether or not to continue with the RFID application. If, during the semi-fundamental test, the readability of RFID is reduced beyond acceptable performance, then it can be determined that RFID is not suitable and, either, select a different equipment, a different application case, adapt the application, or terminate the RFID application study. Otherwise, if the results of the semi-fundamental tests show that the reduction of readability is still within the acceptable ranges for the application, and there are certain measures that can be taken to improve the readability of the tags, then the next phase of testing can be initiated.

5.2.3 Operational Test

The operational tests aim to determine the effects of the operation environment in RFID performance. In this phase of the testing methodology, it is important to choose a good antenna configuration in order to maximize the read area that might be affected by the operation environment. Furthermore, different levels of tagging should be put to test as well as data management systems.

Operational tests can be considered the starting point of a pilot project.With the available information about the operational performance of RFID, it is possible to determine at what level RFID should be implemented, and how to proceed with the overall implementation of RFID. Tuning of equipment, re-design of production processes, and RFID tagging levels should all be included and developed during the pilot phase of the RFID implementation project.

5.3 Application Cases

The applicability of RFID depends on the performance of RFID technology and the implementation environment. A testing methodology composed of three phases was proposed and developed in the previous section. The proposed methodology is a way of identifying key parameters and finding their individual influence on readability performance for a given application scenario. In this section, different application cases will be presented using the proposed testing methodology.

5.3.1 TNT

The Tellitrace project was an initiative of KPN, TNT and Symbol to track and trace mobile phones from the TNT warehouse in Leidschendam to two KPN outlets. Before launching a full RFID pilot project, an initial proof of concept was organized among the project partners to evaluate the technical aspects involved in deploying RFID technology and the impact of applying RFID in a business environment.

The process flow for the distribution of mobile phones at the warehouse in Leidschendam with RFID technology is shown Figure 5.3 .

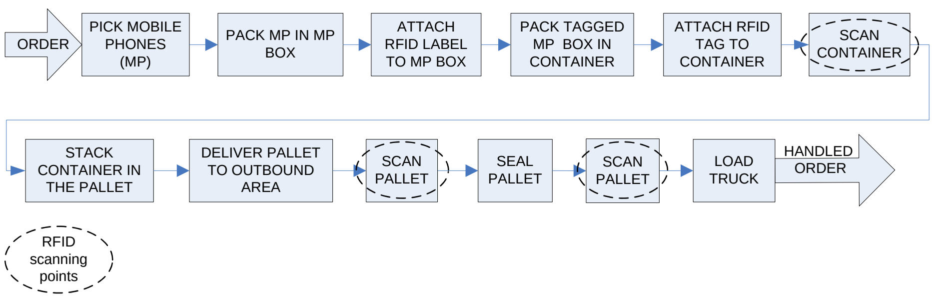


Figure 5.3: Top down view of the communication zone.

The areas where RFID was expected to be implemented were: the packaging table and the outbound area. In the packaging table an RFID tag is attached to every box containing a mobile phone. This box is scanned (to connect the mobile phone to the specific container) and packed in a container that is also tagged with an RFID label. The container is placed on a pallet with the other products that constitute the order. Then, the pallet is packed and scanned (to link the container with the rest of the order) in the outbound area before sealing it. After the pallet is sealed, it is scanned (to link the order to a specific transport truck) once more at the outbound area before loading it into the truck.

Case Description

Performing an RFID readability test in order to identify the best position of the tag on the item (mobile phone box), the item in the container, and the container on the pallet, in an attempt to minimize the impact on current business processes

Requirements

The technology used in this case was UHF Gen 2 RFID technology. The reader and antennas were provided by Symbol. The reader used was the Symbol XR 480 UHF RFID reader for the European market. The antennas used were Symbol High Performance Area antenna, these are circular polarized antennas. Two types of Class 1 Gen 2 tags were used during the fundamental tests, dual dipole tags provided by Symbol and single dipole tags provided by Zebra. Figure 5.4 shows the Zebra tag used and Figure 5.5 shows the Symbol tag used.

Tag type: EPC class 1 Gen 2
Read content: Serial number
Antenna: Short dipole

Figure 5.4: Zebra Tag

Tag type: EPC class 1 Gen 2
Read content: Serial number
Antenna: Dual dipole

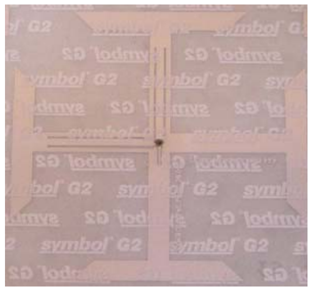


Figure 5.5: Symbol Tag

Objectives

The first objective of the project was to achieve 100% readability at item level and at container level on the packaging table. The second objective was to achieve 100% readability in the outbound gate before dispatching the orders.

Results

In order to study the applicability of RFID, the testing methodology shown in Figure 5.1 was used and adapted to the specifics of the TNT case. The fundamental part of the tests were conducted in the RFID lab at TUDelft. Figure 5.6 shows the set up used during the fundamental tests. Semi-fundamental tests were performed in the RFID lab and in a designated testing space at the TNT warehouse in Leidschendam. Finally, the operational tests were performed on packaging table and at outbound gate of the TNT warehouse in Leidschendam during normal working hours. Detailed results and full technical and operational descriptions of the tests can be found in (Bahlman, 2006) and (Rijswijk, 2006). A summary of the most relevant results will be given in the following paragraphs.

Figure 5.6: RFID Lab at TUDelft

Fundamental test The fundamental tests are based on the (ISO/IEC, 2005). The test definition, procedures and detailed results can be found in (Bahlman, 2006). In order to provide a common reference frame for the results, Figure 5.7shows the axis definition for the tests. The term readability is defined in this thesis as the percentage of successful readings over all the measurement points ($25cm \times 25cm$ squares) in the test area.

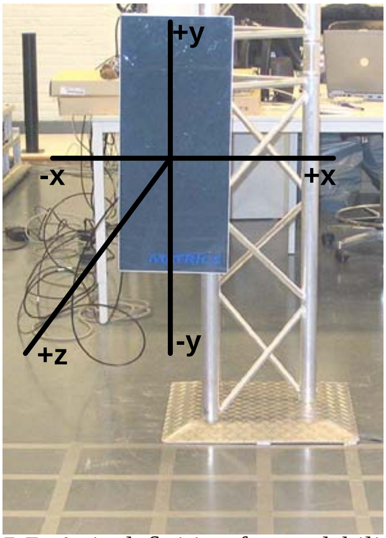
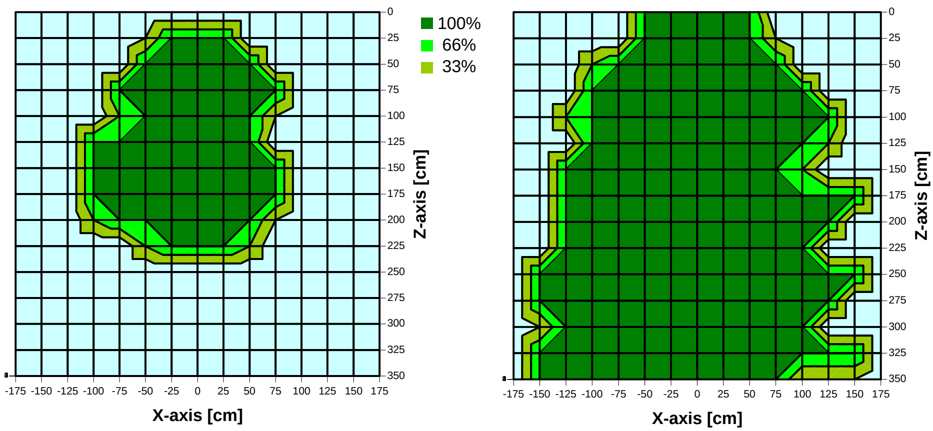


Figure 5.7: Axis definition for readability tests.

Read Area The first performance parameter of the fundamental test is the read area. The read area determines the size of the reading field of the RFID equipment in the interrogation zone. The main objective of this test is to determine the maximum and minimum distances a tag can be read with 100% reliability. The read area for every type of tag under test is determined by measuring the readability of the tag in all the positions of the grid field. The read area plot is a density plot of successful readings. The reader is positioned at the top of the graph at (x=0,z=0). Figure 5.8 shows the read area for the two type of tags used during the case study at TNT. The read area of the Zebra tag is considerably smaller than the one of the Symbol tag. This result is expected due to the antenna type of each tag. The Zebra tag has a short dipole antenna. This means that the amount of energy that can be collected to power the system, highly depends on the position of the tag with respect to the reader. In order to maximize the collected energy, the tag should be place parallel to the polarization field of the antenna. In this case, the readers antenna is circular polarized which reduces the orientation dependency. However, the tag can only collect energy from the electric field propagating parallel to its position. Furthermore, as it was discussed in chapter 4, a polarization loss of 3dB between a circular polarized antenna and a linear polarized antenna should be taken into account.



a. Zebra Tag b. Symbol Tag

Figure 5.8: Read Area.

In the case of the Symbol tag, the type of antenna used is a dual dipole antenna. For this type of tag, the orientation dependency is further reduced since the tag have two dipole antennas arranged orthogonally to one another. This means that the tag has a greater chance to collect energy from one, if not both, of the electric fields propagating from the circular polarized antenna.

Antenna Tag Orientation This performance parameter determines the influence of the tag antenna orientation in overall readability. Figure 5.9 shows some of the tag orientations tested during the fundamental test. These tag antenna orientations showed the most variations in readability performance.

The read area shown in Figure 5.8 was obtained using orientation C. Figure 5.10 shows the readability for different tag orientations for the Zebra tag and the Symbol Tag and the readability for the two types of tags.

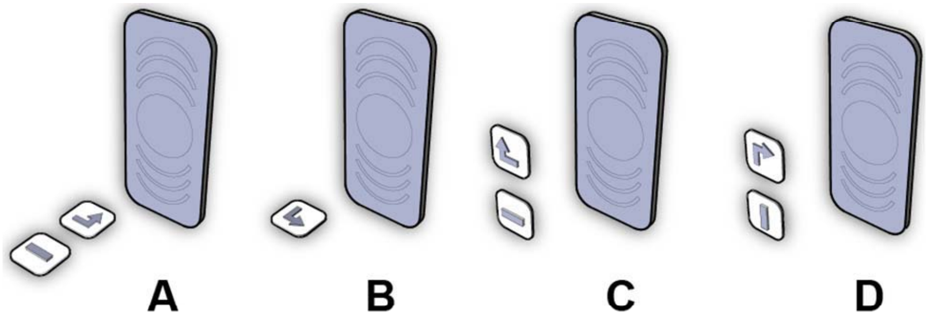
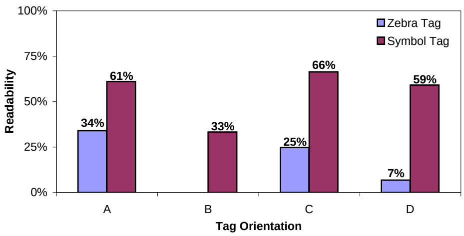
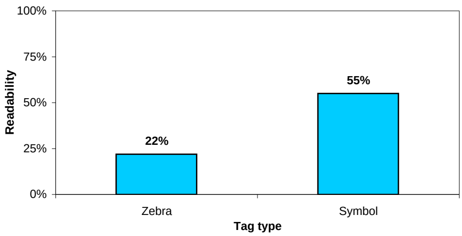


Figure 5.9: Different tag orientation used during the experiments.



a. Readability per tag orientation

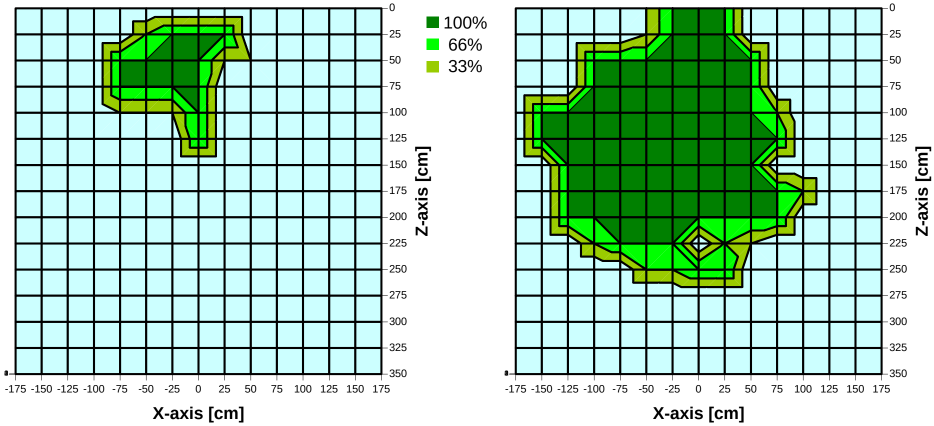


b. Readability per tag type

Figure 5.10: Readability in different tag antenna orientations and readability for every tag type.

The Zebra tag has the best readability performance in orientation A. Although in orientation D the tag is not aligned with the propagation fields of the antenna, there is still a chance that the tag will be read (there is a 7% readability in this orientation) if the tag is placed close enough to the reader. The Symbol tag shows the best readability performance when compared with the Zebra tag. Because of the dual dipole antenna of the tag, the tag can be read in all the orientations tested. However, in orientation B there is almost a 50% reduction of readability performance when compared with orientation C. Figure 5.11 shows the worst read area of the Zebra tag,orientation D, and the worst read area of the Symbol tags, orientation B.

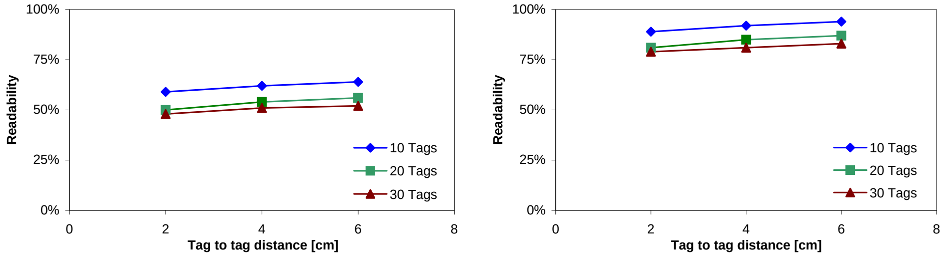
Tag population and tag to tag distance This performance parameter indicates the readability of a tag population. To perform this test, only the best orientation for every type of tag is used. The testing area for this performance



a. Zebra Tag. Orientation D   b. Symbol Tag. Orientation B

Figure 5.11: Worst read area for given tag antenna orientation.

parameter is composed of the points that have 100% readability during the single tag testing procedures. In this case, 100% readability is assigned to the points in the testing area where all the tags of the population are read by the reader. Figure 5.12 shows the readability for different tag populations and different tag to tag distances. The results show that an increase in tag to tag distance leads to an increase in readability and an increase of tag population leads to a decrease of readability. This trend is shown for both types of tags.

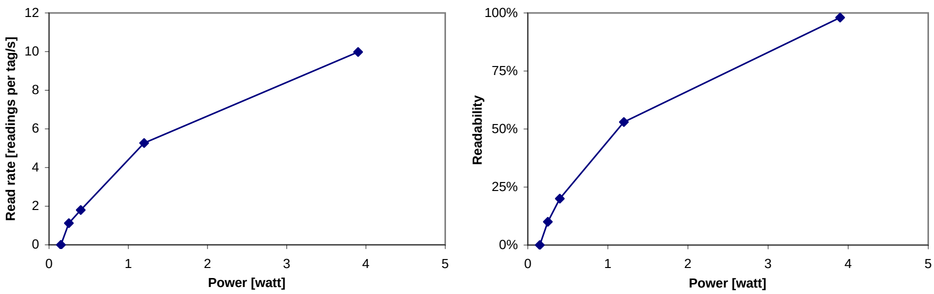


a. Zebra Tag   b. Symbol Tag

Figure 5.12: Readability for different populations of tags and tag to tag distance.

Because of the proximity of the tags and the negative impact this has on readability, it is possible that the reader can not segregate and identify tags if they are too close to each other due to mutual data collisions (tags interfering with each other).

Read rate This parameter is used to determine the read rate (number of readings per second per tag) of the RFID tag and reader combination. This test was performed only for the Zebra tag and a population of 10, 20 and 30 tags. Figure 5.13 shows the results of the tests for a population of 20 tags. If the power is increased, the read rate and the readability also increase. However, after 3 watts the read rate and the readability do not increase anymore. This is in fact expected since the maximum power power that a tag can collect from an incoming signal not only depends on the power of the signal but also, on the effective aperture of the tag's antenna, see chapter 4.



a. Read rate versus Power b. Readability versus power

Figure 5.13: Read rate and Readability.

One unfortunate but real fact about RFID tags is that the quality of tags is currently not consistent, and therefore performance is not consistent. There are considerable variations in performance from one tag to the next, even among tags of the same manufacturer and model. Some models of tags show more variation than others. These variations in tag performance also influence the lack of 100% readability shown in Figure 5.13b.

Semi-Fundamental test The semi-fundamental test are designed to determine the influence of application parameters or application requirements in the overall performance of RFID. Because of the 100% readability requirement at item, container and pallet level, the semi-fundamental tests focused on investigating the influence on readability when moving from one tagging level to the other. During the TNT case, three semi-fundamental tests were performed, these are: the single product test, the container test and the pallet test.

Single product test The goal of this test is to identify the influence of the packaging materials and the contents of the mobile phone boxes in the readability of the tags. During these tests, 10 mobile phone boxes were tagged in three different locations. Different models of mobile phones where used, some of the phones included a CD. During the first set of tests, the CD was removed to limit its influence in the results. During a second set of tests the influence of the CD was investigated. Figure 5.14 shows one of the mobile phone boxes tested. Figure 5.15 shows the three different positions where the tags were placed on the mobile's boxes.

Figure 5.14: Mobile phones used during the single product test.

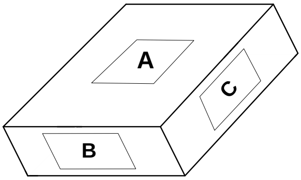


Figure 5.15: Different tag positions on the mobile phone boxes.

Every tagged box was placed in the read field of the antenna where 100% readability for a tag in free space was determined. The power of the reader was varied to determine in what position on the box the tag is less affected by the packaging materials and its contents. Figure 5.16 shows the readability of the tests in the different locations tested.

Figure 5.16 shows that the readability of the tags attached to the boxes increa-

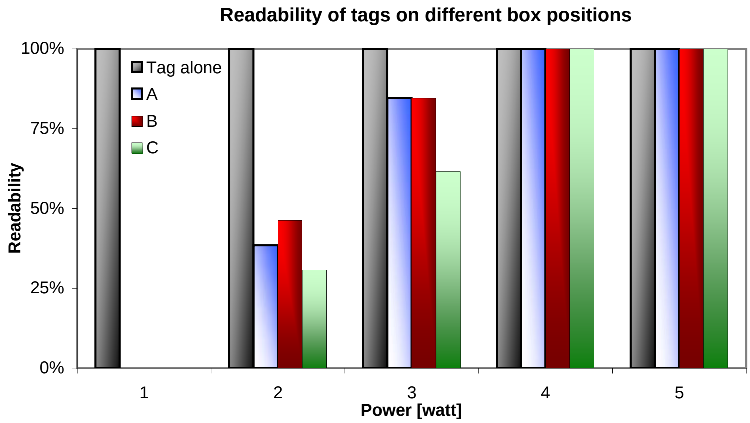


Figure 5.16: Readability of tags on different box locations

ses with the increase of power. The best position to attach the tags for the mobile phones tested is position B. This position corresponds to the position the barcodes were attached to in some of the mobile phones tested. In general, it can be concluded that the best position to place the tag is where a larger air gap between the tag and the contents of the box exists. Furthermore, in (Bahlman, 2006), it was determined that the CD that comes with some of the mobile phones tested reduces the readability of the tags up to 75% if the tag is placed right above the CD, and in 25% if the tag is placed in other positions on the box.

Container test During these tests the readability of the tags attached to the mobile phone boxes and packed inside a container was investigated. During the fundamental tests, it was determined that the distance between tags had a large influence on readability performance. The larger the distance between the tags, the larger the readability. In this case, the maximum distance between tags and the maximum number of tags inside the container are determined by the dimensions of the mobile phone boxes and the way mobile phones are packed in the container. Figure 5.17 shows a fully packed container.

All the mobile phones where tagged on the locations that gave the best readability performance during the single product test. The mobile phones inside the container were packed in three different orientations. For the first test a maximum of 18 mobile phones were packed with their tags in orientation A, see Figure 5.9. For the second test a maximum of 22 mobile phones were packed with their tags

Figure 5.17: Packed container with tags in orientation A.

in orientation C. For the last test a maximum of 23 mobile phones were randomly arranged inside the container. Figure 5.18 shows the readability of the tags inside the container.

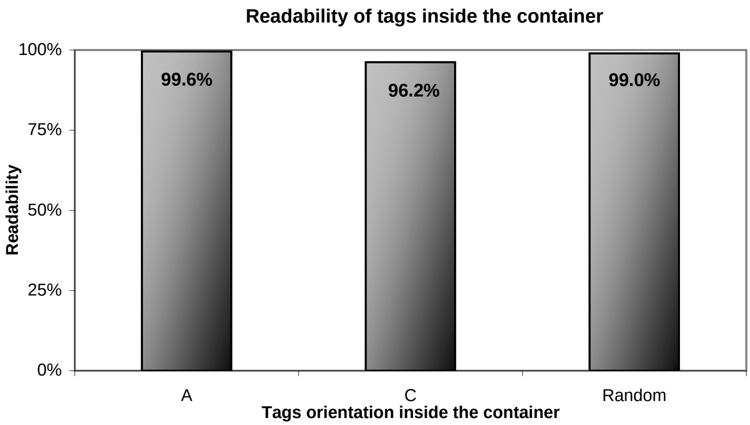


Figure 5.18: Readability of tags inside container.

Figure 5.18 shows that the readability of the tags is best when all the mobile phones are packed with their tags in orientation A. However, the difference in readability is not more than 0.4% when mobile phones are packed in a random way. During the tests, special attention was given to pack the mobile phones with CDs in such a way that the CD is not directly behind nor against another tag. Also, the location of the tag on the container was chosen so there were no mobile phone tags directly behind it. 100% readability was difficult to obtain, specially because of the high variability in tag's performance, and the presence of

RF opaque[1] materials like the CDs.

Pallet test The goal of this test is to determine the readability of the tagged mobile phones inside the container when they are placed on a pallet with regular products. For this test, 22 mobile phones were packed in the container with their tags in orientation A. Three tests were performed to investigate the influence on readability of the regular products in the pallet. During the first test 3 more containers filled with products like car kits, ethernet modems, cables, among others, where place along side with the container containing the tagged mobile phones. In the second test, another set of containers packet with regular products was placed above the first layer. Finally, in the last test, a third and final layer of containers filled with regular products was placed above the first two layers. Figure 5.19 shows the set up for each of the tests preformed.

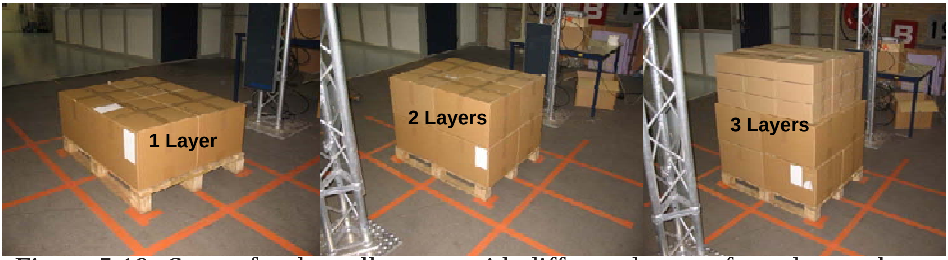


Figure 5.19: Set up for the pallet tests with different layers of regular products.

For each of the three tests performed, the readability of the tags was investigated under two conditions: static and dynamic. The static measurements are the same as the ones performed during the past test. The pallet is placed in the read field of the antenna and the readability of the tags is measured. During the dynamic measurements, the pallet is slowly moved across the read field of the antenna using a hand equipment. Figure 5.20 shows the results of the experiments performed during the pallet test.

Figure 5.20 shows that the readability of the tags improved during the dynamic part of the tests. During the static measurements, the readability is reduced when more layers of products are place on the pallet. The results are strongly influenced by the variability of the tags performance. Furthermore, 100% readability of the tags was achieved during some tests repetitions. This is a result of changing

[1] A material is called RF-opaque if it blocks, reflects, and scatters RF waves (Lahiri, 2005).

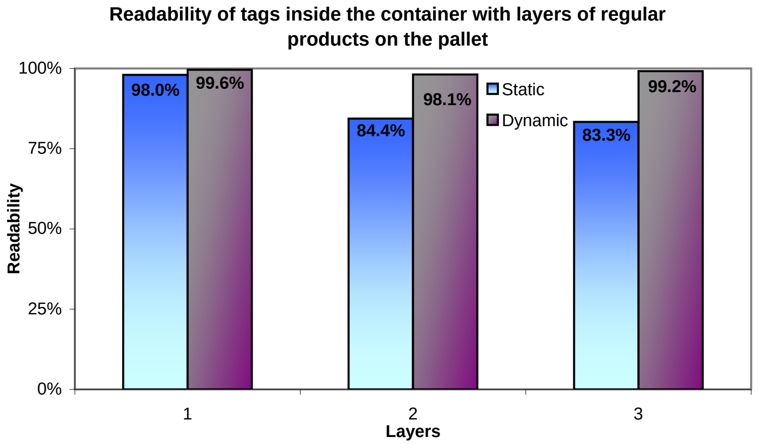


Figure 5.20: Readability of tags inside the container with regular products on the pallet.

some of the tags that were not responding, as well as changing the position of the container on the pallet.

Operational test The operational tests aim to determine the effects of the operation environment in RFID performance. During the semi-fundamental tests became evident that 100% readability was not always possible due to the high performance variability of RFID tags and the type of items contained inside the mobile phones' boxes. During the operational test, the influence of the operational environment was investigated. RFID is expected to be implemented in two places, at the packaging table to scan full stacked containers, and at the outbound gate before sending the pallets with the orders to the retailers. Therefore, the readability of RFID at container level in the packaging table and at pallet level at the outbound gate was researched.

Container in packaging table According to the process described in Figure 5.3, the order of mobile phones is delivered to the packaging table where the boxes are tagged and placed inside a container. After the container is filled, an extra tag is attached to it and the container is scanned. Figure 5.21 shows the RFID arrangement in the packaging table. In this case, the packaging table is equipped with two antennas arranged perpendicular to each other in order to minimize the effect of tag orientations inside the container.

Figure 5.21: Set up of the packaging table

During the tests performed at the packaging table three different orientations of the tags where tested under static and dynamic measurements. Figure 5.22 shows the readability of tags inside the container with different orientations in the packaging table. The highest readability of tags is obtained when the boxes inside the container are arranged in such a way the the tags are in orientation A with respect to the antenna parallel to the wall. With this orientation a maximum of 22 tagged mobile phones were fitted inside the container. For orientations C and Random, the number of tagged mobile phones that were inside the container was 24 and 23 respectively. The readability for all the orientations tested increased during dynamic testing. The tag attached to the container was always readable.

Comparing the results under static measurement in the packaging table and the ones presented in Figure 5.18, it can be seen that at the packaging table there is a decrease in readability performance for all the tag orientations tested. The biggest reduction occurs when the mobiles phone boxes are packed in a random orientation. This reduction is a result of eliminating the precautions taken in the previous case of not placing boxes containing CD's directly against another tagged box. The results presented in Figure 5.22 suggest the need to implement protocols to fill and stack the containers. However, 100% readability at container level will still be difficult to achieve.

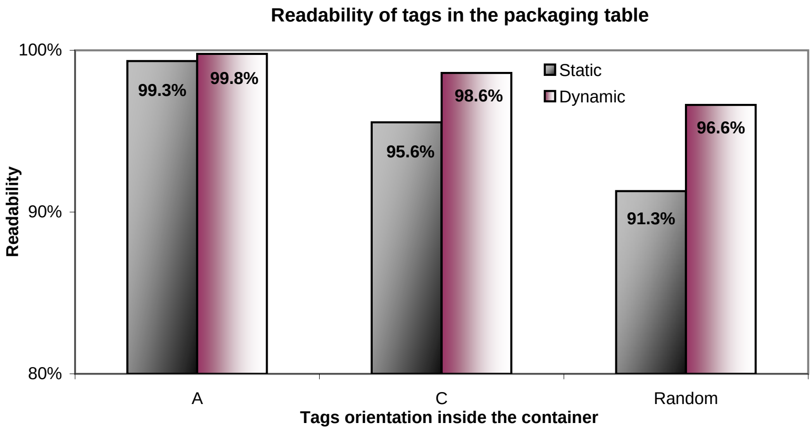


Figure 5.22: Readability of tags in the packaging table

Pallet in the outbound area For this tests, the readability of a bulk load of mobile phones (216) was tested in the outbound area at the TNT warehouse. Figure 5.23 shows the set up at the outbound gate.

Figure 5.23: Set up at the outbound gate.

The readability of the bulk load was tested under static and dynamic conditions. For the first set of tests, the dynamic measurements were obtained using a pallet jacket. Figure 5.24 shows the readability of the static and dynamic test for the bulk load of mobile phones. The results show that the readability of the tags is improved during the dynamic testing. During the dynamic tests, the bulk load of mobile phones is moved across the read field of the antenna at a very slow pace. The movement of the pallet across the read field of the antenna has a positive effect on the readability of the tags.

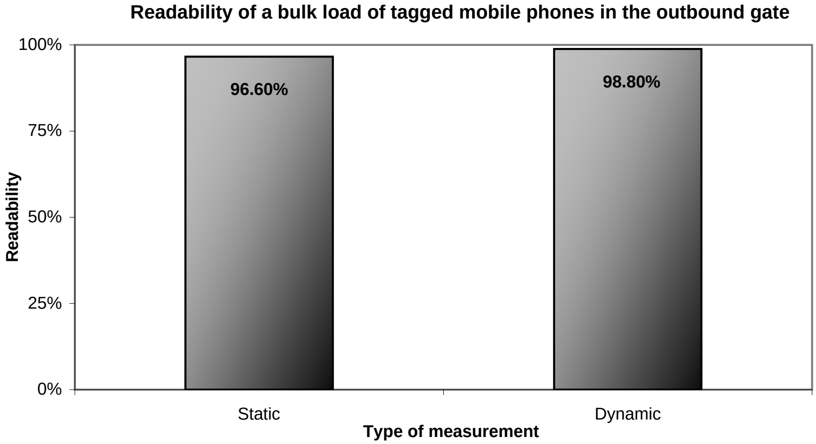


Figure 5.24: Readability of tags at the outbound gate

The second part of these tests were to determine the influence of the handling equipment in the overall readability of the pallet carrying the tagged mobile phones. For these tests, three different handling equipment were used: pallet jack, electric pallet jack, and forklift. Figure 5.25 shows the readability of the tags when different handling equipments are used.

The results show that the readability of the bulk load is reduced when battery assisted or electric vehicles are used. In the case of the forklift, the minimum driving speed was still too high to stay long enough within the reading field of the antennas. A solution to this might be to stop in the reading field and then continue; however this type of strategies will have to be further developed in case RFID is implemented.

Conclusions

The objective of the TNT application case was to read 100% readability of RFID tagged mobile phones at item level, container level and pallet level. In order to

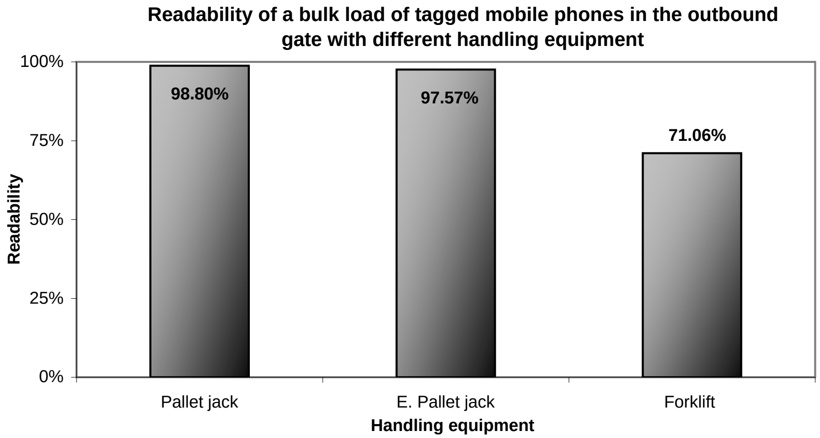


Figure 5.25: Readability of tags at the outbound gate

study the applicability and readability of RFID, the testing methodology shown in Figure 5.1 was used and adapted to the specifics of the TNT case. The fundamental part of the tests were conducted in the RFID lab at TUDelft. During this test phase, the characteristics of the technology and the basic operating principles of RFID were studied. The read area, read rate, antenna tag orientation and tag to tag distance for two different types of tags were determined.

The semi-fundamental tests were performed in the RFID lab and in a designated testing space at the TNT warehouse in Leidschendam. During these tests the readability of the tags under certain application conditions were investigated. It was determined that the packaging material and the contents of the mobile phone boxes have a negative influence in the readability of the tag. Furthermore, in order to optimize the readability of tags inside containers, the mobile phone boxes need to be packed in such a way that the tags are in orientation A with respect to the reader's antenna.

The operational tests were performed on packaging table and at an outbound gate of the TNT warehouse in Leidschendam during normal working hours. For a bulk load of 216 mobile phones, a readability of 98.8% during dynamic measurements was registered. It was determined that electrical assisted handling equipment had a negative influence on total readability.

The readability tests performed showed that 100% readability of tagged mobile phone boxes (item level) is not possible with the current state of the technology. The contents of the mobile phone boxes as well as packaging materials have a negative impact on the readability of the tags. Furthermore, in order to increase readability, the internal processes at the warehouse will need to be re-designed to introduce packaging protocols and RFID scanning protocols to minimize the effect of environment in the readability of the tags.

5.3.2 Application of RFID technology for identifying tubes in concrete

In the modern construction of buildings, pipes for waterworks and sewerage are integrated in walls and floors. The advantage of integrating the pipes is that they are not visible after construction, a disadvantage of this integration is that it is hard to determine the exact location of the pipes.

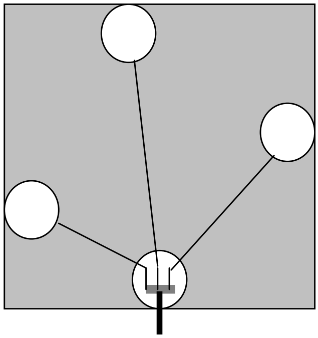
In social house building when prefabricated concrete parts are stacked, the pipes and distribution points for waterworks and sewerage are molded in these concrete parts. Determining the exact location of these units after the parts are stacked can be difficult because of two reasons. The first is that the accuracy of the construction documents is never 100% and the second reason is that the period between molding and installation is about 10 months.

Case description

The company ”AST installatieproducten B.V.”, further referred to as AST, has developed a special system for the integration of the waterworks and sewerage in prefabricated concrete parts of houses. Identification of the exact location of this system is crucial during installation. AST is interested in applying RFID technology to detect and locate the pipes and distribution points inside prefabricated concrete floors (see Figure 5.26).

In Figure 5.26 an schematic example of a prefabricated concrete floor is shown. The white round boxes are the distributions points for waterworks that are going to be integrated in the prefabricated parts. The water is supplied at one point and distributed to the different future water points, like taps, toilet and shower. Figure 5.26 also shows a side-view of such a box. These standardized boxes are used as distribution point or as temporary storage for the piece of flexible pipe that is going to be used to connect the tab to the waterworks.

AST would like to investigate the application of RFID to locate the following units:



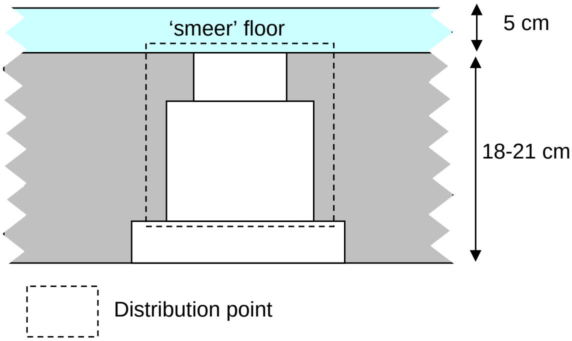


Figure 5.26: Top and side view of the concrete floor with pipe distribution points.

- boxes
- pipes
- water supply and distribution point
- sewage system

In Figure 5.27 a view of a piece of a concrete floor with two integrated boxes is presented.

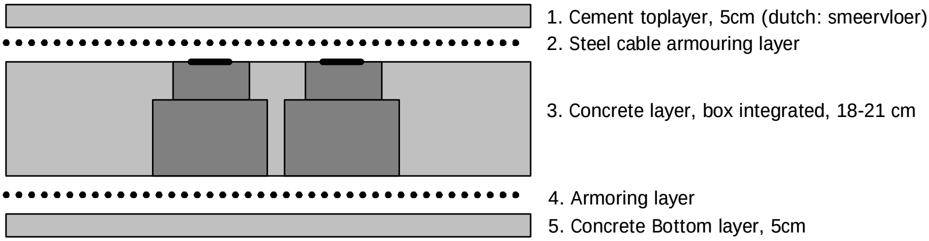


Figure 5.27: Exploded view of a piece of the floor with two boxes

Requirements

According to the specifications from AST the following requirements were infer-red:

- It should be possible to place two boxes side by side inside the concrete structure.This means that the minimum tag-to-tag distance should be 15 cm.

- Tags have to be water resistant. During the fabrication of the floor wet concrete is cast in the mold.

- Tag distance-to-reader can vary between 0,5 cm to 8 cm. In the worst case 5 cm of cement and 3 cm of concrete is between reader and tag.

- The floor contains steel cable armoring at the bottom and at the top. The technology used should be strongly influenced by metal environments.

Considering the specifications of the company AST, short distances and close to a steel construction, High Frequency RFID was selected as the preferred technology to conduct the case study. HF RFID is a standardized technology and largely applied in industry for short distance detection. Another advantage of this technology is that the influence of materials like metal and water is smaller than for UHF RFID technology.

Objectives

The main objective was to determine the applicability of RFID technology for identifying pipes and distribution points in concrete.

Results

In order to study the applicability of RFID, the testing methodology shown in Figure 5.1 was used and adapted to the specifics of the AST case. The fundamental part of the tests determined the readability of the HF RFID equipment. The read area and the tag orientation were investigated during the first series of tests. The semi-fundamental tests focused on investigating the readability of the tags attached to the pvc pipes inside the concrete structure. Detailed results and full technical and operational descriptions of the tests can be found in (Bonjer and Beckers, 2007). A summary of the most relevant results will be given in the next paragraphs.

Fundamental tests HF RFID systems have a shorter read distance than UHF RFID systems. The read distance can vary between some centimeters (for small antennas) to up to 60 centimeters (for large antennas). In order to determine the read area for the HF RFID reader, a grid of 75cm by 45cm, 135 squares of 5cm by 5cm was used. Figure 5.28 shows the axis definition used during the experiments. Figure 5.29 shows the type of tag used during the experiments.

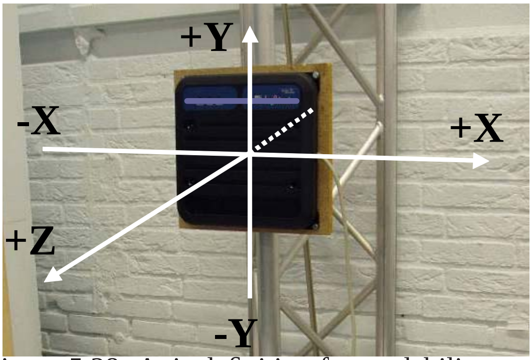


Figure 5.28: Axis definition for readability tests.

Operating frequency:	13.56 MHz
Dimensions:	105mm by 55 mm
Effective coil dimensions:	75mm by 45mm

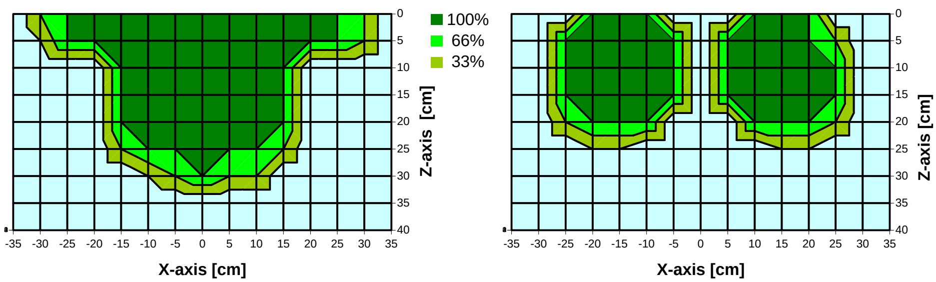
Figure 5.29: HF Tag.

In order to optimize the read area of HF RFID systems, Figure 5.29 shows the orientations in which the tag should be place with respect to the antenna. Theoretically these are the optimal orientations. If the transponder is oriented otherwise it is only readable if it is lying closer to the reader.

Read Area and Tag orientation Figure 5.31a shows the results of testing three different HF tags in orientation A. Figure 5.31b shows the results of three different tags in orientation B.

Figure 5.32a shows the results of testing three different tags in the A orientation when the reader is turned 90 degrees to the left. Figure 5.32b shows the

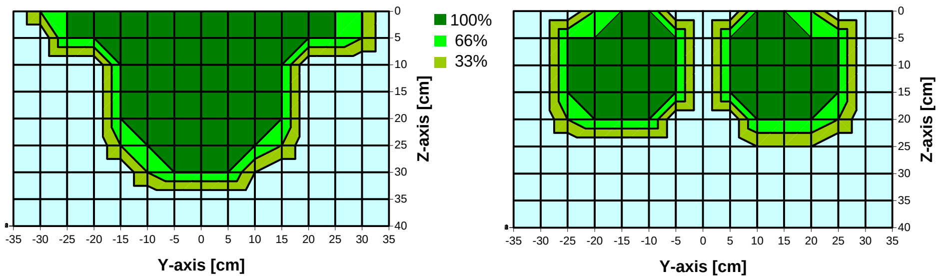
Figure 5.30: Different tag positions to determine the read area of the HF Reader.



a. Orientation A   b. Orientation B

Figure 5.31: Read area of the HF reader for tags in different orientation.

results of three different tags in orientation B.



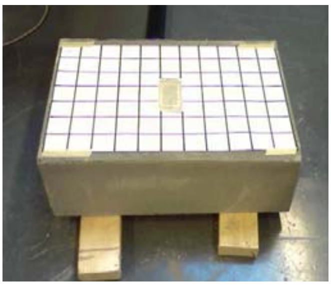
a. Orientation A   b. Orientation B

Figure 5.32: Read area of the HF reader turned 90° for tags in different orientation.

The minimum distance to the reader is 0 cm. The tag is still readable when it is held close to the reader. The maximum read distance is the boundary of the area plot. (the distance is about 33 cm). Rotating the tag from orientation A to B results in a readable area of two rounds. This is in line with the theoretical field as shown in Figure 5.33 market with the line. In orientation A, the results are in line with the theoretical read field shown in Figure 5.33

Figure 5.33: Read field of a HF antenna. (Instruments', 2003)

Semi-Fundamental Test During this phase of the testing methodology, a number of experiments were conducted to determine the influence in readability of different types of pipes. It was concluded that the used pipes did not have a significant impact in readability. However, the position of the tag in the pipe should be taken into consideration at the moment of tagging the pipes (Bonjer and Beckers, 2007). The second phase of the semi-fundamental test was to determine the readability of the tags once they are inside the concrete structure of the floor, see Figure 5.27, and attached to the box collector. In order to perform the second phase of experiments, a new grid on top of the concrete structure was designed. Figure 5.34 shows the new grid used.



0,0%	X-axis (cm)														
Z-axis (cm)	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.34: New grid to determine the position of the tag.

Tag in a box During these experiments the influence on readability when different layers of the of the total floor structure are added, is investigated. Three tests are performed: tag in a box without armoring, tag in a box with armoring and tag in a box with armoring and cement. Figure 5.35 shows the read area of a tag inside a box in a 120Kg of concrete. The readability of the tag is 36.5%.

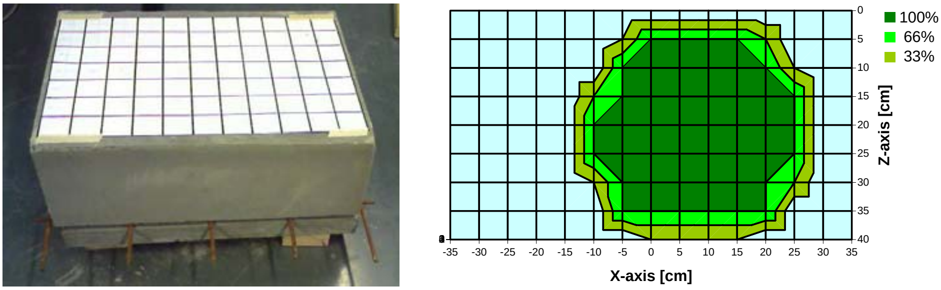


Figure 5.35: Read area of a tag inside a box molded in 120Kg of concrete.

Figure 5.36 shows the read area of a tag inside a box in a 120Kg of concrete with steel armoring on top. The readability of the tag in this case is 20.7%. A reduction in readability of 15,8% is caused by the placing the armoring layer on top of the 120Kg concrete structure.

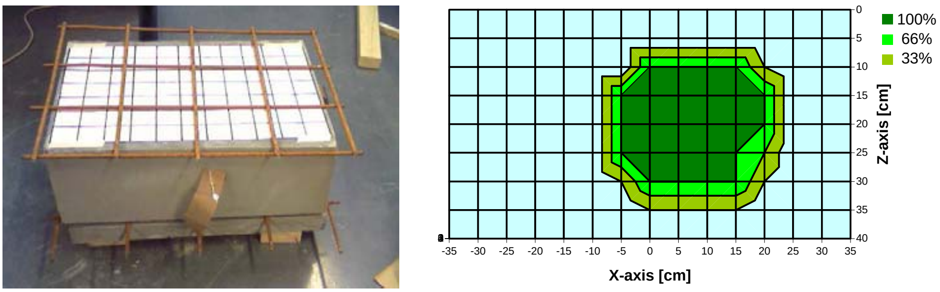


Figure 5.36: Read area of a tag inside a box molded in 120Kg of concrete and steel armoring.

Figure 5.37 shows the read area of a tag inside a box in a 120Kg of concrete with steel armoring and 5cm layer of cement on top. The readability of the tag in this case is 16%. A reduction in readability of 20,5% is caused by placing the steel armoring and the layer of cement on top of the concrete box of 120 kg. Although there is a large reduction on readability, it is still possible to read the tag even under so many layers of materials.

Figure 5.37 shows the readability of the tags when different layers of materials are added to the floor structure. This figure summarizes the results of the previous

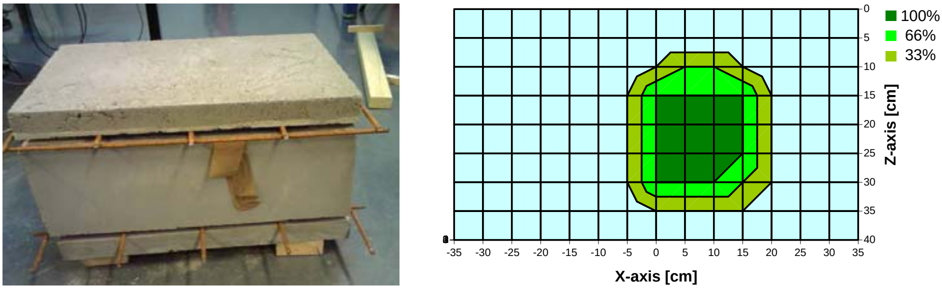


Figure 5.37: Read area of a tag inside a box molded in 120Kg of concrete, steel armoring and cement.

experiments. The readability is significantly reduced, however, it is still possible to read the tags. The reduction on the read area, could be beneficial in determining the exact location of the tag, thus, the exact location of the distribution box. However, conditions like position of the tag inside the box will need to be studied further.

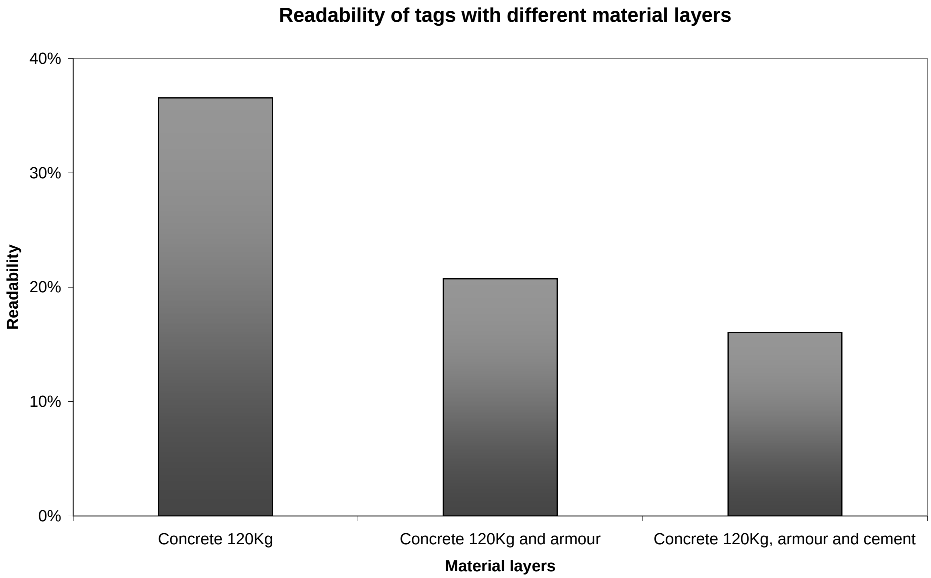


Figure 5.38: Readability of the tags with different layers of materials.

Conclusions

HF RFID technology is suitable technology to use for detecting medium size pipes and distribution points inside concrete structures. For small size pipes, the readability of the tags is very limited and because of the small diameter of the pipe, smaller tags need to be used, reducing the amount of collected energy and seriously affecting readability.

The influence of water should be investigated for the situation that the tag is in direct contact with the water. A water resistant tag is needed for this application. A new tag can be developed or the current tags can be sealed in a way that they are water resistant.

In order to improve the readability of the tags when they are molded inside the concrete structure, the tag should be placed as high as possible within the structure. It should be investigated if it is possible to cut out the armoring around the collectors to increase the readability of the tags.

5.3.3 Performance Evaluation of Deister electronics RFID equipment

Deister electronic develops, manufactures and distributes RFID solutions. One of the most popular products in the catalogue of Deister electonic, is the UHF RFID reader. This is the only reader in the market that is integrated with the antenna. In order to get more insight in the performance of the UHF RFID equipment of Deister Electronic, the fundamental tests of the testing methodology shown in Figure 5.1 were completed. A full overview of the tests and results is available in (van Duijn and van de Langemaat, 2006).

Results

In Figure 5.39 the RFID reader and tag used in this test are shown. Also the device information about this equipment is given.

The reader determines the axes of the field. In the tests, the reader can be in a horizontal or a vertical position. These two orientations and the axis definitions are shown in Figure 5.40.

The tags are tested in different orientations with respect to the reader. Figure 5.41 shows the different orientations in which the tags were tested.

Reader: device info		**Transponder (tag): device info**	
Type	: UDL+500	Transponder type	: EPC class1 GEN2
Cfg	: 20720109	Read content	: serial number
Serial number	: 137001092	Antenna	: Dual dipole
Device	: 0x2072		
Version	: v1.19 SW v1.14 HW		
Operating mode	: portal mode		
Regulatory settings	: ETSI 302 208 Regulation		

Figure 5.39: UHF RFID reader and tag used during the experiments.

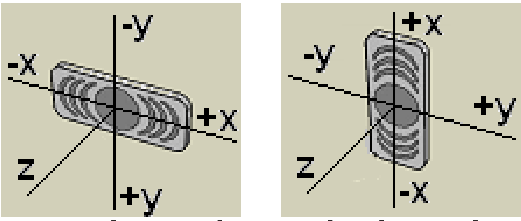


Figure 5.40: Reader axes: horizontal and vertical orientation.

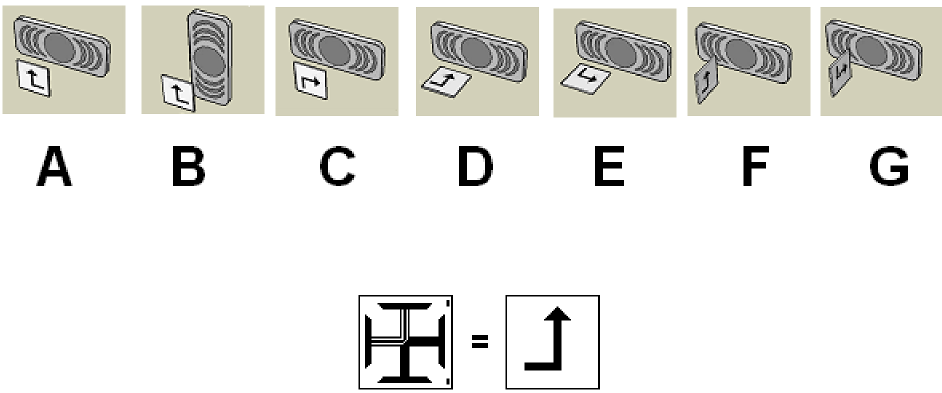
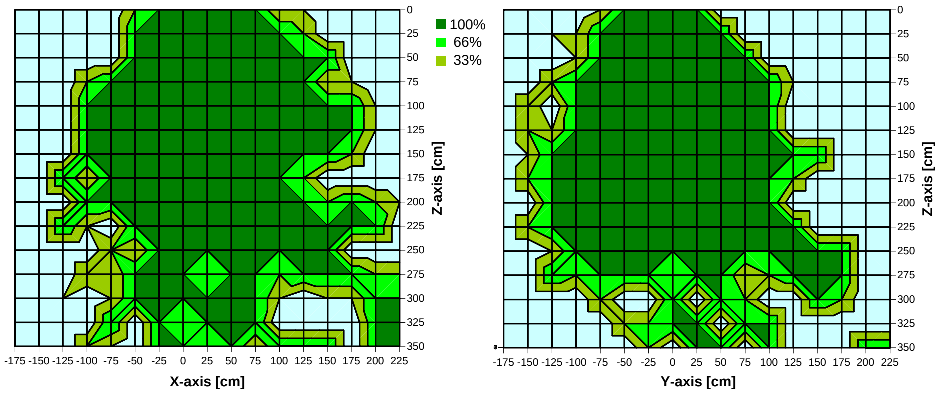


Figure 5.41: All orientations used in tests.

Read Area and Tag orientation The goal of this test is to determine the read area shape and the maximum and minimum distances (borders of the read area). Also the best antenna-tag orientation is determined. The tag is moved along all the positions in the grid field. A map is made in which all the successful readings are plotted. This is done for orientation A - G, for four different tags, and every measurement is made three times to get insight in the accuracy of the measurements. One way to express the performance of the tag is readability. Readability is defined as the percentage of successful readings over all the measurement points (= 25x25 cm squares) in the test area. In this way the best antenna-tag orientation for a tag is determined. After the test, it is clear which tag orientation has the best performance in terms of readability and the size and shape of the several areas. Figure 5.42 shows the read area for the Symbol tag in orientation A and orientation B.



a. Orientation A b. Orientation B

Figure 5.42: Read Area for tag in orientation A and B.

Orientation A has the best readability (the largest area of successful readings). The right side of the plotted area is considerably larger than the left side, as seen clearly in the border plot. This is because the reader has an asymmetric design, with its send-antenna in the left casing and the receive-antenna in the right one (when facing the reader). At z = 175 cm, an indentation is visible at the right border of the area. To get more insight in this phenomenon, the reader has been moved forward 1 meter. The fact that the indentation also moved 1 meter forward contributes to the assumption that this is a property of the reader and not an environmental distortion. At the bottom-right of the area plot an unexpected phenomenon occurs, causing a lot of successful readings outside of the expected scope. This is probably not a property of the reader, but is caused by environmental effects probably because the test environment is not anechoic.

A summary of the readability of the Symbol tag in all the orientations tested is shown in Figure 5.43.

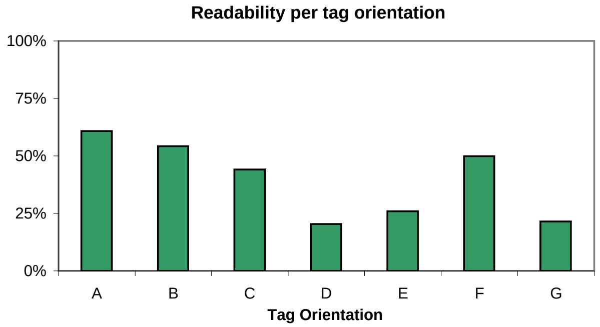


Figure 5.43: Readability in different tag antenna orientations.

Tag population and Tag to Tag distance For this test, orientation A is used to determine the performance of the reader by varying the population size. The goal of this test is to determine the tag-to-tag distance for which the least tag-to-tag distortion is present. Three tag-to-tag distances are considered: 2 cm, 4 cm and 6 cm (measured form tag border to tag border), and the population is varied from 10 tags to 20 tags and 30 tags. A smaller grid is used for this test. The new grid is determined using the previous test. Only the squares with a previous readability result of 100% are considered.

During testing, area plots are made in which all the successful readings are plotted. Not with ones and zeros this time, but with the percentage of tags that are being read successfully. Figure 5.44 shows the results of the tests. All the measurements are subject to the following trend: an increase in tag-to-tag distance leads to an increase in readability, an increase in tag population size lead to a decrease in readability. This shows that the tags are interfering with each other.

Because of the proximity of the tags and the negative impact this had on readability, it is possible to conclude that the reader can not segregate and identify tags if they are too close to each other due to mutual data collisions (tags interfering with each other).

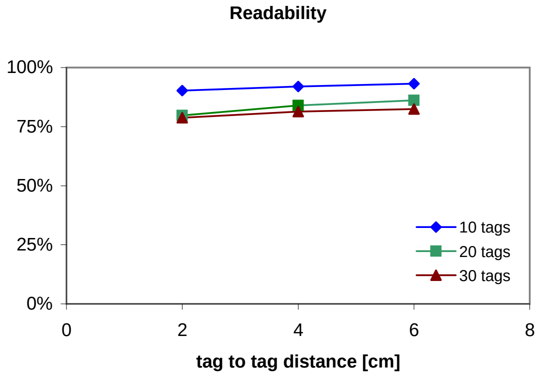


Figure 5.44: Readability for different population sizes and tag-to-tag distances.

Read rate The goal of this test is to determine the read rate (number of readings per second per tag) of the RFID reader. Different settings of the reader are used. During the test a tag population size of 10, 20, 30 and 50 tags is used. A different type of tag was used during this experiments due to a lack of availability of the Symbol tag. The tag used is shown in Figure 5.45.

Transponder (tag): device info

Transponder type	: EPC class1 GEN2
Read content	: Serial number
Antenna	: Single dipole

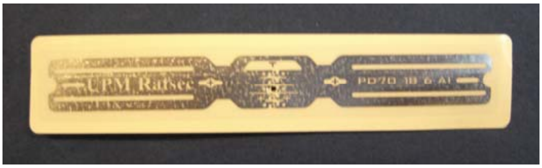
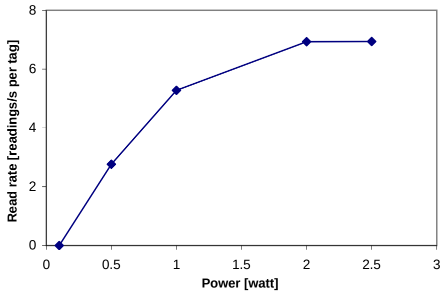


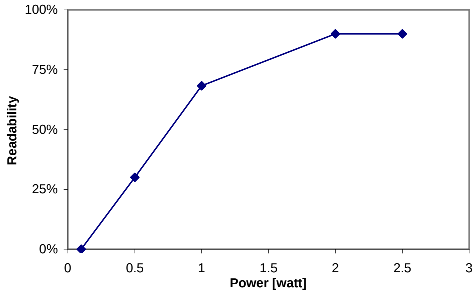
Figure 5.45: RFID tag.

The readability is defined as the ratio of measured tags and tag population size. The read rate and the readability are shown in Figure 5.46.

If the power is increased, the read rate and the readability increase. However, after 2 Watts the readability does not increase anymore. This is in fact expected since the maximum power that a tag can collect from an incoming signal not only depends on the power of the signal but also, on the effective aperture of the tag's antenna, see chapter 4.



a. Read rate versus power



b. Readability versus power

Figure 5.46: RFID rate and Readability.

Dynamic Test The environment, in which the equipment is placed, is different compared with the previous tests. The reader is mounted on the horizontal beam of the aluminium truss and placed on a grid field, over a belt conveyor. The steel sides of the conveyor are shielded with foam, to protect the test environment from reflection. The tags are placed on the belt in populations of 1, 10, 30, 50 and 70 tags. Except for the 1 tag population, the rows are 5 tags wide. When the belt is switched on, the tags will pass along the reader with a specific velocity. The goal of this test is to determine the readability (percentage of the tags that are being read) of the RFID reader with the tags passing along the reader. This gives insight on when the tags are not read anymore (it is expected that this happens at higher velocities and bigger populations of tags). The speed of the conveyor can be altered. Also the combination of the effect of the belt speed and different tag population sizes is measured. Figure 5.47 shows the results of this test.

After the test, it is clear how the velocities and tag population sizes had influenced the readability, also it is clear when tags are not read anymore. The result leads to certain quantitative values, but because the test is done with unique settings (fixed tag-reader distance (50 cm), fixed power (0.5 watt), fixed tag to tag distance (6 cm)), the quantitative values aren't the focus of the test, because with different settings the results will also be different. Instead, the outcome of this test can give insight in the qualitative relationships between velocity, tag population size, readability and the way they influence each other. According to Figure 5.47, the readability decreases when the velocity is increased for tag population sizes equal or larger than 50 tags. This means that for populations $\geq$ 50 tags the decrease in available reading time becomes a restriction to the performance. There are too many tags present, and there is not enough time to read them all.

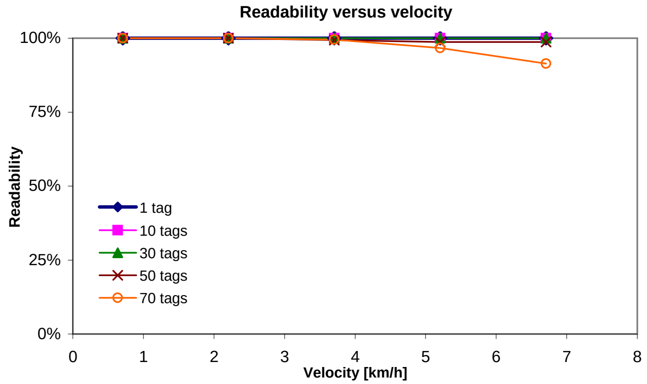


Figure 5.47: RFID rate and Readability.

Conclusions

In this section the performance of the reader as was extracted from the readability test is summarized.

Read Area Test for the dual dipole tag: Orientation A has the best performance, the dual dipole tags have a readability of around 40%. There is only a minor difference in performance of about 1-2%. The maximum read distance for orientation A is approximately 3 meters.

Tag-to-tag distance test for the dual dipole tag: An increase in tag-to-tag distance leads to an increase in readability. An increase in tag population size leads to a decrease in readability.

Read rate test for the single dipole tag: If the power is increased, the read rate and the readability increase.

Dynamic test for the single dipole tag: The readability decreases when the velocity is increased for tag population sizes equal or larger than 50 tags (for the test settings used in this experiment). The number of readings of one tag during one pass decreases when the velocity is increased. Also the number of readings of one tag during one pass decreases when the tag population size is increased.

5.3.4 Tracking and Tracing at Amsterdam Airport Schiphol

Departure delays are usually caused by passengers that check in but do not arrive on time at the boarding gate. This results in flights having to wait because the baggage of the missing passengers has to be offloaded. These type of delays require time and resources, and is costing KLM an estimated €3 million every year. In order to minimize these costs, KLM is keen on preventing passengers missing their flights, and is interest in developing a Passenger Guidance System (PAGUS) based on RFID technology.

Case description

The goal of the project is to research the possibilities to implement RFID at Amsterdam Airport Schiphol (AAS) to prevent departure delays. The focus is on delays caused by passengers who, after the check in, do not arrive on time at boarding gate. Every passenger is equipped with an RFID tagged printed in the boarding pass or via the Flying Blue Pass (a loyalty program card). At AAS, RFID portals are placed in different areas. The portals will be used as reference points to determine passengers location with respect to their corresponding boarding gates. If the system notices that a passenger is in an area with a critical walking distance from the gate, an alert is send to the system to warn the passenger and instruct him to walk as soon as possible to the boarding gate.

Requirements

One of the most important requirement is not to disrupt the normal flow of passengers through Schiphol airport. This means that the RFID portals should be wide enough to allow passengers to move without any restrictions; cover the maximum width of the walking path for the passengers (3.5 meters). The system should also support multiple tag readings and handled multiple tag orientations.

Objectives

The goal of this case is to determine the best configuration for the RFID portal which is able to read the tags carried by the passengers, with the highest reliability.

Results

The equipment used in the experiments was the Deister Electronic UDL 500 reader in combination with passive UHF single dipole tags, see Figure 5.39 and 5.45. The performance of this equipment was presented in the previous case study, and more details can be found in (van Duijn and van de Langemaat, 2006).

In order to determine the configuration for the RFID portal, the testing methodology proposed in this chapter, see Figure 5.1, will be used to evaluate different set ups that meet the requirements of the application. The focus of the tests will be on the semi-fundamental part of the testing methodology. During each test the performance of the set-up is measured. Detailed results and full technical and operational descriptions of the tests can be found in (van Schayk and Mahdaoui, 2007) and (van Aken, 2007). The tests are divided into four phases, from phase 1 to phase 3 readability is defined as as the area of successful readings divided by the total testing area, in phase 4 readability is defined as the number of tags read over the entire tag population. Figure 5.48 shows an example of testing area and grid used for the reading area during the experiments.

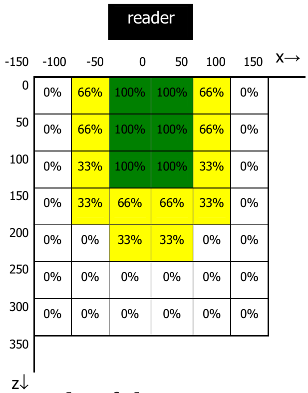


Figure 5.48: Example of the testing area and grid used.

Phase 1 In this part a set-up with one reader is tested. The performance of the set-up is measured when the tag is placed on different body positions on a moving person. The movements of the test person will cover the 3.5 m width of the walking path. Both vertical and horizontal tag orientations are tested, as well as different reader positions on the portal, see Figure 5.49. These tests will give the basic performance of one reader interacting with one person. Different positions to place the tags are chosen based on the typical places passengers normally keep their boarding passes. These are:

- breast pocket
- inside trousers pocket

- inside jacket pocket
- backpack
- purse
- hand baggage trolley

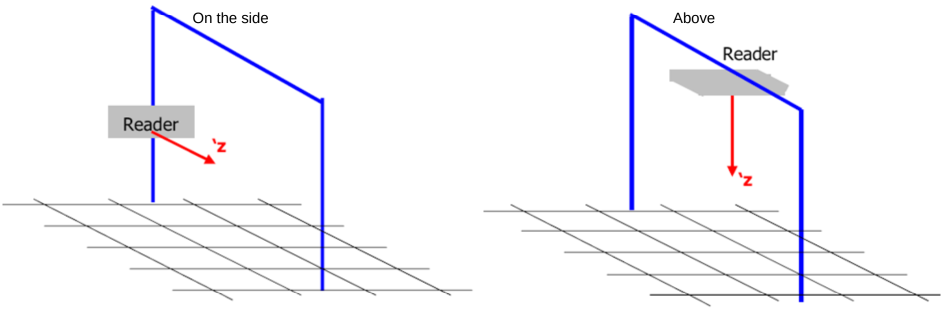


Figure 5.49: Reader positions for the first phase of experiments.

Table 5.2 shows the individual readability for every tag placement tested.

Table 5.2: Readability results for phase 1.

Reader position	on the side	above	Readability
Tag placement			per tag placement
backpack	40.5%	35.0%	37.8%
trolley	36.0%	40.0%	38.0%
purse	19.0%	0.7%	9.9%
jacket pocket	9.1%	0.7%	4.9%
trousers pocket	5.0%	1.4%	3.2%
breast pocket	4.1%	5.0%	4.5%
Readability per reader position	18.9%	13.8%	

Figure 5.50 shows the readability of different tag placements (both vertical and horizontal orientation) for one reader on the RFID portal. The readability shows that there is a large difference in the results obtained for the backpack and the trolley and results obtained for the purse, jacket pocket, trousers pocket and

breast pocket. The influence on readability of the large water content in the human body are clearly shown when the tag is placed in a pocket. However, there is still a small possibility of reading the tags, and this can be increased by adding more readers in the RFID portal.

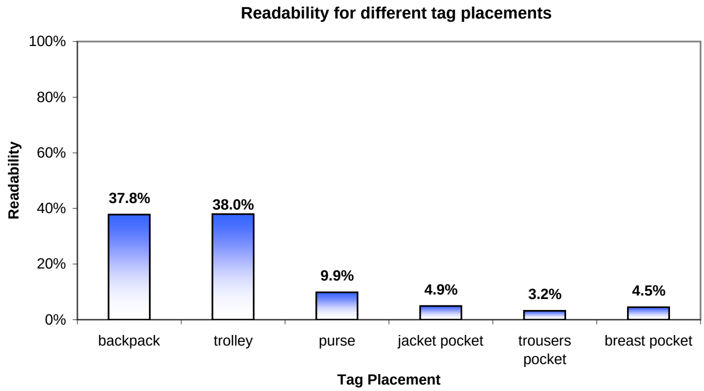


Figure 5.50: Readability for different tag placements.

Figure 5.51 shows the readability for all tag placements when the reader is placed in different positions on the RFID portal. In average, the reader on the side of the portal has higher readability than the reader above. However, the readability of the tags in the breast pocket was higher when the reader was placed in the top part of the portal.

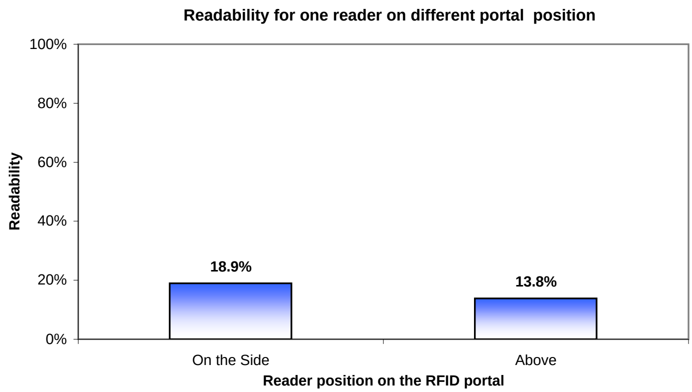


Figure 5.51: Readability for one reader in different positions.

Phase 2 The same measurements that are performed in part 1, will now be performed for a set-up with two readers. This is done to find out in what way the performance increases when two readers are used. Figure 5.52 shows the different reader configurations used for this phase of the experiments. Table 5.3 shows the individual readability for every tag placement tested.

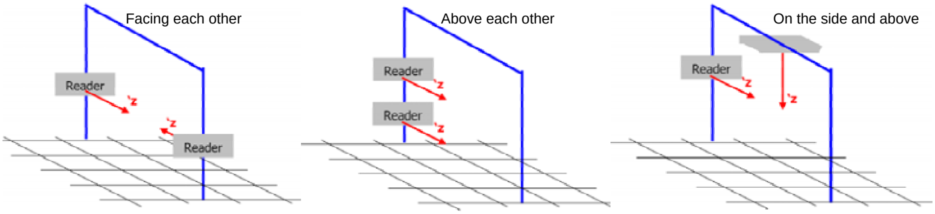


Figure 5.52: Reader positions for the second phase of experiments.

Table 5.3: Readability results for phase 2.

Reader position	Facing each other	Above each other	On the side and above	Readability per tag placement
Tag placement				
backpack	65.5%	68.0%	51.0%	61.5%
trolley	45.0%	63.5%	61.5%	56.7%
purse	31.5%	28.0%	26.5%	28.7%
jacket pocket	17.8%	11.7%	9.4%	12.9%
trousers pocket	14.0%	9.3%	8.5%	10.6%
breast pocket	11.2%	9.4%	4.5%	8.4%
Readability per reader position	30.8%	31.6%	26.9%	

Figure 5.53 shows the readability of different tag placements (both vertical and horizontal orientation) for two readers on the RFID portal. The results show that with a second reader the overall readability of the tags is improved. For each tag placement, the values of the readability per test are much higher than for the previous phase.

Figure 5.54 shows the readability for all tag placements when the readers are placed in different positions on the RFID portal. The results show that the highest readability for all tag placements and positions tested was when the two readers were above each other. However, for a portal configuration with four readers, this

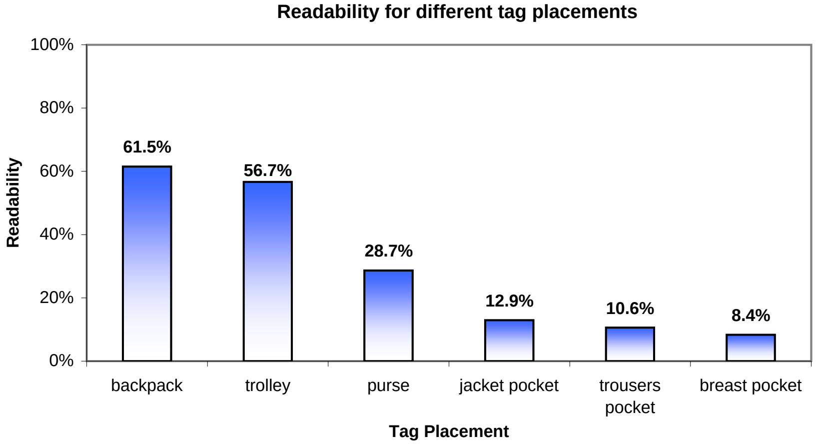


Figure 5.53: Readability for different tag placements.

may not always perform the best, specially in cases with multiple tags in the field.

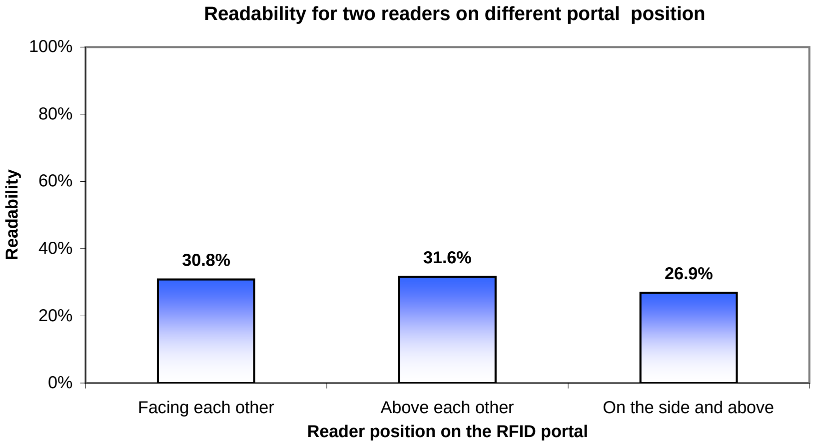


Figure 5.54: Readability for one reader in different positions on the RFID portal.

Phase 3 In this part of the research a set-up with four readers is used. The same measurements are done as in part 1 to measure the basic performance of the set-up. Figure 5.55 shows the different reader configurations used for this phase of the experiments.

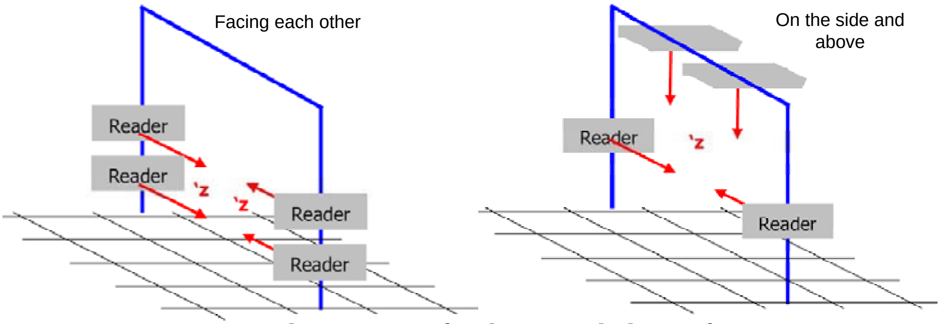


Figure 5.55: Reader positions for the second phase of experiments.

Table 5.4 shows the individual readability for every tag placement tested.

Table 5.4: Readability results for phase 3.

Reader position	Facing each other	On the side and above	Readability per tag placement
Tag placement			
backpack	62.5%	76.5%	69.5%
trolley	63.5%	83.0%	73.3%
purse	47.5%	32.5%	40.0%
jacket pocket	17.0%	17.0%	17.0%
trousers pocket	13.4%	9.4%	11.4%
breast pocket	12.0%	3.7%	7.8%
Readability per reader position	36.0%	37.0%	

Figure 5.56 shows the readability of different tag placements (both vertical and horizontal orientation) for four readers on the RFID portal. The results show that the tag placement backpack and trolley have the best performance. For the backpack and trolley, there were 100% successful readings recorded during some repetitions of the experiments. All the readers set up tested in this phase cover the desired 3.5 meters width of the gate.

Figure 5.57 shows the readability for all tag placements when the readers are placed in different positions on the RFID portal. The results show that the readability for both of the set ups tested is too close to determine the best one. In

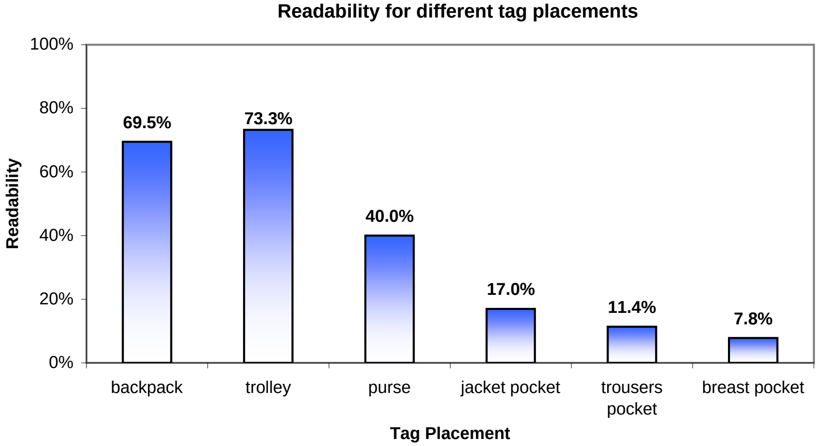


Figure 5.56: Readability for different tag placements.

the next phase of experiments (phase 4), the set-ups are tested with two different populations of people carrying tags. The difference in performance between the two set-ups can be further explored in this phase.

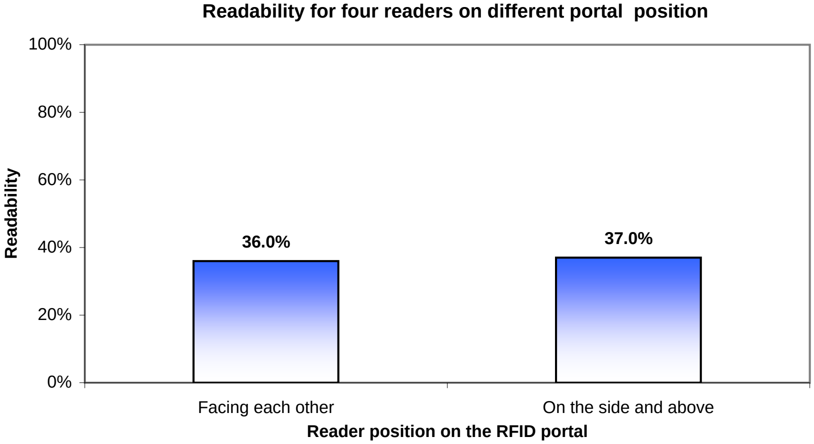


Figure 5.57: Readability for one reader in different positions on the RFID portal.

Phase 4 The set-up with four readers is tested with multiple people passing the set-up with different tag positions. Figure 5.55 shows the different reader configurations used for these experiments. Table 5.4 shows the readability for every population and tag placement tested.

Table 5.5: Readability results for phase 3.

	Population 3		Population 6	
Reader position	Facing each other	On the side and above	Facing each other	On the side and above
Tag placement				
purse	72%	72%	42%	51%
backpack	100%	100%	85%	100%
breast pocket	45%	62%	38%	57%
trousers pocket	51%	76%	52%	36%
Readability per reader position	67%	78%	54%	61%

Figure 5.58 shows the readability of different tag placements (both vertical and horizontal orientation) for four readers facing each other on the RFID portal, and Figure 5.59 shows the readability of different tag placements (both vertical and horizontal orientation) for four readers arrange on the side and above the RFID portal. For a population of 3 people, the back pack tag placement has for both reader configuration 100% readability. The purse tag placement has for both reader configurations 72% readability. The configuration with readers on the sides and above performed better for the breast pocket and trousers pocket. This configuration has a better performance for all tag placements tested.

For a population of 6 people, Figure 5.58 and 5.59 show that the configuration with readers on the sides and above performed better for all tag placements except to trousers pocket. The only tag position which resulted in 100% readability is the back pack.

Figure 5.60 shows the readability for all tag placements when the readers are placed in different positions on the RFID portal. From the results it can be concluded that the configuration with readers on the sides and above performs better than the configuration with two readers on both sides of the portal.

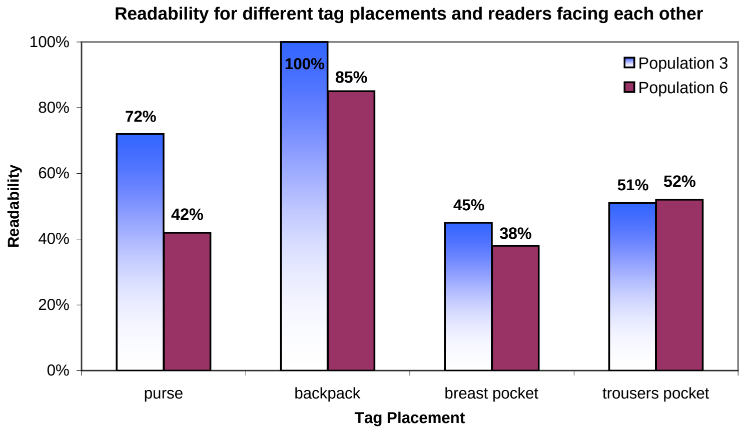


Figure 5.58: Readability for different tag placements.

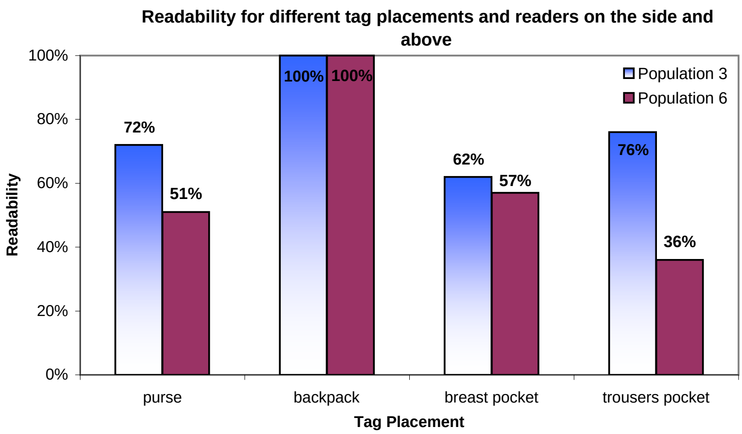


Figure 5.59: Readability for different tag placements.

Conclusions

The results showed that the best configuration for the RFID portal, is composed for two readers facing each other and two readers above. This configuration for different tag positions on person moving through the gate. The chosen reader configuration was tested for two populations of three and six people passing the set-up at the same time. Interference between the tags became obvious for the population of six people. During the measurements, the effect of the accuracy of placing the tag became apparent. If the tag is placed a few centimeter to the left or

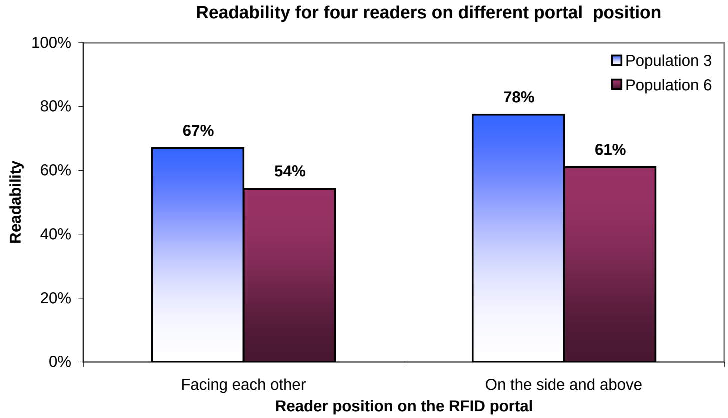


Figure 5.60: Readability for one reader in different positions on the RFID portal.

right, the performance is influenced. The amount of layers of clothes (e.g. t-shirt, blouse or sweater) between the tag and the skin of the test person influences the performance. More layers means more space between tag and body, which has a positive influence on the performance.

5.4 Conclusions

The successful application of RFID systems does not only depend on the technical characteristics of the technology. It depends on several factors of the application as well. In order to implement RFID systems, a testing procedure was developed to evaluate the suitability of RFID in the application. In (Lodewijks et al., 2006), it was suggested that in order to determine the applicability of RFID in a certain application scenario, a testing methodology composed of three main testing procedures should be implemented. In (López de la Cruz et al., 2008), a testing methodology composed of fundamental tests, semi-fundamental tests and operational tests was presented. The fundamental tests focused on evaluating the RF air interface performance by determining functioning conditions like the read field of the tags, the effect of tag orientation and read rate, among others. During the semi-fundamental tests, it is possible to recognize certain characteristics of the application that can be changed or re-designed in order to make the application scenario more RFID friendly. It is important to notice that RFID is far from being a plug and play technology. Whether or not organizations are willing to change their production processes to implement RFID depends on the expected benefits and costs related to re-design their overall production systems. The operational tests asses the influence of the application's environment in the readability of the tags. In this part, test conditions like the packaging of the products, impact of the operational equipment, total number of boxes that can be segregated and identified, accuracy of the system, interaction with the physical environment, and more is analyzed.

The proposed methodology is a way of identifying key parameters and finding their individual influence on readability performance. The outcome of the performance test can affect on which level tagging is applied: freight containers, returnable transport items (RTI), transport units, product packaging, the product itself. After these three series of tests the reliability of an RFID system in a certain application can be evaluated. Whether or not this reliability is sufficient for that specific application depends on the sensitivity of the logistic system to a disruption in objects visibility.

5.5 References

Bahlman, E. (2006). Rfid readability tests at tnt logistics. Research Assignment 2006.TL.7038, Transport Engineering and Logistics, Delft University of Technology.

Bhuptani, M. and S.Moradpour (2005). *RFID Field Guide: Deploying Radio Frequency Identification Systems*. Prentice Hall PTR, Upper Saddle River, NJ, USA.

Bonjer, J. and Beckers, J. (2007). Application of rfid technology for identifying tubes in concrete. Research Assignment 2007.TL.7104, Transport Engineering and Logistics, Delft University of Technology.

Duvall, M. (2007). Wal-mart faltering RFID initiative. Internet, Baseline Magazine. Available On-line, http://www.baselinemag.com/c/a/Projects-Supply-Chain/Cover-Story-WalMarts-Faltering-RFID-Initiative.

Instruments', T. (2003). Hf antenna design notes. Technical Report 11-08-26-2003, Texas Instruments.

ISO/IEC (2005). Information technology - automatic identification and data capture (aidc) techniques - radio frequency identification device performance test methods. Technical Report ISO/IEC TR 18046, The International Organization for Standarization and the International Electrotechnical Comission.

Lahiri, S. (2005). *RFID: A technology overview*. Prentice Hall Professional.

Lodewijks, G., Veeke, H. P. M., and López de la Cruz, A. M. (2006). Reliability of RFID in logistic systems. In *Proceedings of the 2006 IEEE Conference on Service Operations and Logistics, and Informatics*, Shanghai, China.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2008). Performance measurement of RFID. In *Proceedings of the International Simulation Conference 2008*, Lyon, France. EUROSIS.

R.Bakker (2008). Shuitema revolutionizes food quality control through RFID. Internet, Capgemini. Available On-line, http://www.capgemini.com.

Rijswijk, J. (2006). Rfid implementation research at tnt logistics. Research Assignment 2006.PEL.7040, Transport Engineering and Logistics, Delft University of Technology.

Roberti, M. (2007). The truth about RFID adoption. Internet, RFID Journal. Available On-line, http://www.rfidjournal.com/article/view/3665.

van Aken, K. M. (2007). Tracking passengers all the way. Research Assignment 2007.PEL.7215, Transport Engineering and Logistics, Delft University of Technology.

van Duijn, R. and van de Langemaat, G. (2006). Performance evaluation of deister electronic rfid equipment. Research Assignment 2006.PEL.7111, Transport Engineering and Logistics, Delft University of Technology.

van Schayk, M. and Mahdaoui, N. (2007). Research into the application of rfid to track passengers at schiphol. Research Assignment 2007.PEL.7214, Transport Engineering and Logistics, Delft University of Technology.

CHAPTER 6

Automated Maintenance of Belt Conveyor Systems

In chapter 3 the concept of prognostic logistics was discussed. It was possible to recognize two important elements in the concept of prognostics logistics. The first element was the need for an information system where acquisition and processing of timely and accurate information was the main function. The second element was a decision making system where prognoses of possible disturbances based on the available information were generated. With prognostic logistics it is expected that uncertain situations can be reduced, giving the possibility to logistics systems to early detect possible equipment failures, and hazardous situations fast enough to take prompted action. In this chapter the benefits of using active RFID technology as a data capture system for prognostics logistics will be studied using as an application example the automated maintenance of belt conveyor systems. In section 6.1 an introduction to automated maintenance is presented. In section 6.2 strategies for automated maintenance are described. Section 6.3 presents the system description and feasibility of using wireless communication technology in belt conveyor systems. In section 6.4 a simulation model for the control of RF based maintenance system is described. In section 6.5 conclusions are drawn.

6.1 Introduction

Automated maintenance of belt conveyor systems is a promising alternative for outsourcing maintenance, in particularly when looking at the efficiency and accuracy.. Belt conveyors are an important component of logistic systems where large quantities of goods, people or bulk materials need to be transported overland without interruptions (Nuttall, 2007). In bulk commodity logistic systems, belt conveyors usually transport bulk solid materials over distances up to 100km. These belt conveyors are usually exposed to difficult operational conditions. Dust contamination and continuous high loading can strain the system components leading to early failures, belt damage or total shut down of the system (Lodewijks, 2004). Monitoring large belt conveyor systems is considerably labor intensive, and therefore expensive. The amount of data retrieved from large belt conveyor systems is too high to ensure correct interpretation of human inspectors. Furthermore, the final result of the inspection will be subject to the inspectors experience and training. The bearings are the most critical mechanical components of the support system of the belt conveyor. Bearing failure can be hastened by common operation factors like lubricant contamination, shaft misalignment or improper loading. Systems are designed in such a way that at least 90% of the bearings fulfill their lifetime expectancy (Lodewijks, 2004). Hence, a condition radio frequency based monitoring system might be a feasible solution for monitoring idler bearings in order to reduce downtime of the system. Furthermore, the use of radio frequency based sensors to monitor the bearing health is expected to optimize maintenance and reduce the risk of failure due to inaccurate data.

6.2 Strategies for Automated Maintenance of Belt Conveyor Systems

Automated condition monitoring of belt conveyor systems was discussed in (Lodewijks, 2004). The basic concept of condition monitoring was to identify subtle changes in the operation of the belt conveyor components. With constant monitoring it will be possible to detect operational changes, i.e. temperature, vibrations, and thus prevent failures developing and propagating. The timely recognition of possible malfunctions will provide more time to coordinate the maintenance of the machine; avoiding total shutdowns and increasing system capacity.

In (Lodewijks, 2004), the concept of using a trolley to perform inspections and/or carry out maintenance tasks on the rolls of the idlers was described, see Figure 6.1. The monitoring of the rolls focused on monitoring the condition of the bearings in the rolls since rolls fail primarily due to bearing failure. In addition the control of the trolley and the monitoring and maintenance program were described in (Lodewijks, 2004).

Figure 6.1: Maintenance trolley installed on the Richards Bay Coal Terminal, Republic of South Africa (courtesy CKIT).

The concept of using a trolley for both monitoring and carrying out maintenance tasks implies that there is always a time lag between the start of a bearing failure and the time it is detected. This does not have to be a problem if the degradation rate of the rolls is slow enough to allow a timely detection of potential bearing failure. It may in practice, however, lead to unnecessary movement of the trolley for inspection purposes. This observation led to the idea of reducing the functionality of the trolley to carrying out only maintenance tasks and to use different means for the inspection of the rolls. The original trolley was equipped with data processing equipment which generated straight forward information on the condition of the roll. This information could easily be analyzed and used to base replacement decisions or inspection interval decisions on. If the trolley is no longer used for inspection, then the rolls themselves have to provide that information. In theory it is possible to equip each roll with either an acoustic sensor or an accelerometer to pick up vibrations that indicate potential bearing failure. This data however has to be transmitted to the central monitoring unit and processed there. Data conversion in each roll is not viable. This process means that the central monitoring unit has to ’tune in’ with a specific roll and take a measurement based on a certain inspection protocol. The measurement has to be long enough to allow detection of the vibrations in the relevant spectrum. Although technically possible equipping each roll with sensors to pick up vibrations was deemed complex and economically not viable.

6.3 Wireless monitoring of Belt Conveyor Systems

Wireless monitoring of belt conveyor systems is proposed as an option for assessing technical conditions of the bearings by measuring their temperature[1]. The use of a temperature sensor instead of a vibration or acoustic sensor is proposed in order to simplify the sensor node. If a vibration or acoustic sensor is used, extra data processing is needed in the sensor node to transform the data acquired. Furthermore, using a thermocouple sensor will make the nodes economically viable to introduce in the rolls.

Normal operating temperatures of the bearings vary between 20°C and 50°C depending on the environment temperature. If the temperature of the bearings increases to a range of 80°C to 120°C, then this is a clear sign of potential bearing failure. The time between picking up irregularities in bearing behavior and bearing failure using vibration detection sensors is significant larger than when using temperature sensors (Albers et al., 2006). However, if the temperature of the bearings can be measured ”on-line” or if the rolls have the ability to notify the central monitoring unit when temperatures exceed a certain threshold value, then there is still enough time to replace a roll with potential bearing failure before it actually fails.

System Description

Each roll has two bearings, see Figure 6.2; if one of the bearings starts to fail, then the entire roll needs to be replaced. Placing the sensor node in the shaft of the roll, and measuring its temperature, is enough to determine whether or not a bearing is failing since both bearings are supported by the same shaft.

The sensor node is composed of a thermocouple, an RF transceiver and a power source. Every roll is equipped with a sensor node, capable of transmitting information to a central system. Transmission range is usually up to 100 meter in line of sight in free space. Since the node will be cased inside the roll, the

[1]This section is based on (López de la Cruz et al., 2008)

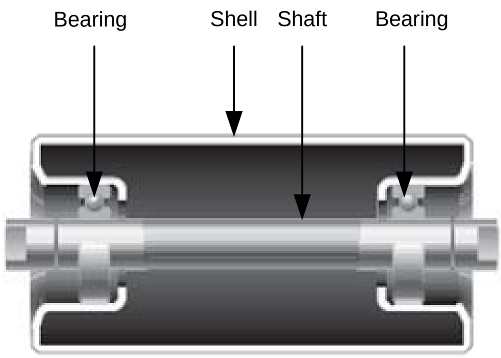


Figure 6.2: Idler roller (courtesy Rulli Rulmeca SPA).

transmission range is expected to be reduced considerable due to environment interference (metal structure) and noise.

In large scale belt conveyor systems, as show in Figure 6.3, the amount of rolls varies from 2,000 in a 1Km belt conveyor to 20,000 in a 10Km one. With this large amount of rolls, and the considerably long distances to reach the central system, it is necessary to implement a different communication scheme.

Every smart roll is equipped with a sensor node. Since the node is embedded with a transceiver, the roll is not only capable of receiving information, but also, it is capable of starting communication, and transmitting information. In order to establish communication, the nodes create a network between them that allow them to send and receive data from its neighbours, and the central system. Using multi hop routing and dynamic networks, the information of one roll can be transmitted from node to node until it reaches its destination. Furthermore, in case one of the nodes fails, the system should be capable to reconfigure the communication network and finds its way to the central system. Figure 6.4 shows direct roll to roll communication.

System constraints

It is possible to divide the implementation constraints of the wireless monitoring system in two main categories: application constraint and technical constraint.

The application constraint refers to the belt conveyor itself and the environment in which it is going to be developed. It determines what can and can not be done regarding the implementation of a monitoring system. In the case of a large

Figure 6.3: Large scale overland belt conveyor in South Africa (courtesy Conveyor Experts B.V.).

belt conveyor system, for the transport of bulk commodities, two main constraints are of interest: extra equipment outside the roll and economical feasibility. It is preferable if no extra equipment is placed outside the roll unit (this includes cables and extra communication devices). This type of belt conveyors is exposed to very hard environmental conditions, besides; exposed cables and other devices may get stolen or damaged if seen at reach. The economical feasibility of the overall system is of big interest for the belt conveyor industry. Nowadays, the price of such a system is seen to increase in 40% the total price of the roll (Lodewijks et al., 2007). This is not acceptable if widespread application is expected. However, with the mass production of the smart roll, it is expected that prices will go low enough (around the 10%) to allow applicability in the near future.

The technical constraints refer mainly to the technology itself. For wireless sensor communication two main constraints are of interest in this application: the

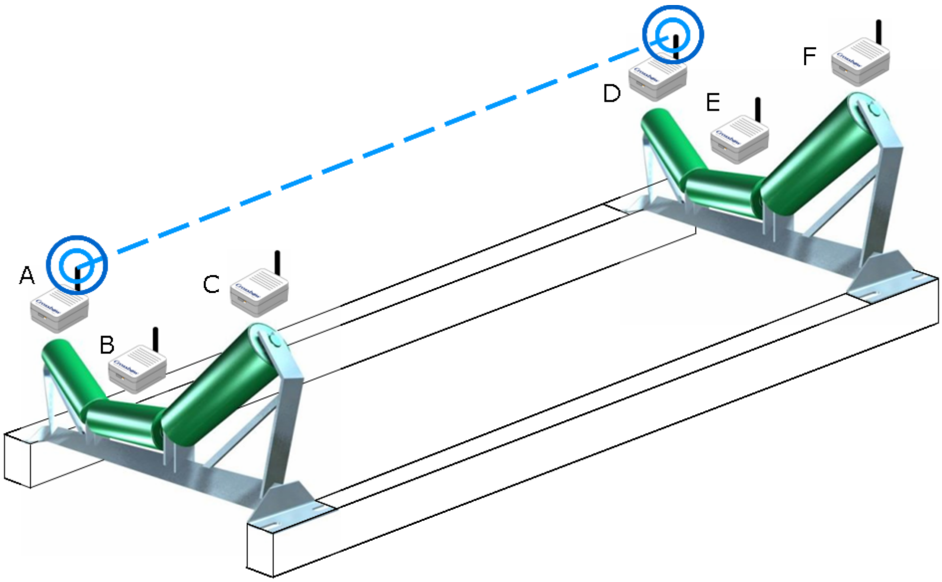


Figure 6.4: Direct roll to roll communication (The nodes are place inside the rolls). (Lodewijks et al., 2007)

wireless communication network and the energy consumption. The communication between nodes should be done using multi-hop routing and dynamic networks (López de la Cruz et al., 2007). The use of multi hop will save energy since short messages are transmitted from node to node or form node to collector until the message reaches the base station. Optimally, the node to node communication is preferable since only the nodes in the idlers will compose the network. However, trying to find a suitable power source for such a network is very challenging. Using batteries will only provide a temporary solution and batteries may be out of order long before the roll itself. Furthermore, in node to node communication the most critical node is the first one. He is in charge of transmitting the data of maybe 20,000 nodes to the central system, this means its battery life is seriously reduced by the end of one cycle. Trying to manage efficiently the communication of a network composed by maybe 20,000 nodes is a difficult task, and more extensive research needs to be done. The energy source of the nodes determines their lifetime. Since the deployments of such nodes in large belt conveyor systems will not allow recharging or changing the batteries of thousands of nodes, the use of energy should be made as efficient as possible for every node and new ways of energy harvesting should be investigated for large deployment applications.

6.3.1 Wireless Communication

The rollers used in bulk handling applications are mostly made of steel. Once the roller is assembled it becomes a complete closed environment. Wireless systems do not function properly near metals or liquids. In order to determine whether or not it is possible to get a reliable signal out of the roller once it is assembled, a set of experiments were performed at Delft University of Technology, faculty of Mechanical, Maritime and Materials Engineering, section Transport Engineering and Logistics with the collaboration of Rulli Rulmeca SPA who provided the idler rolls and frames.

The set of experiments were divided in two stages. The first stage was a fundamental research to determine the technical characteristics of the sensor nodes. The second stage was a semi-fundamental research in which the sensor nodes were tested inside the rollers to determine whether or not a reliable signal could be acquired from such a closed environment.

Fundamental Research

In order to determine the technical characteristics of the sensor nodes a testing protocol was designed following the characteristics of the testing methodology discussed in chapter 5. A total of 10 nodes were tested. For every node 10 samples were taken. The tests were performed with the support of master students in the section of Transport Engineering and Logistics, at Delft University of Technology.

The fundamental testing provided a good overview of the sensor nodes performance in a laboratory environment. The results are presented in terms of the Signal Strength in [dBm]. This parameter indicates the amount of power present in a received signal. It is commonly used to quantify the quality of communication in a wireless network. The use of [dBm] as unit of measure is more convenient than using [mW] when referring to very small power levels. Thus, it is easy to refer to 20dBm as being 100mW and -96dBm corresponding to 25.11×10^{-11} mW. In order to change from [mW] to [dBm] the following formula is used:

$$dBm = 10 * log(mW) \tag{6.1}$$

The sensor nodes combine temperature sensing, computation and RF based wireless communication. The nodes used during these tests are the SOWNet L-Nodes, see Figure 6.5 in page 181. The L-nodes share the same characteristics as the previous version the T-Nodes, see Table 6.3, but they are smaller in size. A comparison between the performance of the T-Nodes and detailed results of the fundamental tests for the L-nodes can be found in (Woudenberg and Vlaar, 2009).

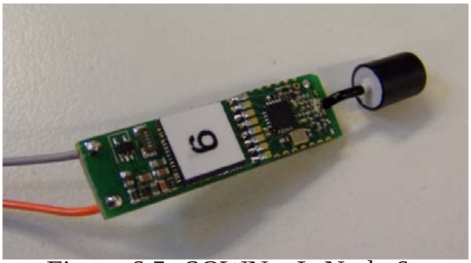


Figure 6.5: SOWNet L-Node 6.

Because of the space restrictions to place the nodes (the nodes and battery source should fit inside the roller's shaft), the power source used was a Lithium 3.6 V AA battery. It was concluded in (Woudenberg and Vlaar, 2009) that this type of battery provides the best performance. The voltage output is more stable and it is comparable to the results obtained when a constant power supply of 3 V was used.

The fundamental tests for the sensor nodes showed the degradation of the signal at increasing distance between the sensor node and the central gateway, see Figure 6.6. The receiver sensitivity for the L-nodes, according to the technical specifications provided by SOWNet, is -105dBm. This is the minimum power of an incoming signal in order to be successfully received by the node. The results of this test provide an insight on the performance of the sensor nodes and their signal strength at different distance from the gateway. In free space the nodes are expected to reach up to 100 meters in range.

Figure 6.6 shows the signal strength of different sensor nodes tested under the same conditions. The behaviour of the nodes shown in 6.6 is quite similar to each other, this is not always the case. During the tests it was possible to receive all the temperature readings in all the tested distances. The average of the signal strength for all the tested sensor nodes in free space is shown in Figure 6.7. The average minimum signal strength in free space is -50dBm$\pm$8.18. A higher absolute value of the signal strength results in increased reading distance.

The large standard deviations in Figure 6.7 show that not all the nodes perform

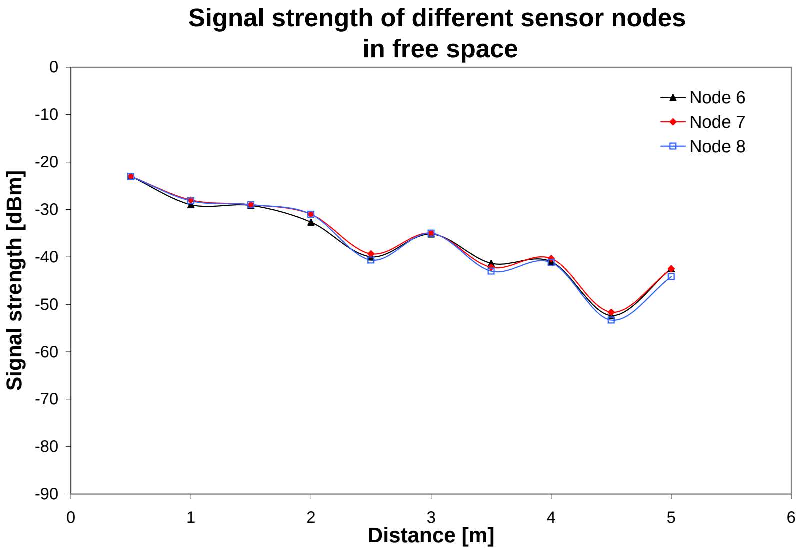


Figure 6.6: Signal strength of different sensor nodes at different distance from the gateway.

the same. However, it is important to notice that the sensor nodes tested here are still a prototype, therefore variations in performance are expected.

Semi-Fundamental Research

One of the application requirements is not to have components at sight. In order to fulfill this requirement the sensor node should be placed completely inside the metal roller. By analyzing the idler structure, it was found that the best location for the node to be placed is inside the shaft. In this place the sensor is kept from being damaged during the production cycle and it can be added at a late stage of the process. Furthermore, the production cycle would not be seriously altered since drilling a hole in the middle of the shaft can be done automatically at the end of the cycle.

Sensor node inside the roller's shaft In the first semi-fundamental test trying to get a signal from the sensor node once it was place inside the shaft was investigated. In Figure 6.8 the experimental setting for this phase of the semi-fundamental tests is shown.

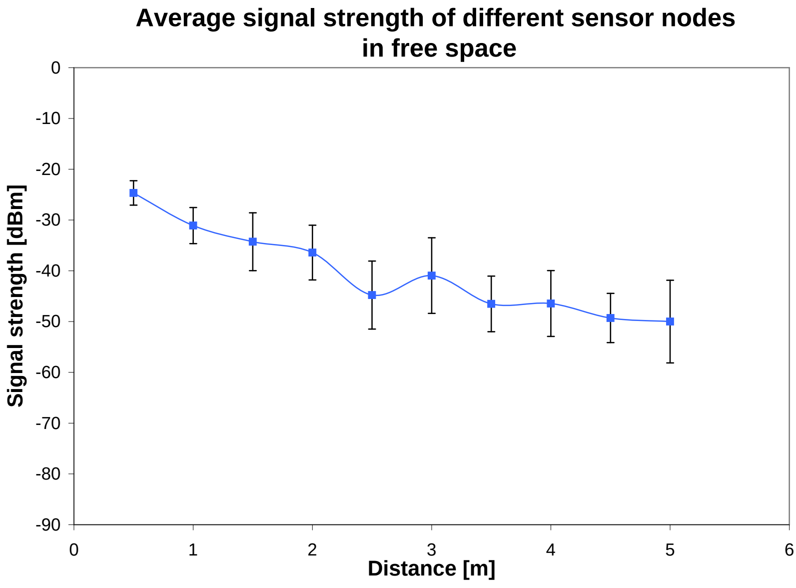


Figure 6.7: Signal strength of different sensor nodes at different distance from the gateway.

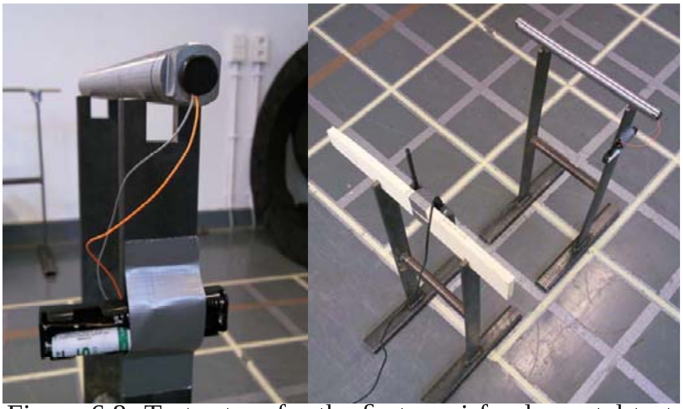


Figure 6.8: Test set up for the first semi-fundamental test.

A completely closed metal environment would not allow getting any signal from the sensor node. To overcome this problem, a plastic cover was placed at the end of the shaft; this will provide a higher probability to get a signal. In (Woudenberg and Vlaar, 2009) two types of antennas were tested and compared to determine which one will provide the best signal strength in such a closed environment. The helical antenna, as the one shown in Figure 6.5, gave the best results. Figure 6.9 shows the signal strength of some sensor nodes when placed inside the metal shaft of the roller.

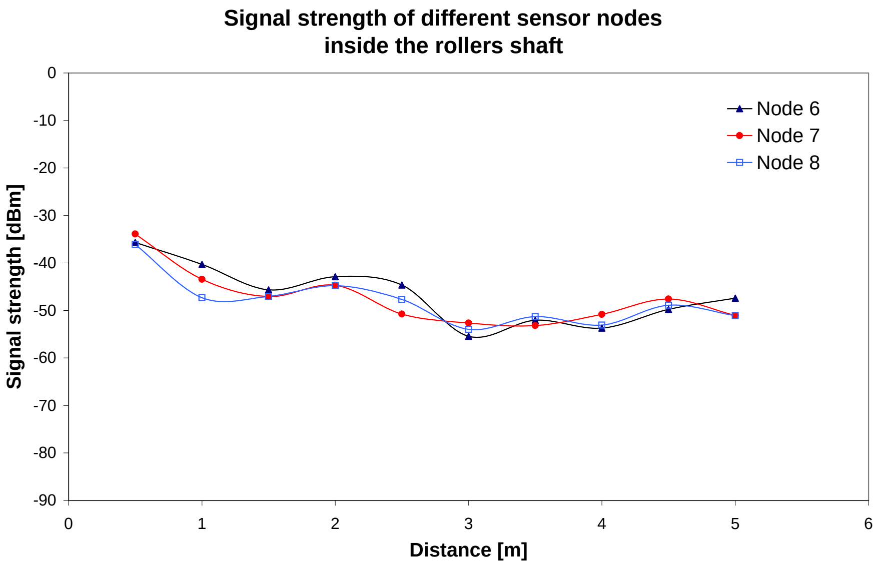


Figure 6.9: Signal strength of different sensor nodes at different distance from the gateway.

Figure 6.9 shows the different signal strength of some of the sensor nodes tested inside the metal shaft of the roller. The results show that every node has a different performance. In some testing points, for example at a distance of 2.5 meters, the three nodes in Figure 6.9 had different signal strength value. An average of the signal strength for all the sensor nodes tested is shown in Figure 6.10.

The minimum average signal strength value is -58.6dBm$\pm$4.5 at a distance of 3 meters from the gateway. In the free space test, the average signal strength at 3 meters from the gateway is -40.9dBm$\pm$7.44, this means that placing the node inside the metal shaft results in a reduction of 17.5dBm in signal strength at 3 meters distance from the gateway. Even with the reduction of the signal strength, during the tests it was possible to received all the temperature readings in all the tested distances.

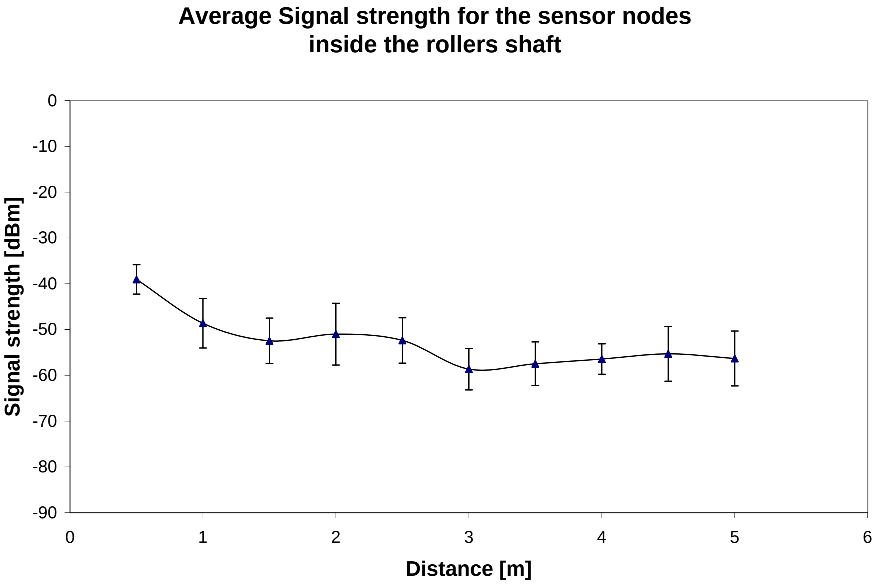


Figure 6.10: Average signal strength of different sensor nodes at different distance from the gateway.

Sensor node inside the assembled roller In the second semi-fundamental test trying to get a signal from the sensor node once it was place inside the assembled roller was investigated. Figure 6.11 shows the experimental setting for this phase of the semi-fundamental tests.

It is important to recognize the minimum value of the signal strength in which all the data samples are still transmitted to the central system. Figure 6.12 shows the signal strength of some sensor nodes when placed inside fully assembled metal rollers.

The signal strength for nodes 7 and 8 goes below -70dBm at a distance of 3.5 meters from the gateway, and at 2.5 meters for node 7. Node 14 (not shown in the Figure)also has a signal strength below -70dBm at a distance of 4 meters. From the data acquired, it was evident that when the signal strength approximates to -70dBm data samples were lost. The exact value of the signal strength at which data samples are lost can not be determined with 100% accuracy from the tests performed. However, by examining the data, it was possible to identify that the closer the signal strength is to -70dBm the more likely it is to lose data samples.

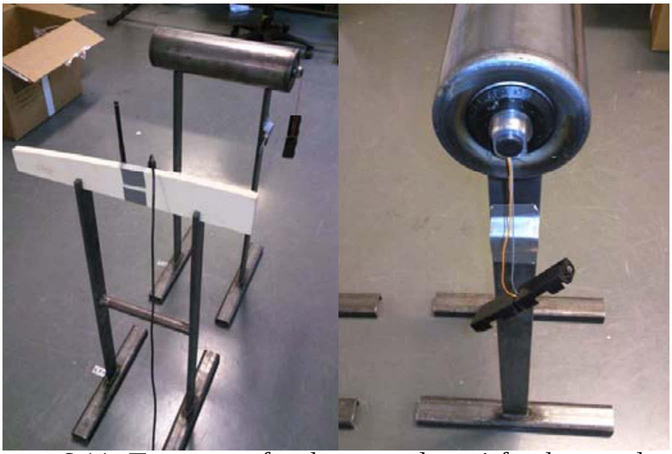


Figure 6.11: Test set up for the second semi-fundamental test.

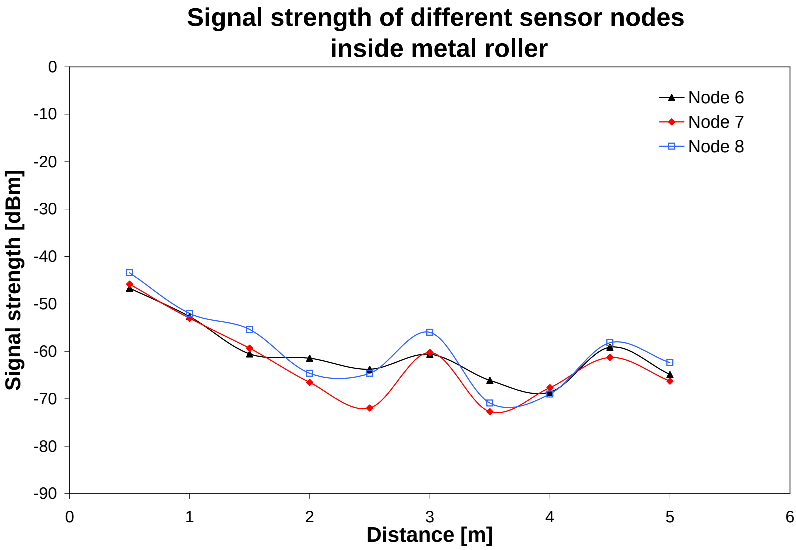


Figure 6.12: Signal strength of different sensor nodes at different distance from the gateway.

The performance of the nodes is very varied and depends on the sensor node. Figure 6.13 shows the average signal strength for all the nodes tested. The large standard deviations are a consequence of the large variability in the performance of the nodes.

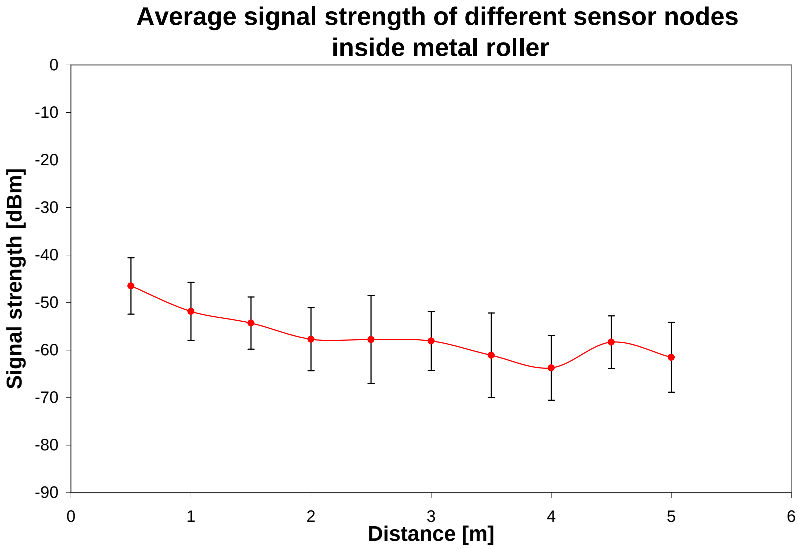


Figure 6.13: Average signal strength of sensor nodes at different distance from the gateway.

The minimum average signal strength value is -63.7dBm±6.8 at a distance of 4 meters from the gateway. In the free space test, the average signal strength at 4 meters from the gateway was -46.4dBm±6.48, this means that placing the node inside the metal roller results in a reduction of 17.3dBm in signal strength at 3 meters distance from the gateway.

Conclusions on test results

The tests performed showed that it was possible to obtain a reliable signal from a sensor node placed inside a metal roller. The metal structure of the roller has a significant impact on the signal strength of the sensor nodes. In Figure 6.14, the impact on the signal strength for the sensor nodes in the situations tested is shown.

In free space, the sensor nodes average minimum signal strength is 50±8.13dBm at a distance of 5 meters from the gateway. Inside the roller's shaft is -58.6±4.5dBm at a distance of 3 meters and inside the fully assembled roller is -63.7dBm±6.8 at a distance of 4 meters from the gateway. There is a large variability in the performance of the nodes, this is reflected in the values of the standard deviations.

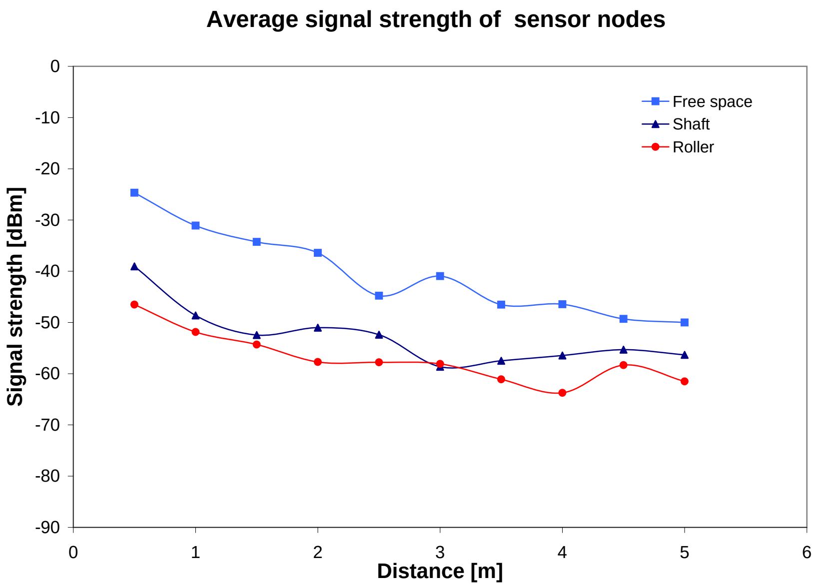


Figure 6.14: Average signal strength of sensor nodes at different distance from the gateway.

During the final test, there were 3 nodes that at certain distance from the gateway had a signal strength close of below -70dBm. Every time this occurred, data samples were missing from the records. Therefore, it is possible to conclude that when the signal strength of a node approximates to -70dBm, data is likely to be lost, making the communication link unreliable.

The tests performed showed promising results for the applicability of wireless monitoring in belt conveyor systems. However, more tests need to be performed. The influence of the metal frames in the signal strength of the rollers still needs to be investigated, as well as the influence of the belt conveyor in operation.

6.3.2 Energy Harvester

It was established that using extra equipment outside the rolls should be avoided in order to prevent damage or stealing. Since the smart rolls require a power source, there are two possibilities that can comply with this restriction: batteries or an alternative energy source integrated in the case of the roll.

Batteries can deliver a reliable solution for a specific period of time. It is possible to use energy efficient communication protocols to optimize the battery life. However, at some moment in time, the batteries will need to be replaced. Taking into account that almost 20,000 batteries will be changed, this solution is far from optimal in terms of labor costs, battery costs, and environmental impact. Furthermore, using batteries will add extra complexity to the system, since it will be necessary not only to monitor the bearings, but the monitoring system itself to determine the remaining battery life.

A more economical, and environmental friendly solution will be to investigate the possibility of using an energy harvester to power the smart rolls. Energy harvesting devices usually consist on collection and storage elements, conversion hardware, and power conditioning and management. An extensive review on energy scavenging can be found in (Thomas et al., 2006). Several energy harvesting concepts are presented and analyzed to determine the potential of using an alternative energy source for small electric systems. In (Paradiso and Starner, 2005), energy harvesting is investigated for powering ubiquitously deployed sensor networks and mobile electronics. It presents different technologies to harvest energy. It concludes that the limited amount of space available for the integration of such devices, limits the amount of energy that can be collected from the environment. In (Penella and Gasulla, 2007), a review of commercial energy harvesting is presented. Some guidelines are given to calculate the power consumption of the node. Also, commercial harvesters are evaluated to determine their capability to power a sensor node. Furthermore, in (Roundy et al., 2002) a survey on various issues and tradeoffs involved in designing and operating an energy harvester in embedded systems is discussed.

Energy Harvester assessment

A wide variety of energy harvesters are available in the market. However, the restrictions of the belt conveyor application reduce the number of options to just a few. Table 6.1 shows the advantages and disadvantages of each option for the smart roll from the application point of view.

From Table 6.1, it is possible to disregard the use of the solar harvester for the smart roll application. The solar harvester is not a feasible option since it basically needs the solar cell to be outside the case, adding complexity and extra equipment to the overall structure. The piezoelectric vibrations harvester needs to be designed and integrated in the basic structure of the roll. In this case it is

Table 6.1: Energy harvesters for the smart roll

Type of Energy Harvester	Advantages	Disadvantages
Solar	Uses the sun light as source	It needs external panels
		It can not be inside the roll
Piezoelectric	High voltages	Difficult to integrate into the system
	No extra source is needed	
Electrostatic	Easy integration	Needs an external power source
Electro-Magnetic	Easy to be inside the roll	Voltages may be too low to power the nodes
Thermal	Small and easy to integrate	Needs high temperatures to provide enough energy
Biomechanical	-	Very low efficiency

necessary to research until what extend the design of the roll needs to be changed to introduce such a material in its fabrication. Furthermore, the costs involved will need to be considered further. The electrostatic vibration system needs an external source of power to start the system. This may be a possibility in combination with batteries. However, as mentioned before, 20,000 batteries will still be required, increasing the costs of the system even more. An electro-magnetic system is quite a convenient solution for this application. The entire system can be integrated inside the roll's case. Costs for inductive sensors are relatively low compared to sophisticated vibration modules. Thermal harvesters are not suitable for the application since temperatures above 50°C are not always expected and biomechanical systems are not developed enough to be considered.

Mechanical energy harvesters are possibly the most suitable solution for the belt conveyor application. Although there are some drawbacks regarding integration, and the use of external power sources, the availability of different harvesters in the market makes it possible to customize the harvester system to tackle these issues.

Energy Harvester for wireless nodes

Table 6.2 shows a list of 4 mechanical energy harvesters available in the market. The first two correspond to the piezoelectric principle, and the last two to the electro-magnetic principle. There are no electrostatic based commercial energy harvesters. The featuring products have dimensions below 10cm so they can easily fit inside the rolls case.

Table 6.2: Mechanical Energy harvesters in the market

Product	$V_{out}[v]$	Output power
Volture; MIDE, in (Mide, 2007)	N/A	43μW at 240mg 120Hz
Cedrat; APA400M-MD, in (Cedrat, 2007)	N/A	40mW at 35μm, 110Hz
FS energy harvester; Ferrosolutions, in (Ferrosolutions, 2007)	3.3	0.4mW at 20mg 9.3mW at 100mg
PMG7-50/60; Perpetuum, in (Perpetuum, 2007)	3.3	0.1mW-0.4mW at 25mg 2mW-5mW at 100mg

The decision to use either one of the above mentioned harvesters depends on the wireless node that will be used in the smart roll. In Table 6.3, there is a list of commercial transceivers used for sensor networks. The required voltage to power the node is one of the design issues that should be taken into account when designing an energy harvesting system. The energy harvester should at least supply high enough voltage to power the system directly or to charge a storage device. Most of energy harvesting systems needs a storage unit to continue operation even if there is no energy to harvest. Some common storage devices are batteries, supercapacitors and fuel cells.

For the belt conveyor system, the wireless monitoring should be active during the operational period of the belt itself. Using battery powered sensors networks, the objective would be to maximize network lifetime under a total energy constraint (the battery life). With an energy harvester, the amount of energy primary depends on the time duration for which the belt conveyor operates. Furthermore, an energy neutral mode design can be used; the system consumes only as much

Table 6.3: Commercial transceivers and power consumption

Sensor Node	Vcc	Power active mode	Power sleep mode
T-Node, SowNet, in (SowNet, 2007)	2.4-3.6V	55.5mW	60μW
Mica2Dot, CrossBow, in (Crossbow, 2007)	2.7-3.3V	55.5mV	3μW
SmartMesh XT M1030, Dust Networks, in (DustNetworks, 2007)	2.75-3.3V	67.5mW	24μW
EM 250, Ember, in (Ember, 2007)	2.1-3.6V	102.7mW	3μW

energy is harvested. With such operation mode the operation lifetime will only be limited to the hardware longevity (Raghunathan and Chou, 2006).

The sensor node influences the power consumption by changing its duty cycle. The duty cycle is the proportion in time a component is operated. For the wireless monitoring system, the duty cycle of the nodes corresponds to how many times the sensor will send information, or received information in a period of time. In order to calculate the maximum duty cycle for the sensor nodes in Table 3 using the commercial listed energy harvesters in Table 2, the average power consumption can be calculated (Jiang et al., 2005):

$$P_{cavg} = D * P_{active} + (1 - D)P_{sleep}, \tag{6.2}$$

where P_{cavg} is the average consumption power, D is the duty cycle, P_{active} is the consumed power in active mode, and P_{sleep} is the consumed power in sleep mode. For a perpetual operation,

$$P_{gen} \geq P_{cavg}, \tag{6.3}$$

where P_{gen} is the average generated power from the energy harvester. The generated power should be equal or larger to the consumed power. From equations 6.2 and 6.3 is possible to determine the maximum duty cycle for the generated power.

$$D = \frac{P_{gen} - P_{sleep}}{P_{active} - P_{sleep}} \tag{6.4}$$

Using equation 6.4, the maximum duty cycles for the sensor nodes using the commercial energy harvesters can be calculated. From Table 6.4, it can be determined that the Cedrat APA400M-MD module provides the higher duty cycle for the sensor nodes. Although this device is feasible to be fit inside the roll, the cost of the harvester is quite high for a large deployment. This is one of the main drawbacks for all the commercial harvesters; however, with the advance in the technology it is possible to expect that in the near future the costs of such devices will be low enough to actually be used for large deployment systems like the one presented in this thesis.

Table 6.4: Commercial transceivers and power consumption

Energy harvester	Volture	Cedrat	FS Energy	PMG7-50/60
Sensor Node				
T-Node	-0.03%	71.96%	0.61% at 20mg	0.07%-0.61% at 25mg
			16.65% at 100mg	3.50%-8.90% at 100mg
Mica2Dot	0.08%	72.07%	0.72% at 20mg	0.17%-0.72% at 25mg
			16.75% at 100mg	3.60%-9.00% at 100mg
SmartMesh	0.03%	59.22%	0.56% at 20mg	0.11%-0.56% at 25mg
XT M1030			13.74% at 100mg	2.93%-7.37% at 100mg
EM 250	0.04%	38.95%	0.39% at 20mg	0.09%-0.39% at 25mg
			9.05% at 100mg	1.94%-4.87% at 100mg

6.4 Maintenance control using RF based systems

The maintenance strategies can be divided into preventive, random, corrective, and predictive maintenance (Lodewijks, 2004). Preventive maintenance is calendar based. The maintenance activities are planned on specific time intervals; it may be based on observed deterioration of components. In this case, only preventive jobs are done. Random maintenance is opportunity based. The maintenance is done when the opportunity arises; the decision to maintain a component may be based on the condition of the component. Corrective maintenance is emergency based. The component malfunctions and needs to be fully repaired. This may cause total shutdown of the system. The repair activity is not scheduled beforehand. Predictive (or prognostics)maintenance is condition based. The components are constantly monitored, when irregularities are discovered, maintenance procedures are scheduled to replace the faulty part.

In this section [2] a concept for the prognostics logistics control of an automated wireless maintenance system for belt conveyors is presented. A logistics simulation model [3] is used to determine the benefits of using prognostics logistics (the effect of timely and accurate information) on automated maintenance strategies. Timely and accurate information is assumed to be acquired using wireless condition monitoring. The maintenance concept is based on the prognostics maintenance concept, using temperature measurements to determine the remaining lifetime of a roll (Lodewijks et al., 2007). The technical lay-out of the maintenance system is based on the application of an automated maintenance robot including a roll replacement robot. Condition monitoring of the roll is done via a system of smart rolls and a central monitoring unit. The following paragraph describes the concept model for a computer simulation.

6.4.1 Simulation model

In the model a number of elements are defined including:

- the belt conveyor,
- the rolls,
- the automated maintenance robot,
- the condition monitoring systems,
- the estimation of the remaining roll lifetime.

[2] This section is based on (Lodewijks et al., 2007)

[3] The simulation model used was part of the experimental assignment of Selim Gungen (Gungen, 2006) with the collaboration of ir. M. Duinkerken and Prof. G. Lodewijks

Belt Conveyor

In the simulation model the belt conveyor can be specified in terms of its length and the idler pitches. The number of idlers then is calculated automatically assuming that the pitch is constant. It is assumed that a carrying idler has 3 rolls and a return idler 2.

Rolls

Each roll has two bearings, which have a minimum life length as specified by the roll and bearing manufacturer. The lifetime of a bearing in a specific roll is allocated via a tabularized distribution. Under and upper limits can be specified assuming a uniform distribution (minimum and maximum lifetime as specified by bearing manufacturer). All distributions can be changed for bearings in the middle and the side rolls of the carrying as well as the return idler sets. The chance of failure of a bearing before reaching the minimum lifetime can also be specified. As a standard this is 10% (L_{10} life is specified by the roll manufacturer). The lifetime of a roll is defined as the minimum of the lifetimes of its two bearings. If at the beginning of a simulation, it is assumed that that the belt conveyor is already in operation, the simulation model accounts for this effect by allocating remaining lifetime to individual operating rolls.

Automated Maintenance Robot

The automated maintenance robot consists of a trolley and of a replacement robot. It travels back and forth over the structure of the belt conveyor at a constant speed. It is assumed that the robot is available 24 hours per day. The replacement robot uses data collected from the condition monitoring system to determine whether a roll needs replacement. An aged roll is always replaced by a new roll of the same type. The total replacement time consists of a fixed setup time (seconds/per frame) to setup the replacement robot on location and of a replacement time (seconds/roll), in which the old roll is replaced with a new one.

Condition Monitoring

Systems Condition monitoring of the rolls can be performed by a system of smart rolls and a central monitoring unit. For simplicity, it is assumed in this study that all smart rolls and other wireless components have endless battery life. The estimation of the remaining lifetime of an individual roll is based on temperature measurements, which are read by the condition monitoring system from the sensors on the shafts of the rolls. The actual time it takes to monitor a sensor is considered negligible, since all data is transmitted via radio waves.

Estimation of the Remaining Roll Lifetime

The remaining lifetime of a roll is estimated, by measuring the temperature of its shaft. The remaining lifetime of the roll is defined as the minimum of the remaining lifetimes of its two bearings. The shaft is equipped with a temperature sensor that communicates with the central monitoring unit. For the simulation, the temperature-vs.-time curve of a bearing is modeled as shown in Figure 6.15 below. The normal operation temperature of a bearing is assumed constant (T_{Normal}) for the major part of its life. A short period, before failure of a bearing, the temperature will start to rise abruptly. Depending on the failure mode, failure can be due to damage in the bearing structure or due to contamination of the lubricant. In the final stage of either failure mode, increased friction between the bearing components causes this fast rise in temperature.

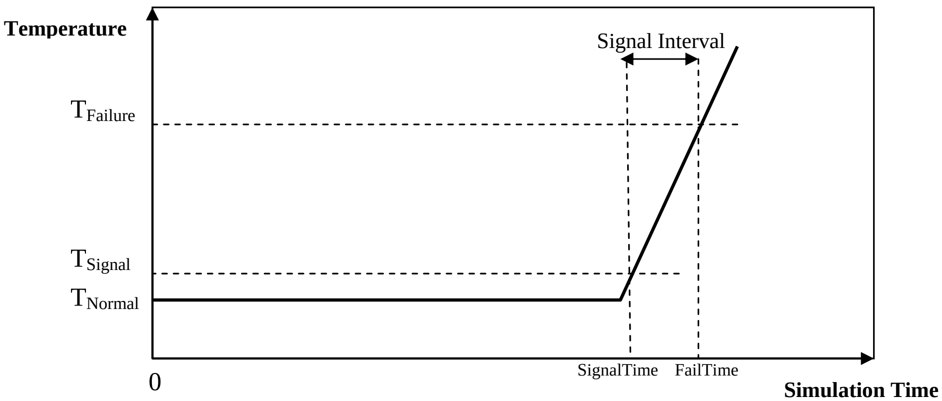


Figure 6.15: Temperature versus time curve of a roll bearing.

A smart roll is assumed to be programmed to autonomously send a warning signal to the central monitoring unit, when the temperature measured from one of the bearing sensors starts to rise above a specified limit temperature T_{Signal}. From this point onwards, the temperature will continue to rise until actual failure of the roll's bearing (and thereby of the roll) at $T_{Failure}$. The time period, during which the temperature rises, is called ”Signal Interval”. For the simulation, the specific Signal Interval for each bearing is allocated via a uniform distribution. Minimum and Maximum values for the uniform distribution can be specified. The discrepancy between a bearing’s actual temperature at a given point in its Signal Interval and the measured temperature is simulated with 2 parameters. The Measured temperature is a sample from a normal distribution with as mean the current ”actual temperature” of the bearing. The deviation of this distribution determines the accuracy of the measured temperature and is controlled by the first parameter (d). With the second parameter (f), a bias is introduced. The estimator of the measured temperature becomes conservative, biased towards overestimating the temperature.

The Measured temperature is defined by:

$$M = A + d * (F - A) * X + f(F - A) \tag{6.5}$$

Where F is the fail temperature of the roll, A is the current actual temperature of the roll, X is a random variable sampled from a Normal(0,1)-distribution, d is the deviation as fraction of the residual temperature (until fail temperature) and f is a safety factor as fraction of the residual temperature (until fail temperature).

A sample of X is drawn for the normal distribution each time a measurement is required. If f equals zero, the temperature measurement is unbiased. The probability that the measurement underestimates the temperature is 50%. This could result in late replacement of a roll, which is unwanted. With $f > 0$ the measurement becomes biased towards overestimating the temperature. The deviation and safety factor are a fraction of the residual temperature $(F - A)$. This means that the closer the current Actual Temperature is to the Fail temperature, the closer the value of the deviation and the bias f of the measurement get to zero. When the current actual temperature equals the fail temperature, M is 100% accurate. The effect of different values for d and f on the behavior of the temperature measurement can be seen in Figure 6.16. The proper value for d depends on the physical properties of the robot and must be determined experimentally during validation of the model. Then, the simulation model can be used to determine the optimal value for f.

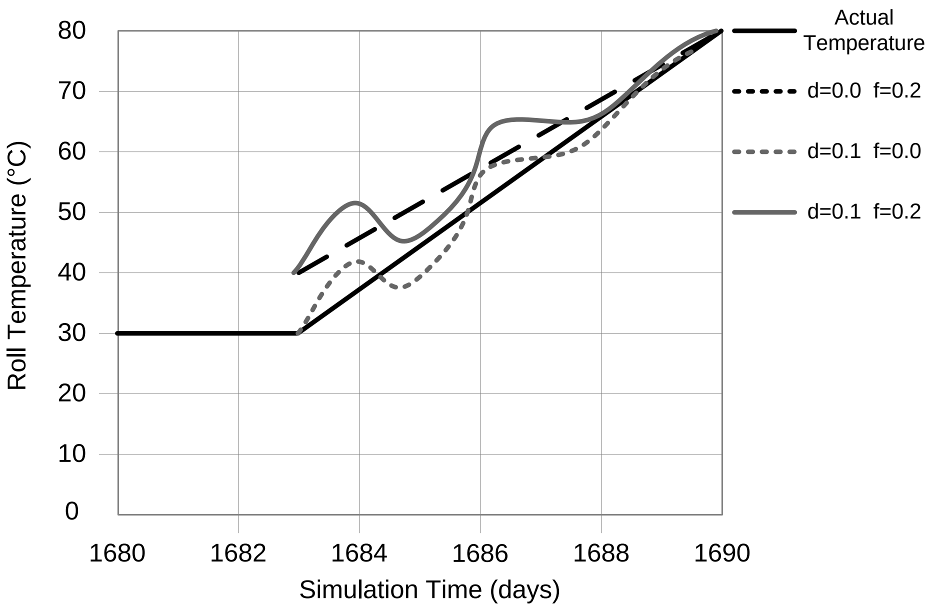


Figure 6.16: Behavior of the measured temperature for different values of d and f.

6.4.2 Planning and Control

In (Lodewijks, 2004), the condition monitoring of the rollers was done via vibration analysis. It was assumed that the maintenance trolley was equipped with the sufficient data processing equipment on board to perform the data acquiring and data mining functions. In (Lodewijks, 2004), the maintenance robot performed inspections on a regular (fixed intervals) or not regular time intervals. Choosing between fixed intervals and non-fixed intervals depends among other things on the ratio between the time the trolley needs to travel the conveyor versus the inspection interval time. The travel time not only depends on the length of the conveyor but the number of inspections, the inspection itself and the servicing time. Each cycle interval, the trolley travels the conveyor forward to the end then back to the beginning of the belt. During the cycle, four maintenance strategies where considered in (Lodewijks, 2004):

- Strategy 1: Inspection is performed only forward, data mining and servicing (if required) is done immediately after inspection.
- Strategy 2: Inspection and servicing both forward and on return. Data mi-

ning right after inspection.

- Strategy 3: Inspection is done forward. Servicing only on return. Data mining is done at some stage after inspection before starting the servicing round.

- Strategy 4: Inspection is done forward. Servicing on return. Data mining is done upon arrival to the tail. In this case the information is transmitted to a central system that communicates the final servicing list to the trolley.

Whether or not to inspect a roll in (Lodewijks, 2004), depended on the inspection strategy. With a fixed inspection strategy, each roll would be inspected every cycle of the trolley (the cycle was specified at the beginning of the simulation program). This would have resulted in long cycle times and unnecessary inspections. Thus, a flexible inspection strategy defined the inspection time. The inspection time defined the time interval before the end of the (estimated) lifetime in which a roll must be inspected by the robot.

In (Lodewijks et al., 2007), a wireless monitoring system was proposed to further automate the maintenance activities of large belt conveyor system. In this case, the trolley is no longer used for inspection since the belt conveyor is assumed to be equipped with smart rollers. The condition monitoring of the rolls in performed independent of the trolley movement at fixed monitoring intervals, for example once or twice a day. Once the roll's temperature reaches T_{signal}, the smart roll will autonomously send a warning signal to the central system. From that point onwards, the temperature of the roller will be monitored at more frequent intervals. Every temperature measure above T_{signal} is used to estimate the remaining life of the roll. Every smart roll communicates its status to a central system where it is determined if service is required. The condition monitoring system process the data collected from the rollers and updates a list of rollers that need to be serviced. It is not explicitly assumed that the servicing is performed by the trolley, it can be done by men as well. In the latter case the servicing time and cost would change, but the strategy will remain the same.

6.4.3 Simulation Settings

The settings used in the simulations are presented in this section.

Belt conveyor The length and frame distance determines the number of frames and the number of rolls in the conveyor belt.

Table 6.5: Conveyor belt settings.

Length [m]	10000
Frame distance [m]	2
Resulting number of frame	5001
Resulting number of rolls	21671

Bearings The lifetime of a bearing is distributed uniformly between L_{Min} and L_{Max}. A certain rate of the bearings fails between 0 and L_{Min}. This failure is uniformly distributed between 0 and L_{Min}. From these specifications the average lifetime of each type of bearing can be calculated. The lifetime of a roll is the minimum of the lifetime of two bearings.

Table 6.6: Bearing Lifetimes.

Life time distribution	L_{Min} [days]	L_{Max} [days]	Failure rate	Average [days] [days]
Upper, side roll	1750	2083	0.10	1812.4
Upper, middle roll	1667	2000	0.10	1733.5
Lower, side roll	1875	2208	0.10	1931.1

The Signal Interval (See Figure 6.16) of a bearing is distributed uniformly between an indicated minimum and maximum value:

Table 6.7: Signal Interval.

	Minimum	Maximum
Signal Interval [days]	7	10

During the above mentioned Signal Interval, the bearing temperature will rise from the normal operation temperature to the fail temperature, see Table 6.8.

Table 6.8: Bearing Temperature characteristics.

Bearing Temperatures	Degrees Celsius [°C]
Normal Operation	30
Fail Temperature	80

General settings It is assumed that the belt conveyor is equipped with smart rolls and that the maintenance trolley with robot travels when required. The maintenance interval is therefore flexible and not fixed (Lodewijks, 2004). The Safety Criterion defines a temperature above which a roll is replaced by the robot. Roll failure makes the belt liable for belt rupture which means major down time. If the Safety Criterion is too low, the rolls will be replaced too early which is not feasible. If the Safety Criterion is too high, the rolls will be replaced too late, which is even worse. Two safety temperatures can be distinguished: T_1 and T_2. T_1 is the roll temperature that triggers replacement by the maintenance trolley. T_2 is the temperature (lower than T_1) at which the trolley also replaces a roll. The idea behind this is that while the roll that triggered the trolley to move along the conveyor definitely needs replacement, other rolls may reach T_1 quite soon afterwards, triggering the trolley to replace them[4]. Therefore, in order to prevent this situation a second safety temperature T_2 is defined.

Three options as far as temperature settings are discussed:

- T_1=37°C, T_2=35°C
- T_1=71°C, T_2=69°C
- T_1=71°C, T_2=35°C

Other simulation setting are:

- Simulation length = 100 days
- Monitoring interval = 24 hours
- Trolley speed 0.5m/s

[4]Notice that the trolley returns to the beginning of the belt conveyor after finishing replacing a roll.

Performance indicators

The performance of the smart roll system combined with the maintenance robot is determined by two factors. Most important is the number of rolls that are replaced too late. Too late replacement means that the roll already failed; this could cause damage to the conveyor belt. Note that the model settings did alter the predictions of the remaining lifetime of the rolls. Roll failure just happened, did not depend on the model settings.

The other performance indicator is the average time between replacement and lifetime of the roll. Replacing rolls with a large residual lifetime is a waste. The following results are presented:

- Average cycle time for the robot
- Average number of inspections per cycle
- Percentage of early replaced rolls
- Average time between early replacement and lifetime roll
- Percentage of late replaced rolls
- Average time between lifetime roll and late replacement

The performance is summarized with two performance indicators:

Failure: percentage of rolls replaced (too) late
Waste : average time rolls are replaced before the end of their lifetime

6.4.4 Simulation Results

In this section the results of the simulations are discussed and compared with the results discussed in (Lodewijks, 2004) where the robot performed the inspections and monitored the rolls. It should be noted that it is assumed that in both cases, whether smart rolls are used or whether the trolley is used for inspection purposes, the trolley is used for maintenance(roll replacement).

Table 6.9: Results with different values for the deviation.

Settings		Cycle		Early replaced		Late replaced	
d	f	Nr Cycles	Avg. Time [days]	% Early	Avg. Early [days]	% Late	Avg. Late [days]
0.00	0.00	98	0.52	100.0%	7.0	0.0%	0.0
0.25	0.00	99	0.52	100.0%	7.1	0.0%	0.0
0.50	0.00	99	0.52	100.0%	7.0	0.0%	0.0

Setting 1: T_1=37°C, T_2=35°C

The results of the simulations with T_1=37°C, T_2=35°C are presented in Table 6.9.

The results of the simulations can be summarized as follows:

- Safety criterion 2 is close to criterion 1; both are relatively low
- Number of cycles shows that strategy results in daily robot cycles
- No late replacements
- Average waste per replaced roll is 7 days

Setting 2: T_1=71°C, T_2=69°C

The results of the simulations with T_1=71°C, T_2=69°C in Table 6.10.

Table 6.10: Results with different values for the deviation.

Settings		Cycle		Early replaced		Late replaced	
d	f	Nr Cycle	Avg. Time [days]	% Early	Avg. Early [days]	% Late	Avg. Late [days]
0.00	0.00	94	0.52	100.0%	1.2	0.0%	0.0
0.25	0.00	94	0.52	99.6%	1.5	0.4%	0.1
0.50	0.00	98	0.52	99.5%	3.3	0.5%	0.1

The results of the simulations can be summarized as follows:

- Safety criterion 2 is close to criterion 1; both are relatively high

- Number of cycles shows that strategy results in daily robot cycles.
- Percentage late replacements is higher if deviation is higher
- Average waste per replaced roll is 1 to 3 days

Setting 3: T_1**=71°C,** T_2**=35°C**

The results of the simulations with T_1=71°C, T_2=35°C are presented in Table 6.11.

Table 6.11: Results with different values for the deviation.

Settings		Cycle		Early replaced		Late replaced	
d	f	Nr Cycle	Avg. Time [days]	% Early	Avg. Early [days]	% Late	Avg. Late [days]
0.00	0.00	16	0.80	99.9%	4.4	0.1%	0.1
0.25	0.00	24	0.69	100.0%	5.3	0.0%	0.0
0.50	0.00	87	0.53	100.0%	6.9	0.0%	0.0

The results of the simulations can be summarized as follows:

- Safety criterion 2 is high; safety criterion 1 is low
- Number of cycles low (1 per 6 days) for $d = 0$; towards daily with $d = 0.25$
- Percentage late replacements is (almost) zero
- Average waste per replaced roll is 4 to 7 days

Conclusions on simulations

The results of the simulations are summarized in Table 6.12.

From Table 6.12 the following conclusions can be drawn:

- T_1 should be chosen sufficiently high, for example at 71°C.
- T_2 should be also be chosen high (for example 69°C) since d is expected to be very low using RFID technology

Table 6.12: Results all simulations.

Setting	T_1	T_2	Failure	Waste
1	37°C	35°C	0%	7 days
2	71°C	69°C	0%-0.5%	1 - 3 days
3	71°C	35°C	0%	4-7 days

- The accuracy of the data is assume to be 100% using the smart rolls, this is d=0.
- With T_1=71°C and T_2=69°C the failure will be 0% and rolls will hardly be replaced early (waste is 1 day)

6.4.5 Performance comparison

In (Lodewijks, 2004) the performance of the monitoring and maintenance trolley was discussed. It should be realized that there is an important difference between the technology discussed in (Lodewijks, 2004) and the smart rolls introduced in (Lodewijks et al., 2007). In (Lodewijks, 2004) the monitoring was frequency based, here it is temperature based. However, a case that is comparable is presented below in Table 6.13.

Table 6.13: Results with different cycle interval setting, $d = 0.10$ and $f = 0.25$ (Table 8 from (Lodewijks, 2004)).

Settings			Cycle		Early replaced		Late replaced	
Cycle Interval	Safety time	Inspection time	Avg. Time [days]	Nr. Inspect	% Early	Avg. Early [days]	% Late	Avg. Late [days]
30	30	60	3.02	5879	100%	25.4	0%	0.0
20	20	40	2.25	4288	100%	17.0	0%	0.0
10	10	20	1.44	2462	100%	8.5	0%	7.5
5	5	10	0.98	1380	100%	4.2	0%	8.8

When Table 6.13 is compared with the results presented in the previous paragraphs it can be concluded that the results shown in the last row of Table 6.13 are comparable with the results of **Setting 2** in the simulations above. In (Lodewijks,

2004) the cycle time is 0.98 days where in Table 6.11 it is 0.8 days. This is caused by the fact that in (Lodewijks, 2004) the robot was also used for inspection where that function in this case is taken over by the smart rolls and the inspection does not take time. The waste is comparable.

In general it can be said that:

- With the smart rolls a failure rate of 0% can be achieved assuming that the safety temperatures are set correctly.
- With the smart roll system the waste, in terms of days of early replacement, can be reduced to a minimum.
- Simulation is an excellent tool to determine the correct settings of the monitoring system.
- The time available between a possible failure warning and the final failure is much shorter when temperature monitoring is used than in the case when using vibration monitoring. This may have an affect in practice on the failure rates. This needs to be investigated in practice.
- Thus, timely and accurate information improves the performance of logistics control system.

6.5 Conclusions

Wireless monitoring is an alternative solution to automate maintenance procedures in belt conveyor systems. The system consists of wireless sensor nodes that constantly monitor the bearing temperature. Based on the data acquired, the remaining lifetime of the bearing is determined, and in case a failure is detected, maintenance procedures are schedule to replace the malfunctioning roll. Wireless sensor nodes are mainly powered by batteries. If the projected lifetime of the roll is only a few years, then the batteries provide the easiest and most versatile power source. However, if the projected lifetime of the node is more than just a few years, then an alternative power source needs to be considered. Energy harvesting is an alternative to primary batteries. The mechanical structure in large belt conveyor systems is exposed to high level vibrations. Vibrations can be transformed into electrical energy to power the thousands of sensor nodes that a wireless monitoring system would deploy. This natural source of energy would replace the use of batteries and would make the duty cycle of the sensor dependant on the component life instead of the battery charge. The maximum duty cycle for sensor nodes using commercial energy harvesters was presented in Table 6.4. Although specific considerations can not be drawn from these figures since the duty cycle depends on the network configuration and communication protocols, using an alternative energy source is definitely a possibility for wireless monitoring of belt conveyor systems.

There are some energy harvesters that are part of the sensor nodes (they are specifically customized to the system needs); the ones presented in this chapter are available as standalone systems. Thus, their applicability depends on their capacity to adapt to the belt conveyor application. Finally, the economical constraint would limit the possibility to use a commercial energy harvester as the ones introduced. These modules price is around €500, this is almost 17 times the cost of one roll, and with such high price the use of commercial harvesters is not feasible for large belt conveyor implementation. Nonetheless, the fast development in the area makes it possible to expect that the prices of such devices will be reduced to allow large system implementation.

In this chapter, an application of prognostics logistics in the maintenance control system of belt conveyors was presented. A simulation model was used to study the effect of timely and accurate information in the maintenance control of belt conveyors. The monitoring system used in the simulation is temperature based. Although the time available between a possible failure warning and the final failure is much shorter when temperature monitoring is used, the simulation results showed that with timely and accurate information provided by the RF monitoring system the number of rolls that are replaced too late is reduced to 0%. Thus, the performance of the existing logistics control system is improved by avoiding total breakdown due to bearing failure.

The majority of the simulations focused on the effect of timely information, i.e. safety temperature settings, while assuming 100% accuracy of the data. If less than 100% accuracy in the measured temperature is assumed, then the value of the parameter d needs to be change in the simulation model. It is expected, however, that a change in the accuracy of the temperature measurement will have an effect in the number of rolls that are replaced, either to early or too late, depending on whether the measured temperature is over or under the actual temperature of the roll. In either case, a tuning of the safety temperature settings would need to be made.

The smart rolls were introduced as a mean of monitoring the performance of idler rolls. One important issue is the costs of the technology. Today in its prototyping stage it is too expensive. However it is believed that when it can be produced in large numbers the costs will be small compared to the costs of a single roll. In that case the technology is feasible for both small scale as well as large scale applications. The setting of the trolley, or alternatively the instructions given to maintenance personnel, used for the replacement of rolls that are close to failure can be investigated by using simulation. An important issue for that determination is the accuracy of the model used to predict the raise of the rolls temperature in time. Finally it should be realized that the RFID technology introduced in this chapter can also be used for other components than the rolls. The smart rolls introduced here are believed to be the first step to a future where ”smart dust” sensors can be used to monitor all relevant components of a belt conveyor.

6.6 References

Albers, A., Burger, W., Sovino, R., and Dickerhof, M. (2006). Monitoring lubrication regimes in sliding bearings - using acoustic emission analysis. *Practicing oil Analysis Magazine*, (200605). University of Karlsruhe, Institute of Product Development.

Cedrat (2007). Vibration energy harvesting with apa400m-md product specification. Internet, Cedrat. Available On-line, http://www.cedrat.com.

Crossbow (2007). Mica2dot product specification. Internet, Crossbow. Available On-line, http://www.xbow.com.

DustNetworks (2007). Smartmesh-xt product specification. Internet, Dust Networks. Available On-line, http://www.dustnetworks.com.

Ember (2007). Em250 product specification. Internet, Ember. Available On-line, http://www.ember.com.

Ferrosolutions (2007). Veh-360 electromechanical vibration energy harvester product specification. Internet, Ferrosolutions. Available On-line, http://www.ferrosi.com.

Gungen, S. (2006). Strategies for automated maintenance of belt conveyors by means of wireless temperature monitoring. Experimental Assignment 2006.TL.7112, Transport Engineering and Logistics, Delft University of Technology.

Jiang, X., Polastre, J., and Culler, D. (2005). Perpetual environmentally power sensor nodes. *Proceedings of the fourth international symposium on information processing in sensor networks*.

Lodewijks, G. (2004). Strategies of automated maintenance of belt conveyor systems. *Bulk Solids Handling*, 24:16–23.

Lodewijks, G., Duinkerken, M., López de la Cruz, A. M., and Veeke, H. (2007). The application of RFID technology in belt conveyor systems. *Proceeding of the BeltCon 14 Conference*.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2007). Applicability of RFID in prognostic logistics. In *Proceedings of the 2007 IEEE Conference on Service Operations and Logistics, and Informatics*, Philadelphia, USA.

López de la Cruz, A. M., Veeke, H. P. M., and Lodewijks, G. (2008). Wireless monitoring of belt conveyor systems. *Proceedings of the 2008 bulkeurope conference*.

Mide (2007). Piezo energy harvester product specification. Internet, Mide. Available On-line, http://www.mide.com.

Nuttall, A. (2007). *Design Aspects of Multiple Driven Belt Conveyors*. PhD thesis, Delft University of Technology.

Paradiso, J. A. and Starner, T. (2005). Energy scavenging for mobile and wireless electronics. *IEEE Pervasive Computing*, 4(1):18–27.

Penella, M. T. and Gasulla, M. (2007). A review of commercial energy harvesters for autonomous sensors. *Proceedings of the Instrumentation and Measurement Technology Conference*.

Perpetuum (2007). Vibration energy harvester product specification. Internet, Perpetuum. Available On-line, http://www.perpetuum.com.

Raghunathan, V. and Chou, P. H. (2006). Design and power management of energy harvesting embedded systems. *Proceedings of the 2006 international symposium on Low power electronics and design*.

Roundy, S., Wright, P. K., and Rabaey, J. (2002). A study of low level vibrations as a power source for wireless sensor nodes. *Computer Communications*, 26:1131–1144.

SowNet (2007). T-node product specification. Internet, SowNet. Available On-line, http://www.sownet.nl.

Thomas, J. P., Qidwai, M. A., and Kellogg, J. C. (2006). Energy scavenging for small-scale unmanned systems. *Journal of Power Sources*, 159:1494–1509.

Woudenberg, R. and Vlaar, W. (2009). Intelligent metal rollers for belt conveyor systems. Research Assignment 2009.TL.7356, Transport Engineering and Logistics, Delft University of Technology.

CHAPTER 7

Conclusions and Recommendations

In this thesis, the concept of prognostics integrated logistics is introduced. Prognostics integrated logistics or prognostics logistics is the combination of using timely and accurate information into a decision making system to generate prognoses of possible disturbances in order to improve the performance of logistics systems. The idea behind this research is to investigate the use of technological tools for continuous monitoring and data gathering in order to do accurate prognostics on logistics requirements; i.e.: maintenance procedures, stock replenishment policies, manufacturing planning, transportation operations, delivery schedules, among many others.

In the introduction of the thesis two research questions are asked:

- What is necessary to integrate prognostics into logistics systems?
- What are the benefits (if any) of using prognostics integrated logistics?

In order to answer the first research question, it is necessary to identify the main elements in the concept of prognostics logistics. Two main elements are recognized. The first element is an information system where acquisition, communication and processing of timely and accurate information is the main function. It is important to have an information system monitoring objects (i.e products and equipments)in order to have the right information when needed, where needed. The monitoring frequency depends on the change rate of the aspects of the system, this condition requires a system that can capture and transmit information in real or near real time. Furthermore, the information system should be capable of automatic data capture in order to limit human involvement and reduce errors.

The level of data capture of the information system is application dependant. However, no matter the application, it is desired for the information system to support a large flow of information and be pervasive, so information about products, equipments, environmental conditions, location, among many others, can be made available to support the decision making system. Thus, four important features of the information system are identified: unique identification of objects, location information, physical environmental information and communication.

The second element in prognostic logistics is a decision making system where prognoses of possible disturbances based on the available information are generated. The availability of possible object level information, including unique identification, location, status and operational condition can fundamentally enhance control approaches for logistics systems. Prognostics logistics intends to influence decision making systems or control systems by using timely and accurate information to generate prognoses, and create a suitable time window to react and, either prevent or correct, the possible effects of a disturbance. With accurate prognoses, the logistic system is expected to timely allocate resources where needed, continuously reduce operation and labor costs, and optimize the planning, scheduling and control of activities

The accuracy of the predictions in prognostic logistics relies on timely and accurate data. Acquiring timely and accurate data depends on the type of data capture system used. Auto identification technologies (Auto- ID) have been used in the past to improve the quality of the data capture in logistics systems. In this field, Radio Frequency Identification technology (RFID) stands out against all the other technologies presented. Although prognostics logistics is a technology independent concept, RFID is investigated as one of the possible technologies that can support data capture in the information system of prognostics logistics. This technology alone, offers unique identification of objects, location sensing is possible with proximity analysis (this enables track and tracing capabilities), it can be used in combination with sensors to capture physical environment information, and it can communicate, passively or actively, information about objects. However, it was found out that applying RFID involves more than just connecting a reader and a series of antennas to the application's network. In fact, in order to implement an RFID based solution to support logistics systems, the compatibility of the technology and the application need to be tested and most likely, the application itself needs to be re-designed. Thus, in order to have a comprehensive view on the capabilities and limitations of RFID as a data capture system for prognostics logistics, a testing methodology is designed and used in several application environments. The goal of the testing methodology is to provide a scientific approach to determine the applicability of RFID in a certain application, as well as to determine the level of data capture needed to support prognostics in logistics systems.

A testing methodology composed of fundamental tests, semi-fundamental tests and operational tests is designed. The fundamental tests focus on evaluating the RF air interface performance by determining functioning conditions like the read field of the tags, the effect of tag orientation and read rate, among others. During the semi-fundamental tests, it is possible to recognize certain characteristics of the application that can be changed or re-designed in order to make the application scenario more RFID friendly. The operational tests asses the influence of the application's environment in the readability of the tags. In this part, test conditions like the packaging of the products, impact of the operational equipment, total number of boxes that can be segregated and identified, accuracy of the system, interaction with the physical environment, and more is analyzed. The proposed methodology is a way of identifying key parameters and finding their individual influence on readability performance. The outcome of the performance test can affect on which level tagging is applied: freight containers, returnable transport items (RTI), transport units, product packaging, the product itself. After these three series of tests, the reliability of an RFID system in a certain application can be evaluated. Whether or not this reliability is sufficient for that specific application depends on the sensitivity of the logistics system to a disruption in objects visibility. So, in conclusion, the successful implementation of RFID technology not only depends on the performance of the RFID equipment, but also, on the compatibility of the technology with the application. This implies, in many if not all cases, changes in the application environment. Thus, whether or not organizations are willing to change their production processes to implement RFID will at the end depend on the expected benefits and costs related to re-design their production systems.

In order to answer the second research question, an RF based monitoring system for large belt conveyor systems is used as an application example. First, the feasibility of using RF based sensors to monitor the temperature inside the rollers is investigated. The system consists of wireless sensor nodes that constantly monitor the bearing temperature. Based on the data acquired, the remaining lifetime of the bearing is estimated, and in case a failure is detected, maintenance procedures are scheduled to replace the malfunctioning roll. Fundamental and semi-fundamental tests, based on the testing methodology proposed, were designed and performed using the metal idler rollers and frames provided by Rulli Rulmeca SPA. The tests performed showed promising results for the applicability of wireless monitoring in belt conveyor systems. However, more tests need to be performed. The influence of the metal frames in the signal strength of the rollers still needs to be investigated, as well as the influence of the belt conveyor in operation. Furthermore, it is expected that the signal strength will be considerably affected once the full metal frame structure is assembled.

After determining the feasibility of applying an RF monitoring system in belt conveyors systems, the benefits of using prognostics logistics was investigated using a simulation model to determine the effect of prognostics logistics (accurate and timely information) on the system performance of belt conveyors. The maintenance concept was based on the prognostics maintenance concept, using temperature measurements to estimate the remaining lifetime of a roll. The technical lay-out of the maintenance system was based on the application of an automated maintenance robot including a roll replacement robot. Condition monitoring of the roll was done via a system of smart rolls and a central monitoring unit. Although the time available between a possible failure warning and the final failure is much shorter when temperature monitoring is used, the simulation results showed that with timely and accurate information provided by the RF monitoring system the number of rolls that are replaced too late is reduced to 0%. Thus, it can be concluded that the direct benefit of integrating prognostics in the logistics control of belt conveyors is the improvement in the performance of the system by avoiding total breakdown due to bearing failure. Derived benefits include: simplification of maintenance procedures, reduce downtime costs, on time delivery schedules, improved transportation operations, reduced safe inventories among many others.

In conclusion with prognostic logistics it is possible to reduce uncertain situations and avoid disturbances, changing logistics control systems from reactive (passive systems) to more proactive systems. However, how far prognoses can be generated and how good the prognoses are, ultimately depends on acquiring timely and accurate information.

7.1 Recommendations

Integrating prognostics into today's logistics systems involves the combination of timely and accurate data in decision making processes, and more responsive logistics systems to timely react and prevent possible disturbances. Further applications of prognostics logistics should not only consider the type of technology used for data gathering, but also, the ability of the logistics system to be prepared and react (adapt) to situations that in previous cases could have severely disrupted the normal functioning of the overall logistics system. The anticipated benefits of using prognostics integrated logistics are substantial improvements in e.g. logistic services, safety, reliability and flexibility.

The following topics are particularly recommended for further research:

- The use of a general supply chain simulation model to study the effects of timely and accurate information in, for example: inventory and transportation strategies, demand forecast and order processing.
- The extension of the testing procedure to include other types of technologies in order to study their compatibility with the application scenario.
- Developing an RFID application database in which data about all the studies involving RFID implementations can be retrieved in order to aid researches when similar applications appear. With such a database, it will be possible to determine if it is actually necessary to perform the tests, or to avoid doing the semi-fundamental tests and start immediately in the operational phase of the testing procedure.

For the smart roll application study, the following are the recommendations and topics for further research:

- The antenna of the sensor nodes should be either outside and aligned with the plastic cap or the metal rollers should be replaced with a more RF friendly material like plastic or some other polymer.
- Energy harvesting techniques should be investigated as an alternative to primary batteries. The mechanical structure in large belt conveyor systems is

exposed to high level vibrations. Vibrations can be transformed into electrical energy to power the thousands of sensor nodes that a wireless monitoring system would deploy. .

- The costs involve in the production of the smart rolls should be studied. Today in its prototyping stage it is too expensive. However it is believed that when it can be produced in large numbers the costs will be small compared to the costs of a single roll. In that case the technology is feasible for both small scale as well as large scale applications.
- The setting of the trolley used for the replacement of rolls should be investigated by means of simulation. An important issue for that determination is the accuracy of the model used to predict the raise of the rolls temperature in time.
- Finally, the temperature raise for a roll from normal operation condition to failure, should be measured via an experimental set up.

Summary

In this thesis, the concept of prognostics integrated logistics is introduced.The idea behind this concept is to investigate the use of technological tools for continuous monitoring and data gathering in order to do accurate prognostics on logistics requirements; i.e.: maintenance procedures, stock replenishment policies, manufacturing planning, transportation operations, delivery schedules, among many others. Two main elements of the prognostics logistics concept were recognized. The first element is an information system where acquisition and processing of timely and accurate information is the main function. The second element is a decision making system where prognoses of possible disturbances based on the available information are generated. With prognostic logistics it is expected that uncertain situations can be reduced, giving the possibility to logistics systems to early detect possible equipment failures, and hazardous situations fast enough to take prompted actions. However, how far prognoses can be generated and how good the prognoses are, ultimately depends on the timely and accuracy of the information acquired.

Auto identification technologies (Auto- ID) have been used to improve the quality of the data capture in logistics systems. With the use of software platforms, designed to share information among different members in logistics systems, information sharing has improved. In this field, Radio Frequency Identification technology (RFID) has been intensely investigated because of the large interest generated in logistics and supply chain management communities. The interest in this technology relies on the fact that RFID is perceived as a technology that

can provide a cost effective solution for constant monitoring, and sensing in large scale logistic systems.

There are different sources investigating what RFID can do and how to implement RFID in the organization. However, there was not a clear and scientific approach to determine the applicability of RFID in a certain application. In this thesis, a testing methodology composed of fundamental tests, semi-fundamental tests and operational tests is presented. The fundamental tests focus on evaluating the RF air interface performance by determining functioning conditions like the read field of the tags, the effect of tag orientation and read rate, among others. During the semi-fundamental tests, it is possible to recognize certain characteristics of the application that can be changed or re-designed in order to make the application scenario more RFID friendly. It is important to notice that RFID is far from being a plug and play technology. Whether or not organizations are willing to change their production processes to implement RFID depends on the expected benefits and costs related to re-design their overall production systems. The operational tests asses the influence of the application's environment in the readability of the tags. In this part, test conditions like the packaging of the products, impact of the operational equipment, total number of boxes that can be segregated and identified, accuracy of the system, interaction with the physical environment, and more is analyzed. The proposed methodology is a way of identifying key parameters and finding their individual influence on readability performance. The outcome of the performance test can affect on which level tagging is applied: freight containers, returnable transport items (RTI), transport units, product packaging, the product itself. After these three series of tests the reliability of an RFID system in a certain application can be evaluated. Whether or not this reliability is sufficient for that specific application depends on the sensitivity of the logistics system to a disruption in objects visibility.

The proof of the prognostics logistics concept was accomplished using an RF based monitoring system for large belt conveyor systems as an application example. The first part was to study the feasibility of using RF based sensors to monitor the temperature inside the rollers. The system consisted of wireless sensor nodes that constantly monitor the bearing temperature. Based on the data acquired, the remaining lifetime of the bearing is estimated, and in case a failure is detected, maintenance procedures are scheduled to replace the malfunctioning roll. Fundamental and semi-fundamental tests, based on the proposed testing methodology, were designed and performed using the metal idler rollers and frames provided by Rulli Rulmeca SPA. The tests performed showed promising results for the applicability of wireless monitoring in belt conveyor systems. However, more tests need to be performed. The influence of the metal frames in the signal strength of the rollers still needs to be investigated, as well as the influence of the belt conveyor in operation. Furthermore, it is expected that the signal strength will be considerably affected once the full metal frame structure is assembled. Therefore, it is recommended that the antenna of the sensor nodes be either outside and aligned with the plastic cap or that the metal rollers be replaced with a more RF friendly material like plastic or some other polymer.

The second part to proof the prognostics logistics concept was accomplished using a simulation model to determine the effect of prognostics logistics (accurate and timely information) on the system performance of belt conveyors. The maintenance concept was based on the prognostics maintenance concept, using temperature measurements to estimate the remaining lifetime of a roll. The technical lay-out of the maintenance system was based on the application of an automated maintenance robot including a roll replacement robot. Condition monitoring of the roll was done via a system of smart rolls and a central monitoring unit. Although the time available between a possible failure warning and the final failure is much shorter when temperature monitoring is used, the simulation results showed that with timely and accurate information provided by the RF monitoring system the number of rolls that are replaced too late is reduced to 0%. Thus, integrating prognostics in the logistics control of belt conveyors improves the performance of the system by avoiding total breakdown due to bearing failure.

With prognostic logistics it is expected that uncertain situations can be reduced, giving the possibility to logistics systems to early detect possible equipment failures, and hazardous situations fast enough to take prompted actions. However, how far prognoses can be generated and how good the prognoses are, ultimately depends on acquiring timely and accurate information.

Samenvatting

In die proefschrift wordt het concept van prognostische logistiek gentroduceert. Het idee achter dit concept is te onderzoeken of het gebruik van technische gereedschappen voor het continu bewaken en verzamelen van gegevens kan bijdragen aan een accurate voorspelling van logistieke eisen, bijvoorbeeld bij onderhoudsprocedures, voorraadstrategieën, productieplanning, transportoperaties, afleveringsschema's en vele andere. Er worden twee hoofdelementen onderscheiden in het concept. Het eerste is een informatiesysteem waarvan de hoofdfunctie is de acquisitie en verwerking van tijdige en nauwkeurige gegevens. Het tweede element is een besluitvormingssysteem waar voorspellingen worden gedaan over mogelijke verstoringen, gebaseerd op de beschikbare informatie. De verwachting is dat met behulp van prognostische logistiek de onzekerheid van situaties kan worden verminderd, waardoor logistieke systemen in staat zijn vroegtijdig verstoringen van apparatuur te ontdekken, en snel genoeg op gevaarlijke situaties kunnen inspelen. Hoe ver vooruit voorspellingen kunnen worden gedaan en hoe goed de voorspellingen zijn, hangt echter af van de tijdigheid en nauwkeurigheid van de verzamelde informatie.

Auto identification technologiën (Auto-ID) worden gebruikt om de kwaliteit te verbeteren van het verzamelen van gegevens in logistieke systemen. Door gebruik te maken van hiervoor speciaal ontworpen software platforms, is de informatiedeling tussen de verschillende deelnemers aan een logistiek systeem verbeterd. Radio Frequency IDentification technologie (RFID) is hiertoe intensief onderzocht. Voor RFID is grote interesse ontstaan in gemeenschappen van logistiek en supply chain management. De interesse in deze technologie is een gevolg van het feit dat RFID wordt beschouwd als een technologie die een kosteneffectieve oplossing kan bieden voor continue bewaking van (de toestand van) elementen in grootschalige logistieke systemen.

Er zijn verschillende bronnen die de mogelijkheden van RFID onderzoeken en de wijze waarop het in de organisatie moet worden geïmplementeerd. Er was echter geen wetenschappelijke benadering om de toepasbaarheid van RFID in een bepaalde applicatie te bepalen. In dit proefschrift wordt een testmethodiek gepresenteerd, die bestaat uit fundamentele, semifundamentele en operationele tests. De fundamentele tests richten zich vooral op het evalueren van de RF prestatie in het luchtmedium door functioneren en condities te bepalen als het leesveld van de tags, het effect van tag oriëntatie en de leessnelheid etc. Gedurende de semifundamentele tests is het mogelijk bepaalde eigenschappen van de applicatie te bepalen die veranderd of herontworpen kunnen of moeten worden om het applicatiescenario meer geschikt voor RFID te maken. Het is belangrijk om op te merken dat RFID absoluut geen plug-and-play technologie is. Of organisaties bereid zijn hun productieprocessen aan te passen om RFID te implementeren, hangt af van de verwachte opbrengst en kosten gerelateerd aan het herontwerp van het totale productiesysteem. De operationele tests bepalen de invloed van de applicatie omgeving op de leesbaarheid van de tags. Hierbij worden testcondities geanalyseerd als de verpakking van producten, de invloed van de operationele middelen, het totaal aantal dozen dat kan worden gescheiden en geïdentificeerd, de nauwkeurigheid van het systeem, de interactie met de fysieke omgeving etc. De voorgestelde methodiek is een manier om belangrijke parameters te identificeren en hun individuele invloed op de leesbaarheidsprestatie. Het resultaat van de performance test kan van invloed zijn op welk niveau tagging toegepast: containers, returnable transport items (RTI), transporteenheden, verpakking, het product zelf. Na deze drie series van testen kan de betrouwbaarheid van een RFID systeem in een bepaalde toepassing worden geanalyseerd. Of de betrouwbaarheid voldoende is voor de specifieke toepassing hangt af van de gevoeligheid van het logistieke systeem voor een verstoring in de zichtbaarheid van objecten.

Het bewijs van het concept ’prognostische logistiek’ wordt geleverd met behulp van een op RF gebaseerd systeem voor grootschalige transportbandsystemen als voorbeeld. Eerst is de haalbaarheid onderzocht van RF-gebaseerde sensoren om temperatuur te meten binnen de rollers. Het systeem bestaat uit draadloze sensor nodes die continu de lagertemperatuur meten. Op basis van de verzamelde gegevens wordt de resterende levensduur van het lager geschat, en in geval een naderende storing wordt gedetecteerd, worden onderhoudsprocedures gepland om de haperende rol te vervangen. Fundamentele en semifundamentele tests op basis van de voorgestelde methodiek zijn ontwikkeld en uitgevoerd, waarbij de metalen rollen en frames door Rulli Rulmeca SPA zijn geleverd. De uitgevoerd tests toonden veelbelovende resultaten voor de toepasbaarheid van draadloos meten min transportbandsystemen. Er moeten echter nog meer tests worden uitgevoerd. De invloed van de metalen frames op de signaalsterkte van de rollers moet nog worden onderzocht, evenals de invloed van de transportband in bedrijf. Bovendien wordt verwacht, dat de signaalsterkte aanzienlijk zal worden beïnvloed als het metalen frame volledig is geassembleerd. Daarom wordt geadviseerd dat de antenne van de sensor nodes ofwel buiten de roller worden geplaatst (afgeschermd door een plastic kapje), of dat de metalen rollers worden vervangen door een meer RF-vriendelijk materiaal zoals plastic of een ander polymeer.

Het tweede deel van het bewijs van het concept ’prognostische logistiek’ wordt geleverd met behulp van een simulatiemodel om het effect van prognostische logistiek te bepalen (nauwkeurige en tijdige informatie) op de prestatie van transportbandsystemen. Het onderhoudsconcept werd gebaseerd op signalen van temperatuurmetingen, waarmee de resterende levensduur van een roller kan worden geschat. De technische lay-out van het onderhoudssysteem bestaat uit een geautomatiseerde onderhoudsrobot en een robot voor het vervangen van rollen. Conditiebewaking van een rol wordt gedaan via en systeem van ”slimme”rollen en een centrale bewakingseenheid. Hoewel de tijd, die beschikbaar is tussen een waarschuwing voor mogelijk falen en de uiteindelijke storing kort is bij temperatuursignalering, toonde de simulatie aan dat met tijdige en nauwkeurige informatie door middel van het RF meetsysteem het aantal te laat vervangen rollen reduceert tot 0%. Daarom kan men concluderen, dat de integratie van prognostiek in de logistieke besturing van transportbandsystemen, de prestatie van het systeem verbetert door totale stilstand als gevolg van lagerstoring te voorkomen.

Het is de verwachting dat met prognostische logistiek de onzekerheid van situaties kan worden gereduceerd, waardoor in logistieke systemen de mogelijkheid ontstaat om vroegtijdig storingen te ontdekken in apparatuur, en snel genoeg gevaarlijke situaties te herkennen om tijdig actie te kunnen nemen. Hoe ver vooruit voorspellingen kunnen worden gedaan en hoe goed de voorspellingen zijn, hangt echter volledig af van de tijdigheid en nauwkeurigheid van de verkregen informatie

Biography

Adriana M. López de la Cruz was born on May the 15^{th} 1980 in Bogotá, Colombia. After graduating from the Liceo Segovia School in 1997, she studied Electrical Engineering at Los Andes University. In 2003 she received her BSc degree and was awarded with a full scholarship from the Netherlands Fellowship Programmes (NFP) to pursue her MSc studies in Electrical Engineering at Delft University of Technology. She received her MSc degree in 2005 and then joined the Transport Engineering and Logistics section at the Faculty of Mechanical, Maritime and Materials Engineering to start her PhD research under the supervision of Prof. Gabriel Lodewijks. During this period she cooperated with TNT, TNO, KLM, among others and supervised several master students in RFID and logistics related subjects.