Experimental Research into the Role of Radio Frequency Identification (RFID) Based Real-Time Location System (RTLS) in Production Logistics

Experimenteel onderzoek naar de rol van ware-tijd-lokalisatie door middel van identificatie met radiogolven in productielogistiek

Ihsan Arkan

Promotor: prof. dr. ir. H. Van Landeghem
Proefschrift ingediend tot het behalen van de graad van
Doctor in de Ingenieurswetenschappen: Bedrijfskundige Systeemtechnieken
en Operationeel Onderzoek

Vakgroep Technische Bedrijfsvoering
Voorzitter: prof. dr. E.-H. Aghezzaf
Faculteit Ingenieurswetenschappen en Architectuur
Academiejaar 2014 - 2015

UNIVERSITEIT GENT

ISBN 978-90-8578-780-8
NUR 950
Wettelijk depot: D/2015/10.500/24

Acknowledgments

This dissertation has been made possible with the guidance, help and support of the great people mentioned here. Thank you all for your contribution to science!

First and foremost, I would like to thank my advisor, Professor Hendrik Van Landeghem, for his excellent advice and guidance and for being a true mentor throughout this research.

I am grateful to the members of the committee, Professors El-Houssaine Aghezzaf, Johannes Cottyn, Wim De Waele, Gerrit Janssens and Birger Raa for their interest in my research and their invaluable suggestions.

I had the pleasure to supervise and work with three masters students who did graduation work related to the topic of my Ph.D. thesis. The work of Marta Sala Soria and Marcel Vidal Mansilla helped me while conducting the first case study. Simon De Buyser helped me carry out part of the experimental research.

I thank Kurt De Cock, fellow traveler and true friend, for his technical support; Veerle Van Beversluys, thank you for always being helpful and kind; to all my former and current colleagues at the department of Industrial Management, it was a pleasure to work with you in such a nice atmosphere.

I am very grateful to Melis Arin, Sinan Erol, Patrick De Jaeger and Ilse Van Renterghem for their significant contributions to this research and text. Ilse, I would like to express my gratitude for the last-minute proofreading you did.

I gratefully acknowledge the financial support for this research from the vehicle industry innovation consortium Flanders Drive, funded by the Flemish Government.

Finally, I would like to give a very special thank-you to my parents and brother for their never-ending love and support.

Gent, February 2015
Ihsan Arkan

Table of Contents

Acronyms

AGV	Automated Guided Vehicle
AMT	Advanced Manufacturing Technology
AOA	Angle of Arrival
Auto-ID	Automatic Identification
EDI	Electronic Data Interchange
EPC	Electronic Product Code
GPS	Global Positioning System
HF	High Frequency
IT	Information Technology
JIT	Just In Time
kNN	k-Nearest Neighbors
KPA	Key Performance Area
KPI	Key Performance Indicator
LF	Low frequency
MDM	Metrics Development Matrix
MES	Manufacturing Execution System
MSDP	Measurement System Development Process
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturing
QC	Quality Control
RFID	Radio Frequency Identification
ROI	Return On Investment
RTLS	Real Time Location System
TDOA	Time Difference of Arrival
TOA	Time of Arrival
VBA	Visual Basic for Applications
VPN	Virtual Private Network
WIP	Work In Process
UHF	Ultra High Frequency
UWB	Ultra Wide Band

List of Figures

List of Tables

Summary

Production logistics is the management of the flow of goods between procurement and distribution logistics, from the supply of production processes to the delivery of products to the warehouse. Nowadays, it is becoming more complex to manage and meet the increase in customer requirements, especially in the automotive industry. Manufacturers are confronted with the challenge of tracking and organizing the flow of goods due to larger product variety, fluctuating demand and inflexible capacity. They often struggle to pursue adequate up-to-date workflow information to maintain a robust and efficient production logistics. Workflow measurements such as the speed of material flow are generally measured ineffectively or by no means. The old-established measurement tools such as stopwatches and video analysis are not sufficient and accurate enough anymore to measure fast-paced complex operations. The lack of access to necessary shop floor information adversely affects to maintain robustness in manufacturing.

RFID (Radio Frequency Identification) technology possesses a potential benefit to provide sufficient up-to-date workflow visibility. RFID systems can automatically collect real time data on the identity and position of tags attached to objects. It enables to track and monitor physical objects by linking them into the virtual world of information systems. Conventional RFID systems have been mostly used in supply chain management for goods identification and stock counting purposes. These tracking systems collect real-time field data only at fixed locations such as at the entrance of a distribution center. The rest of the facility is not in the tag detection space. An RFID-based RTLS (Real Time Location System) is an advanced set up of an RFID system for automatic and continuous tracking of target objects in a pre-defined space. It collects work in process data. Hence, it is a more effective time and motion measurement tool for production operations than its previous alternatives. However, the reported applications on production

logistics have been only to monitor objects in real-time, for locating and counting purposes, but not the profound analysis for workflow optimization. This dissertation explores the potential in doing that.

We analyze diverse use cases of RFID-based RTLS based on the experimental research and case studies in the automotive industry. They are unique applications enhancing up-to-date access to workflow information visibility. Moreover, these applications are for measuring work measurements efficiently, evaluating workflow performance regularly, advancing production flexibility and optimizing production logistics. The workflow data is collected through on-line measurements attaching RFID tags on loads and vehicles. RFID system automatically generates real-time and detailed set of data that could not be achieved before with current measurement tools. The data is processed in order to provide accurate results about the trajectory of tagged objects. We have developed practical RFID data analysis methods concerning to improve enterprise information systems and tested these methods within the companies. Our analysis methods include data filtering, data cleaning and complex event processing techniques. The data filtering techniques contain middleware development, and time, displacement, speed and route filters. The data cleaning is based on the elimination of duplicate readings and inaccurate location measurements. The event processing techniques are composed of the extraction of key performance indicators, operation time queries, route detection algorithm and work space utilization. The major analysis results deliver insight about the performance of workflows in order to evaluate and improve the robustness and efficiency of production logistics.

Production logistics improvement studies are reviewed in Chapter 2 in the topics of manufacturing strategy, performance, plant floor visibility, tracking technology, RFID and measurement systems. We have discussed best RFID practices and data analysis methods. We contribute to the literature with the elaborate applications and empirical analysis methods in order for a manager to be able to evaluate the value of an RFID investment.

Chapter 3 describes a methodological study to integrate RTLS into enterprise information systems to improve production logistics activities.

Firstly, a new enterprise data architecture model is proposed. It is designed to obtain high level actionable information by exploiting an RFID system. In the new model, RFID data analysis methods follow two different applications: trajectory analysis and real-time performance monitoring. Secondly, key performance indicators of in-plant logistics vehicles and material flow are listed. Thirdly, the findings of the first experiment are demonstrated. The experiment is a simplified example of an RFID-enabled shop floor to illustrate the implementation of the trajectory analysis and to allow experimental validation. Lastly, the findings of the second experiment are presented. The experiments are conducted at the RFID lab in XiaK/ Kortrijk/ Belgium. A performance dashboard is designed and tested for real-time vehicle performance monitoring. It employs RFID-based RTLS data to extract key performance indicators (KPIs).

Chapter 4 presents the findings of three case studies from automotive industry. These studies are part of a collaborative research project on RFID in-plant logistics, funded by the Flemish government through Flanders Drive. They aim at internal logistics improvement by exploiting RTLS. We gather and investigate the work in process data of materials and vehicles in order to diagnose the settings and propose improvements. The first case study is conducted in the quality control department of a first tier automotive supplier in order to assess the performance of the workflow and work organization with six operators. The study resulted in efficiency benefits in the quality control department. The results indicate that RFID-enabled RTLS can provide more up-to-date, automatically acquired, detailed shop floor measurements than traditional measurement tools. The second case study is conducted in another first tier automotive supplier in order to monitor and optimize shop floor vehicle traffic. In this case, technological drawbacks of the system come into prominence. The third case study is conducted in the factory of a vehicle original equipment manufacturer in order to investigate vehicle traffic between the factory site and an outside supplier area. An RFID-based RTLS tracks the vehicles at the main gate of the factory and collects traffic data. The study aims to optimize a time schedule and documenting the traffic. The results provided the information required for the optimization. This study yields new insights into traffic control in factories.

The summary of the theoretical and practical contributions, and suggestions for further research are presented in Chapter 5.

Nederlandse samenvatting

Productielogistiek beheert de goederenstroom tussen inkoop en distributie, vanaf het bevoorraden van de productie tot het afleveren van afgewerkte producten in het magazijn. Heden ten dage deze opdracht is meer en meer complex geworden omwille van de stijgende vragen van de klant, vooral in de automobielindustrie. Producenten hebben het steeds moeilijker om de goederenstroom te organiseren en op te volgen, omwille van de stijgende variëteit van producten, schommelende vraag en flexibele capaciteit. Vooral het accuraat houden van informatie omtrent de werkstroom blijkt moeilijk, maar nodig voor een robuuste en efficiënte productielogistiek. Kenmerken van de goederenstroom, zoals de snelheid, worden meestal niet of ondoelmatig gemeten. De instrumenten van vroeger, chronometers en analyse van videos, zijn onvoldoende krachtig en accuraat voor snel wisselende complexe operaties. Het gebrek aan de nodige informatie omtrent de werkvloer ondermijnt de robuustheid in productie.

RFID (Radio Frequentie identificatie) technologie heeft het potentieel voordeel om voldoende up-to-date zichtbaarheid te geven op de werkstroom. RFID systemen verzamelen automatisch real-time gegevens omtrent de identiteit en locatie van tags, geplaatst op een object. Dit laat toe om fysieke objecten op te volgen en als zodanig ze te verbinden met de virtuele wereld van informatiesystemen. Conventionele RFID systemen worden meestal gebruikt in supply chain beheer, voor het identificeren van goederen en het bijhouden van de voorraadposities. Deze systemen verzamelen real-time gegevens op vaste locaties, zoals de ingangen van een distributiecentrum. De rest van het gebouw blijft onzichtbaar. Een RFID gebaseerd RTLS systeem (Real Time Locatie Systeem) is een geavanceerde RFID configuratie voor het automatisch en continu volgen van doelobjecten in een afgebakende ruimte. Op die manier meet het de goederen in bewerking. Daardoor is het een meer effectief tijd en bewegingsmeetinstrument dan de vorige alternatieven. Niettemin blijven de gepubliceerde RTLS case studies in

productielogistiek tot op heden beperkt tot de traditionele tel- en localisatiemetingen. Deze dissertatie exploreert het potentieel van het grondig analyseren van werkstroom gegevens voor optimalisatie doeleinden.

We analyseren diverse gebruiksscenario's van RFID-gebaseerde RTLS systemen, vanuit experimentele hoek en in case studies binnen de automobielindustrie. Elk op zich vormen unieke toepassingen die zichtbaarheid verlenen op up-to-date werkstroom informatie. Deze toepassingen kunnen parameters van werkplaatsen meten, performantie evalueren, de flexibiliteit verhogen en de productielogistiek optimaliseren. De gegevens worden bekomen door on-line metingen van tags die op voertuigen en objecten zijn bevestigd. Deze meetgegevens worden verwerkt tot accurate trajectories van de gevolgde objecten. Dit onderzoek heeft praktische data analysemethoden ontwikkeld om de informatie bruikbaar te maken voor de bedrijfsinformatiesystemen, en heeft deze getest binnen reële bedrijven. Deze methodes omvatten gegevensfiltering, opkuis van data en het detecteren van complexe evenementen. Data filtering omvat middleware software, en tijd-, verplaatsing-, snelheid- en routefilters. Het opkuisen van data is gebaseerd op het elimineren van dubbele registraties en foute locaties. Het detecteren van evenementen gebruikt key performance indicators, queries over verstreken tijd, routedetectie en werkruimte gebruik. De voornaamste resultaten geven inzicht over de performantie van de werkstroom, zodat de robuustheid en efficiëntie kan worden vastgesteld en verbeterd.

In hoofdstuk 2 worden de verbeteringsstudies inzake productielogistiek besproken, op niveau van productiestrategie, performantie, zichtbaarheid van de fabrieksvloer, tracking technologie, RFID en meetinstrumenten. De beste gepubliceerde RFID praktijken worden besproken. Het overzicht geeft een unieke bijdrage aan de manager die een RFID investering dient te evalueren.

Hoofdstuk 3 beschrijft de methodologische aanpak om RTLS te integreren in het bedrijfsinformatiesysteem voor de productielogistiek. Een nieuw gegevensarchitectuur model wordt voorgesteld, voorzien van beslissingsondersteunende informatie gebaseerd op RFID. Het model omvat twee verschillende toepassingsdomeinen: trajectorie-analyse en real-time

performantie opvolging. Daartoe worden de KPI's van interne logistieke voertuigen en materiaalstromen opgelijst. De eerste experimenten met de RTLS technologie worden beschreven, gebaseerd op een laboratoriumopstelling. De aldus verworven inzichten en na het testen van de basisalgoritmen, leiden tot een tweede experiment, waarbij een dashboard voor performantieverhoging van logistieke voertuigen wordt ontwikkeld en getest. Alle experimenten gingen door in het RFID laboratorium van de campus Kortrijk van de UGent, waar een "Human-centered Manufacturing and logistics system" laboratorium werd ingericht.

Hoofdstuk 4 beschrijft de bevindingen van empirisch onderzoek op 3 verschillende case studies uit de automobielindustrie. Deze case studies werden uitgevoerd als deel van een collaboratief onderzoeksproject van Flanders Drive, gefinancierd door de Vlaamse Regering, en waaraan alle grote OEM fabrieken hebben meegewerkt. De eerste case studie werd uitgevoerd binnen de kwaliteitsafdeling van een eerstelijnsleverancier van een OEM automobielfabriek. De RTLS metingen van de stroom van de producten doorheen de afdeling liet toe om de werkstroom te analyseren en de performantie ervan te bepalen. Op basis van deze informatie werden dan verbeteringen in de werkstroom en de arbeidsorganisatie voorgesteld, en deze werden door middel van een simulatiemodel geverifieerd. De aldus bekomen nieuwe situatie werd dan ingevoerd in de kwaliteitsafdeling, waarbij opnieuw RTLS metingen werden uitgevoerd. Deze aanpak toonde onverwachte resultaten in groot detail, waardoor de verbeteringen nauwkeuriger konden worden getest. Dit resultaat was rechtstreeks te danken aan het gebruik van RTLS. Met dit empirisch onderzoek werd aangetoond dat RFID gebaseerde RTLS in staat is om gedetailleerde, up-to-date werkstroomgegevens te meten op een automatische wijze, en op die manier veel beter dan de traditionele methodes. De tweede studie diende om AGV's en vorkheftrucks op te volgen in een fabriek teneinde het gebruik ervan te optimaliseren. In deze studie werden talrijke technologische euvels ontdekt, te wijten aan de zeer specifieke, low-cost configuratie van de tags om een RTLS functie te realiseren. De derde case studie was bedoeld om JIT leveringen van onderdelen naar een OEM automobielfabriek, uitgevoerd met vrachtwagens, automatisch op te volgen. De metingen werden daartoe aan de ingang van de fabriek opgezet. Dit gaf opnieuw nieuwe inzichten omtrent de

betrouwbaarheid van de technologie, de specifieke opzet en configuratie van de installatie, enz.

Hoofdstuk 5 vat de theoretische en praktijkgerichte bijdragen van dit onderzoek samen en suggereert richtingen voor toekomstig onderzoek. Het toont aan dat dit onderzoek innovatief was in de combinatie van RTLS metingen en het toepassingsdomein, de productielogistiek. Dit innovatiegehalte werd bevestigd door publicaties in internationale journals en conferenties, en tevens werd door de technologieleverancier een video gemaakt die als voorbeeld dient voor haar klanten en toekomstige klanten.

1. Introduction

This dissertation investigates the potential role and the impact of radio frequency identification (RFID) on production logistics at an operational and strategic level.

According to Council of Supply Chain Management Professionals: "Production logistics deals with planning, implementing and controlling efficient and effective flow and storage of materials, semi products, final products and related information in production processes of enterprises for the purpose of conforming to customers' requirements." Nowadays, the increase in customer requirements has heightened the complexity of production systems, and production logistics has become more challenging since it now has to deal with tracking and controlling larger product variety, fluctuating demand and inflexible capability.

Production environments demand complete process visibility to control and improve workflow at all times. Production companies, however, often struggle to maintain sufficient up-to-date workflow information, which is needed to ensure a robust and smooth production flow. Work related measurements such as worker utilization and material flow speed are often measured inefficiently or not at all. The traditional tools of the past, e.g. stopwatches, are purely manual, time consuming, prone to errors and no longer effective enough to measure the large number of complex operations. Recently, video capturing technology and on-screen analysis have improved

quality-wise. Both can be used for semi-automatic operation measurement. To convert visuals to managerial data, however, is time consuming. It requires a lot of up-front programming and the results are often inaccurate. This lack of access to complete process data causes low production flexibility, which is insufficient to keep up with the customer specifications and unstable product demand.

RFID technology has received considerable critical attention from a wide range of industries, which all wish to use it to enhance the accessibility of process data (Ivantysynova, 2008). The technology enables the linking of real physical objects to the virtual world of IT (Information Technology) systems. By attaching tags to objects RFID readers can obtain real time information about the identity and position of the objects. RFID systems can automatically track tagged objects within time and space, which makes them effective automatic time and motion measurement tools. It is an instrument that is more advanced and more fit to measure current day production operations than the previous alternative measurement tools discussed above.

Today's RFID systems provide automatic and wireless object identification solutions with increased tag memory, reduced tag prices and improved capability to detect multiple tags without requiring a line of sight. However, currently its main applications remain largely limited to supply chain management. Goods identification, tracking at the gates of distribution centers and stock counting are the most common application areas (Ferrer, 2010). Production logistics applications have also been reported on but success stories with a profound analysis of the role of RFID in this field are few in number. Some advanced RFID-based cases include dispatch rules (Zhong et al., 2012), and the management of assets, tools, returnable containers and pallets in closed-loop systems (Schmitt et al., 2008).

It is still not clear if and when an RFID system is a better option compared to the alternative systems. For instance, is RFID a better solution than bar code scanning as an object identification tool or is it a better investment than video capturing technology as an object tracking tool? In manufacturing, there is a lack of wide spread RFID applications and models, which could be used by managers to evaluate the value of an RFID investment. Enterprise systems need precise shop floor information for accurate decision-making.

Unfortunately, manufacturers do not have such accurate and real-time data collection systems in operation (Zhong et al., 2013).

A significant step to improve plant floor visibility has been the recent development of RTLS (Real Time Location System). RTLS can be considered as an accurate indoor version of GPS (Global Positioning System). RTLS will be explained in detail in section 1.2. Generally speaking, RTLS has been used in manufacturing just to monitor objects in real time, for locating and counting purposes. Few successful cases of RTLS solutions that were able to collect and transform data streams into enhanced enterprise level information have been reported. The implementation and utilization of RTLS for production logistics optimization has not been widely studied before and this offers new research opportunities. This study aims to improve RTLS-based production logistics by use of RFID-based RTLS. This type of RTLS tracks target objects, for example pallets, and provides real time information, e.g. location in time, for which alternative RTLS cannot effectively be implemented.

The research presented in this dissertation develops and empirically tests RFID-based RTLS data analysis methods. The methods introduced are based on experiments conducted at the RFID lab (XiaK/Kortrijk/Belgium) and within the scope of an industry project funded by Flanders' Drive, Belgium that includes three practical RTLS applications in the automotive industry. We develop methods for analysis as well as supporting computer tools to help refine current production logistics models.

1.1. Contribution

This doctoral dissertation analyses the use of RFID-based RTLS in production logistics. We answer the following main research question and associated sub-questions:

- Can RFID-based RTLS be developed into a system that delivers insight about the performance of workflows in order to evaluate and improve the robustness and efficiency of production logistics?
  - What are the key production process measurements and performance indicators to evaluate the robustness and efficiency of production logistics? Which of them can be based on RFID-generated data?
  - How can we process and assess RFID data in order to provide accurate results about the trajectory of tagged objects?
  - Can RTLS real time data be used to analyze complex operations involving human operators?
  - What is the potential use of RTLS real time data in visualizing production logistics performance?

An outline of our main results can be found below.

- This thesis analyzes potential benefits and challenges of applying RFID technology in production logistics. The research approach used here was to conduct experiments both in a controlled lab setting as well as in company case studies. An empirical study on efficient RFID data processing techniques allowed us to conduct the case studies efficiently. This research strategy with one empirical and three case studies enabled us to gain new insights into the data accessibility of plant floor operations through RFID measurements. Despite all the benefits, the technological hurdles we faced during the RFID implementation process posed considerable challenges, which are also faced by organizations that want to use RFID as a strategic enabler. This thesis aims to provide RFID-based RTLS applications for production logistics improvements not found in literature.

- The thesis itemizes key performance indicators and time-motion measurements of plant floor vehicles and materials. We propose general and case specific performance indicators that are considered for manufacturing performance evaluation. With our analysis of key performance indicators and measurements, it is possible to determine which sort of RFID data is required for specific cases.
- Another contribution is to show how RFID data processing can be modeled and integrated into enterprise information systems. We have developed an enterprise data architecture model integrating RFID systems. The model shows the steps of RFID data processing needed to obtain enterprise level information. All process steps are validated by the empirical study and case studies. In the final step, we built a performance dashboard to evaluate production logistics performance.

1.2. RFID technology as RTLS solution

Real Time Location System (RTLS) is an automatic and continuous positioning system that identifies and tracks target objects in a pre-defined space. Fundamentally, RTLS precisely informs/indicates precisely where something is and has been. These systems for indoor usage generally utilize active RFID tags that transmit periodically to RFID reader antennas surrounding a particular area in order to precisely track moving targets (Roberti, 2010).

The difference between conventional RFID systems that are mostly used in supply chain and RFID-based RTLS lies in the continuous tracking of objects. In conventional RFID systems or asset tracking systems, a tag communicates with a reader only at fixed locations (e.g. the entrance of a distribution center). The rest of the facility is out of the systems' interaction space and remains a black box. Moreover, conventional RFID systems are generally incapable of tracking objects while in motion, which severely limits their usability and increases errors caused by failed reads. RTLS on the other hand, is configured for real time visibility of tagged objects through automatic and continuous reporting. The difference between the two systems is represented in Figure 1.1.

RFID-based RTLS extends tag detection space by offering approximate location of objects in real time. Basically, the system employs 4 to 12 RFID readers in a cell (i.e. the cubic area covered by the readers) and each reader antenna has a broad sight up to 100 m. The readers calculate the location of a tag with an accuracy between 1 m to 30 cm and the system is capable of updating the location of a tag each couple of milliseconds. RFID-based RTLS reader antennas usually operate at higher frequency levels than conventional RFID systems in order to enable rapid location update intervals. The system typically operates at Ultra Wide Band (UWB) and in some cases at Ultra High Frequency (UHF).

RFind is a type of RTLS configuration utilized in one of our case studies (see section 4.2) where it is employed to track plant floor vehicles, which in this particular case are automated guided vehicles (AGVs) and tugger trains. RFind uses tags to locate tags. Hence, it is a tag to tag communication technology. The appeal to use this kind of RTLS is to minimize the costs by replacing expensive RFID readers with cheap reference tags. RFind's RTLS locates and tracks objects by using reference tags as readers that create a spatial map (Saxena et al., 2007). Reference RFID tags are placed at fixed points around a site. They create a virtual space by marking these fixed points and basically locate a tagged asset to the reference tag with the highest proximity. The default system configuration and location algorithm are:

- Nearest Neighbors Configuration and Algorithm: The system uses a number of reference tags to locate an asset tag (valid values range from 1 to 8). The default configuration is 8. The algorithm for using this value is:
  - The algorithm's default rule is 'highest signal'. Among 8 nearest reference tags to the asset tag, the one with the highest signal strength (the one closest to the asset tag) is returned. The output value is the identification number of that reference tag.

The main industrial applications of RFID-based RTLS are in manufacturing, healthcare services, transportation/logistics, entertainment, military and security (AT&T, 2011). The value in manufacturing applications is created in tracking business-critical and high-value assets such as forklifts, trains and

automatic guided vehicles (AGVs) in internal logistics. Nevertheless, any object that has a tracking value, a material or an operator, can be included in the system.

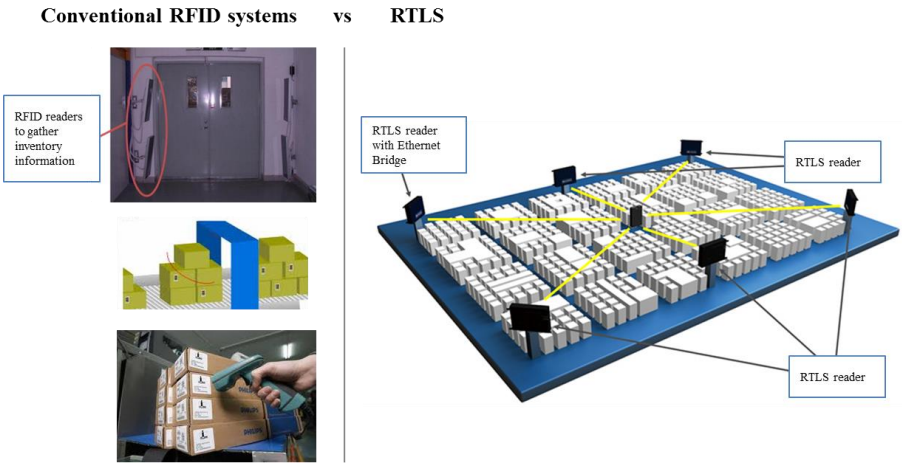


Figure 1.1: Conventional RFID systems vs. RFID-based RTLS

1.3. Research Procedure

This section gives an overview of the structure of the following chapters.

Chapter 2 investigates production logistics performance improvement studies and technical foundations regarding object identification and tracking systems. The performance metrics, measures, measurement systems and visibility of production logistics are briefly reviewed. RFID systems and some other significant object identification and tracking tools are explored and we discuss RFID data process methodologies.

Chapter 3 describes the methodology and associated algorithms to attain and process RFID data of in-plant logistics objects. First, the integration of the RFID data in enterprise data architecture is discussed and an RFID-based enterprise data architecture model design is presented. After this, we list key performance indicators of in-plant logistics vehicles and material flow. Then the findings of an empirical study are demonstrated. During this study we

employed a prototype RFID-based RTLS in an RTLS lab. In order to derive key performance indicators of an AGV from RTLS data, we modeled the activities of an automated guided vehicle (AGV) on a shop floor. In the last section of chapter 3, we describe the design and in-lab testing of a performance dashboard of in-plant logistics vehicles.

Chapter 4 presents the findings of three case studies from the automotive industry. The studies aim at internal logistics improvement by exploiting RTLS. The first case study resulted in efficiency benefits for the quality control department. In the second one, technological drawbacks come into prominence. The third case study yields new insights into traffic control in factories.

Chapter 5 summarizes the theoretical and practical contributions of this research and directions for further research are proposed.

2. Literature Review

The aim of this research is to investigate how to use automated tracking technology in production environments to streamline production logistics. This chapter will therefore provide an overview of production logistics improvement studies to date in the topics of manufacturing strategy, performance, plant floor visibility, tracking technologies and measurement systems. The potential benefits and applications of RFID systems and RTLS integrated with these topics are the main focus points of this literature review.

The outline of the chapter is as follows. In section 2.1., the relationship between manufacturing objectives, performance measurement systems and improvement programs is provided. In section 2.2., different RTLS solutions are discussed. In section 2.3., a comprehensive literature study on RFID systems is presented. Finally, in section 2.4., the conclusion of this chapter is given.

2.1. Convergence among manufacturing strategy, improvement programs and wireless manufacturing

Substantial connections among manufacturing strategy, improvement programs and wireless manufacturing have been established over the last decades. Figure 2.1 shows a schema demonstrating the links from a top-down business perspective in relation to time. The schema basically shows the integration of RFID technology in manufacturing. The components of this schema will be explained further.

Ever since Skinner (1969) pointed out the importance of manufacturing strategy by emphasizing the missing link between corporate and manufacturing strategy, manufacturing strategy has received much attention in both literature and industry (Hayes and Wheelwright, 1984), (Gunn, 1987), (DTI, 1988), (Platts and Gregory 1990), (Kotha and Swamidass, 2000), (Boer and Drejer, 2005).

With the rise of the new manufacturing philosophies in the late 1990s, Sackett et al. (1997) addressed the interface between high level business strategy and manufacturing strategy, and managed to reach a convergence between those two types of strategies. He listed the general competitive dimensions of this convergence as quality, flexibility, time, cost and environment. The prominence of these dimensions changes in relation to the strategy, performance measurement and improvement projects of organizations (Gelders et al., 1994). Among the dimensions of manufacturing strategy, flexibility has been considered of great importance from the early 1990s when mass customization emerged after the eras of crafts and mass production (Johnson, 2008), (Golden and Powel, 2000), (Das and Patel, 2002), (Lim et al., 2007). Mass customization increased product variety in order to meet customer specifications (Duray et al, 2000). Production companies are concerned whether their level of flexibility enables them to adapt to changes in the production process, because the increment in product variety inevitably increased the number of production process steps.

The technological and competitive changes, and the enhancement of organizational innovation unfortunately increased production flow complexity (Damanpour, 1996), (Hynek and Janecek, 2011). Complete visibility of production activities degraded with the increase of both complexity and organizational size. Production planners lack clear visibility into the status of item progress throughout operations, which leads to difficulties to reduce waste and non-value-added activities (Fullerton and Wempe, 2009). Moreover, item level visibility has emerged as an important field of interest among manufacturing management, where the early batch production systems have been turned into item level "flow" production systems (i.e. Toyota production systems) (Coffey and Crandall, 2004). The adoption of a new manufacturing paradigm to improve plant floor visibility has become crucial, especially in discrete manufacturing.

Recently, accessing real-time information by tracking objects has received much attention from manufacturing companies (Zhong et al., 2013). Particularly, automatic and wireless identification and tracking systems that collect and utilize real-time data are in favor (Hu et al., 2014). These kinds of systems are currently being developed as a next generation AMT (Advanced Manufacturing Technology), namely Wireless Manufacturing (Huang et al., 2009). Within wireless manufacturing applications, RFID is being reported a successful system capable of improving manufacturing visibility, metrics and performance.

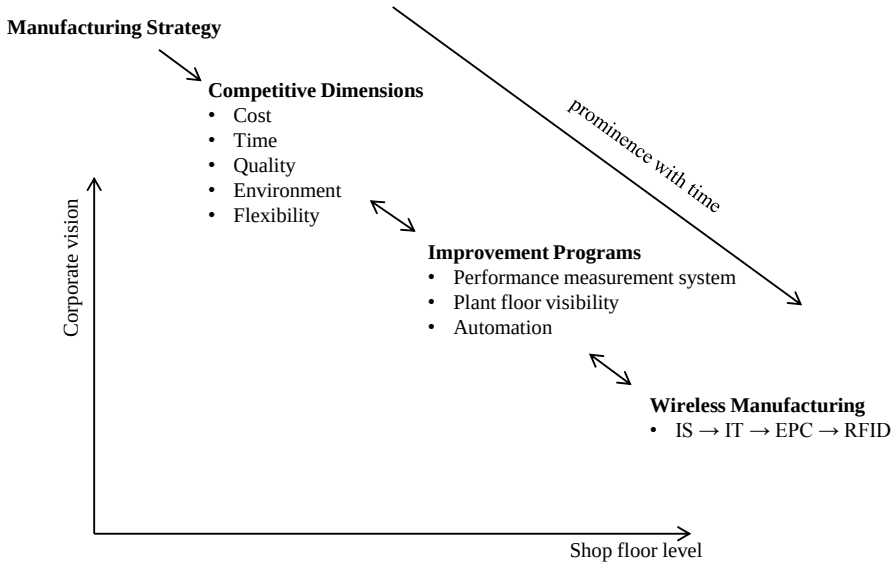


Figure 2.1: Convergence among manufacturing strategy, improvement programs and wireless manufacturing

2.1.1. Manufacturing performance metrics, measures and measurement systems

Performance measures and measurement are critical to the tracking, management and improvement of the competitive performance of manufacturing organizations (Gomes et al., 2011). Most manufacturing companies realize that the performance metrics of a production process need to be measured, managed and improved, and that they should be easily adaptable (Gunasekaran et al., 2001). It is valuable to develop accurate metrics to quantify relevant improvement criteria to assess and direct the organizations' ongoing improvement programs. The improvement programs differ according to companies' manufacturing strategy (Choudhari et al., 2013). Nevertheless, companies in the same manufacturing sector can show similar interests when it comes to improvement criteria. Automotive companies can define their goals towards continuous improvement and cutting costs depending on the competitive marketplace (Al-Aomar, 2002).

Manufacturing performance **metrics**, which are the performance indicators into graded indices, have been categorized within the different dimensions of manufacturing strategy (Gunasekaran and Kobu, 2007). Among these various dimensions, flexibility, productivity, efficiency, quality, time and costs have been considered the most important by manufacturing managements to make the right decisions to contribute to improved organizational competitiveness. Key quantitative metrics are listed in Table and it is important to note that certain indicators interrelate with multiple dimensions. Gelders et al. (1994) stated that the key shop floor performance indicators are lead-time, manufacturing costs, delivery reliability, quality, production and volume/day.

The manufacturing performance metrics are measured based on management categories (Gunasekaran and Kobu, 2007). Some categories are “financial / nonfinancial”, “quantitative / non-quantitative”, and “traditional / modern”. The nonfinancial and quantitative measures of production are the main focus of this research. They rely on operational performance based on time, length, amount and statistical measurements such as mean and standard deviation (Rho et al., 2001), (Gelders et al., 1994).

Manufacturing performance **measurement systems** perform data collection, analysis and reporting of production activities (Neely et al., 2000). Basic data collection methods such as measuring with a stopwatch and surveys have been shifting towards automation by video records and auto-id systems (Ferdows and Meyer, 1990), (Windt et al, 2008). The important aspects of the design of these systems have been highlighted by Maskell (1989) as follows:

“(1) The measures should be directly related to the firm's manufacturing strategy.
(2) Non-financial measures should be adopted.
(3) It should be recognized that measures vary between locations - one measure is not suitable for all departments or sites.
(4) It should be acknowledged that measures change as circumstances do.
(5) The measures should be simple and easy to use.
(6) The measures should provide fast feedback.
(7) The measures should be designed so that they stimulate continuous improvement rather than simply monitor.” (Neely et al., 2000)

Table 2.1: Key quantitative metrics of production

Authors	Metrics	Dimensions					
		Flexibility	Time	Productivity	Efficiency	Cost	Quality
Gunasekaran and Kobu, 2007 Gunasekaran et al., 2001 Gelders et al., 1994 Gomes et al., 2011	product range	x					
	development speed	x					
	production speed	x		x			
	setup time/cost	x					
	length of fixed production schedule	x					
	process cycle time	x	x				
	on-time delivery		x				
	lead-time		x				
	throughput time		x				
	accuracy of scheduling		x				
	setup time		x				
	down time		x				x
	product and process development time	x	x				
	batch size	x		x			
	labor productivity			x			
	work in progress			x			
	production volume/time			x			
	delivery reliability		x	x			
	capacity utilization				x	x	
	overall equipment effectiveness (OEE)				x		
	unit production cost					x	
	overhead costs				x	x	
	rework cost					x	x
	information carrying cost					x	
	quality conformance						x
	scrap						x

2.1.2.Plant floor visibility

Plant floor visibility has often been considered a non-quantitative performance criterion (Gunasekaran and Kobu, 2007). But, the improvement of information technology in complex production environments has played an important role in monitoring and controlling plant floor activities, and in including visibility as a quantifier. Sensors, cameras, auto-id technology, EDI (electronic data interchange) and network services have all been used to improve visibility and advance manufacturing. Recently autonomous logistics control has started to be considered significant and it is expected that real-time information visibility will shift decision making from production planning towards production control (Windt et al., 2010).

Production management generally demands complete and continuous process visibility and precise workflow measurements to refine internal logistics activities (Sauer, 2007). The utilization of automatic and continuous object tracking systems have not advanced to the plant floor (Huang et al., 2009). The provision, behavior, flow and sequence of products, assets, tools, materials and workers have been an important research areas to improve production monitoring systems (Schleipen et al., 2010).

Production monitoring systems are usually linked to manufacturing execution systems (MES) and their main function is to indicate and avoid possible problems during a production process. The identification of objects has for long been the missing link between the constant tracking and the information flow. Automatic identification technology has emerged to cope with this challenge (McFarlane et al., 2003). However, a few unanswered questions impediment the implementation of such technologies:

- What to track in value?
- How to visualize the data?
- How to ensure system robustness?
- What is the ROI (return on investment)?

2.2.Comparison of RTLS solutions

The choice of an RTLS depends on the application requirements. RTLS solutions include different wireless technologies that can provide different levels of visibility. To assess the applicability of RTLS, a number of parameters are considered, including accuracy, precision, complexity, scalability, costs, positioning algorithm, battery consumption, data rate, frequency, encryption, latency, indoor/outdoor, possible interference, range and robustness (Deak et al., 2012), (Curran et al., 2011), (Koppers, 2009), (Liu et al., 2007). Based on the requirements of the companies in the case studies, we compare the accuracy, precision, robustness, data rate, range and frequency benchmarks. Thereafter, based on these benchmarks we make a comparison between and discuss the selection of an optimal solution among different systems below.

Accuracy (location error) is the most essential requirement of RTLS (Liu et al., 2007). The requirement of the case studies presented in this research is to obtain high accuracy with wide area coverage. But, positioning systems generally have the constraint of providing high accuracy (<30 cm) in a small area or providing lower accuracy in a large area (Curran et al., 2011). When judging precision, the consistency of location accuracy is taken into consideration as a measure of robustness (Liu et al., 2007). Together with the consistency of a system, robustness is thought to allow the computation of the location even when some signals are not available (e.g. the signal from a tag is blocked). High location precision and robustness are required for the case studies, as is a system capable of providing high data rate. Data rate is the data acquisition frequency of an RTLS.. The operating frequency range of a system is expected not to interfere with the existing wireless network infrastructure.

Wireless technologies often used in production systems for location sensing include: RFID, Wi-Fi, ZigBee, Bluetooth, Infrared, IEEE 802.11., UWB, Ultrasonic and also hybrid systems (Ahmed et al., 2014), (Deak et al., 2012), (Koppers, 2009), (Ni et al., 2004). Figure 2.2 shows an overview of the classification of wireless-based positioning systems based on application situations. UWB and Ultrasonic solutions provide high location accuracy

and high data rate. UWB (Ubisense) with the use of active tags has very high precision, approximately 15 cm for 95% of the readings (Deak et al., 2012). Location accuracy and data rate are not guaranteed in Wi-Fi systems and many others. The operating frequency range of microwave, low and high frequency does not interfere with existing infrastructure. Liu et al. (2007) addressed that the advantages of active RFID lay in the smaller antennae and in the much longer range (can be tens of meters). Active tags are suitable for the identification of high value assets with stable tag-reader communication for wider area coverage. Active RFID system based on UWB is a better RTLS solution than its alternatives based on the specific requirements of our case studies.

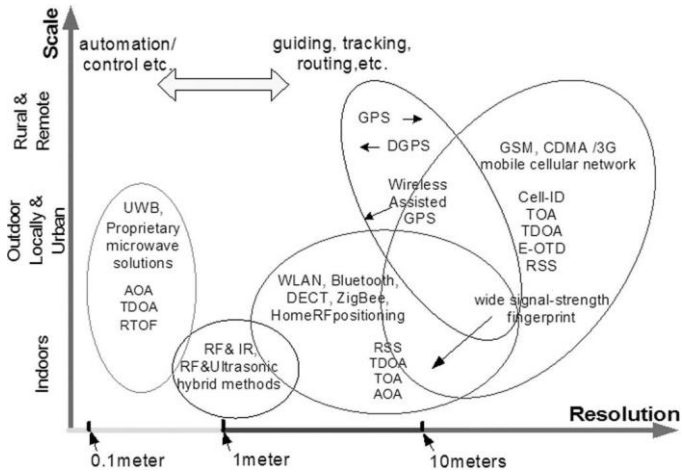


Figure 2.2: The characteristics of RTLS based on their application situation (adapted from Liu et al., 2007)

2.3. RFID System

2.3.1. A brief history of radio frequency identification

Radio Frequency Identification (RFID) was first applied during World War II to determine the friendly aircrafts of the Allied by radar interrogation of transponders (Nambiar, 2009), (Palmer, 2004). Back then, the system was just a covert listening device and was not used for specific object identification. The first patent for the identification of an object by a transponder with memory was submitted by Mario Cardullo in 1973. The first commercial application of this technology can be found in a toll system for vehicle identification in Europe in the 1980s and was followed by the USA when it was used in a highway electronic tolling system (Reyes and Frazier, 2007). The major development and adoption period of RFID started in 2003 when Wal-Mart Company mandated its largest suppliers to use RFID tags on all cases transported to its warehouses. Wal-Mart intended to decrease the costs of logistics activities and to increase inventory visibility (Stapleton-Gray, 2004). In 2005 Wal-Mart announced that it had managed to reduce the number of out-of-stock products on store shelves by 16 percent and to eliminate excess store inventory costs. The next major RFID adopters in their supply chain were Target Corporation (USA), Metro Group (Europe), US Department of Defense, Tesco Corporation (UK) and Albertson's (USA).

RFID systems have now widely been applied to the domains of manufacturing, transportation, healthcare, construction, agriculture and many other services (Reyes and Frazier, 2007), (Ngai et al., 2008), (Hu et al., 2014). This literature study basically covers in-bound logistics applications. Nevertheless, a few noteworthy applications other than manufacturing are summarized below. The main reasons for implementing RFID in manufacturing have been to decrease lead times, reduce inventory costs and improve throughput. Successful production logistics applications are listed in Table 2.2.

- Shipping and transportation: Vehicle tracking at shipping yards (Kim et al., 2008); UPS, USPS and Federal Express track shipments, loading, unloading and terminal operations (McFarlane and Sheffi, 2003)
- Healthcare: monitoring patients to reduce their waiting times; workflow management (Kim et al., 2010)
- Construction: material management, tool tracking for maintenance, tracking pipe spools, personnel management (Jaseiskis and Ei-Misalami, 2003) etc.

Table 2.2: Successful RFID applications in production logistics

Authors	Topic	Field: Company
Schmitt et al., 2008	the management of assets, tools, returnable containers and pallets in the closed-loop systems	automotive: DaimlerChrysler, BMW and Volkswagen
Huang et al., 2008	work in process inventory management of parts and subassemblies	original equipment manufacturing (OEM): Pearl River Delta region, China
Karkkainen and Holmstrom, 2002	on-time delivery management by tracking parts	automotive: Toyota
	parts replenishment management by a new wireless kanban system	automotive: Ford
Chappel et al, 2003	maintenance management by tracking equipment; visibility improvement by tracking materials, work in process, finished goods and assets	paper, plastic and aluminum consumer products and food service packaging: Paxko

2.3.2. RFID technology

RFID technology basically consists of tags, readers and a server. A tag is a transponder including a microchip and an antenna. Tags store and transmit data to readers by radio waves (Nambiar, 2009). Kou (2006) indicates that three types of RFID tags exist: *passive*, *semi-passive* and *active*. This categorization of tags is basically based on their battery specification,

detection range, data transmission model and frequency limit. Table 2.3 lists the characteristics of the three tag types. *Active* tags are generally used for RTLS applications. The main differences between an *active* tag and a *passive* and *semi-passive* tag are the fact that an *active* tag can broadcast continuous signals independent from readers and that it has a longer range of up to 100 m.

Table 2.3: Characteristics of the three tag types

Passive	**Semi-passive**	**Active**
Without battery	With battery	With battery
Cheap	Expensive	Expensive
Limited memory	Moderate memory	Large memory
Short detection range: few centimeters to 10 m	Long detection range: 30 m -100 m	Long detection range up to 100 m
Discontinuous transmission	Discontinuous transmission	Continuous transmission

Readers receive data from tags, send them to a server and the server processes the data. The working principle of RFID is quite similar to a bar-code system. But, unlike earlier bar-code technology, readers can read multiple tags without requiring a line of sight and from further distances (Want, 2006). An RFID reader contains one or more antennas to read tag signals. The three major reader types are fixed (e.g. a reader mounted to ceiling), mobile mounted (e.g. a reader mounted to a forklift) and handheld (Kou et al., 2006). The range of a reader is limited depending upon the frequency band used and the tag type (Curtin et al., 2007). The operating frequency ranges of RFID systems and the interrelation with the tag types are shown in Table 2.4.

Table 2.4: Most popular RFID read range frequencies (adapted from Curtin et al., 2007)

Frequency range	Feature	Application area
LF (Low frequency) 125 – 134 kHz	slow transmission rate short distances (passive tags, < 50cm) penetrates nonmetallic materials (e.g. water) expensive	access control Animal ID livestock wireless commerce
HF (High Frequency) 13.56 MHz	moderate transmission rate short distances (passive tags, to 1m) penetrates nonmetallic materials (e.g. water) lower cost	smart cards ticketing wireless commerce libraries
UHF (Ultra High Frequency) 860 – 930 MHz	high data rate moderate distances (passive tags 1-2m, active tags 10-30m) does not penetrate water and metal low to medium cost	supply chain item management toll roads parking lot access
UWB (Ultra Wide Band) or Microwave Frequency 2.45 GHz	high data rate large data storage long distances (active tags 20 – 100m) do not penetrate water partially effective around metals medium to high cost	internal logistics item management airline baggage

RFID systems generally use active tags to communicate with readers over long ranges (Heo et al., 2006). The readers locate the coordinates of tags through positioning algorithms such as triangulation, k-neighboring algorithm, conventional proximity sensing, Time Difference of Arrival (TDOA), Time of Arrival (TOA) and Angle of Arrival (AOA) (Karl, 2009),

(Heo et al., 2006). A datum that contains the coordinates, the time of a reading and a tag number is then sent to a server. Institutions and providers contributing to the active RFID technology are Auto-ID labs, EPC (Electronic Product Code) Global, Ubisense, Alien Technology, Impinj, Motorola, Zebra and RFind.

Although many RFID applications have been reported, RFID system is still not widely used because of technological limitations. Significant issues that are foreseen to be overcome include standardization, security, cost, collision, location accuracy, amount of data and application requirements (Kaur et al., 2011). For instance, the automotive industry is driven towards an ISO standard to adopt an application-independent cross industry perspective (Hellstrom and Wiberg, 2009). However, some other interrelated industries use the EPC global-standard. The limitations can also be illustrated by the deterioration of location accuracy while tracking fast moving tags without a clear line of sight. When the reader-tag line of sight is obstructed, e.g. by a metallic structure, this can cause reader-tag signal deterioration resulting in wrong coordinate calculations.

RFID **middleware** works as a communication platform between readers, tags and an operating system to handle RFID application requirements. The middleware enables data stream management, application development and process integration (Kou et al., 2006). RFID middleware is significantly useful when collecting and filtering data through continuous data queries of readers (Zhang et al., 2011). For example, IBM (2005) by WebSphere provides RFID with a middleware solution to eliminate duplicate or false data reads, and identifies RFID events.

2.3.3. Methodological Background

This section briefly reviews RFID data mining methods and results, focused on studies about production logistics. The main topics that will be discussed are RFID data acquisition, cleaning, volume reduction algorithms, queries and KPIs.

In a production logistics context, the objects to be tracked are usually products, product parts, materials or assets, such as forklifts, and tools. The

tags that are attached to these objects basically send temporal and spatial data through RFID readings (Wang et al., 2006). Fast and continuous data collection from the tags poses many challenges for data processing and management. The database stores massive amounts of observations with implicit meanings and contains many duplicate records. To cope with these challenges, many studies have focused on how to adjust *data acquisition frequency*, how to select *effective filter methods* and how to transform *implicit data* to *semantic data*.

RFID data acquisition

RFID *data acquisition frequency* is the automatic tag signal reading interval of networked RFID readers (McFarlane et al., 2003). RFID readers can detect signals from multiple tags at high speed (100s per second). The adjustment of the data acquisition frequency is useful to avoid high data streaming and to collect necessary information (Jeffery et al., 2006). The speed of the tags is the main identifier to adjust the data acquisition rate (Ngai et al., 2007). For example, an item can stay at the same location for a long time and collecting location data frequently will be unnecessary in such a case. On the other hand, a forklift can regularly move fast on a shop floor and long location update intervals such as one location update per 10 second can lead to miss important trajectories.

Effective filter methods help to preprocess data to eliminate duplicate and misread records (McFarlane et al., 2003). Many readers are capable of preprocessing data and sending them to a database. However, the readers are still not effective enough and databases need to be post-processed. There are generally two types of RFID applications: history-oriented object tracking and real-time oriented object monitoring (Wang et al., 2006). In history-oriented purposes, data streams are stored in the database and in real-time oriented purposes it is not necessary to store the data. In history-oriented applications the database can be post-processed and preprocess flaws can be debugged.

Gonzalez (2006) demonstrates that the format of RFID data is basically: (*EPC, location, time*) where *EPC* is the identity of a tag with digits, *location* is the position of a tag at the time it is being scanned and *time* is the moment

a reading takes place. RFID records are stored according to a time sequence. An example of a raw RFID database for a single tag where EPC is indicated with *r*, *location* with *l* and *time* with *t* is:

Raw RFID records

r_1	l_1	t_1
r_1	l_1	t_9
r_1	l_1	t_{10}
r_1	l_1	t_{20}
r_1	l_2	t_{23}
r_1	l_2	t_{30}

RFID data cleaning

Data cleaning should be performed to eliminate redundant data from raw RFID records. One notable data cleaning method is clean stay records of a form (EPC, *location*, *time_in*, *time_out*) (Gonzalez et al., 2006). *The time_in* is the moment when a tag arrives at a *location* and *time_out* is the moment when a tag departs from a *location*. The clean stay records filtered from the raw RFID records from the example above can then be displayed as:

Clean stay records

r_1	l_1	t_1	t_{20}
r_1	l_2	t_{23}	t_{30}

Another data cleaning approach is SMURF, which is the "smoothing filter" proposed by Jeffery et al. (2006). In this approach, RFID data streams are statistical samples of tags, and tools such as sliding window, binomial sampling and π-estimators are used to drive the cleaning process. The mechanism takes multi tag speed into account and filters the errors that are caused by speed.

Clean data is basically used for event processing, which is to transform *implicit data* to *semantic data* (Wang et al., 2006). A clean stay record can be named a single event. For example, if 1,000 boxes stayed in location l_A between time t_1 (*time_in*) and t_2 (*time_out*), an event can be registered as (*prod*, l_A, t_1, t_2, 1000) where *prod* is the products' identity and 1000 is the count (Gonzalez et al., 2006). Event-oriented processing can be achieved

either going from single events to complex events or by first defining complex events and then detecting simpler events.

Volume reduction algorithms and queries

Algorithms and queries differ according to the application purpose of the RFID system. Mainstream queries and algorithms to process production logistics data and related data streams include the works of Wang et al. (2006), Gonzalez et al. (2006), Kim et al. (2010) and Furey et al. (2012), and are listed in Table 2.5.

Table 2.5: Mainstream RFID data mining approaches and applications

Authors	Method	Summary
Wang et al. (2006)	complex event processing	Formulation of a declarative rule based approach for automatic RFID data transformation. A graph-based RFID complex event detection engine (RCEDA) is built.
Gonzalez et al. (2006)	path selection queries	Paths of items are queried from RFID-Cuboids (stay, info, map).
Kim et al. (2010)	time-series analysis	Analysis of mean waiting time of patients and automatic workflow management in a health promotion center.
Furey et al. (2012)	node-path analysis	Applying discrete Bayesian filter to estimate future steps of human models based on pre-movement patterns. HABITS (History Aware Based Indoor Tracking Systems).

KPIs from RFID data

Transformation of RFID data to decision-making criteria, including KPIs, is decisive for enterprises to manage their functional operations. The value of RFID-enabled shop floor for enterprises is to retrieve sophisticated real-time

information to advance production planning and scheduling (Zhong et al., 2012). Despite the fact that the technology has been in use for two decades, shop floor applications with successful results are few in number. Published successful works which indicate KPIs extensively are listed in Table 2.6.

Table 2.6: Successful RFID applications and KPI results

Authors	KPI	Result	Company
Karkkainen and Holmstrom (2002)	parts receipts efficiency	reducing production delays	Toyota
	parts replenishment efficiency	modification between storage area and the assembly line	Ford
	assembly conveyor flexibility	benefits by combining the mass production and make-to-order	QSC Audio Products
Bendavid et al., (2009)	minimum downtime	operator level improvements	Electricity utility companies
	cost per operation hour	decrease in cost	
	replacement time	reduction of maintenance time	

2.4. Conclusion

The literature review shows that nowadays numerous manufacturers are aiming to improving their process visibility and flexibility to cope with the changes in production volumes, the production flow complexity and the introduction of new products, which arises from changes in customer requirements. Wireless manufacturing applications are receiving much attention from companies to track production logistics activities and to control complex production processes. Within many applications, active RFID-based RTLS based on UWB communication holds more promises for wide area coverage, stable communication, uninterrupted network, and fast object tracking. However, most of the RFID applications are in use for real time object monitoring solutions. Real time or history oriented data analysis to evaluate production logistics activities are scarce in literature, and the ones found are presented as frameworks. The lack of successful RFID-based RTLS solutions is due to the technological drawbacks (i.e. read rate inaccuracy, inaccuracy of the location estimates, operational difficulties in the presence of metal), data process difficulties (i.e. big data processing) and difficulties to integrate RFID into existing enterprise information systems.

In the next two chapters, we will focus on improving production logistics visibility and flexibility by using RTLS and reducing functional limitations. Chapter 3 presents the experimental research and Chapter 4 demonstrates three case studies on real time and history oriented data analysis.

3. Empirical research: Enabling RFID technology for production logistics information visibility

This chapter presents a methodological study focused on the integration of an RFID-based RTLS into an enterprise information system for improving production logistics activities. In order to reach effective RFID data management, we provide a new enterprise data architecture model and RFID data mining procedures. To validate this we conducted RTLS-based object tracking experiments at the RFID lab XiaK in Kortrijk/Belgium.

The outline of the chapter is as follows. In section 3.1., an enterprise data architecture model that integrates RFID data process methodology in enterprise information systems is proposed. In section 3.2., the key performance indicators of vehicle operations are defined. In section 3.3., a prototype RFID system is described and evaluated. In section 3.4., a performance dashboard design for dynamically processing RFID data in real-time is provided. Finally, in section 3.5., the conclusion of this chapter is given.

3.1. Model of enterprise data architecture

RFID systems can bridge the information gap between the virtual and the physical world, where objects are hard to track and monitor. To achieve this, a new enterprise data architecture model is needed to accommodate an RFID system into an existing enterprise information system and to obtain system integration. Figure 3.1 shows the new data architecture model we propose. The model was designed to obtain high-level actionable information by exploiting an RFID system. Similar enterprise data architecture models based on RFID exist (Zang and Fan, 2007), (Wang et al., 2006), (Dai et al., 2012) and are usually designed for complex event processing to improve operational performance. However, they lack the combination of real-time performance monitoring and history oriented object tracking (see section 2.2.3 for more detail). Our model combines both applications. It contains a history oriented events analysis and a real-time performance dashboard.

The new RFID system components (displayed by the orange boxes in Figure 3.1) are: RFID data, a data process engine and a performance dashboard. A pre-filter configuration pre-processes RFID data to filter redundant data by e.g. eliminating duplicate readings and rectifying errors. The data process engine then cleans pre-filtered RFID data and combines it with operational data to extract events. An event is the occurrence of a singular task such as a forklift loading operation or an uninterrupted movement between two points. While raw positional and timed data from RFID has little meaning, events are meaningful in the context of logistic operations. Events can therefore be used to calculate key performance indicators in the next step. Finally these KPIs feed a performance dashboard. The add-in RFID system components are explored more throughout this chapter.

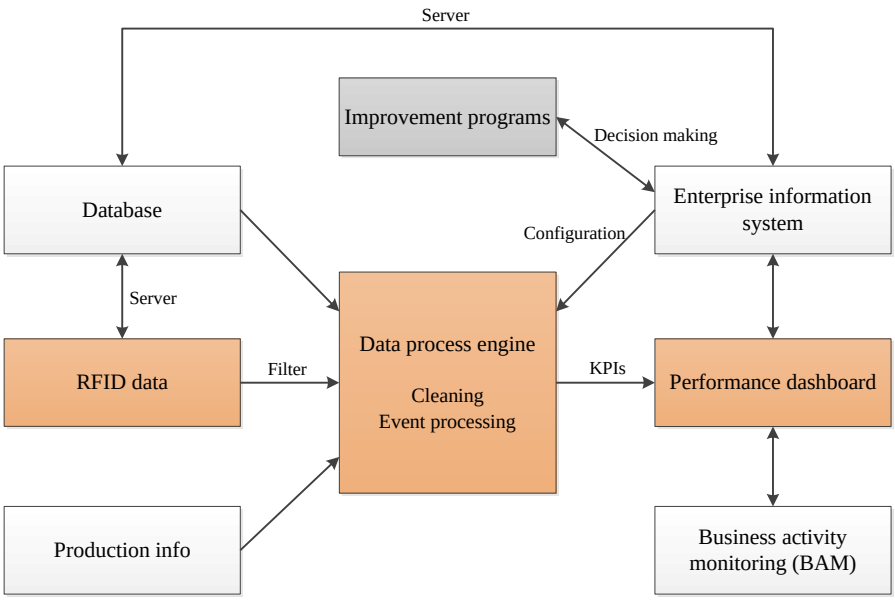


Figure 3.1: Enterprise data architecture model based on an RFID system

3.2. Elaborate KPIs of production logistics vehicles

Table 3.1 lists appropriate KPIs of production logistics vehicles, among which are forklifts, tugger trains or automated guided vehicles (AGVs). The KPIs are categorized in five strategic dimensions of manufacturing and listed in non-financial operational categories (see section 2.1.1). The equations for calculating the KPIs are derived from metrics, which address what needs to be measured. The metrics and the KPIs are discussed further in the prototype system and performance dashboard design sections of this chapter.

Table 3.1: Elaborate KPIs of production logistics vehicles

Strategic dimension	KPI	Equation
Productivity	overall speed	standard speed/ average speed
	order fulfillment	# orders delivered/ total orders
	flow rate	order volume/ time
Efficiency	route efficiency	length of the shortest possible route/ length of the actual route
	loading efficiency	standard loading time/ actual loading time
	unloading efficiency	standard unloading time/ actual unloading time
	loading/unloading variance	loading time/ unloading time
	overall utilization	work time/ total time
	order efficiency	actual time per order/ expected time per order in order list
Time	time ratio	standard cycle time/ actual cycle time
	transportation time	standard transportation time/ actual transportation time
	on time delivery	total number of deliveries on time/ total number of deliveries
Quality	vehicle reliability	lost time due to maintenance/ total time
	transportation reliability	lost time due to wrong deliveries/ total time
Visibility	work in progress	driving, (un)loading, idle =? order list

3.3. Experiments I: A prototype RFID system

We used a simplified example of an RFID-enabled shop floor to illustrate the implementation of the model and to allow experimental validation. This prototype system was initially employed in 2009 for developing the described algorithms before validating them on industrial applications (described in Chapter 4). This empirical research had enabled us to conduct the case studies efficiently. Moreover, it had allowed us to develop RFID-

based RTLS applications with trajectory analysis that were not adequately found available in the literature.

Figure 3.2(a) and 3.2(b) show pictures of the same cross-section of the RFID lab in Xiak with two different setups. Metal blocks were placed in the second setup to simulate a drop in signal transmission. A miniature train represented an AGV and was tagged with an active Ubisense series 7000 compact tag. 4 UWB series 7000 IP RFID sensors were situated at the four corners of a rectangular field forming a detection area of approximately 36 m^2. The sensors were situated at a default height of 3 m and each of them was facing the ground at a 45^0 angle. The sensors located an active tag with at least 2 sensor sightings for a 3-dimensional fix and with a precision of up to 30 cm. Presence detection of the tag was based on conventional RF technology in a 2.4 GHz ISM-band. The sensors were networked and synchronized by timing synchronization via timing cables. One of the sensors was arbitrarily chosen as a master sensor and the rest of the sensors ("slaves") were connected to the master sensor by the cables. An Ethernet switch connected the sensors with network cables. The switch itself was connected to a server computer via Ethernet switch-to-server connection and to a DHCP (Dynamic Host Configuration Protocol) server.

Figure 3.2(a): Photo from RFID lab

Figure 3.2(b): Layout with metal blockages

The server computer was running the Ubisense software. This software performed data collection, allowed system configuration and contained a spatial map to monitor tag motion. The system configuration or cell plan was basically to configure sensors, location algorithms and tags. Table 3.2 lists the system configurations, significant for effective filtering.

Table 3.2: RTLS filter configurations

	Filter Configuration	
Configure	**Parameter**	**Value**
Sensor	Max standard error (0 -1)	0.1
Location algorithm	Location algorithms	AOA, TDOA
Tag	Sleep state (second)	10
	Update interval (millisecond)	109
	Max valid position variance	4
	Horizontal position std dev	2
	Vertical position std dev	1

Max standard error

A standard error parameter determines to which extent measurements have to correspond for a computed tag location to be accepted as valid. It shows the dispersion of the error (the amount by which a location datum differs from its expected value) in the collected data. The max standard error is then, the maximum acceptable standard error for a sighting to be considered as good.

Location algorithms

Location algorithms estimate the tag position based on sensor measurements. Every algorithm can have a number of parameters that control the behavior of the algorithm, and can include known constraints on the motion of tracked tags. The readings are raw position estimates computed by Angle of Arrival (AOA) and Time Difference of Arrival (TDOA) algorithms.

Tag sleep state

A tag contains an automatic sleep feature to save battery. When a tag is immobile for 10 s it automatically goes into "sleep" mode and stops signaling. The tag "wakes up" and returns to continuous signaling when it starts to move again. By using the sleep mode, a tag consumes almost no battery when stationary, but can be tracked multiple times per second when moving.

Tag update interval

The tag update interval is the time interval of a tag-to-reader signal transmission for position calculation. A rapid location update interval, for example 109 ms, allows fast pace tag tracking without missing critical trails.

Max valid position variance

The max valid position variance is the maximum variance of the position observation that should be reported as a valid sighting. It is the sum of the squares of error in x, y and z. So a setting of 4 means that if the tag position is not known to under 2 m, it will not generate a sighting. Note that this is a one sigma point default configuration.

Horizontal position standard deviation

The filter models the motion of the tag as static, but with noise on position. Thus the predicted position of a tag is where it was seen last, but the accuracy in that prediction decreases with time. The horizontal position standard deviation is the rate of increase in the standard deviation of the position in x and y over time. A setting of 1 means that if the tag position was known exactly, one second later the prediction would have a standard deviation of 1 m in each of x and y.

Vertical position standard deviation

As above but for the vertical position of the tag.

Spatial map

Tags can be monitored on an interactive map referred to as a spatial map (Figure 3.3). The map provides a real-time 2D or 3D graphic representation of tag motion space as detectable by the sensors. The map can illustrate the trails of the tags' motion. Any building data such as walls or machines can be graphically represented.

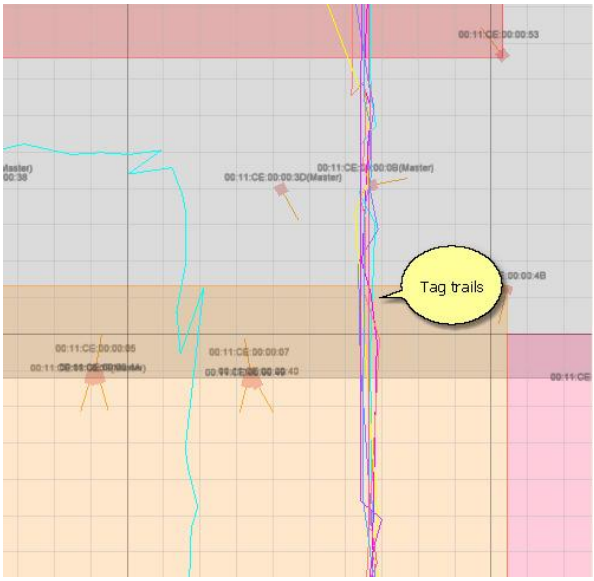


Figure 3.3: Trails of multiple tags on a spatial map

3.3.1. Experimental material flow

A miniature train automatically moved on a miniature railway based on a schedule that demonstrated shop floor vehicles' slow pace operations such as loading, unloading and moving between stations. The schedule followed the material flow model illustrated in Figure 3.4. The train departed from point A to Zone BC to pick up goods. Next, the goods were unloaded at Zone DE. The train stopped at the loading station to carry out the loading process. It arbitrarily moved back and forth to carry out the unloading process. An order cycle was completed when the train reaches point F, after which the train returned to point A for a new cycle. Figure 3.6 plots the rail plan and RTLS layout.

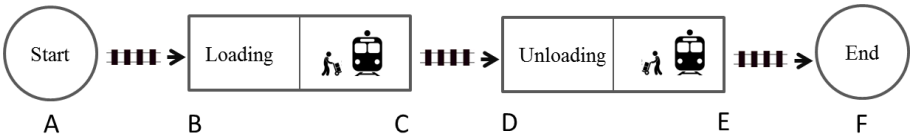


Figure 3.4: Material flow model

Table 3.3 summarizes the essential information about the material flow. The train completed an order cycle in around 35 s and the order list was completed in 13 minutes. The train had two speed limits. One was a slow pace of 0,156 m/s and the other was a fast pace of 0,317 m/s.

Table 3.3: Material flow information

Material flow info	
Total schedule time	13 minutes
Average order cycle time	35 seconds
Variation of cycle time	25 – 43 seconds
Train speed limit	0,156 m/s (slow pace)
	0,317 m/s (fast pace)

3.3.2. Database

The database server was a remote pc suite that could be placed in any available space. The server had a remote access function making the database accessible from different computers within a virtual private network (VPN).

The database contained the data streams of each tag for the complete schedule time and was 774 kb. Data was received in a .csv (comma-separated values) file, which is a compressed plain-text form. Each row in the file contained the instant readings of a tag with default records separated by a semi colon:

- DateTime;x;y;z;Cell;TagID;TagName;BatteryLevel
  - “DateTime” shows the date and time of the instant reading.
  - “x;y;z” are the position coordinates of the tag.
  - “Cell” is a number that represents different RFID-enabled rooms, only used for multi RFID-enabled systems.
  - “TagID” is the serial number of the tag.

- "TagName" is the name given by user to a tag or to the object it is attached to in order to distinguish between the objects.
- "BatteryLevel" displays the battery level of the tag.

3.3.3. Data errors

The unreliable readings or data collection errors can be categorized into three main problem divisions: false negative readings, false positive readings and duplicate readings (Mylyy, 2006). Below they are described further in these three categories.

False negative readings
RFID readers sometimes do not detect tags and this way prohibits readings that are to be collected. This is generally caused by signal interferences, RF collisions or physical obstruction of the signal. False negative readings were barely observed in this particular case, except when the tag was obscured by the metal shielded tunnels (which were put there exactly for this purpose). Only **2%** of the readings failed. The calculation of false negative readings can be described as follows:

- The expected number of readings per second with a 109 ms tag update interval was 9 or 10. The expected total number of rows for 13 minutes of a 109 ms tag update interval was 7155. In reality the actual total number of rows was 7002, so 153 readings failed. The ratio of failed readings to the expected total number of rows was therefore 2%.

False positive readings
RFID data might contain unexpected extra readings. A reader might read a tag where the tag was not actually present, i.e. if readers periodically send wrong tag information. This can be caused by noise in signal transmission, reader response latency or environmental reasons (such as signal reflection). Unexpected extra readings mainly happen in multiple tag environments, where a reader reads a tag it wasn't meant to read. False positive readings were not observed in this scenario.

Duplicate readings

RFID data might contain duplicate observations of readers. This generally occurs when unsynchronized multiple readers in overlapping tag detection areas read and transmit readings independent of each other. In our case four readers were synchronized and a "master" sensor controlled the "slave" sensors. The number of readings per second with a 109 ms tag update interval never exceeded 10, which indicates that duplicate readings were not observed in this scenario.

3.3.4. Location inaccuracy

RFID observations might contain inaccurate tag position estimates. The noise in signal transmission is the main cause of inaccurate positioning. Metallic structures in the environment mostly cause signal deterioration in this prototype system. Location inaccuracy was detected by anomalies in tag motion.

Tag displacement measurements for this experiment were expressed in centimeters for every 109 ms interval. Tag displacement was one of the detection criteria for detecting tag motion anomalies. Displacement measurements exceeding certain control limits indicated tag motion anomalies. Figure 3.5 plots the displacement chart with these control limits, i.e. the train's maximum displacement limit and the system's error tolerance of displacement. Displacement measurements exceeding both the vehicle speed limit and the system's error tolerance were outliers to the system. The percentage of outliers was **3,6%**. The percentage of observations exceeding the maximum vehicle speed limit was **17%**. The calculation of error limits is shown below:

0. Declarations of the variables

n =record time

x_n =vertical coordinate of current time

y_n =horizontal coordinate of current time

d_{tmax} =train's maximum displacement in 109 ms

d_{smax} =system's error tolerance of displacement

d_{xy} =displacement in 2D

d_{xymax} =maximum displacement error limit

1.Displacement limits and formula

$d_{tmax} \quad = 3{,}5\ cm$

$d_{smax} \quad = 30\ cm$

$$d_{xy} \quad = \sqrt{\left(x_n - x_{n-1}\right)^2 + \left(y_n - y_{n-1}\right)^2} \tag{3.1}$$

$$d_{xymax} = d_{tmax} + d_{smax} = 33{,}5\ cm \tag{3.2}$$

Figure 3.6 shows the trail of the tag for the complete experiment. The error areas indicate the locations of frequent inaccurate position estimates. A metal desk and the metal shields, which, as already mentioned, were situated at the same location of these error areas indicate that metallic objects were a primary source of precision loss.

Figure 3.5: Tag displacement chart with error limit

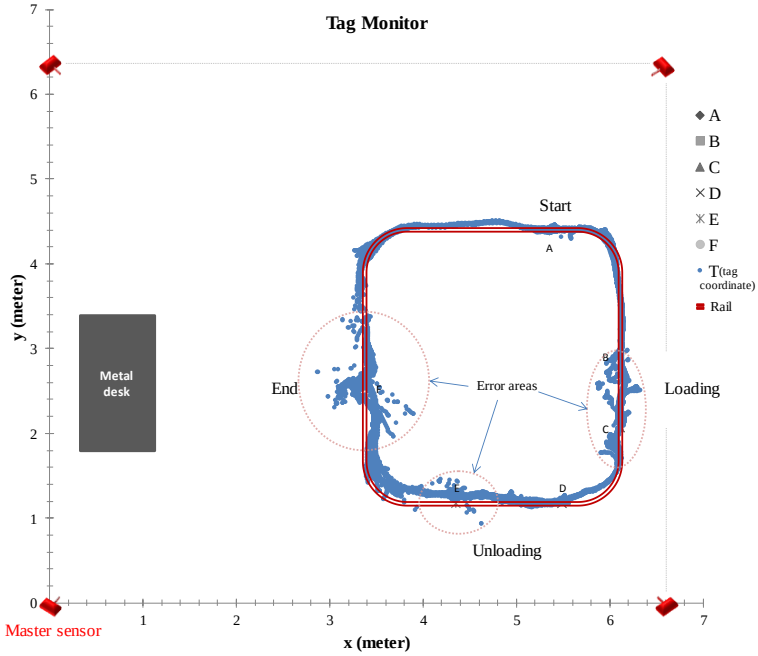


Figure 3.6: Tag monitor with RTLS layout and material flow plan

3.3.5. Data filtering and cleaning

The raw data from the RFID system contained redundant and inaccurate data streams. Therefore it had to be filtered and cleaned in order to be reliable for further event processing and to support potential decision making by company management. Without higher-level data transformation, the raw data cannot be used in enterprise applications. We compared, developed and applied efficient data filtering and cleaning techniques, which can be further integrated into RFID applications. This section does not intend to describe all known RFID data cleaning techniques. We only describe the data cleaning techniques for the inaccurate location measurements we encountered during RFID data inspection. After all, location inaccuracy is one of the main problems in continuous object tracking applications and middleware solutions. Our solution approach is based on tag dynamics and time-location analysis. We applied temporal filters to improve raw data. Two types of filters, displacement and speed, will be described below.

Filter 1: Displacement filter

We developed a displacement filter, which allowed to remove unacceptable system instability errors, namely the tag displacement measurements exceeding the maximum displacement error limit. The max displacement error limit has been described in section 3.3.3.. However, the moment a fault reading occurred did not represent the time span of an actual error. This was because, when a tag signal was momentarily blocked, the readers considered the next readings as almost static for a second. According to the Ubisense software, an actual error extends to a time span of one second, beginning before the time of an instant error. The motion model of the tag was of position with Gaussian Noise on position. The filter then located the actual errors of a second and filtered them from the database. The algorithm of the displacement filter is:

t As Second
$d_{xymax} = 33{,}5\ cm$
For $t = 0$ to EndTime
If $d_{xy}(t) > d_{xymax}$ Then Remove $RowsRange[t-1, t]$
Next t

Filter 2: Speed filter

The speed filter was activated after the displacement filter. It handled two error types: it eliminated *uncertainty* in tag readings and corrected *instant errors* based on tag speed. *Uncertainty* is used to describe the fact that readings carry a lot of noise and are unreliable. *Instant errors* indicate a low noise level, which can be corrected.

First the filter detected speed errors, after which it sorted them according to the two error types. Based on this, it either removed noise readings or corrected *instant errors*.

A speed error was a speed measurement exceeding the speed limit tolerance of the system. A speed measurement was the instant speed of the tag in between two consecutive readings. The speed limit tolerance was 2-sigma above the mean of the speed measurements. The speed measurements

followed a Gaussian distribution. The speed limit tolerance is represented with s_{max}:

$$s_{max} = \bar{s} + 2\sigma_{\bar{s}} \text{ (m/s)} \tag{3.3}$$

Uncertainty represented noise readings within a one second time period during which the number of speed errors exceeded one. According to the data filter configuration settings, the time range of one second indicated the time span of an actual error. The speed filter detected and removed the noise in readings by using a sliding window. This is a window with a certain size that moves with time (Bai et al., 2006). A window had a time coordinate of [t_1, t_1 + window_size], after τ, the coordinate became [t_1 + τ, t_1 + window_size + τ]. The following rule presents the algorithm. It first scans for speed measurements higher than s_{max} and then spots the one second time frames with two or more speed errors. In the final step the algorithm removes rows of data containing uncertainty.

OBSERVATION ($s \geq s_{max}$)
OBSERVATION (Count $s \geq 2$)
within (s_t, s_{t+1})
IF Correct
$\Rightarrow$ REMOVE: $RowsRange[t-1, t+1]$

Instant errors were location measurement errors in a 109 ms time frame. However, an actual error occurred in a one second time frame (see Filter 1). A one second time frame approximately contained nine fault readings. A smoothing window corrected the coordinates of the errors based on reliable readings just before and after their occurrence. The window interpolated nine points at equal intervals between reliable readings. The distance between two reliable points depended on the line type. The line can be straight, curved or combination of both. The interpolation of the smoothing window for a straight line for *n* errors begins after time *t* is:

$$x_{en} = x_t + \frac{n*(x_{t+1}-x_t)}{10} \text{ n = 1,2,…,9} \tag{3.4}$$

$$y_{en} = y_t + \frac{n*(y_{t+1}-y_t)}{10} \text{ n = 1,2,…,9} \tag{3.5}$$

3.3.6. Event processing

Event processing is a method of data analysis to derive high level information from sets of low level data. It is important to integrate this method into RFID applications to obtain more valuable, actionable and business oriented information out of primitive or low level data (Zang and Fan, 2007). The approach can be integrated into manufacturing activity monitoring and system management.

Events were generated by the analysis of the clean data that was obtained from the previous data filtering and cleaning section.

An event is an occurrence of interest in time (Wang et al., 2006), e.g. a loading activity. Events were categorized into *single* and *complex events* and the relationships between them were causal. A *single event* was a loading, an unloading or any other single activity within a *complex event*. A *complex event* was, in this case, the cycle of the train to fulfill one order. We first detected *complex events* and then extracted *single events*.

In the following discussion, E represents the event type and e is an event instance.

Definition 1: RFID data contains the primitive reader observations (instant readings of tags) of vehicle activities. A primitive reading is in the format of (TagID, *x*, *y*, *t*), where "TagID" is the serial number of the tag, "*x*, *y*" are the position coordinates of the tag and "*t*" shows the time of the instant reading. The start and end time of the instances are equal, $t_{start}(e) = t_{end}(e)$. A *single event* represents the temporal expression of a single activity formed by a distinguishable pattern of primitive reader observations over a period of time. *Single events* were only loading and unloading activities in this case. The events were categorized according to the functions velocity, distance and time $E_s = (\vec{\boldsymbol{v}}, d, t_{start}, t_{end})$. Figure 3.7 illustrates the functions as used in *single event* expressions.

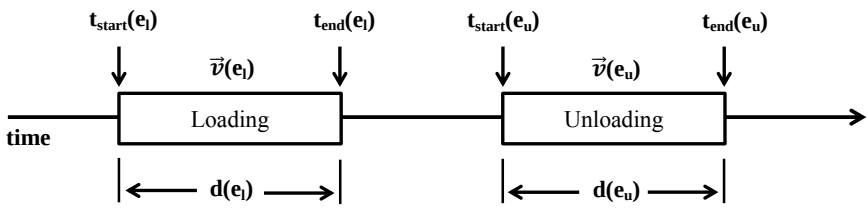


Figure 3.7: Single events

Velocity denotes the direction of the vehicle. Velocity with a negative sign represents the backward movement of the vehicle, more precisely the counter-clockwise direction. The sign notation is calculated based on Figure 3.8:

(x_o, y_o) = the coordinates of the origin of the rail layout
(x_t, y_t) = the coordinates of the tag position at time t

If $(x_{t-1} - x_o)(y_t - y_o) - (y_{t-1} - y_o)(x_t - x_o) < 0$ then the train moves forward (notation: 1)
If $(x_{t-1} - x_o)(y_t - y_o) - (y_{t-1} - y_o)(x_t - x_o) > 0$ then the train moves backwards (notation: -1)

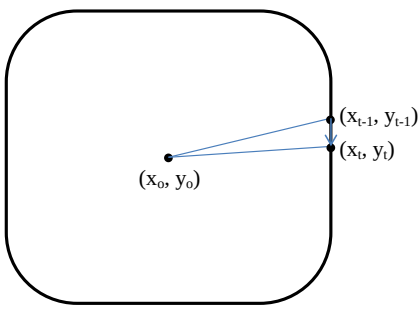


Figure 3.8: Tag direction

Table 3.4 lists all *single events*, in this case the loading and unloading activities.

Table 3.4: All single events

Single event	***x* , *y* (m)**	**distance (m)**	**average speed (m/s^2)**	**t_{start} (hh:mm:ss.000)**	**t_{end} (hh:mm:ss.000)**	**backwards (sec)**
Loading						
El1		0.56	0.152	10:49:00.649	10:49:04.288	
El2		0.86	0.196	10:49:47.526	10:49:51.834	
El3		0.75	0.193	10:50:35.322	10:50:39.890	
El4	x_{start} = 6,11	0.99	0.225	10:51:25.109	10:51:29.436	
El5		0.88	0.184	10:52:13.000	10:52:17.763	
El6	x_{end}= 6,11	0.87	0.208	10:53:02.900	10:53:06.180	
El7		0.89	0.177	10:53:50.725	10:53:55.630	
El8		1.13	0.170	10:54:40.469	10:54:43.957	
El9	y_{start} = 2,92	0.87	0.192	10:55:28.250	10:55:32.763	
El10		0.86	0.198	10:56:19.000	10:56:23.360	
El11	y_{end} = 2,073	0.66	0.159	10:57:08.886	10:57:12.961	
El12		1.29	0.093	11:21:37.725	11:21:43.326	
El13		1.78	0.138	11:22:37.398	11:22:41.834	
El14		1.04	0.092	11:23:39.635	11:23:48.540	
El15		0.90	0.118	11:24:37.379	11:24:44.833	
Unloading						
Eu1		1.55	0.187	10:49:09.705	10:49:17.923	1.2
Eu2		1.56	0.180	10:49:56.957	10:50:05.596	1.3
Eu3		1.62	0.170	10:50:44.924	10:50:54.417	1.0
Eu4	x_{start} = 5,49	1.69	0.205	10:51:34.199	10:51:42.416	1.6
Eu5		1.47	0.195	10:52:23.700	10:52:30.526	1.3
Eu6	x_{end}= 4,355	1.97	0.192	10:53:10.540	10:53:20.706	2.5
Eu7		1.88	0.221	10:54:00.544	10:54:08.980	2.3
Eu8		1.85	0.229	10:54:48.872	10:54:57.900	2.3
Eu9	y_{start} = 1,17	1.63	0.178	10:55:37.776	10:55:46.834	1.2
Eu10		1.77	0.195	10:56:28.653	10:56:37.635	1.5
Eu11	y_{end} = 1,17	2.03	0.137	10:57:19.109	10:57:29.710	2.2
Eu12		2.39	0.177	11:21:48.654	11:21:58.379	2.5
Eu13		1.50	0.148	11:22:48.635	11:22:58.597	2.8
Eu14		2.12	0.160	11:23:54.330	11:24:03.559	3.9
Eu15		1.54	0.132	11:24:50.218	11:25:01.815	3.0

Definition 2: A *complex event* represents the temporal expression of a set of logically related *single events*, such as a complete order cycle. The cycle in this case is displayed in Figure 3.4. A *complex event* is categorized according to the functions velocity, distance and time $E_c = (\vec{v}, d, t_{start}, t_{end}; E_s)$. Single constituent events are combined by event constructors:

- SEQ(:) : Sequence of two events such as E_{c1} and E_{c2}, $E_{c1} : E_{c2}$, occurs when E_{c2} occurs given that E_{c1} has already occurred.
- NSEQ(;) : Two events occur non-sequential or in a different order to each other. This gives flexibility to consider related but non-sequential events within a *complex event*.
- AND(∧) : Conjunction of two events such as E_{l1} and E_{u1}, $E_{l1} \wedge E_{u1}$, occurs when both events occur disregarding their occurrence order.
- OR(∨) : Disjunction of two events such as E_{l1} and E_{u1}, $E_{l1} \vee E_{u1}$, occurs when either E_{l1} or E_{u1} occurs.
- NOT(¬) : Negotiation of an event E, ¬E, occurs if no instance of E ever occurs.

3.3.7. Results

In this section we present the computational RFID data analysis results of the experiments on the prototype system. The results contain the qualitative evaluation of the data and the statistics of the significant events. Only results that aim to demonstrate possible contributions of an RFID system to current material flow information are described below.

Data quality

The quality of the *raw* and *clean data* was assessed. Table 3.5 summarizes the results of this evaluation.

The quality of the *raw data* or basically the RFID system was evaluated based on two categories: read rate and location accuracy. The read rate accuracy was the percentage that remains from the database after data errors had been excluded from it. The total amount of data errors was 2% and these errors were failed readings of the readers. Therefore, the read rate accuracy of the system was **98%**. The location accuracy was the percentage of the database remaining after inaccurate measurements of location had been excluded. The inaccurate measurements of location were the combined set of outliers of displacement measurements and off the track points on the tag monitor. The total percentage of outliers and off the track readings was 20,5%. Therefore, the location accuracy of the raw data was **79,5%**.

The quality of the *clean data* was evaluated based on two categories: removed redundant data and location accuracy. The redundant data was constituted by the errors eliminated by the displacement and speed filter. The percentage of filtered out redundant data was 13%. Therefore, the percentage of the *clean data* without redundancy and data errors was **87%**. As described above, after the redundant data had been removed, inaccurate location measurements were corrected by the speed filter. Eventually, the location accuracy improved to **100%** as all tag positions were within control limits.

Table 3.5: Quality of the raw and clean data

Data quality		
	Raw data	Clean data
Read rate accuracy	98%	-
Location accuracy	79,5%	100%
Row count	7002	6087
Data reduced (%)	-	13%
Errors eliminated by displacement filter	-	2,7%
Errors eliminated by speed filter	-	10,3%
Errors corrected by speed filter	-	7,5%

Events

Event statistics are the result of the analysis of the complex and single events. In total 15 order cycles including loading and unloading activities were detected within a 13 minutes time frame. Both velocity and time functions of these events were examined. The representation of these events is:

$$\sum_{n=1}^{15} E_{cn} = \sum_{n=1}^{15} (\vec{v}_n, t_{startn}, t_{endn}; E_{ln}: E_{un}) \qquad (3.6)$$

Figure 3.9 illustrates the speed distribution graph of the complete flow with loading and unloading speeds. The loading and unloading activities were

performed at slow pace speed. The two operational speeds of the train (see section 3.3.1.) were observable at the peaks of the graph.

The statistical results about the direction of motion are summarized as follows:

- In the total flow the train moved backwards 4% of the time.
  - After 19 seconds till 22 seconds the cycles started, the train moved backwards 73% of the time.
  - After 28 seconds till 33 seconds the cycles started, the train moved backwards 33% of the time.

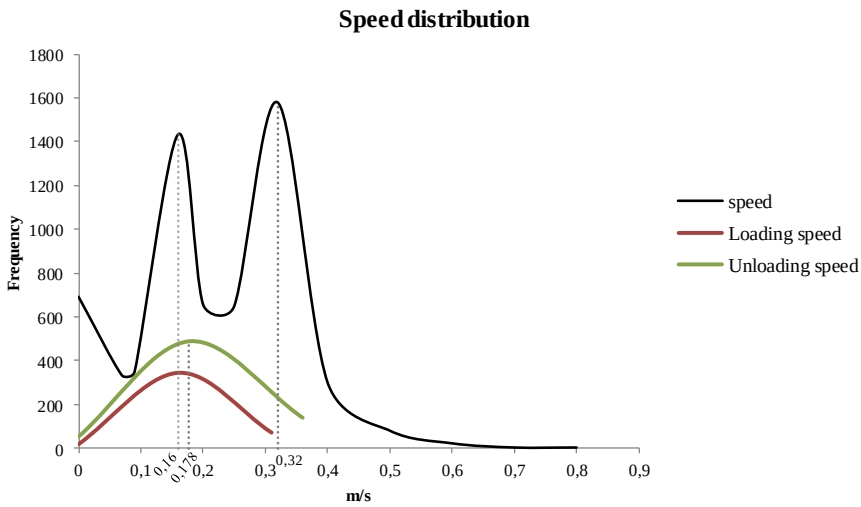


Figure 3.9: Speed distribution graph

Table 3.6 summarizes the time distribution of cycles, loading and unloading activities.

Table 3.6: Time distribution

Time distribution in seconds		
	Mean	SD
Cycle time	38	5
Loading time	5	2
Unloading time	9	1

3.3.8. Comparison with real case scenarios

We compared the prototype RFID system with manufacturing applications. The utilization of the RFID system is likely to differ when scaled up to a shop floor level. Because the average shop floor area is much larger, e.g. 300 m^2 in comparison to the lab case of 36 m^2, the number of readers will probably have to be increased to cover this bigger space. A lot more tags will be needed to track many different objects and one can assume that the vehicles on the shop floor will move faster than the toy train. Tag signal interferences might be higher because of the crowded and metallic infrastructure characteristic for shop floors. Vehicles and materials will move between racks, machines etc., which can cause signal blockages. Tag read update rate is likely to be higher than 109 ms, and might even run up to seconds or minutes. This increment will decrease the data acquiring frequency and reduce the database size. Moreover, the RFID system will probably be utilized for longer periods of time, for example an entire shift, and if the system is used in a history-oriented approach, this can cause an enormous increase in database size. To avoid exceeding the database server size limit, data pre-filtering will be significant. Lastly, the location error tolerance limit will increase due to larger work spaces and longer distances between working units. The overlap of location data will be reduced and therefore location inaccuracy will be less significant.

The list of observations relevant for scaling up the prototype system to shop floor level can be summed up as follows:

- More RFID readers to cover wider area
- More than one tag scenario

- Crowded and metallic infrastructures increase signal interferences and blockages
- Less frequent tag read update rate
- Faster tag speed
- A lot more RFID system utilization time and higher database size
- Data pre-filtering to avoid exceeding database server size limit becomes a priority
- Wider working areas, longer distances between work units and less significant location inaccuracy

As part of the research performed for an innovation project within automotive companies, we investigated several industry-size cases, which exhibit the characteristics mentioned above. We refer to chapter 4 for a full description of this research and its results and findings.

3.4. Experiments II: Real-time performance monitoring of in-plant logistics' vehicles based on RFID data

A performance dashboard was designed and tested for vehicle performance monitoring. The purpose of this dashboard was to support dynamic analysis of in-plant logistics activities and employed RFID-based RTLS data to extract KPIs of vehicles. This kind of RFID performance monitoring system was up to now largely missing in literature. It provided detailed performance metrics through RTLS data analysis. The dashboard was tested at the RFID lab in XiaK/Kortrijk/Belgium. Figure 3.10 shows a picture of the lab with the rail setup. The area as well as the RTLS installation was the identical to the ones as in the previous experiment. In this case a different rail setup was used. Figure 3.11 presents the layout of the rail. The test results showed that the dashboard accurately monitors the performance of the vehicle in near real-time.

In this section, a performance measurement system is defined first. Secondly, the dashboard design and algorithms are provided. Thirdly, the test set up at the RTLS lab is described. Lastly, the test results are presented.

This study was also published as a master thesis under my supervision (Buyser, 2011).

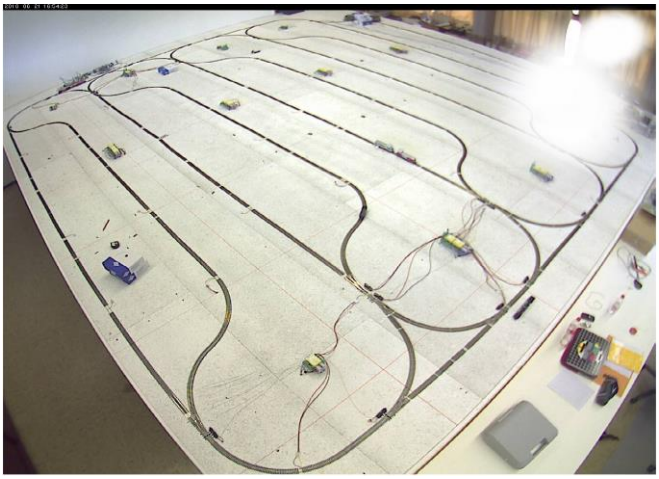


Figure 3.10: A picture of the new rail setup from the RFID lab

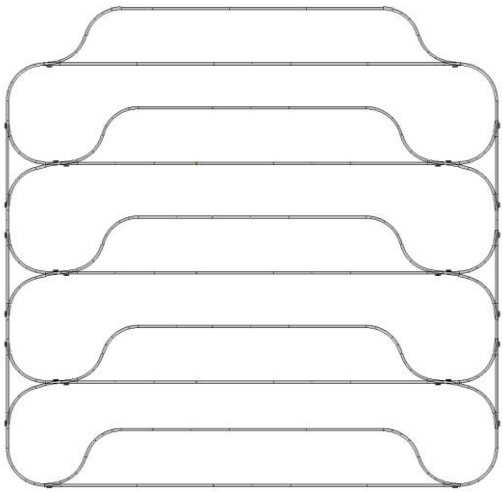


Figure 3.11: The rail layout of the second experiment

3.4.1. Performance measurement system

A performance measurement system was defined to be able to measure the performance of in-plant logistics activities. The system contained a set of processes and tools that were used to monitor the functioning of a unit of interest, e.g. an internal logistics department, allowing the user to draw conclusions and take action if necessary. The system was based on the utilization of an RFID-based RTLS.

The Measurement System Development Process (MSDP) of EERL at Virginia Tech was employed as a guide to design the performance measurement system (Chearskul, 2010). MSDP is a dynamic analysis tool that assures that the measurement system remains in line with business objectives and is updated when the units of analysis change. MSDP consists of six steps which all have to be executed to obtain system integrity. We apply these steps to the case at hand in what follows.

Step 1: Define the need for measurement

The purpose of the measurement system and the required information to execute the necessities were determined in the first step. The goals of the measurement system were:

- To monitor the performance of internal logistics.
- If multiple vehicles are deployed at the same time, check if the workload is equally divided amongst all the logistics vehicles.
- Check for improvements in:
  - Work method: Are the work methods used efficiently?
  - Equipment: Are there too many breakdowns due to bad equipment?
  - Layout: Are there obstructions that can hinder the vehicles' movements or are the distances between different work areas too far?

The information requirements to execute the necessities based on the available RFID system were:

- RFID data: location of the vehicle(s)
- Order list: contains the details of the orders that need to be fulfilled

Step 2: Define what we do

This step is to determine the mission and the vision of the internal logistics management. The mission to employ RFID in internal logistics is basically to deliver logistics services when needed. It is aimed at delivering an on-time, accurate and efficient flow of goods. The vision can be to reach a higher rank in internal logistics management by obtaining a flexible and predictable flow of goods throughout the plant. Therefore, the reliability, flexibility and efficiency of internal logistics are significant for the mission and the vision of internal logistics management.

Step 3: Define what we must excel at

This step is essential to define success or key performance areas (KPAs) of internal logistics vehicles. The KPIs in section 3.2. are modified here to fit into the dashboard. KPAs were:

- **Efficiency**: Improve the efficiency and keep the cost of the internal logistics to a minimum.
- **Reliability**: Improve the reliability of the internal logistics and analyze the causes of lost time. Quality and time strategic dimensions in section 3.2. are merged here under the title of reliability.
- **Productivity**: Increase the productivity of internal logistics.
- **Visibility**: Improve the visibility of internal logistics processes.

Step 4: Define how we know if we're successful

Specific metrics to build KPAs were determined. Metrics Development Matrix (MDM) was used for the data entry of metrics and as a checklist to determine if the metrics were valuable. The value of the metrics was assessed by the amount of required data collected and based on to the weighting factor of the metrics given by the user. The data entries of MDM were:

- Metric Specification:
  - Metric (Name)
  - Operational definition and/or formula
  - Purpose of the metric
  - Metric owner
- Graphical Representation:
  - Portray update frequency
  - Type of data
  - Portrayal tool
- Data Collection Plan:
  - Tracking tool
  - Data available
  - Data collection responsibility
  - Data collection tool(s)
  - Data collection frequency
- Utilization:
  - Implementation date
  - Metric goal

Some of these parameters were unnecessary for this empirical study and were therefore excluded from MDM. Table 3.7 shows the essential parameters of the 19 metrics that were chosen for MDM. The complete MDM can be found illustrated in the appendices (Appendix A: Metrics Development Matrix).

Table 3.7: Significant metrics of in-plant logistics vehicles

Number	Metric	Operational definition or formula
KPA: Visibility		
1	Location of the vehicle	Coordinates + Area of location (=zone)
2	Status of the vehicle	Driving, waiting, (un)loading, idle or error
3	Order list progress	Display the current order and progress in order
KPA: Efficiency		
4	Overall efficiency	Actual total time per order/ expected time per order
5	Transportation efficiency	Expected transportation time/ Actual transportation time
6	Average speed	Average speed while status = 'Driving'
7	Route efficiency	Length of the shortest route possible/ Length of the actual route
8	Loading efficiency	Standard loading time/ Actual loading time
9	Unloading efficiency	Standard unloading time/ Actual unloading time
10	Load/Unload time variance	Loading time/ Unloading time
11	Overall utilization	Work time/ Total time
12	Percentage loaded	km driven while loaded/ total number of driven km
KPA: Reliability		
13	Lost time percentage	Total lost time/ Total time
14	Vehicle reliability	Lost time due to defects/ Total time
15	Mean time to repair	Average duration of a defect
16	Route reliability	Lost time due to 'Off track'/ Total time
17	Picking reliability	Lost time due to wrong deliveries/ Total time
KPA: Productivity		
18	Orders picked per time	# of orders picked/ hour
19	Orders picked/ distance	# of orders picked/ km

Step 5: Implement the measurement system

The measurement system for our case was the dashboard design, which is explained in the next section.

Step 6: Utilize the measurement system

The purpose of this step was to test the dashboard and to evaluate the results. The test results demonstrated the performance of the vehicles and the measurement system. Any change necessary in the measurement system had to be redefined in step 1.

3.4.2. Dashboard design and algorithms

We designed a dashboard to acquire information about how the production logistics vehicles were currently performing and what to improve to best fit the needs and interests of a plant manager.

The proposed dashboard consisted of multiple screens. A central '**Summary view**' presented the overall performance of the vehicles through basic metrics. This central screen displayed multiple vehicles. A more in-depth view of a vehicle or its KPAs was accessible through the links '**Visibility**', '**Efficiency**' and '**Reliability**'. Although '**Productivity**' was not on the main screen, it could be automatically displayed on the results screen. Productivity was only calculated for the complete schedule time. Smaller time frames could lead to miscalculations, because productivity was based on distance and per order. Each screen is discussed further below.

Screen 1: Summary view

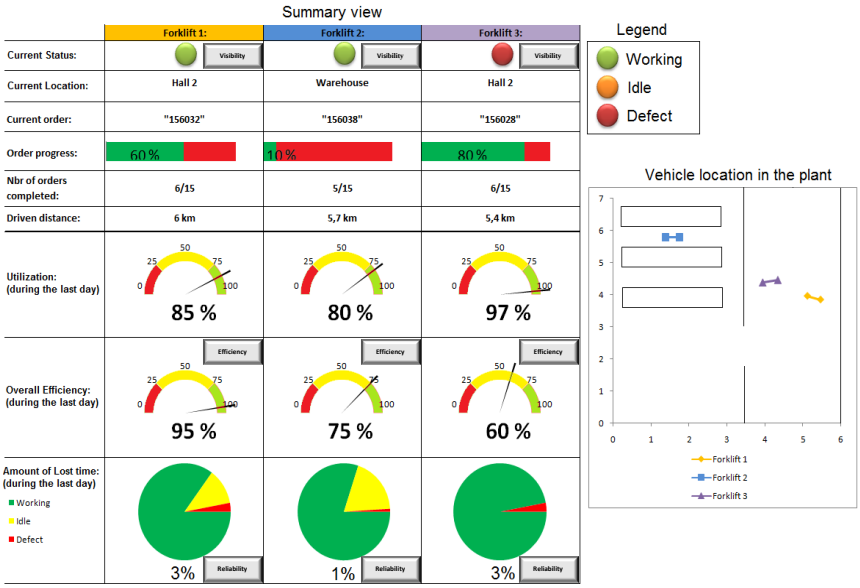


Figure 3.12: Screen 1: Summary view

The summary view displays the performance of each production logistics vehicle. Figure 3.12 presents an example of three forklifts with a couple of metrics for easy comparison of their performance.

The metrics are computed and displayed in two time frames: *current time* and *last day*.

The upper part of the screen, which contains 'Current status', 'Legend', 'Current Location', 'Current order', 'Order progress', 'Nbr of orders completed', 'Driven distance' and 'Vehicle location in the plant' displays information about the *current time*. Whenever occasional errors occur or when wanting to check the progress in the order list, the best option is to look at the current time. 'Current status' shows the three states of a vehicle with a green (working), yellow (idle) or red (defect) sign. A green sign indicates that a forklift is working on the current order. It does not give any information about the activity it is performing such as loading or unloading

(go to Visibility screen). A yellow sign indicates that a vehicle is in a parking spot located outside of the work area. A red sign indicates an error state, which is when a vehicle stands still in an unexpected area or it is situated off the track. 'Current Location' lists the name of the plant floor division where a vehicle is. 'Vehicle location in the plant' shows the exact tag locations on a dynamic map. 'Current order' gives the order number. 'Order progress' presents the progress of the current order with a green progress bar as well as in percentages. 'Nbr of orders completed' displays the number of completed orders in the order list. 'Driven distance' shows how many kilometers vehicles have traveled until the screen time during the current order.

The *last day* time frame can best be used for a general view or a quick overview of the performance. The lower part of the screen displays the performance of the last day by 'Utilization', 'Overall Efficiency' and 'Amount of Lost time'. 'Utilization' is shown with a gauge meter. The color scale on a gauge indicates good (green), low (yellow) and unacceptable (red) conditions in percentages. 'Overall Efficiency' is also shown with a gauge meter. This allows a dashboard user to quickly respond when utilization or efficiency decreases to a low level. 'Amount of Lost time' is presented on a pie chart with defect percentage. The color scale on the chart shows the working (green), idle (yellow) and defect (red) time distribution.

Algorithms for Summary View

The algorithms of 'Current status', 'Vehicle location in the plant' and 'Order progress' are presented here:

- The 'Current status' sign selects the color by finding the match between vehicle speed, instant coordinates, layout info and order list. The layout is divided into three sections according to the order list: working lanes, driving lanes and park spots. Working lanes represent loading and unloading areas. Driving lanes are the routes between working lanes. If a tag is in a working lane or moving in a driving lane then it is working. If it is at a parking spot, then it is in idle state. If it is out of working lane or parking spot, or stops on a driving lane, then it is defect.

The algorithm is simply:

for *OrderList*$_n$ select *WorkingLanes*, *DrivingLanes*, *ParkSpots* from *LayoutInfo*
If *Coordinates* within *WorkingLanes* And If *Speed* > 0 within *DrivingLanes* Then display *GreenSign(Working)*
ElseIf *Coordinates* within *ParkSpots* Then display *YellowSign(Idle)*
ElseIf *Coordinates* off (*WorkingLanes*, *ParkSpots*) Or *Speed* = 0 within *DrivingLanes* Then display *RedSign(Defect)*

- 'Vehicle location in the plant' displays exact coordinates (x, y) of vehicles on a dynamic map.

- 'Order progress' algorithm uses this formula to present order progress rate:

$$Order\ progress = \frac{Time\ passed\ for\ the\ order\ (Green\ bar)}{Standard\ order\ completion\ time\ (Red\ bar)} \times 100 \quad (3.7)$$

Screen 2: Visibility

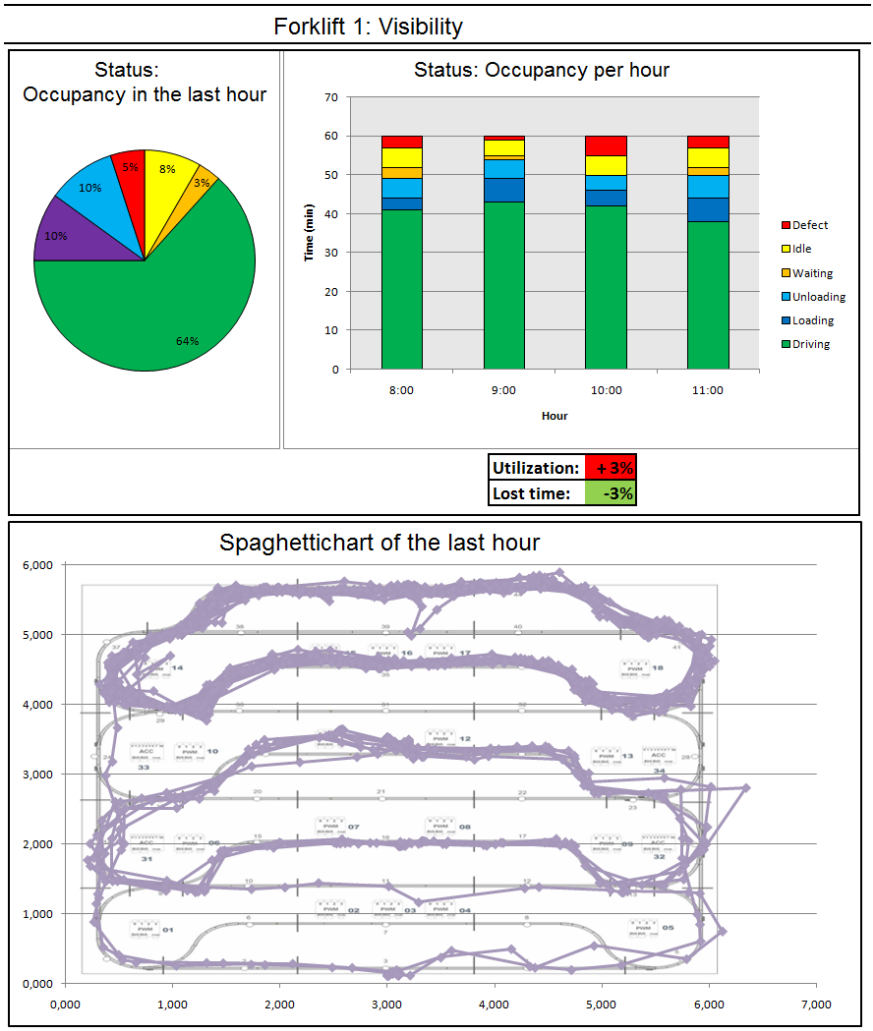


Figure 3.13: Screen 2: Visibility

This screen illustrates the status and trail of a vehicle in detail. Figure 3.13 displays an example of a forklift visibility screen. The status of a vehicle is presented in two time frames: hourly and daily. The 'Status: Occupancy in the last hour' as well as the 'Spaghetti chart of the last hour' show the situation hourly and 'Status: Occupancy per hour' provides the daily status of the forklift. 'Status: Occupancy in the last hour' and 'Status: Occupancy

per hour' illustrate the distribution of defect, idle, waiting, unloading, loading and driving status in the charts per hour. The change in utilization and lost time in the last hour is indicated in percentages. In the bar below 'Status: Occupancy in the last hour' we compare the changes that occurred between 11:00 and 10:00. An improvement is indicated with a green mark and a negative percentage (e.g. Lost time was reduced by 3%). A decline is indicated with red mark and a positive percentage (e.g. Utilization declined by 3%). The color representation and percentages are provided to improve the overall legibility of the dashboard. 'Spaghetti chart of the last hour' displays the trail of the vehicle for the last hour.

Screen 3: Efficiency

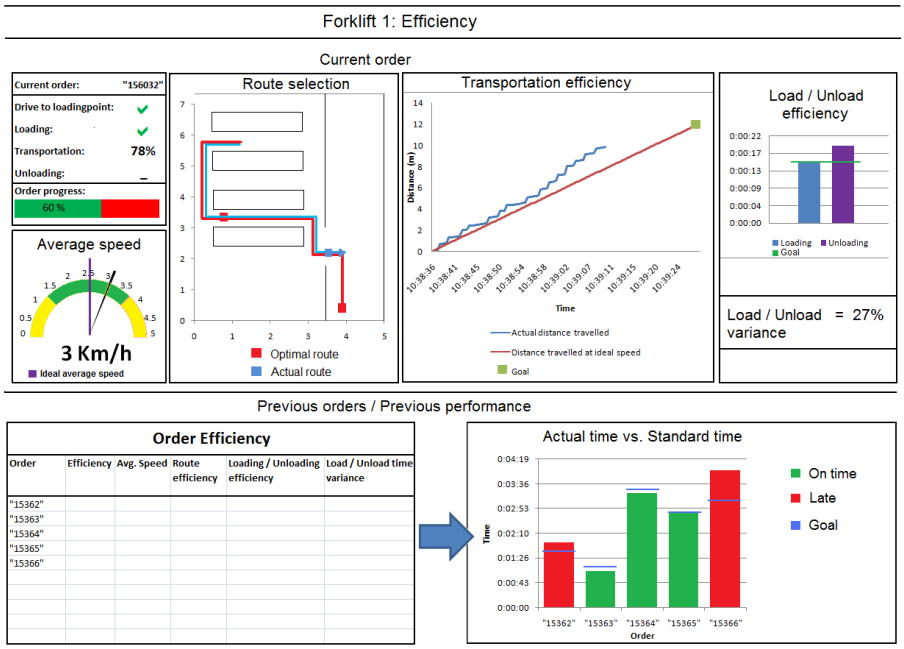


Figure 3.14: Screen 3: Efficiency

The efficiency screen (Figure 3.14) is divided into two parts:

- *Current order*
- *Previous orders/Previous Performance*

C*urrent order* shows the efficiency for the elapsed time per order. The first table presents the status of the current order. 'Average speed' displays the mean speed and ideal average speed in km/h during the current order fulfillment in the status table. 'Route selection' visualizes the optimal and actual route on a dynamic map. 'Transportation efficiency' illustrates a visual comparison between distance traveled at ideal speed (red line) and actual distance traveled (blue line). The ideal situation is the shortest possible route with ideal average speed. 'Load/unload efficiency' shows loading and unloading times with the standard time, and the load/unload variance in percentages.

Previous orders/Previous Performance shows the efficiency results of completed orders. 'Order efficiency' table summarizes the results. The 'Actual time vs. Standard time' bar chart displays the overall utilization of completed orders. A green bar indicates an order was fulfilled on time or faster than expected. A red bar indicates an order was completed later than expected.

Algorithms for Efficiency

Overall efficiency compares the actual time of an order to the expected time of that order. The Time per order contains four steps:

1) Transportation to the loading point
2) Loading
3) Transportation to the unloading point
4) Unloading

The overall efficiency is basically calculated to spot and improve the efficiency loss. Figure 3.15 shows a general view into the efficiency loss calculation.

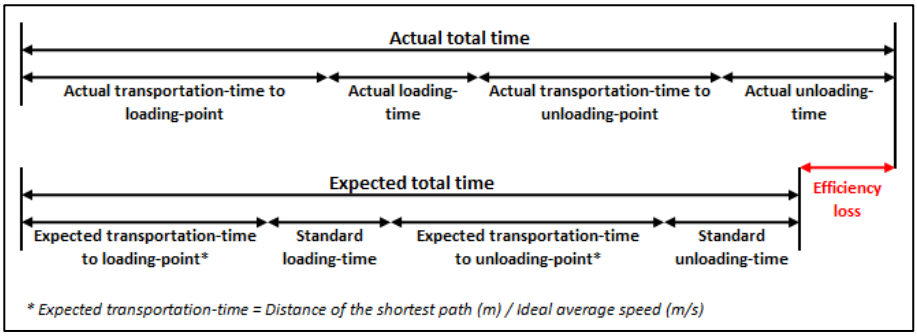


Figure 3.15: Efficiency loss

Average speed is calculated for a period of time, between t_{start} and t_{end}:

$$Average\ speed = \frac{\sum_{=t_{start}+1}^{t_{end}} \sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2}}{t_{end} - t_{start}} \tag{3.8}$$

Route efficiency is calculated for each completed order. The optimal route is computed at the beginning of an order for the known loading and unloading stations. A shortest path algorithm finds this optimal route. To obtain this, we used Dijkstra's algorithm with non-negative edge path. A graph or network with nodes (vertices) and arcs (edges) is constructed. The nodes represent loading and unloading stations, and the arcs are the driving lanes connecting nodes. The algorithm with given start point (Loading) and endpoint (Unloading) is summarized below (Aghezzaf, 2009):

0. Declarations of the parameters and variables
1. Initialization
2. Build priority-queue Q from V[G]-K
3. Relax (u,v,w) for each v in Adj[u]
4. While Q is not empty repeat steps 2 and 3

The length of actual route for a completed order from start time (t_{start}) until end time (t_{end}) is:

$$Length\ of\ actual\ route = \sum_{t=t_{start}+1}^{t_{end}} \sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2} \tag{3.9}$$

Screen 4: Reliability

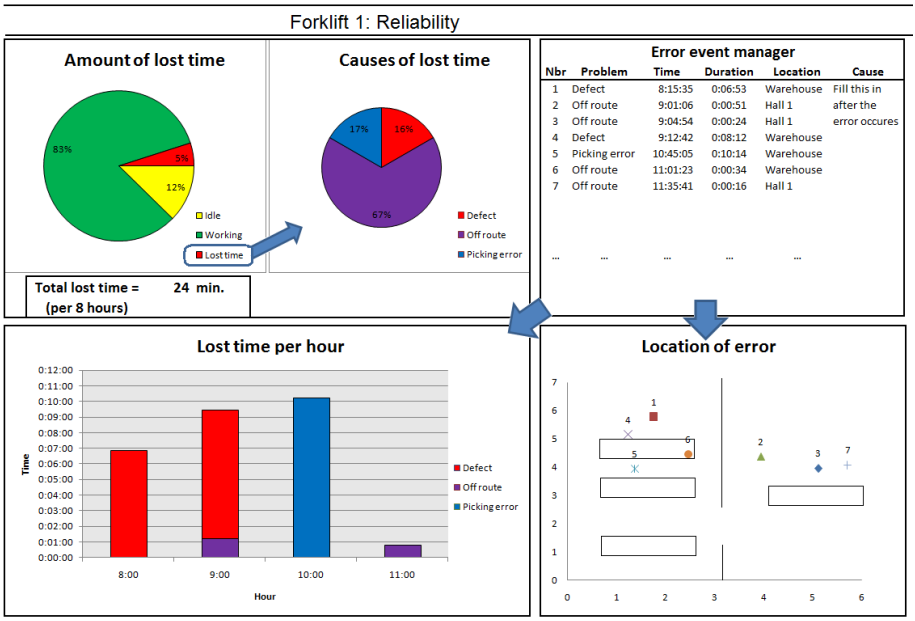


Figure 3.16: Screen 4: Reliability

The Reliability screen emphasizes lost time and errors by figures. This screen can be displayed in many time frames, in hours or daily. However, it is better to display in long time frames, because the occurrence rate of the errors is more explicit in a longer time interval. Figure 3.16 shows a practical demonstration of a forklift reliability screen for a shift of 8 hours. ‘Amount of lost time’ illustrates the idle, working and lost time rate for the complete shift. Total lost time in minutes is also provided. Arrows indicate the exploration of lost time and errors. The ‘Error event manager’ table defines errors in detail. It contains two more figures: The ‘Lost time per hour’ bar chart shows lost time per hour and the ‘Location of error’ map displays the exact location of the errors.

3.4.3. Test set up at RTLS lab

A test set up was implemented at the RFID lab in XiaK/Kortrijk/Belgium. The RFID system was the same as the one was mentioned in section 3.3., with altered railway with parallel aisles layout to represent the typical layout of a warehouse or factory. Figure 3.17 illustrates the new layout with gray tracks. The railway layout is divided into lanes based on a route plan. The route plan determined and divided the loading, unloading and other areas.

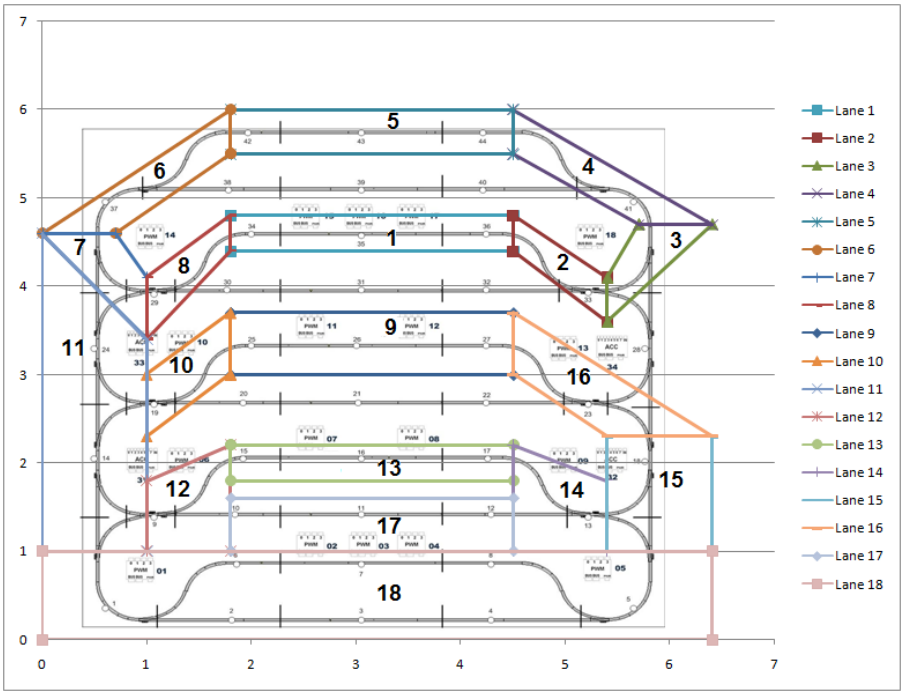


Figure 3.17: Railway layout and defined lanes

A sample order list was defined for the vehicle (Table 3.8). The vehicle pretended to pick up an object from one loading station and to drop it off at an unloading station for each order. To simulate this the train simply stayed for a certain time at the loading and unloading stations.

Table 3.8 : The order list of the train

Order #	Load zone	Unload zone	Standard loading time (sec.)	Standard unloading time (sec.)
1	Lane 2	Lane 5	10	10
2	Lane 7	Lane 3	10	10
3	Lane 4	Lane 8	10	10
4	Lane 7	Lane 3	10	10
5	Lane 2	Lane 5	10	10
6	Lane 7	Lane 3	10	10
7	Lane 5	Lane 7	10	10
8	Lane 2	Lane 5	10	10
9	Lane 7	Lane 3	10	10
10	Lane 2	Lane 5	10	10
11	Lane 2	Lane 5	10	10
12	Lane 2	Lane 5	10	10
13	Lane 2	Lane 5	10	10
14	Lane 18	Lane 9	10	10
15	Lane 18	Lane 9	10	10
16	Lane 9	Lane 13	10	10
17	Lane 9	Lane 13	10	10

3.4.4. Test Results

The order list in Table 3.8 was fulfilled in 45 minutes. RFID data was dynamically processed in MS Excel at micro and macro level. The dashboard screen in Figure 3.18 shows the summary of significant results. The screen is a combination of essential items collected from different screens (see 3.4.2.). The time frames of the screen were “current time”, “last 10 minutes of total process” and “total time”.

‘Current status’ and ‘”Current order’ show 17 orders were completed and the train had been working to complete order 18. ‘Utilization in last 10 minutes’ was 33%, which indicated that the train was not working efficiently, because the train was either in idle, waiting or error status. The error charts allowed us to detect what, when and where things went wrong. ‘Status: Occupancy in

last 10 minutes' identified the cause of efficiency loss and pointed out that 67% of efficiency loss was caused by the error. 'Causes of lost time in last 10 minutes' identified what went wrong. It presented the error type as well as the error distribution. The train was in defect status for a long time, about 398 s. 'Status: Occupancy per 10 minutes' compares the status for every 10 minutes and displays the change in utilization and lost time in percentages. Furthermore, 'Spaghetti chart (last 10 minutes) + Error location' displays the location of errors on a dynamic map. The 'Error Event Manager' table lists all the problems.

The overall efficiency of the train was 44%. 45% of the 56% of errors was planned to test the performance of the dashboard. The remaining 11% was caused by inaccuracy of the RFID data.

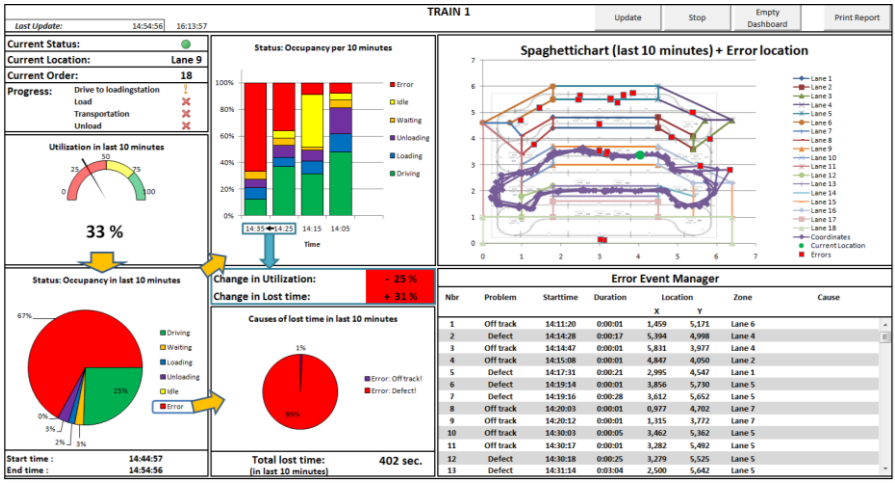


Figure 3.18: Test Results

3.5. Conclusion

The empirical research shows that RFID-based RTLS holds many promises for improving production logistics activities while also exhibiting new challenges. The use of RFID technology can help to trace the assets and products automatically, and assists in analyzing the performance of production logistics.

The methodology for integrating RFID into existing enterprise data architecture developed in this chapter aims to provide decision-oriented information for enterprise systems. This includes methods of track records analysis and real-time performance monitoring. Our findings from the experimental research will be used in various stages of the implementation process of the case studies.

Despite the high potential of RFID-based RTLS, manufacturers have to consider a number of issues before employing the system, not in the least the operational difficulties in the presence of metal and dealing with big data. The next chapter analyzes these challenges in the context of the automotive industry.

4. Case Studies in Automotive Industry

With any emerging technology, case studies provide an excellent opportunity for explorative research. This will not only quickly uncover any weaknesses of the new technology, but it will also reveal potentially valuable application possibilities and thus provides a framework for more focused and theoretical follow-up research.

As part of a collaborative research project on RFID in-plant logistics, funded by the Flemish government through Flanders Drive, we conducted three case studies. We analyzed process data from the internal material flow of three different automotive companies in the region. The process data were obtained through on-line measurements using RFID tags on vehicles and loads at the company facilities. As each company had its own requirements for the research and the production processes were different at each facility, we developed a specific approach for each of them accordingly to conduct this research project. To distinguish between the companies we will refer to them as company A, B and C. An overview of each case study is provided below.

- **Company A:** Between March and September 2010, an RFID-based RTLS object tracking system was used at the quality control department

of a first tier automotive supplier in order to evaluate the performance of its the workflow and work organization before and after redesign.

- **Company B:** An RTLS was deployed in this first tier automotive supplier in May 2011 in order to monitor and improve the in-plant vehicle traffic on the production line.

- **Company C:** During September and October 2011 an RFID-based RTLS was used outdoors at the gate of the factory of a vehicle original equipment manufacturer (OEM), in order to investigate the vehicle traffic between the factory site and an external supplier area. The ultimate goal was to optimize the time schedule and documentation of the trailer traffic.

4.1. Case study at company A: Evaluating the performance of a discrete manufacturing process using RFID

This case study presents an RFID-based RTLS solution for obtaining multi-item work-in-process visibility within a manufacturer. It delivers detailed performance metrics through RTLS data analysis in order to evaluate the workflow performance. The case study illustrates the various steps of this methodological approach including measurements before and after a workflow redesign.

The purpose of the research was twofold:

- to identify the potential of RFID location tracking in workplace redesign
- to validate these findings in an industrial setting

The RFID-based RTLS was implemented at the quality control (QC) department of a company that produces plastic bumpers and spoilers for passenger cars. By attaching tags to the product items themselves we were able to collect the trajectories of these products automatically as location data streams. These data were then processed by a middleware which pre-filtered redundant data before storing the remainder in the database. From

the database we then calculated productivity and other key performance indicators (KPIs) connected to time and motion analysis, such as cycle time and speed. In a follow-up study the workflow was redesigned via a simulation model. (The redesign step will only be described succinctly, since it is not the main focus of this section, but nevertheless forms an integral part of the case study.)

Subsequently, the redesign was implemented and a new measurement cycle was executed. This allowed us to track any changes in productivity and KPIs. The significant level of detail of productivity and KPIs could not have been achieved before RTLS with alternative measurement tools. This kind of beneficial application of RFID was up to now largely missing in literature. The case was a first in its kind, and has been documented as such in an extended video by hardware supplier Ubisense UK.

The case was also published as a journal paper (Arkan and Van Landeghem, 2013).

The remainder of this section is organized as follows; in subsection 4.1.1, an overview of the shop floor and the workflow are given; in subsection 4.1.2, the RTLS implementation is defined; in subsection 4.1.3, the middleware is described; in subsection 4.1.4, the data mining process which allows to obtain the KPIs is outlined; in subsection 4.1.5, the results are presented and discussed.

4.1.1. Shop floor overview

The QC department is a small cell with an area of 375 m^2 between the paint shop and the warehouse for final part assembly of the products. At the facility 32 types of plastic bumpers and spoilers for passenger cars are produced. The average bumper is 1.5 m in length and 0.5 m in width. The dimensions for the average spoiler are1.5 m by 0.2 m.

At the QC department the operators carry the lightweight and fragile products between work islands where they assemble them. Figure 4.1 shows a cross-section of the QC department. The characteristics of the shop floor are as follows:

- The work units are located approximately 1 to 2 meters from each other.
- The infrastructure consists of multi-item carrier skids, process tables, WIP (Work In Process) conveyors and storing units, which are mostly made of metallic materials.
- The shop floor can hold up to 52 items as WIP.
- The incoming skids carry 3, 4, 5, 6, 8 or 12 pieces depending on the type of item.

Figure 4.1: Cross-section of the QC department

The workflow follows the process steps depicted in Figure 4.2. Items arrive at this department from the paint floor according to the production schedule. They are carried on skids moving on a rail. The process is divided into two steps named QC1 (Quality Control 1) and QC2 (Quality Control 2) respectively.

The process before redesign goes as follows:

1. The items on the incoming skids are taken by two operators to conduct a first manual quality control. This is carried out either on a QC1 table or operators perform the task quickly while holding the part in hand. Afterwards, the operators place the items randomly on conveyors according to space availability. In case of a defect the item is moved to the scrap unit. The conveyor belts serve as WIP buffers between QC1 and QC2. The

spoilers are placed on the upper shelf and the bumpers that will be mounted onto them are put on the lower shelf of the same conveyor belt.

2. On the other side of these buffers, in QC2, six operators process the items. The workflow in QC2 is sequentially:

a. A part is removed from a conveyor.
b. A second quality check is conducted on a QC2 table or while holding the item in hand.
c. Two pieces are assembled on an assembly desk if necessary.
d. The item is scanned.
e. The item is placed on a rack with available space.

In case of a defect, the item is placed in the scrap unit.

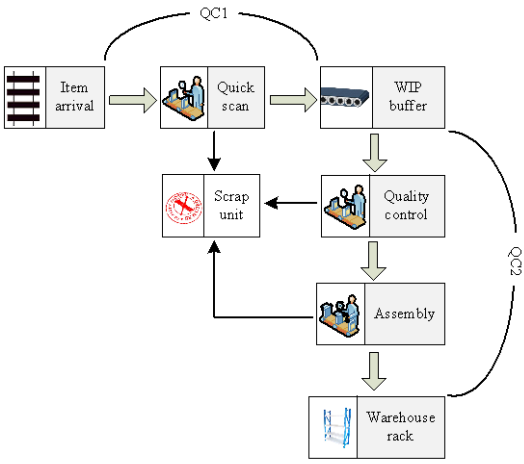


Figure 4.2: Item production cycle in the quality control department

4.1.2. RTLS deployment

Requirements analysis

An object tracking technology is required to track the items wirelessly and automatically through their cycle, and to assess the performance of the workflow. A robust system solution is necessary to accommodate to the requirements and challenges of the shop floor:

- Up to 52 items of WIP require rapid location data.
- The location measurements should be accurate enough to distinguish between work islands, as some of them are less than a meter from each other.
- The metallic infrastructure of the work environment can cause signal deterioration.

The comparison of different kinds of wireless indoor work measurement tools to register time and motion is illustrated in Table 4.1, together with more classic tools such as a stopwatch and image processing of video records. The representation of the characteristics of indoor positioning technologies (Kou et al., 2006), (Heo et al., 2006), (Kelepouris and McFarlane, 2010) is expanded in this table.

The challenges of precise and fast tracking of multiple items demands a stable communication platform of radio frequency and ultrasound technologies (Thiesse and Fleisch, 2008). Besides, to track an item throughout the shop floor, the antenna network has to have a clean line of sight, penetrating the whole area. Conventional RFID systems such as gate antenna systems cannot detect the tag's location within a defined space. An RTLS solution based on UWB communication with active RFID tags was therefore selected.

Table 4.1: Comparison of indoor time and motion measurement tools

Tool / Parameter	Stopwatch	Video Record	Conventional RFID	RTLS
Sight	Line of sight	Line of sight	Non-line of sight	Non-line of sight
Read range	Few meters	Hundreds of meters	Passive tags , 1-2 m active tags, 10-30 m	Active tags, 20-100 m
Scan	One unit at a time	One unit at a time	Several units	Multi-units
Cost	Low	Medium to high	Medium	Medium to high
Measurement process	Static	Continuous	Static	Continuous
Location accuracy	N/A	N/A	1-3 m	15 cm
Communication spectrum	N/A	VHF	UHF	UWB
Location positioning	Manual	Semi-automatic	Automatic	Automatic
Update rate	Seconds	Milliseconds	2-5 s	Milliseconds

Implemented solution

The RTLS consisted of some *hardware* components and system *software*. Nine UWB readers, a hand held tag reader, 52 active tags and a database server constituted the *hardware* components. Figure 4.3 represents the shop floor layout with the implemented RTLS solution.

The readers were strategically located to avoid signal deterioration, to reach ± 10cm position accuracy and to precisely locate a tag with as many readers as possible. 52 active tags were deployed to track the maximum number of items of WIP. A handheld tag reader was used to read and match the tag data automatically with the item info on an Excel sheet. The database server was capable of storing a high volume of data.

The system implementation did not affect the production process, since the readers were mounted on the ceiling, the database server was a remote pc

suite that could be placed in any available space and the tags were easily placed unto the incoming items using a plain rubber band.

The tag placement started at the entrance of the department where the skids arrived from the paint floor. We intended to tag as many items on a skid as possible without influencing the production speed. At least the first and the last item on a skid were tagged (260 out of 558 items were tagged during the process before redesign). The operators removed the tags from the pieces at the end of the process cycle and sent them back to the entrance to be reused.

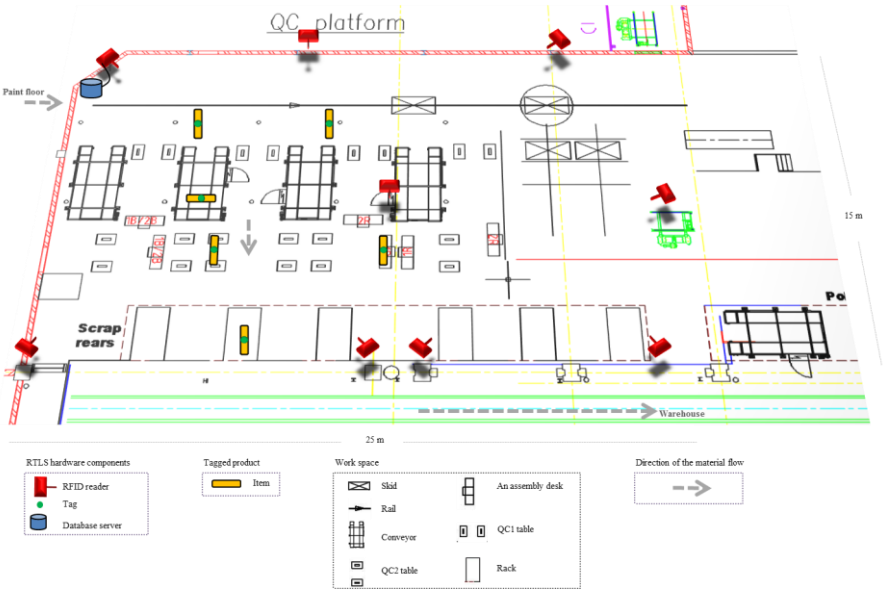


Figure 4.3: RTLS layout and shop-floor layout combined

The system *software* contained a tag location engine to manage data streams and a 2D spatial platform for real-time monitoring of tag motions on a map. The engine converted the received tag signals into the form: (EPC, time, location) (see section 2.2.3 for more detail). The location engine was fine-tuned according to the workflow parameters, since each data aggregation changes with different shop floor parameters. The important parameters of this workflow tracking were:

- tag read update rate
- level of filtering of immobile items
- accuracy in location measurements

The tag read update rate is the time interval for a tag to transmit signals to the readers for position calculation and needs to be configured according to the speed of the material flow. The high speed movements of tags in the quality control department, when the operators were carrying and handling the items, required fast location update rates so items could be tracked without missing critical trails. At certain points of the operation the items could reach a speed of more than 1 m/**s** (e.g. when the operators were taking them off the skids)**.** After critical trials, the tag read update rate was set by the technology supplier to 0.432 s in accordance with the maximum speed of the items.

Secondly, the items would remain immobile in WIP for a considerable amount of time, sometimes up to more than 5 minutes. This could result in unnecessary location data accumulation in the database. To filter out tag immobility the option to switch on the "sleep state" feature of the active tags was used (see section 3.3 for more detail). The minimum amount of time an item spent on a buffer in one particular phase was 4 s, so the sleep state was set to be activated after this time had elapsed.

Finally, the location data had to be reliable. This was achieved by configuring the RTLS filter (see section 3.3.4 for more detail). The maximum valid position variance was configured to 3 m, the critical distance between the work units.

The RTLS was monitored for 3 hours and the tag location data for this period was stored during the production process. The database of the initial workflow consisted of the data streams of 260 tagged items, but only 250 of them completed their production cycle in three hours. In the new layout, 218 items were tagged and 199 items were completely tracked. Before redesign, the system generated 228,000 location measurements (26 MB). This amount of data was considered too large to analyze directly. To solve this problem, a middleware feature was developed to filter redundant data during its retrieval and to facilitate further analysis.

4.1.3.Middleware development

An RTLS middleware was designed to reduce the database size and speed up the data analysis process. A high volume of data streams is redundant in many cases. For example, similar readings occur when items are on hold in buffers. These excessive data streams lead to huge database capacity requirements and increase data cleaning times. They are considered one of the major problems of RFID applications.

Many different data reduction methods have been proposed in literature to cope with this challenge. However, most of them work on stored data (Gonzales et al, 2006), (Bleco and Kotidis, 2009), (Bai et al., 2006). Instead we opted to filter the data directly during its acquisition by RTLS by developing the middleware.

Similar to the data aggregation methods proposed by Bleco and Kotidis, 2009 and Gonzales et al, 2006 to convert basic tuples (EPC, location, time) to stay records of (EPC, $location_i$, time_in, time_out), we developed this type of records at middleware level. These middleware *stay records* shall be referred to as *event records.* For example, when an item is placed and assembled on an assembly table, the process can be considered as an event and only the record (EPC, $Z_{assembly1}$, time_in, time_out) of the event needs to be kept in the database. The event-based data streaming consists of the following three steps:

- Defining event types and events
- Formatting the data structure for these events
- Designing RTLS middleware platform

The first step is to define event types and events of the workflow in the middleware. The workflow is a network that can be structurally described by node-arc topology. The node and arc represents two different types of event. A “node” or work represents an item being processed at a fixed location and an “arc” or flow is a linear trip from one fixed location to another. The fixed locations consist of the incoming rail, QC tables, assembly desks, conveyors and racks. And the arcs represent movements across the production platform,

as lines to circumvent the difficulty of accurate distance calculations and indexing. Each node and arc is therefore a simple event. The combination of these simple events builds the complex events such as QC1 or QC2. The overall event is then the cycle of an item.

The second step is to format the data structure. Two types of events are aggregated from the data: A stay record, which represents an entry and exit information when a tagged item passes a node into a designated zone (Chow et al., 2007), and a flow record, which indicates a departure and an arrival between two zones. Each entry and exit data should be written separately to be able to combine two types of event. Then, a single data row contains either an entry or exit information with tag identity, zone identification and the time: (EPC_i, $Zone_i$, $time_i$, In/Out).

The third step is to design an RTLS middleware platform. An event-based filtering algorithm is applied by spatial management of RTLS platform (Figure 4.4). The space covered by RFID readers sighting is spatially configured by the middleware on top of visual software. The RTLS software contains a dynamic map to monitor the RTLS readers' defined space. The nodes are defined as rectangular zones in the middleware platform, so when a tag enters or leaves a zone a data row is collected. The shapes of the zones differ for each workbench, depending on the area that a bench covers. Specific zones are labeled as follows:

- Z_{rail} = Rail
- Z_{qci} = Quality control tables ; i є {1,…, 9}
- $Z_{assemblyi}$ = Assembly tables ; i є {1,…, 6}
- $Z_{bufferi}$ = WIP buffers ; i є {1,…, 4}
- Z_{racki} = Racks ; i є {1,…, 6}

Figure 4.4 displays an example of middleware data filtering. In the figure a tag's data stream is shown with a line of red and green dots. The tag EPC_1 moves away from Zbuffer1 and arrives at Zqc1. The red dots indicate unnecessary trails and are therefore filtered out. Only the green dots are transferred to the database. The collected data are (EPC_1, Z_{rail}, $time_1$, Out), (EPC_1, $Z_{buffer1}$, $time_2$, In), (EPC_1, $Z_{buffer1}$, $time_3$, Out) and (EPC_1, Z_{qc1}, $time_4$,

In). This pre-filtering reduces the database size dramatically without losing critical information.

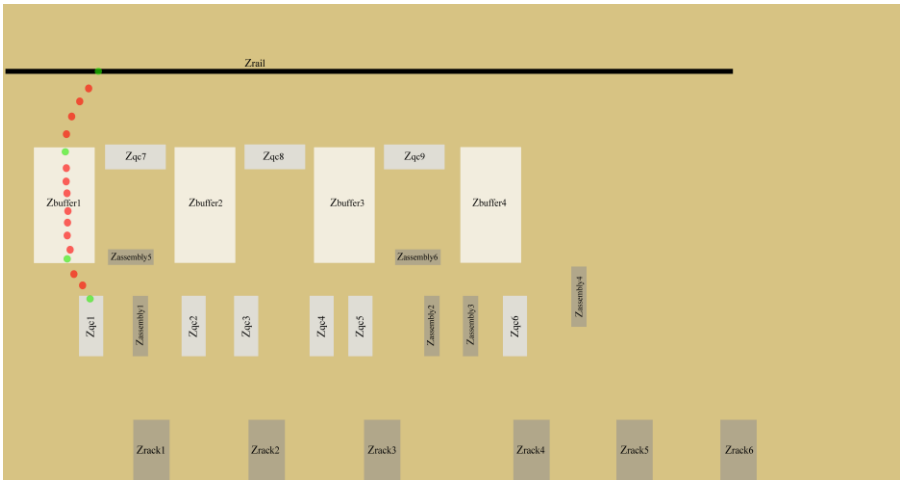


Figure 4.4: Pre-data filtering by the middleware

4.1.4. Research method

The aim of the research method is to generate and provide elaborate KPIs to company A using reliable RTLS data. Before these were based on conventional, manual and less frequent observations. Moreover, the company can remotely assess the workflow performance in near real-time. In order to achieve this, two development steps are required. The first one is data mining: to clean and cluster the filtered RTLS data in order to prepare them to be analyzed. The second step is to generate KPIs for the shop floor to attain lean visibility and to define RTLS data analysis algorithms to calculate these KPIs.

Our RFID data mining model follows an approach similar to the first two steps of the framework provided by Zhong et al. (2012):

- Data cleansing of duplicate records.
- Data clustering to recognize patterns and to retrieve the data streams of the item production cycles.

Generating KPIs

This step defines KPIs for the workflow on the shop floor. The selection of appropriate performance measures has to be in line with the organization's requirements (Jayaram et al., 2010), (Gelders et al., 1994), (White, 1996). Three key performance areas are specified here: (i) Time, (ii) Speed, and (iii) Efficiency.

(i) Time

Both cycle and task times, which form the basis for process control (Reichert et al., 2010), are the main KPIs that can be calculated from time measurements. The cycle of an item is studied here as a complex event, consisting of a network that is formed from simple events. The task time represents the meaningful events that are extracted from cycles such as QC1, QC2 and assembly operations. If we organize the events from complex to simple, the time measurements we can deliver are:

Cycle time => QC1, QC2 task time => stay time (i.e. buffer, assembly bench) and flow time (i.e. buffer to assembly bench)

The specific variables are defined as follows:

t_{end} = end of cycle time
t_{start} = attachment time of a tag to item
t_{rack} = to a rack placement time
t_{scrap} = the time that an item fails quality control and is removed

The time measurements are calculated as:

Item cycle time (t_{cycle}) = $t_{end} - t_{start}$, $t_{end} = \{t_{scrap}$, if defect; t_{rack} , if qualified$\}$ (4.1)

Item QC1 time (t_{QC1}) = $t_{(Zbufferi,\ In)} - t_{Zrail}$ (4.2)

Item QC2 time (t_{QC2}) = $t_{end} - t_{(Zbufferi,\ Out)}$ (4.3)

A stay time (t_{node}) = $t_{(Zonei,\ Out)} - t_{(Zonei,\ In)}$ (4.4)

A flow time (t_{arc}) = $t_{(Zonei,\ In)} - t_{(Zonei\text{-}1,\ Out)}$ (4.5)

(ii)Speed

The production speed of materials has a significant influence on productivity (Jayaram et al., 2010). High speed can have an effect on the quality (scratches and bumps) and slower speed can result in lower productivity. The item speed here is calculated for cycles QC1 and QC2. The speed equations are:

$$\textit{Item cycle speed } (s_{cycle}) = (\sum distance_{cycle})/\ t_{cycle} \tag{4.6}$$

$$\textit{Item QC1 speed } (s_{QC1}) = (\sum(distance_{(Zbufferi,\ In)} - distance_{Zrail}))/ (t_{(Zbufferi,\ In)} - t_{Zrail}) \tag{4.7}$$

$$\textit{Item QC2 speed } (s_{QC2}) = (\sum(distance_{end} - distance_{(Zbuffer,\ Out)}))\ / (t_{end} - t_{(Zbuffer,\ Out)}) \tag{4.8}$$

(iii) Efficiency

Efficiency is expressed in terms of workspace utilization. We therefore must consider both workload allocation and bottleneck operations. The workload allocation is needed to compute the division of tasks in the same work group. The shop floor has five different work groups: WIP buffers ($Z_{bufferi}$), assembly desk operations ($Z_{assemblyi}$), rack transfer units (Z_{racki}), QC1 and QC2 table operations (Z_{qci}). The WIP buffers are the main focal point, because they are the material tracking areas where movements of various materials can be traced and controlled (Huang et al., 2008). The bottleneck operations of the material flow is needed to distinguish the outliers in the process. The visualization was obtained here by drawing a material flow diagram based on position data streams using Inkscape freeware (see figure 4.6). Both product type and color are distinguishable in the diagram. The diagram helps to analyze the workflow and allow to obtain a complete overview. The diagram is shown and explained more in the results section.

4.1.5. Results and Discussion

In this section, we present how a workflow redesign was evaluated using RTLS data analysis. A simulation model was used in a separate study to improve the work organization through redesign of the workflow layout of the QC area described above. The company accepted the proposal and requested an evaluation of the redesign to assess whether the new layout should be kept or whether further improvements had to be introduced. To assess the new layout, we collected shop floor data before and after the redesign. Multi-item position data were collected during 3 hours of production before and after the redesign. The data analysis was performed with MS Excel. The simulation model, RTLS data analysis (consisting of productivity and KPIs), and the discussion of the results, will be described in this section.

RTLS data accuracy is not discussed here, since the system was configured precisely as described in the implemented solution section 4.1.2. Data quantity is summarized in Table 4.2. The accurate location data was reduced by 98.6% by applying the middleware and further data cleaning reduced the data from the middleware by 96.1%. The clean zone data was then analyzed to obtain the productivity and KPIs.

Table 4.2: Database size reduction through data processing

RTLS database after redesign	**Location Data**	**Raw Zone Data**	**Clean Zone Data**
During 3h of production, 218 items tagged and tracked			
Database size:	73 MB	1 MB	40 KB
Row count:	610.143	14.708	1.000
Improvement in size (%):	-	98,60%	96,10%

Simulation model

A simulation of the operations of the QC department was designed in Flexsim® software and simulation parameters were obtained from the workflow profiles. The process times followed normal distribution for every material. A snapshot of the simulation is shown in Figure 4.5. Based on the

observation of the simulation model a new workflow organization was proposed. All changes to the workflow layout were applied after collecting initial RTLS data. The simulation study itself has been described in detail in Sala and Vidal (2010).

Figure 4.5: A snapshot from the simulation of the QC department in Flexsim®

Table 4.3 summarizes the workflow parameters of the simulation model before and after the workflow redesign. Two major organizational changes were applied: switching from random to dedicated item allocation to WIP buffers and removing one QC2 operator. The objective was to decrease the excessive idle times of QC2 operators while keeping the same production rate or even reaching the maximum capacity of 50 skids/hour.

Table 4.3: Comparison of the workflow parameters

Workflow parameters		**Before redesign**	**After redesign**
Total number of operators		8	7
QC1 operators		2	2
QC2 operators		6	5
Item distribution to WIP buffers		Random	Specific
Idle time of operators	QC1 operators (%)	14	12
	QC2 operators (%)	26	15
Average Production rate	(skids/hour)	45	45
	(items/3hour)	558	558
Max. production rate	(skids/hour)	-	50

RTLS data analysis results

Productivity

The production rate estimates of the simulation model (Table 4.3) were elaborately evaluated by RTLS data analysis. Its results are presented in Table 4.4. The redesign by the simulation model was evaluated not to be an improvement in comparison to the previous workflow. The average production rate parameter in Table 4.3 is represented by the number of processed items in Table 4.4. Compared to the previous production flow the number of processed items was decreased by 25% after the implementation of the redesign. Even though the number of item arrivals was planned identically in both production schedules, after the redesign had been applied, the number of item arrivals also dropped 21%. The bottleneck operations causing the low levels of productivity in the new workflow layout were identified via the KPIs.

Table 4.4: Comparison of the workflow parameters with RTLS data analysis

Workflow parameters	Before redesign	After redesign	Improvement (%)
Number of skid arrivals (skids/ 3hour)	133	127	-5
First hour (skids/ hour)	47	36	-23
Second hour (skids/ hour)	45	47	4
Third hour (skids/ hour)	41	44	7
Number of item arrivals (items/ 3hour)	592	470	-21
Number of processed items (items/ 3hour)	556	419	-25

KPIs

The shop floor performance of the new workflow was then compared to the previous workflow. Table 4.5 shows the comparison based on the time and speed measurements between pre-redesign data provided by the company and pre-and post-redesign data obtained through RTLS data analysis. The level of obtaining process information that was reached by the company was improved upon by the utilization of RTLS. Additional measurements and parameters, such as speed, per period and single flow, were also provided by RTLS data analysis. The per period parameter represents the available measurements in any time interval during the production process, e.g. average speed of QC1 per 15 minutes or per hour. The flow and stay records were defined in section 4.1.4.

After redesign, the average cycle time was increased by 105%. The average speed of items was decreased by 100%. The most noticeable degradation was observed in QC1. The operation time in QC1 was increased by 4.5 minutes and the speed was declined by 0.03 m/s. The most problematic time period in QC1 appeared during the first hour of the production flow. Note that no operators were removed from QC1.

Table 4.5: KPI results

KPI's	Before RTLS (data from company)				With RTLS (before redesign)				With RTLS (after redesign)			
	Mean	SD	Per i.t.	Per period	Mean	SD	Per i.t.	Per period	Mean	SD	Per i.t.	Per period
Time (mm:ss)												
Cycle (t_{cycle})	6:00	6:00	✓	X	9:02	7:17	✓	✓	18:31	6:39	✓	✓
QC1 (t_{QC1})	0:27	0:07	✓	X	1:57	1:13	✓	✓	6:27	3:09	✓	✓
QC2 (t_{QC2})	1:49	0:28	✓	X	3:17	5:36	✓	✓	4:45	5:16	✓	✓
Single flow (t_{node})	X	X	X	X	✓	✓	✓	✓	✓	✓	✓	✓
Single stay (t_{arc})	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
Speed (m/s)												
Cycle (s_{cycle})	X	X	X	X	0,04	0	✓	✓	0,02	0,01	✓	✓
QC1 (s_{QC1})	X	X	X	X	0,04	0,1	✓	✓	0,01	0,01	✓	✓
QC2 (s_{QC2})	X	X	X	X	0,06	0,1	✓	✓	0,04	0,08	✓	✓

SD = standard deviation, i.t. = item type, **X** = not available, ✓ = Available

The exact location of the main bottleneck operations during the first hour of the production process was detected using the material flow diagram, which is illustrated by Figure 4.6. The operations in this area often took more than 6 minutes longer to process an item with low speed (often less than 0,01 m/s). The skid arrivals were paused intermittently during the production and its number was 23% less in comparison to the first analysis results (see Table 4.4). The problematic area was close to the exit of empty skids. Consequently, we concluded that the decrease in production rate and performance was caused when WIP had reached maximum capacity (note that one operator was removed from QC2), or by pausing the skid arrivals when QC1 operators were removing all items from the skids approaching the exit , or when QC1 operators were carrying items and looking for the right conveyors to put them on.

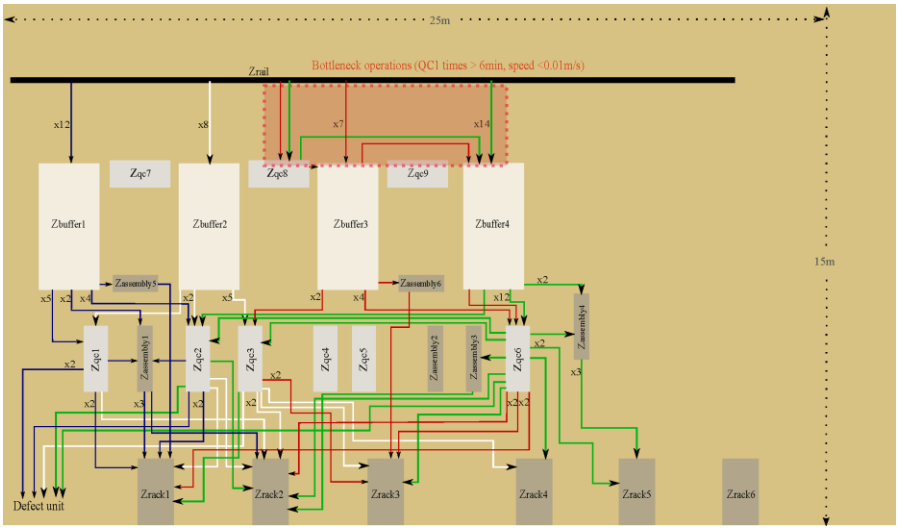


Figure 4.6: Material flow diagram representing one production hour with workflow flaws

The bottleneck operations affected the item production cycle times adversely. Figure 4.7 shows the changes in cycle times with a continuous distribution plot in detail. The cycle time observations by the company prior to the use of RTLS were based on 60 measurements by stopwatch. The company only kept mean and standard deviation records. The first RTLS data analysis results were based on 250 measurements and represented each cycle time separately. They demonstrated an increment in cycle times over time, which is why a workflow redesign was considered to be necessary. After the redesign was implemented, the RTLS data analysis results were based on 218 measurements and they demonstrated that the average cycle time had more than doubled.

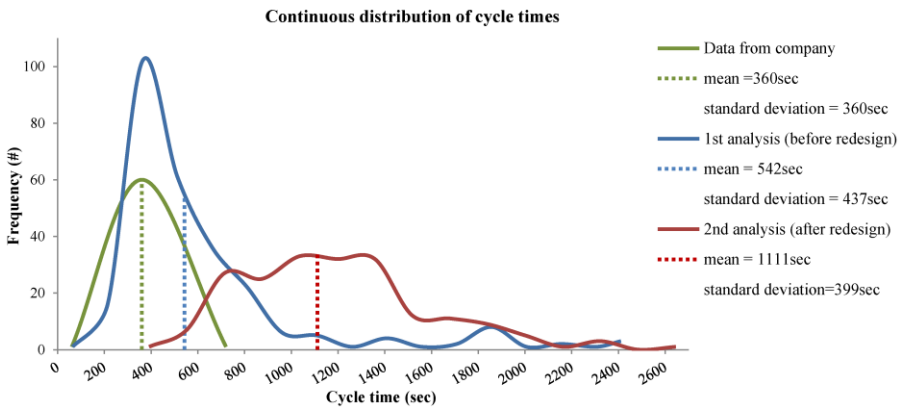


Figure 4.7: Continuous distribution of item production cycle times

Discussion

The RTLS was used on the same day the implementation of the redesign was started. Because the QC1 operators had to learn to work with the new allocation plan in which 18 items were to be distributed to 4 conveyers, a lot of time was lost while they were trying to find and place these items correctly. In QC2 operations ran less smoothly as well since the operators were not yet accustomed to working with one person less. Further process analysis when all operators have gotten used to the new work scheme could provide more accurate results regarding the effectiveness of the redesign. However, the RFID project had to be conducted within certain time constraints and the RTLS equipment was no longer at our disposal to conduct this second analysis. Nevertheless, the aim of this RFID project was to provide advanced and up-to-date information to evaluate redesign efforts, not to optimize workflows.

4.2. Case study at company B: RFind's RTLS for tracking assets

This case study presents the investigation of the vehicle traffic in the production plant of company B, aimed at verifying the RFind's RTLS that was deployed there (see section 1.2 for RFind). The fore-mentioned vehicles were five AGVs (Automated Guided Vehicles) and two manually driven tugger trains.

Company B, an automotive supplier, produces plastic fuel tanks. The components of these fuel tanks are carried to the production line by the vehicles. The company wanted to improve the visibility of the vehicle traffic and increase its control over it. An automatic vehicle identification and tracking system, the RFind's RTLS, was used to track the vehicles and collect traffic data. It had been deployed firstly in 2009 and was still in compatibility verification phase after one and a half years. The company therefore requested system verification from us, to determine whether some specific events were detectable from the data. We inspected the data reliability from May 24, 2011 until 30 May 2011. The event analysis contains the AGVs' waiting time at certain loading stations, the frequency of their appearance on the molding route and the traffic of tugger trains between the production line and the supermarket.

Based on the data analysis results, the system was proven to be **inadequate** for this particular application.

4.2.1. System components and data gathering

This section provides necessary information about RFind, the production setting it operated in and the company's requests for inspection.

The information about RFind was obtained from the system provider. RFind software was tested on Windows XP Professional operating system. The software operated with the SQL Server database and the server required the installation of additional applications of Microsoft .NET Framework and Internet Information Services (ISS).

Figure 4.8 illustrates the plant layout and the company's requests for inspection. In the plant layout, each serial number represents a reference tag (a reader) and shows its fixed location. The location of the reference tags with their coordinates is shown in Appendix B. The reference tags were mounted to the ceiling, the underside of a metal gangway. (Note that the environment was full of metal structures, consisting of multi-level storage racks, elevated gangways, machines, etc.) They tracked the AGVs and tugger trains, each tagged with active asset tags, which were the size and shape of a hockey puck (see section 1.2. for more details about the location algorithm). The specific system features were as follows:

- RFind tags used active RFID technology to communicate with each other. They sent signals to gateways, which relayed messages to a server.
- Reference tags were placed approximately 10 meters from each other.
- The circular detection area of a reference tag was about 7 meters in radius.

The four questions that the company wanted us to investigate were:

1. When do the tugger trains enter and leave the supermarket?
Figure 4.9 shows the route of a tugger train between the production line and the supermarket. Tugger trains pass firstly under reference tag 103015 and then under reference tag 102981 to enter the supermarket. They leave the supermarket passing under reference tag 102981 first and then moving past reference tag 103015. A tugger train always stays more than one minute at the supermarket.

2. How many times do AGVs stay at the loading station between reference tags 102990 and 102984 for more than one minute?

3. How often do three AGVs stay together for more than one minute under reference tags 102996, 102999 and 103007?

4. How many times and when do AGVs move away from the molding area?

They follow the route with the red line (Figure 4.8) and pass firstly under reference tag 102974 and then under reference tag 102975.

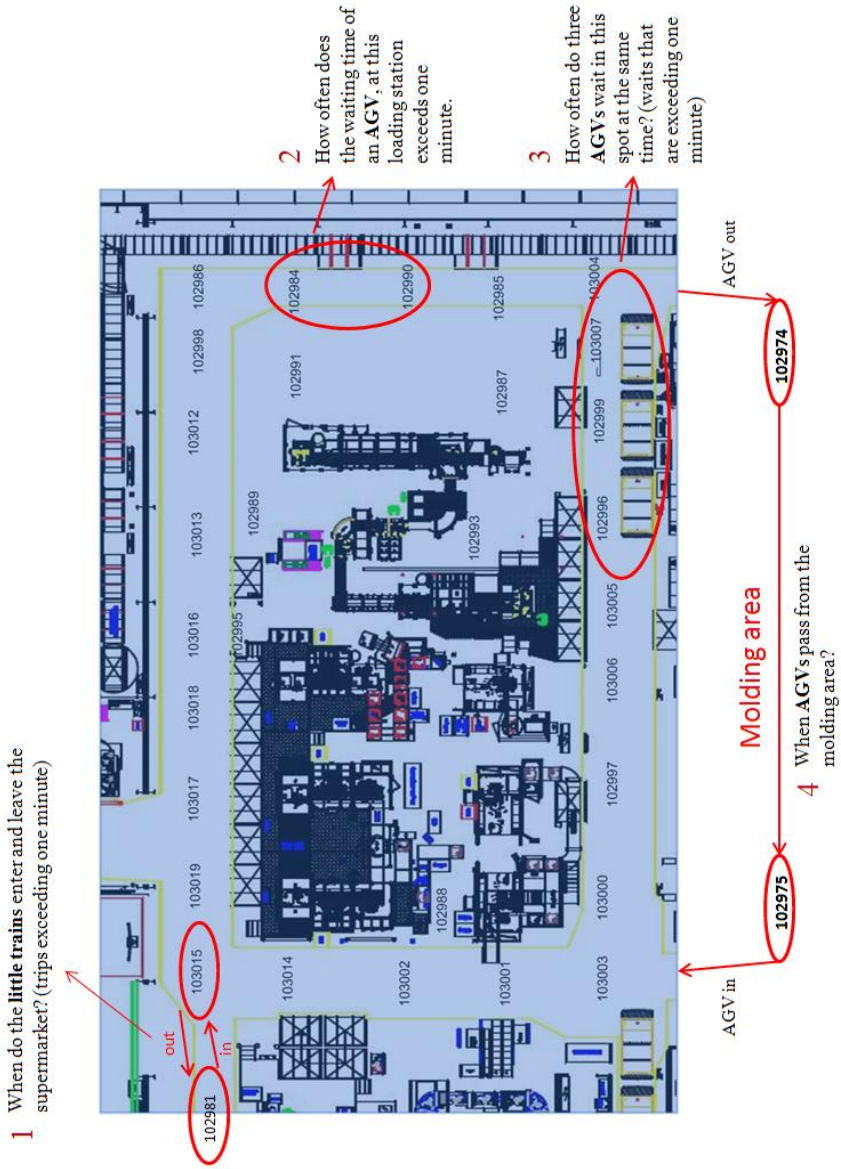


Figure 4.8: The plant layout and requests for analysis

The database contained the data of the asset tags, which were basically the records of the date, time and location of the readings. It held more than four million rows, going all the way back to the first use of the system in 2009. The data update interval was 2 s.

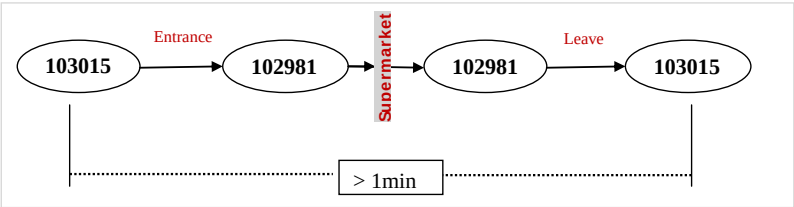


Figure 4.9: The route of a tugger train for supermarket stopover

4.2.2. Data analysis

Each question was answered by creating and running database queries in VBA (Excel). The queries to analyze the questions were simply:

1. The number, date and time of the stopovers at the supermarket were queried. The query to find a supermarket stopover was:

n ={Tugger1, Tugger2}
t=time of a reading, increment of 1 is to the next record
for $tagID_n$
AND(If loc_t = "103015"
If loc_{t+1} = "102981"
If loc_{t+2} = "102981"
If loc_{t+3} = "103015"
If [t+3] – [t] > 1 min)

2. If the stopover time of any AGV between the two reference tags 102990 and 102984 exceeded one minute, the stopover time and the date were recorded. The query to find a stopover at the loading station was:

n ={ AGV1, AGV2, AGV3, AGV4, AGV5}
t=time of a reading, increment of 1 is to the next record
for $tagID_n$
AND(If loc_t = "102990"
If loc_{t+1} = "102984"
If [t+1] – [t] > 1 min)

3. The first AGV has to arrive and wait under reference tag 103007, the second one under 102999 and third one under 102996 (Figure 4.10). The data order of such an event as queried is shown in Table 4.6.

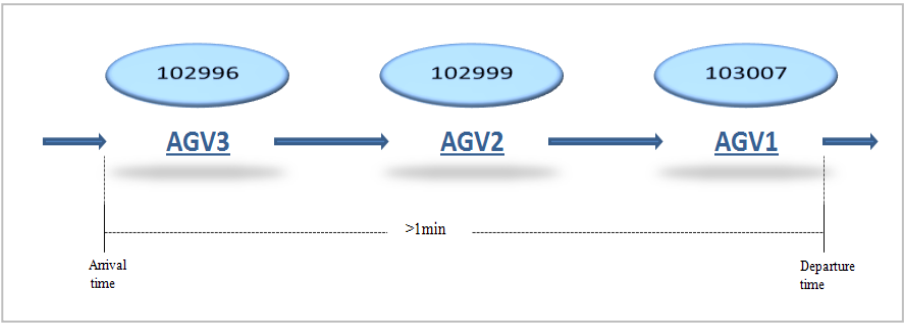


Figure 4.10: Standstill zone of three AGVs

Table 4.6: The data order of three AGVs at the waiting zone

TagID	Ref. Tag	State	Time (min)
AGV1	103007	Arrival	t
AGV2	102999	Arrival	
AGV3	102996	Arrival	
AGV1	103007	Departure	t + 1 + k

4. The query to find the stopover time at the molding area was:

n = {AGV1, AGV2, AGV3, AGV4, AGV5}
t = time of a reading, increment of 1 is to the next record
for $tagID_n$
AND (If loc_t = "102974"
If loc_{t+1} = "102975") Then
t = stopover time

4.2.3. Results and Discussion

The results of the data analysis show that RFind's RTLS was unreliable when compared to the real case. The answers of the four questions were:

1. 36 supermarket visits were detected in six days while the expected number was more than 100 visits. Figure 4.11 illustrates the supermarket traffic volume of the tugger trains. On 5/25/2011, the system only detected supermarket departures. On 5/28/2011, the system only detected supermarket arrivals. On 5/29/2011, no supermarket stopovers were detected.

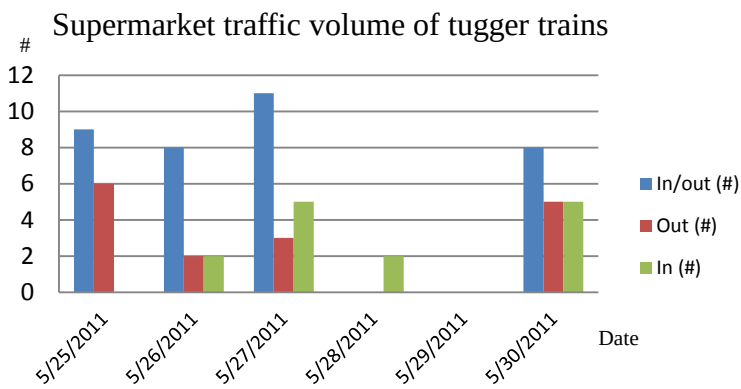


Figure 4.11: Supermarket traffic volume of tugger trains

2. Table 4.7 lists the stopover records of the AGVs' at the loading station. On average, an AGV waited 62 times per day at the loading station with a

standard deviation of 29. On average, every 4,5 minutes an AGV stopped at the loading station. In reality, an AGV stopped 20 to 30 times a day at that loading station. The results were therefore unrealistic. The frequency of stopovers was excessive.

Table 4.7: The number of stopovers at the loading station

TagID\ Date	05/25/11	05/26/11	05/27/11	05/28/11	05/29/11	05/30/11	Average
AGV1	85	88	79	59	22	75	
AGV2	50	53	44	40	21	42	
AGV3	41	33	46	28	21	41	
AGV4	100	123	101	68	37	98	
AGV5	96	103	91	60	32	84	
Average							**62**

3. There was no match for this case. In reality, three AGVs were together at many instances in this zone during a single shift. Moreover, inaccurate events were detected. Two AGVs were indicated as waiting under the same reference tag, which was impossible.

4. The results show that the AGVs only left three times in six days from the molding area. The five AGVs normally stop by more than ten times a day at the molding area.

Discussion

The main reason of system unreliability was most probably the **signal deterioration caused by the presence of the metallic infrastructure**. The observation of the inference is based on the motion errors detected during data analysis. Vehicles appeared to be passing through concrete walls, were using unrealistic routes and were seemingly speeding excessively. Based on the data, the vehicles would have been moving backwards approximately 20% of the time, which was impossible, because in reality the AGVs and tugger trains moved only forward. The speed of the AGVs reached up to 20 km/h, where the maximum speed of an AGV was 5 km/h. These unrealistic changes in tag displacement were basically signal reflection errors, which usually occur in the presence of metal (Kaur et al., 2011).

A secondary reason proved to be the premature deterioration of the readers' batteries, which was difficult to detect without analyzing actual measurements.

Even if this one instance cannot provide us with conclusive evidence, it is a strong indicator that the RFind has severe limitations, and therefore is not advisable to be when precise routings, fast moving targets and timed events need to be monitored. From this case study, it became apparent that this technology can only be used reliably if the reader tags are out of each other's sight, and hence, placed at large distances from one another. This renders any accurate determination of speed or direction of a vehicle ineffective.

4.3. Case study at company C: Outdoors skid traffic monitoring through an RFID system

This case study presents the investigation of vehicle traffic between company C and a JIT supplier location in order to optimize the time schedule and document the trailer traffic for invoice control purposes. The vehicles were trucks carrying empty package skids. Active RFID tags were attached to the trailers and an RFID-based RTLS tracked the trailers at the main gate of the factory and collected traffic data.
Company C had requested us to provide information about the departure time variations of the skids. We provided the information of the time variations based on the results of an RFID data analysis. Initially, we investigated the RFID system validity and additionally, we paired the theoretical time schedule with an arrival list based on the RFID data. The results provided the information required for optimization.

4.3.1. Data gathering

This section provides information about the requests of the company, in-plant logistics and the RFID system. The information was gathered from company C and the system provider.

Company C requested to know whether the predicted timing and skid departure stations of the theoretical time schedule were accurate enough to

validate or needed to be improved. They provided data about the *plant layout*, the *theoretical time schedule*, and the *outside area arrival list* for schedule examination. Figure 4.12 illustrates the *plant layout*, which is called C. The skid stations are marked as green areas (Cab Trim, West, Noord, Oost and Zuid). Skids leave the plant through the main gate and are transported to an outside area, which is called S. S is the packaging pool where empty packages are unloaded and from there, these packages are transported to all suppliers. The unloaded skids at S are returned back to C.

Practical information:

- Approximate duration to drive between C and S is 30 minutes.
- Driver stops at the main gate 1 to 2 min to check-out and check-in.
- A skid rarely passes in front of the main gate to go from the south (Zuid area) to the north (Noord, Oost, West, Cab Trim), or vice versa.

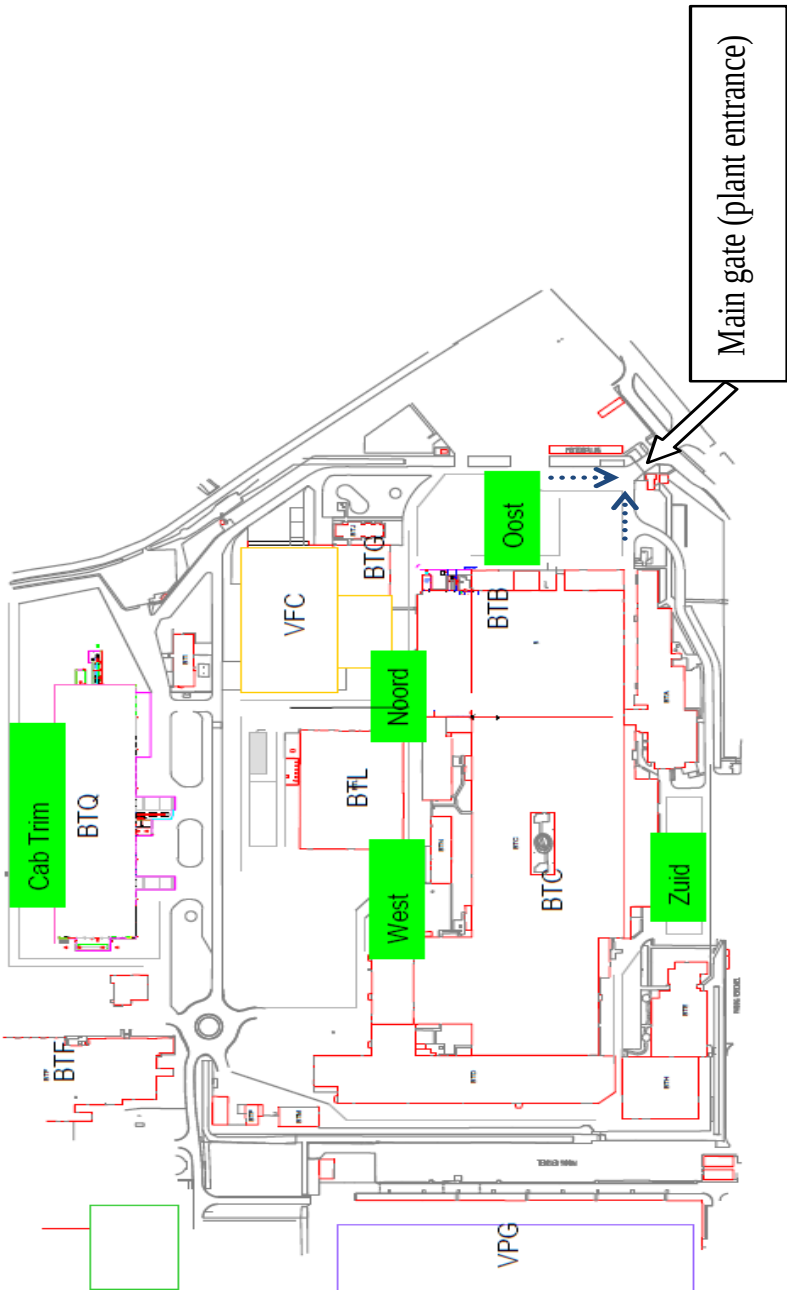


Figure 4.12: C plant layout

Table 4.8 lists the *theoretical time schedule*. Every day 11 skids usually leave from a specific location (e.g. Noord, Oost) at a certain time (Departure time from C) to S. Only 10 skids are transported on Fridays.

Table 4.8: Theoretical time schedule (Valid from WKXX)

Transport number	Departure time from C	Monday	Tuesday	Wednesday	Thursday	Friday
1	6:30	Noord	Noord	Noord	Noord	Noord
2	8:00	Cab Trim	Oost	Oost	Noord	Oost
3	9:30	KN	KN	KN	KN	KN
4	11:00	Noord	Noord	Noord	Noord	Noord
5	12:30	Noord	Noord	Noord	Noord	West
6	14:00	Oost	Cab Trim	Cab Trim	Cab Trim	Cab Trim
7	15:30	Noord	Noord	Noord	Noord	Noord
8	17:00	West	Zuid	Cab Trim	West	Cab Trim
9	19:00	Noord	Noord	Noord	Noord	Noord
10	20:30	Zuid	Zuid	Zuid	Zuid	Zuid
11	22:00	Cab Trim	Noord	Noord	Zuid	

An *outside area arrival list* holds the records for skid arrivals at S. Table 4.9 demonstrates the arrival list of a given date. The table exhibits the date, skid arrival time, place of the skid in S, departure origin from C and identity of the skid.

Table 4.9: An outside area arrival list of a date

Date	Arrival time	Place	From	Skid
4/10/2011	6:30	3	Noord	vh262
4/10/2011	9:10	3	Oost	vh358
4/10/2011	9:50	3	KN	vh204
4/10/2011	11:19	3	Noord	vh200
4/10/2011	13:00	3	noord	vh205
4/10/2011	14:25	3	Cab Trim	vh263
4/10/2011	15:55	3	Noord	vh358
4/10/2011	17:35	3	Zuid	vh357
4/10/2011	20:31	102	Noord	vh206
4/10/2011	22:35	102	Cab Trim	vh264

The automation company provided the RFID data for 29-30 September and 3-4-5 October 2011. They deployed the RFID-based RTLS at the main gate of C, to track in and out traffic of specific skids. The system components were RFID readers and tags and were the same ones used in the prototype system in Chapter 3 and for case company A. Two active RFID tags were placed on each skid, one mounted to the left and the other one to the right side, in order to have an uninterrupted line of sight with the readers for both directional postures. 9 UWB readers were located close to the main gate (on yellow "⌋" shape zone) to monitor a particular blue "⌋" shape zone, ranging 90 m to north and 70 m to south (Figure 4.13). The system was implemented to detect the direction of tags, to distinguish between the paths of the vehicles.

The RTLS collected a vast amount of data. To avoid unnecessary data collection, RTLS middleware design was developed similar to the one in section 4.1.3. The track zone was virtually divided into six smaller zones:MainGateIn, MainGateOut, DiretionP1in, DiretionP1out, DiretionBTGin and DiretionBTGout (Figure 4.14). The aim of the virtual layout was to detect predictable patterns when vehicles moved in a certain path to north and south. A path was a linear trip of a skid from one virtual zone to another. The data streams in a virtual zone were aggregated to the stay records (see section 4.1.3 for more detail).

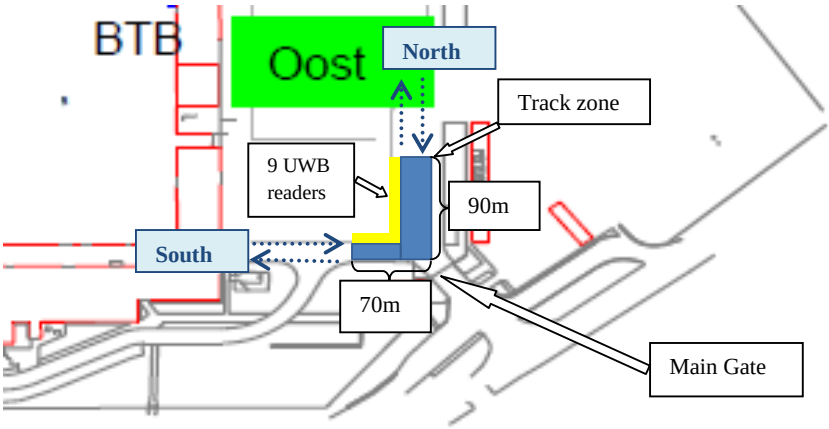


Figure 4.13: Readers' track zone at the main gate of C

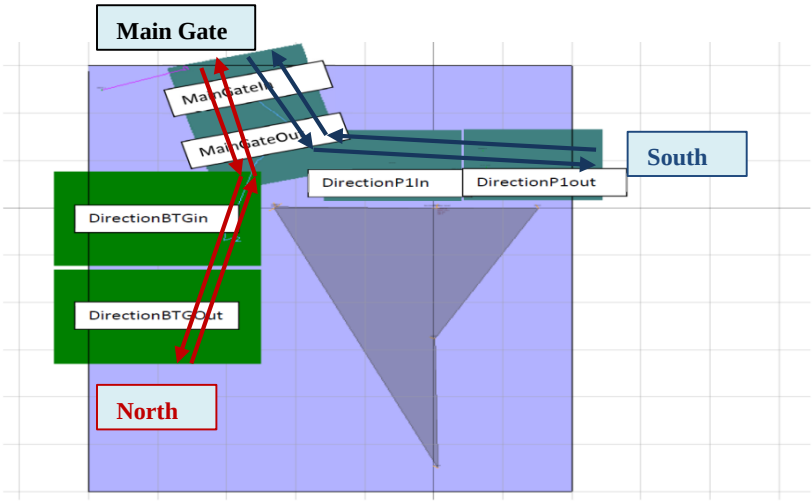


Figure 4.14: Track zone divided into six smaller zones in the RFID middleware

RTLS collected two kinds of RFID data: *position data* and *zone data*. The *position data* was collected to assess the accuracy of the *zone data*. When the *zone data* was not accurate, then position data was used for the data analysis. The *position data* contained tag coordinate measurements in time. A datum contained the date of an incident (Date), the error rate of a measurement (StdErr), tag identification number (TagID) and tag name (TagName). 'TagName' identified on which skid the tag was mounted and on which side of the skid the tag was placed (i.e. TagName = VH204_L, Vehicle number 204, to the left side). The measurements were updated in milliseconds. The record of an instant reading is represented below:

DateTime	x	y	StdErr	TagID	TagName

The *zone data* contained the date and time of incidents (DateTime), zone identification (ZoneName), information of either an entry to or exit from the zone (InZone), tag identification number (TagID) and tag name (TagName). The record of an instant reading is presented below:

DateTime	ZoneName	InZone	TagID	TagName

"ZoneName" and "InZone" values have twelve combinations between them. The six zones and their entry or exit information are shown below and their combinations will be used in data analysis.

- ZoneName = {$z_{MainGateIn}$, $z_{MainGateOut}$, $z_{DiretionP1in}$, $z_{DiretionP1out}$, $z_{DiretionBTGin}$, $z_{DiretionBTGout}$}
- InZone = {True, False}

4.3.2. Data Analysis

The objective of the data analysis is mainly to evaluate the read rate accuracy of the system, but also to inspect the theoretical time schedule and to match the theoretical time schedule with the outside area arrival list. Our data analysis followed two steps:

- Identifying skids
- Extracting event data

The read rate accuracy was assessed by the percentage of the events determined by the RFID data. The event data contained information to inspect and match the theoretical time schedule.

Identifying skids

RFID data did not contain a record that solely tracked a skid. Two active RFID tags on a skid had different TagID and TagName. Therefore, a record "Skid" was added to unite the two tags of a skid. An example of a conversion is:

TagID	TagName	**Skid**
250-000-010-115	VH261_R	**VH261**
250-000-010-116	VH261_L	**VH261**

Extracting event data

An event is a skid transport. The events were determined from the RFID data analysis at the main gate of the company. The event data held the information of the routes the skids followed and the times of the events. The route information is one of the four routes or lines shown in Figure 4.14. The time of an event is the appearance time of a skid in the readers' detection field, either an arrival time to or a departure time from C.

Each event was distinguished by the fact that the time of the next transport of the same skid took place more than an hour later. An event time query detected the events` start and end time. The data streams in between start and end times were further queried to attain the event data. A pseudo-code description of the query for a skid is:

```
k = event number
i = row number or the number of a reading

while (getNextSkid()) do
    for k =1 to End.Events
        for i = 1 to End.Row
            t1 = tEvent1StartTime
            if ti+1 - ti > 1 hour then
            ti = tEventkEndTime
            ti+1 = tEventk+1StartTime
            end if
    next i
    next k
end while
```

The event data was extracted from *zone data* by a straightforward event query. The event query detected the sequence of the zones the tag passed by and matched its path with one of the four routes defined in the database. We built the database of all possible routes based on "ZoneName" and "InZone" inputs:

- Route South to Main Gate: $\mathbf{z_{(DiretionP1out,\ True)}}$, $z_{(DiretionP1out,\ False)}$, $z_{(DiretionP1in,\ True)}$, $z_{(DiretionP1in,\ False)}$, $z_{(MainGateout,\ True)}$, $z_{(MainGateout,\ False)}$, $z_{(MainGatein,\ True)}$, $\mathbf{z_{(MainGatein,\ False)}}$
  Departure time from C: $tz_{(DiretionP1out,\ True)}$
- Route Main Gate to South: $\mathbf{z_{(MainGatein,\ True)}}$, $z_{(MainGatein,\ False)}$, $z_{(MainGateout,\ True)}$, $z_{(MainGateout,\ False)}$, $z_{(DiretionP1in,\ True)}$, $z_{(DiretionP1in,\ False)}$, $z_{(DiretionP1in,\ True)}$, $\mathbf{z_{(DiretionP1out,\ False)}}$
  Arrival time to C: $tz_{(MainGatein,\ True)}$
- Route North to Main Gate: $\mathbf{z_{(DirectionBTGout,\ True)}}$, $z_{(DirectionBTGout,\ False)}$, $z_{(DirectionBTGin,\ True)}$, $z_{(DirectionBTGin,\ False)}$, $z_{(MainGateout,\ True)}$, $z_{(MainGateout,\ False)}$, $z_{(MainGatein,\ True)}$, $\mathbf{z_{(MainGatein,\ False)}}$
  Departure time from C: $tz_{(DirectionBTGout,\ True)}$
- Route Main Gate to North: $\mathbf{z_{(MainGatein,\ True)}}$, $z_{(MainGatein,\ False)}$, $z_{(MainGateout,\ True)}$, $z_{(MainGateout,\ False)}$, $z_{(DirectionBTGin,\ True)}$, $z_{(DirectionBTGin,\ False)}$, $z_{(DirectionBTGout,\ True)}$, $\mathbf{z_{(DirectionBTGout,\ False)}}$
  Arrival time to C: $tz_{(MainGatein,\ True)}$

At least two inputs were necessary to detect a route. The time of the first input (reading) was the event time.

Event data was extracted from *position data* by performing first the route filter and then the route detection algorithm. The route filter extracted the necessary data for the route detection algorithm. From the vast amount of an event data, 60 rows were selected. The filter gathered the first, middle and last 20 readings of the events. The selection of 20 readings was to determine the reliable position estimates of the system. The first, middle and last reading were selected to determine the direction of the skids accurately. The query to collect this readings is:

- **for** each event
  Select Rows$[t_{EventStartTime1}$, $t_{EventStartTime20}]$,
  Rows$[t_{EventMidTime-10}$, $t_{EventMidTime10}]$,
  Rows$[t_{EventEndTime-20}$, $t_{EventEndTime1}]$

Route detection algorithm

This algorithm converted data from the route filter to route information such as “South to Main Gate”. The data contains the records “Time”, “x”, “y”, “StdErr” and “TagName”. Figure 4.15 presents the pseudo-code description of the algorithm. The input contains the initialization works, including classification of data. The output of the algorithm is a route represented by a route number.

In the first for-loop of the method, ten readings in each data set with the smallest standard error values was returned and the median point of the returned data sets was calculated. This provided the most reliable coordinate measurements from each start, middle and end points.

The second for-loop determined the route of the skid. Initially, two linear equations between the median coordinates of “Start - Middle” and “Middle - End” were calculated. These two equations were matched with a route by querying the database of Cartesian coordinate system allocation. The allocation divided the plant layout into definite route segments based on the in-plant logistics activities. Then, the “TagName” record validated the detected route. This record specified the directional posture of a vehicle. For example, if a skid was moving south and the tag at the left side of the skid (i.e. VH204_L) was read most of the time, this indicated vehicle moves from the south to main gate, since there was a direct line of sight between the left tag and the readers, and the right side tag was blocked by the vehicle.

Algorithm Route detection

Input: Data from route filter with data sets Start, Middle and End
Database of Cartesian coordinate system allocation
Output: Route of each event
Method:
for each data set of an event **do**
Return n (=10) records with minimum "StdErr"
Calculate the median coordinates of the returned values
end for
for each event **do**
Calculate line equation between median coordinates of Start – Middle and Middle – End
if two line equations fit one direction in Cartesian coordinate system allocation **AND**
if the route number matches with tag side "TagName" **then**
Assign the route number
if no **then**
Undetected route
end if
end if
end if
end for

Figure 4.15: Route detection algorithm

Matching RFID data, theoretical time schedule and arrival list

We filled out a match table that lists all the matches between events, theoretical time schedule and arrival list (Appendix C). The match table shows the traffic between C and S. The event data and arrival list corresponds to the skid number. The theoretical time schedule and S arrival list corresponds to the "From" record, which shows the origin of the skids. "Direction" record indicates the route followed.

4.3.3. Results

In this section, we present the results of five days of skid traffic. Based on these results, the RFID system provider observed the system reliability and the company assessed the schedule accuracy in near real-time.

The RTLS data read rate accuracy was around 45%. 45 out of 99 skid transports were determined by the analysis of position data. Table 4.10 shows the events on each date. The system was unable to detect 54 events. Some files of the first, second and fifth day were missing in the database. We reported this issue to the system supplier and they discovered a network disconnection on these particular days

Table 4.10: Detected events at the main gate of C

Date	# of Transports	Total Match	Arrival	Departure
9/29/2011	20	1	1	0
9/30/2011	19	5	5	0
10/3/2011	20	13	7	6
10/4/2011	20	16	10	6
10/5/2011	20	10	5	5
Total	99	45	28	17

14 out of 45 events were determined by the zone data. Some of the zone files were not in the database, because, the virtual zones were misallocated when compared to the reality. Therefore, the zone data was less accurate and less usable than the location data. Figure 4.16 displays all readings on the allocated zones. The middleware was unable to collect all necessary zone data, because the areas where the driver stops to check-in and checkout were mainly not in the detection zone. Nevertheless, the middleware was successful in avoiding collecting data from an irrelevant zone where tags were read while vehicles were parked at a parking spot.

The location measurements were accurate 43 times out of 45. In the match table in Appendix C, one observation on 9/30/2011 with transport number 2 and another one on 10/04/2011 with transport number 9 were inaccurate

based on the comparison between the RFID data and the S arrival list. These two observations showed arrivals, which in reality were departures.

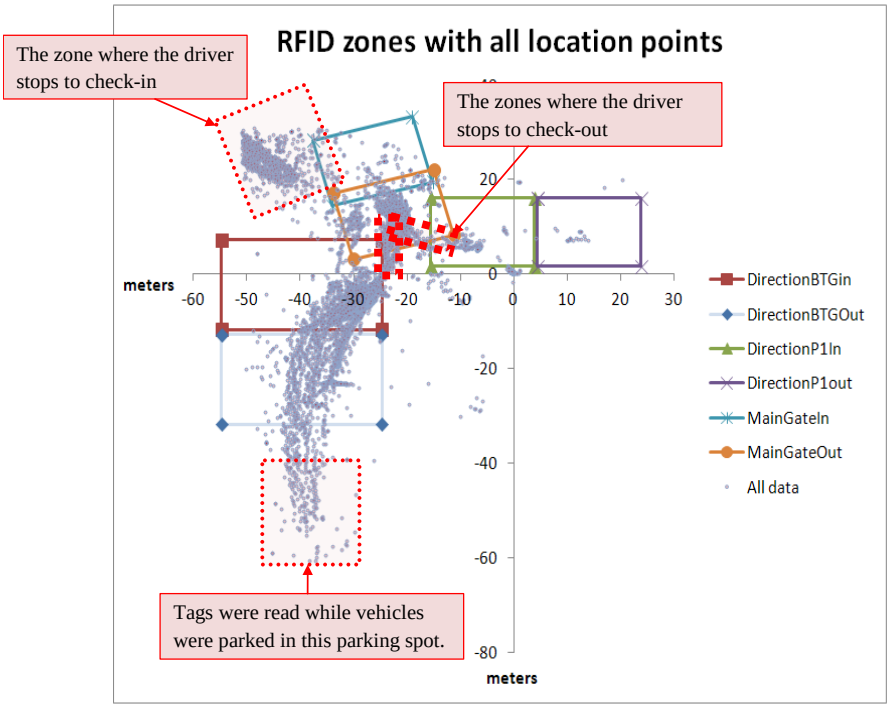


Figure 4.16: RFID map

The theoretical time schedule (Table 4.8) was accurate with a few minutes of time difference between the RFID timestamp and the schedule time. Within 14 departures, the schedule lagged behind 10 times by an average of 8 minutes and 4 times schedule was ahead by an average of 5 minutes. The schedule lagged behind by maximum 20 minutes and it was ahead by maximum 10 minutes. Figure 4.17 and 4.18 display the distribution of time difference for all departures. In one case only, on 10/3/2011 the transport number 9 was incorrect. The departure time was 17:30 instead of 19:00.

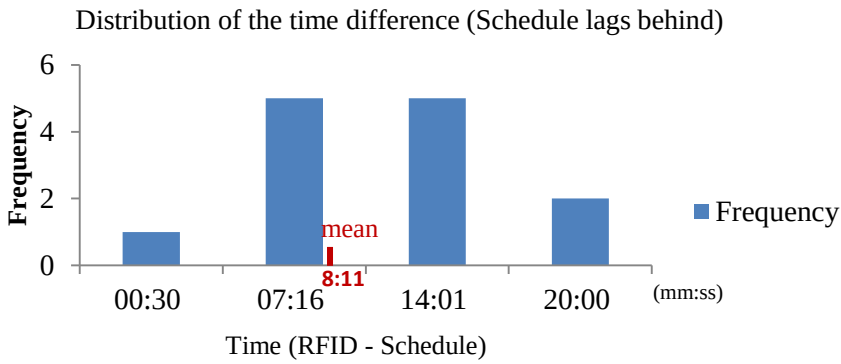


Figure 4.17: Distribution of the time difference between RFID time stamp and the scheduled time when the schedule time lagged behind

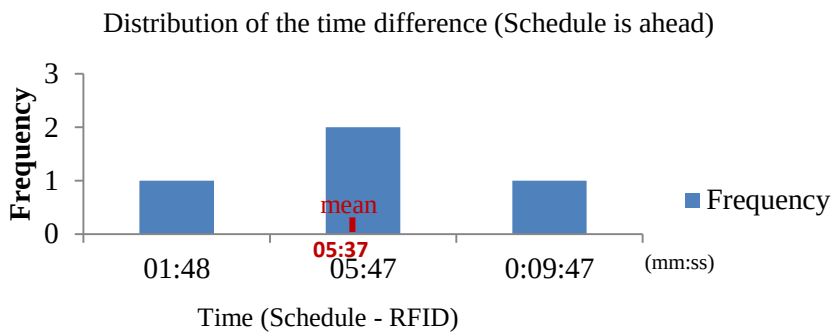


Figure 4.18: Distribution of the time difference between RFID time stamp and the schedule time when the schedule time was ahead

The predictions for the point of departure of the theoretical time schedule were accurate 17 out of 18 departures. Only for 10/3/2011, the transport number 9 was “Oost” instead of “Noord”.

4.4. Conclusion

Each company had different requirements. The RTLS and data mining processes were customized based on the particular needs of the companies. Two different RTLS solutions were used for the three cases: RFID-based RTLS for the first and third case, RFind's RTLS for the second. The RFID system was found to be more reliable, robust and scalable than the tag-to-tag communication system. The different data process steps show which process methods and technologies are most suitable to counter the challenges in a manufacturing environment.

Nevertheless, the case studies validated the various steps of the methodological study developed in Chapter 3. The data filtering options (i.e. the analysis of the speed of the tagged items to adjust the data acquisition rate), the process to obtain elaborate KPIs from RFID data in low-level context and the functionality of the system in the presence of metal were all proven to be valid. Moreover, the data filtering and cleaning procedures as described in Chapter 3 were improved upon by developing more filtering and cleaning options.

The increased level of detail from RFID measurements yields new insights into shop floor actions and the real effects of redesign efforts. The results clearly indicate that RFID-enabled RTLS can provide up-to-date, automatically acquired, rich and detailed shop floor information for enterprise systems. Besides, the material flow data from a robust RTLS is fairly straightforward to clean, which allows detecting main events and spot errors.

5. Conclusion

This dissertation evaluates the use of RFID-based RTLS in the manufacturing industry. Based on two experimental and three case studies we analyze five use cases for RTLS. They are unique RTLS applications facilitating access to the process data more effectively than its alternatives. These applications are aimed at linking physical objects to RFID-enabled IT systems, providing real time information, improving material flow visibility, automating asset tracking, measuring work measurements efficiently, advancing production flexibility, and optimizing production logistics.

Despite the fact that RFID-based RTLS offer substantial benefits, the technology has yet to be widely adopted in production logistics applications. The reasons for this are twofold: several challenges remain in establishing the technology for plant floor processes and manufacturers are concerned about the return on investment. The main challenges are the system instability in certain physical conditions, dealing with big data and the integration of RFID into enterprise information systems.

These challenges can, however, be countered by taking certain measures. The use of RFID in the presence of metal or major physical obstacles can be improved by accurate positioning of the correct hardware. To deal with big data, one can pre-filter redundant data, by means of a middleware, before storing it into a database. To cope with the integration of RFID into enterprise information systems, a company can develop a new RFID-

integrated data architecture model. The deployment of such a model could not only lead to efficiency and productivity improvements on the shop floor, but to improvements in process visibility as well, thus allowing to detect production variations. Apart from addressing these issues, this dissertation also aims to disprove the lack of applications with diverse RFID use cases in production logistics.

5.1. Research Questions

This thesis dealt with the following main research theme:

"*Can RFID-based RTLS be developed into a system that delivers insight about the performance of workflows in order to evaluate and improve the robustness and efficiency of production logistics*?

By conducting experiments and researched case studies, we found answers to the research questions presented in Chapter 1:

"*What are the key production process measurements and performance indicators to evaluate the robustness and efficiency of production logistics? Which of them can be based on RFID-generated data?*"

Based on a diverse literature study and discussions with production logistics experts, we were able to categorize key performance metrics within the varied dimensions of manufacturing strategy. Table 2.1 lists the key quantitative production performance metrics. The measurement, management and improvement of these metrics were discussed in Chapter 2. We were able to obtain metrics and KPIs in non-financial operational categories (see section 3.2) from the analysis of RFID data. Moreover, we identified and validated different and more extensive KPI's from data analysis. The enhanced KPI's were presented in Chapter 3 and 4. The RFID system provided real-time, automatically generated and detailed set of data, which enabled us to obtain more up-to-date, effective and easily accessible KPIs. The availability of the new measurements, such as speed, per period and single flow parameters (see section 4.1.5) maximized the use of real-time analysis and evaluation methods.

"*How can we process and assess RFID data in order to provide accurate results about the trajectory of tagged objects?*"

We developed RFID data analysis methods to improve enterprise information systems. A new enterprise data architecture model to adopt an RFID system into a current enterprise information system was proposed in Chapter 3. In the new model, RFID data analysis methods followed two different trajectories: *real-time performance monitoring* and *trajectory analysis*. The *real-time performance monitoring* was discussed through a new production performance dashboard design in Chapter 3, section 3.4,. The *real-time performance monitoring* system derived the metrics listed in Table 3.7 from both current time and the position data of objects. The *trajectory analysis* of tagged objects was demonstrated in the empirical study in section 3.3 and in the case studies. Our analysis methods included methods for RFID-based RTLS data filtering, data cleaning and event processing. Table 5.1 lists all analysis methods and the sections they appeared in.

We assessed the quality of raw RFID data in all experiments and case studies. The assessment of data quality was based on read rate and location accuracy.

Table 5.1: RFID-based RTLS data analysis methods

	Analysis method	**Section**
Data filtering	Displacement filter	3.3.5
	Speed filter	3.3.5
	Middleware development	4.1.3, 4.3.1
	Time filter	4.3.2
	Route filter	4.3.2
Data cleaning	Elimination of inaccurate location measurements	3.3.5
	Elimination of duplicate readings	4.1.4
Event processing	Extraction of KPIs	3.3.6, 4.1.4, 4.2.2, 4.3.2
	Stopover or operation time query	3.3.6, 4.2.2, 4.3.2
	Route detection algorithm	4.2.2, 4.3.2
	Work space utilization	4.1.4, 4.2.2

"*Can RTLS real time data be used to analyze complex operations involving human operators?*"

The case study in section 4.1 demonstrated an RTLS data analysis method to evaluate the performance of a multi-item production process. It delivered sufficient up-to-date workflow knowledge, containing measures of material flow, worker utilization and various complex activities to the company. One of the main contributions of this study is that it deals with the challenge of precise and fast tracking of multiple items without missing critical trails. The items can irregularly fluctuate more than 1 m/s in motion velocity. Another contribution is that it improves multi-item work-in-process visibility by delivering a near real time performance evaluation before and after a workflow redesign.

"*What is the potential use of RTLS real time data in visualizing production logistics performance?*"

The enhancement of production logistics information visibility plays an important role in monitoring and controlling plant floor activities. Manufacturers can have flexible flow of goods, capacity and can handle complexity if they consider the competitive visibility terms (i.e. continuous tracking, monitoring and real-time) successfully. RTLS addresses these terms and helps to improve production monitoring systems. By employing RFID-based RTLS real time data, we were able to increase the visibility of plant floor objects by providing better information about their location, state and performance throughout the production logistics.

We designed and tested an RFID performance monitoring system, a performance dashboard for vehicle performance monitoring, in chapter 3, section 3.4.. The system performed RTLS data collection, analysis and reporting of production activities of vehicles. The test results showed that the dashboard provides an accurate and detailed set of vehicle performance information. In addition to the performance dashboard, we delivered performance figures in the other experiment and case studies. Table 5.2 summarizes these figures, which provided answers to the managerial requests of performance metrics in visuals.

Table 5.2: List of performance figures

Request	Visualization	Figure
Event times	Time distribution graphs of item and vehicle cycles, loading and unloading activities	4.6 4.17 4.18
Work area utilization	Spaghetti diagram RFID map	4.7 4.16
Production speed	Speed distribution graph of production with loading and unloading activities	3.8

5.2. Future Research

The results of this dissertation provide interesting managerial insights and indicate several directions for future research.

Adoption of RFID-based RTLS into enterprise information system

Manufacturing practitioners expect from RTLS to deliver useful information in real-time. The enterprise systems need, yet still do not have the integrated real time data collection systems in operation delivering accurate and to the point shop floor information for accurate decision making (Zhong et al., 2013). The challenge in delivering this lay in the fact that RFID-based RTLS is required to quickly and continuously generate big data in a low-level context. The big data then has to be transformed into high-level context without exceeding database capacity. We have dealt with these issues by developing a middleware in real-time, with higher level data transformation and by developing a performance dashboard in near-real time. Further research could be the adoption of RFID-based RTLS into an enterprise information system by applying the findings of this research. The evaluation of the business value of using RTLS and the economic viability of adopting the system can be another future research direction and the testing and validation of a real-time performance monitoring system on a real case could be a pilot application.

New or hybrid RTLS solutions

Some action has already been taken to develop the support of multiple wireless technologies, wireless combined with other technologies and the combination of data mining steps in a theoretically optimal way (Ahmed et al., 2014). In our case studies, which were conducted with the most up-to-date technology at the time, the location precision of RFID system observations was reduced in the presence of metal. Especially in the second case study this appeared to be very challenging. Future research can be the employment of a new or hybrid RTLS to improve read rate and location accuracy in this type of problematic environment. When it comes to readability, the placement of the hardware is, however, in equal importance to the selection of appropriate hardware. Many studies are being performed and more future research can be done to improve RTLS robustness in challenging environments.

In-plant traffic control systems

Driven by customer requirements, the complexity of in-plant logistics is constantly increasing due to incessant introductions of new products and parts to the production line. This makes it more difficult to detect congestion and other problematic activities. During the production process pre-defined production planning can rapidly become obsolete because of unforeseen changes in complex production environments. RTLS can counter this by helping to control traffic in multi-item and multi-vehicle plant floors, thus allowing for plant floor objects to be tracked and congestions to be detected in real time. The system can make it possible to take necessary actions to control traffic speed, density and routes either automatically or manually. The real-time information of the location, state and performance of both materials and vehicles throughout the production process can shift the decision making from production planning towards autonomous production control, dynamic production planning and scheduling. Further research can be conducted to develop autonomous traffic control methods or to create generic algorithms based on RTLS data allowing production logistics objects to render and execute their own decisions.

References

Aghezzaf, E.H., 2009, Introduction to Operations Research, Industrial Management, Faculteit Ingenieurswetenschappen, UGent, *Chapter 'Network problems'*, 2-7.

Ahmed A., K. Hasnan, B. Aisham and Q. Bakhsh, 2014, Integration of Value Stream Mapping with RFID, WSN and ZigBee Network, *4th International Conference on Mechanical and Manufacturing Engineering*, 769 – 773.

Al-Aomar, R., 2002, A Methodology for Determining Process and System-Level Manufacturing Performance Metrics *SAE Transactions* 111, 1043-1056.

Arkan, I., Van Landeghem, H., 2013, Evaluating the performance of a discrete manufacturing process using RFID: a case study, *Robotics and Computer-Integrated Manufacturing* 29 (6), 502–512.

AT&T, 2011, RTLS and RFID, cited 2 February 2015, available from https://developer.att.com/developer/forward.jsp?passedItemId=2400556

Bai, Y., F. Wang, P. Liu, 2006, Efficiently filtering RFID data stream, *CleanDB Workshop*, 50–57.

Bendavid, Y., E. Lefebvre, L. A. Lefebvre, and S. Fosso-Wamba, 2009, Key performance indicators for the evaluation of RFID-enabled B-to-B e-commerce applications: the case of a five-layer supply chain, *Information Systems and E-Business Management* 7, 1-20.

Bleco, D., and Y. Kotidis, 2009, RFID Data Aggregation, *3rd International GeoSensor Networks Conference*, 5659, 87-101.

Boer, H., and A. Drejer, 2005, Managing Innovative Manufacturing, *International Journal of Operation and Production Management* 25, 96-216.

Buyser S.D., 2011, Dynamic analysis of in-plant logistics based on RFID data, Master thesis (Ghent University, Belgium), p:105.

Chappel, G., L. Ginsburg, P. Schmidt, J. Smith, and J. Tobolski, 2003, Auto-ID on the Line: The Value of Auto-ID Technology in Manufacturing, Auto-ID Center Massachusetts Institute of Technology.

Chearskul, P., 2010, An Empirical Investigation of Performance Measurement System Use and Organizational Performance, Phd dissertation, Virginia Tech, p: 381.

Choudhari, S. C., G. K. Adil, and U. Ananthakumar, 2013, Configuration of manufacturing strategy decision areas in line production system: five case studies, *International Journal of Advanced Manufacturing Technology* 64, 459-474.

Chow, H. K. H., K. L. Choy, W. B. Lee, 2007, A dynamic logistics process knowledge-based system - An RFID multi-agent approach, *Knowledge-Based Systems* 20, 357-372.

Coffey, B. S., and R. E. Crandall, 2004, Facilitating and implementing change: Batch to lean is not an easy journey, Paper presented at the Management Sciences and Global Strategies in the 21st Century, Vols 1 and 2, Maaco.

Curran, K., E. Furey, T. Lunney, J. Santos, D. Woods and A. McCaughey, 2011, An evaluation of indoor location determination technologies, *Journal of Location Based Services* 5:2, 61 – 78.

Curtin, J., R. J. Kauffman, and F. J. Riggins, 2007, Making the 'MOST' out of RFID technology: a research agenda for the study of the adoption, usage and impact of RFID, *Information Technology & Management* 8, 87-110.

Dai, Q., R. Y. Zhong, G. Q. Huang, T. Qu, T. Zhang, and T. Y. Luo, 2012, Radio frequency identification-enabled real-time manufacturing execution system: a case study in an automotive part manufacturer, *International Journal of Computer Integrated Manufacturing* 25, 51 – 65.

Damanpour, F., 1996, Organizational complexity and innovation: Developing and testing multiple contingency models, *Management Science* 42, 693-716.

Das, S. K., and P. Patel, 2002, An audit tool for determining flexibility requirements in a manufacturing facility, *Integrated Manufacturing Systems* 13, 264-274.

Deak G., K. Curran and J. Condell, 2012, A survey of active and passive indoor localisation systems, *Computer Communications* 35, 1939 – 1954.

DTI, 1988, Competitive manufacturing: a practical approach to the development of a manufacturing strategy (*IFS Publications*, Bedford).

Duray, R., P. T. Ward, G. W. Milligan, and W. L. Berry, 2000, Approaches to mass customization: configurations and empirical validation, *Journal of Operations Management* 18, 605-625.

Ferdows, K., and A. De Meyer, 1990, Lasting Improvement in Manufacturing Performance: In Search of a New Theory, *Journal of Operations Management* 9, 168-184.

Ferrer, G., N. Dew, and U. Apte, 2010, When is RFID right for your service?, *International Journal of Production Economics* 124, 414-425.

Fullerton, R. R., and W. F. Wempe, 2009, Lean manufacturing, non-financial performance measures, and financial performance, *International Journal of Operations and Production Management* 29, 214-240.

Furey, E., K. Curran, and P. McKevitt, 2012, HABITS: a Bayesian filter approach to indoor tracking and location, *International Journal of Bio-Inspired Computation* 4, 79-88.

Gelders, L., P. Mannaerts, and J. Maes, 1994, Manufacturing Strategy, Performance Indicators and Improvement Programs, *International Journal of Production Research* 32, 797-805.

Golden, W., and P. Powell, 2000, Towards a definition of flexibility: in search of the Holy Grail?, *Omega-International Journal of Management Science* 28, 373-384.

Gomes, C. F., M. M. Yasin, and J. V. Lisboa, 2011, Performance measurement practices in manufacturing firms revisited, *International Journal of Operations and Production Management* 31, 5 – 30.

Gonzalez, H., J. Han, X. Li, and D. Klabjan, 2006, Warehousing and Analyzing Massive RFID Data Sets, *International Conference on Data Engineering (ICDE06)* 1-10.

Gunasekaran, A., and B. Kobu, 2007, Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995-2004) for research and applications, *International Journal of Production Research* 45, 2819-2840.

Gunasekaran, A., C. Patel, and E. Tirtiroglu, 2001, Performance measures and metrics in a supply chain environment, *International Journal of Operations and Production Management* 21, 71-87.

Gunn, T. G., 1988, *Manufacturing for competitive advantage: becoming a world class manufacturer* (HarperBusiness, Cambridge).

Hayes, R. H., and S. C. Wheelwright, 1984, *Restoring Our Competitive Edge: Competing Through Manufacturing* (Wiley).

Hellstrom, D., and M. Wiberg, 2009, Exploring an open-loop RFID implementation in the automotive industry, Paper presented at the IEEE 14th International Conference on Emerging Technologies & Factory Automation, ETFA 2009.

Heo, J., M. W. Pyeon, J. W. Kim, and H. G. Sohn, 2006, Towards the optimal design of an RFID-Based positioning system for the ubiquitous computing environment, *2nd International Conference on Rough Sets and Knowledge Technology* Toronto, Canada, 331-338.

Hu, J., F. L. Lewis, O. P. Gan, G. H. Phua and L. L. Aw, 2014, Discrete-Event Shop-Floor Monitoring System in RFID-Enabled Manufacturing, *IEEE Transactions on Industrial Electronics* 61, 7083 – 7091.

Huang, G. Q., P. K. Wright, and S. T. Newman, 2009, Wireless manufacturing: a literature review, recent developments, and case studies, *International Journal of Computer Integrated Manufacturing* 22, 579-594.

Huang, G. Q., Y. F. Zhang, and P. Y. Jiang, 2008, RFID-based wireless manufacturing for real-time management of job shop WIP inventories, *International Journal of Advanced Manufacturing Technology* 36, 752-764.

Hynek, J., and V. Janecek, 2011, Shall We Invest in Advanced Manufacturing Technology?, *Finance and the Performance of Firms in Science, Education, and Practice*, 179-186.

IBM, WebSphere RFID Premises Server cited 2 August 2013, available from http://www-306.ibm.com/software/pervasive/ws_rfid_premises_server/

Ivantysynova, L., 2008, RFID in Manufacturing: Mapping the Shop Floor to IT-Enabled Business Processes, Phd dissertation, p: 210.

Jayaram J., A. Das, M. Nicolae, 2010, Looking beyond the obvious: Unraveling the Toyota production system, *International Journal of Production Economics*, 128, 280-291.

Jeffery, S. R., G. Alonso, M. J. Franklin, W. Hong, and J. Widom, 2006, Declarative support for sensor data cleaning, *Pervasive Computing* 83-100.

Johnson, A. R., 2008, An investigation of internal logistics within a lean production system via simulation: A case study, Master thesis (State University of New York, Binghamton).

Karkkainen, M., and J. Holmstrom, 2002, Wireless product identification : enabler for handling efficiency , customisation and information sharing, *Supply Chain Management: An International Journal* 7, 242-252.

Karl, N., 2009, Ubisense Real-time Location Systems (RTLS) training, Waarschoot, Belgium.

Kaur, M., M. Sandhu, N. Mohan, and P. S. Sandhu, 2011, RFID Technology Principles, Advantages, Limitations & Its Applications, *International Journal of Computer and Electrical Engineering* 3, 151-157.

Kelepouris, T., D. McFarlane, 2010, Determining the value of asset location information systems in a manufacturing environment, *International Journal of Production Economics*, 126, 324-334.

Kim, J., C. S. Ok, S. Kumara and S. T. Yee, 2010, A market-based approach for dynamic vehicle deployment planning using radio frequency identification (RFID) information, *International Journal of Production Economics*128, 235 – 247.

Kim, J., K. Tang, S. Kumara, S. T. Yee, and J. Tew, 2008, Value analysis of location-enabled radio-frequency identification information on delivery chain performance, *International Journal of Production Economics* 112, 403-415.

Koppers, J., 2009, Location based services, Master thesis (Radboud University of Nijmegen, Netherlands).

Kotha, S., and P. M. Swamidass, 2000, Strategy, advanced manufacturing technology and performance: empirical evidence from US manufacturing firms, *Journal of Operations Management* 18, 257-277.

Kou, D., K. Zhao, Y. Tao, and W. Kou, 2006, Enabling technologies for wireless e-business, *RFID Technologies and Applications* (Springer, New York).

Lim, B., F. Ling, and G. Ofori, 2007, Flexibility management in the changing competitive environment, *CME 2007 Conference - Construction Management and Economics: 'Past, Present and Future'* 689-698.

Liu, H., H. Darabi, P. Banerjee and J. Liu, 2007, Survey of wireless indoor positioning techniques and systems, *IEEE Transactions on Systems Man and Cybernetics Part C-Applications and Reviewers* 37, 1067 – 1080.

Maskell, B. H., 1989, Performance measures for world class manufacturing, *Journal of Strategic Performance Measurement* 71, 32-33.

McFarlane, D., S. Sarma, J. L. Chirn, C. Y. Wong, and K. Ashton, 2003, Auto ID systems and intelligent manufacturing control, *Engineering Applications of Artificial Intelligence* 16, 365-376.

McFarlane, D. C., and Y. Sheffi, 2003, The Impact of Automatic Identification on Supply Chain Operations, *International Journal of Logistics Management* 14, 1-17.

Mylyy, O., 2006, RFID Data Management, Aggregation and Filtering, Hasso Plattner Institute at the University of Potsdam, Germany.

Nambiar, A. N., 2009, RFID Technology: A Review of its Applications, Paper presented at the Wcecs 2009: World Congress on Engineering and Computer Science San Francisco, USA.

Neely, A., J. Mills, K. Platts, H. Richards, M. Gregory, M. Bourne, and M. Kennerley, 2000, Performance measurement system design: developing and testing a process-based approach, *International Journal of Operations and Production Management* 20, 1119-1145.

Ngai, E. W. T., T. C. E. Cheng, K. H. Lai, P. Y. F. Chai, Y. S. Choi, and R. K. Y. Sin, 2007, Development of an RFID-based traceability system:

Experiences and lessons learned from an aircraft engineering company, *Production and Operations Management* 16, 554-568.

Ngai, E. W. T., K. K. L. Moon, F. J. Riggins, and C. Y. Yi, 2008, RFID research: An academic literature review (1995-2005) and future research directions, *International Journal of Production Economics* 112, 510-520.

Ni, L. M., Y. H. Liu, Y. C. Lau, and A. P. Patil, 2004, LANDMARC: Indoor location sensing using active RFID, *Wireless Networks* 10, 701-710.

Palmer, M., 2004, Seven Principles of Effective RFID Data Management (Progress Software-Real Time Division.

Platts, K. W., and M. J. Gregory, 1990, Manufacturing audit in the process of strategy formulation, *International Journal of Operations and Production Management* 10, 5-26.

Reichert, F., A. Kunz, R. Moryson, K. Wegener, 2010, A Key Performance Indicator System of Process Control as a Basis for Relocation Planning, *43rd CIRP Conference on Manufacturing Systems*, Zurich, 805-812.

Reyes, P. M., and G. V. Frazier, 2007, Radio frequency identification: past, present and future business applications, *International Journal of Integrated Supply Management* 3, 125-134.

Rho, B. H., K. Park, and Y. M. Yu, 2001, An international comparison of the effect of manufacturing strategy-implementation gap on business performance, *International Journal of Production Economics* 70, 89-97.

Roberti, M., 2010, What Is the Difference Between RFID and RTLS? (*RFID Journal Magazine*) cited 2 August 2013, available from http://www.rfidjournal.com/expert/entry/7773/

Roy, S., S. Bandyopadhyay, M. Das, S. Batabyal, and S. Pal, 2010, Real time traffic congestion detection and management using active RFID and GSM technology, *International Conference on Intelligent Transport Systems Telecommunications*, 9-11.

Sackett, P. J., D. J. Maxwell, and P. A. Lowenthal, 1997, Customizing manufacturing strategy, *Integrated Manufacturing Systems* 8, 359-364.

Sala, M. S., and M. M. Vidal, 2010, Study and redesign of the Quality Control department of Plastal, Master thesis, Department of Industrial Management, Ghent University , 113.

Sauer, O., 2007, Production monitoring linked to object identification and tracking - A step towards real time manufacturing in automotive plants, Paper presented at the Digital Enterprise Technology: Perspectives and Future Challenges.

Saxena, A., S. Ganguly, S. Bhatnagar, and R. Izmailov, 2007, RFInD: An RFID-based system to manage virtual spaces, *Fifth Annual IEEE International Conference on Pervasive Computing and Communications Workshops*, 382-387.

Schleipen, M., O. Sauer, N. Friess, L. Braun, and K. Shakerian, 2010, Production Monitoring and Control Systems within the Digital Factory, *Proceedings of the 6th Cirp-Sponsored International Conference on Digital Enterprise Technology*, 711-724.

Schmitt, P., F. Thiesse, and E. Fleisch, 2008, Adoption and diffusion of RFID technology in the automotive industry *(Auto-ID labs, 15th European Conference on Information Systems, St.Gallen, Switzerland)*.

Skinner, W., 1969, Manufacturing - Missing Link in Corporate Strategy, *Harvard Business Review* 47, 136-145.

Stapleton-Gray, R., 2004, Vulnerable link in supply chain; Radio tags are boon to logistics, but adversaries may be listening in, *Armed Forces Journal*, 26-27.

Thiesse, F., and E. Fleisch, 2008, On the value of location information to lot scheduling in complex manufacturing processes, *International Journal of Production Economics* 112, 532-547.

Wang, F. S., S. R. Liu, P. Y. Liu, and Y. J. Bai, 2006, Bridging physical and virtual worlds: Complex event processing for RFID data streams, *Advances in Database Technology*, 588-607.

Want, R., 2006, An introduction to RFID technology, *IEEE Pervasive Computing* 5, 25-33.

White, G.P., 1996, A survey and taxonomy of strategy-related performance measures for manufacturing, *International Journal of Operations and Production Management* 16,42-&.

Windt, K., T. Becker, and I. Kolev, 2010, A comparison of the logistics performance of autonomous control methods in production logistics, *43rd CIRP International Conference on Manufacturing Systems* Vienna) 576-583.

Windt, K., F. Bose, and T. Philipp, 2008, Autonomy in production logistics: Identification, characterisation and application, *Robotics and Computer-Integrated Manufacturing* 24, 572-578.

Yu, J., W.S. Ku, M.T. Sun, and H. Lu, 2013, An RFID and Particle Filter-Based Indoor Spatial Query Evaluation System, *Proceedings of the 16th International Conference on Extending Database Technology, 263 - 274*.

Zang, C., and Y. Fan, 2007, Complex event processing in enterprise information systems based on RFID, *Enterprise Information Systems*, 1(1), 3–23.

Zhang, X. B., L. L. Cheng, and Q. M. Zhu, 2011, Improvement of Filtering Algorithm for RFID Middleware Using KDB-tree Query Index, *Journal of Software* 6, 2521-2527.

Zhong, R. Y., G. Q. Huang, Q. Y. Dai, and T. Zhang, 2012, Mining SOTs and dispatching rules from RFID-enabled real-time shopfloor production data, *Journal of Intelligent Manufacturing*, 1-19.

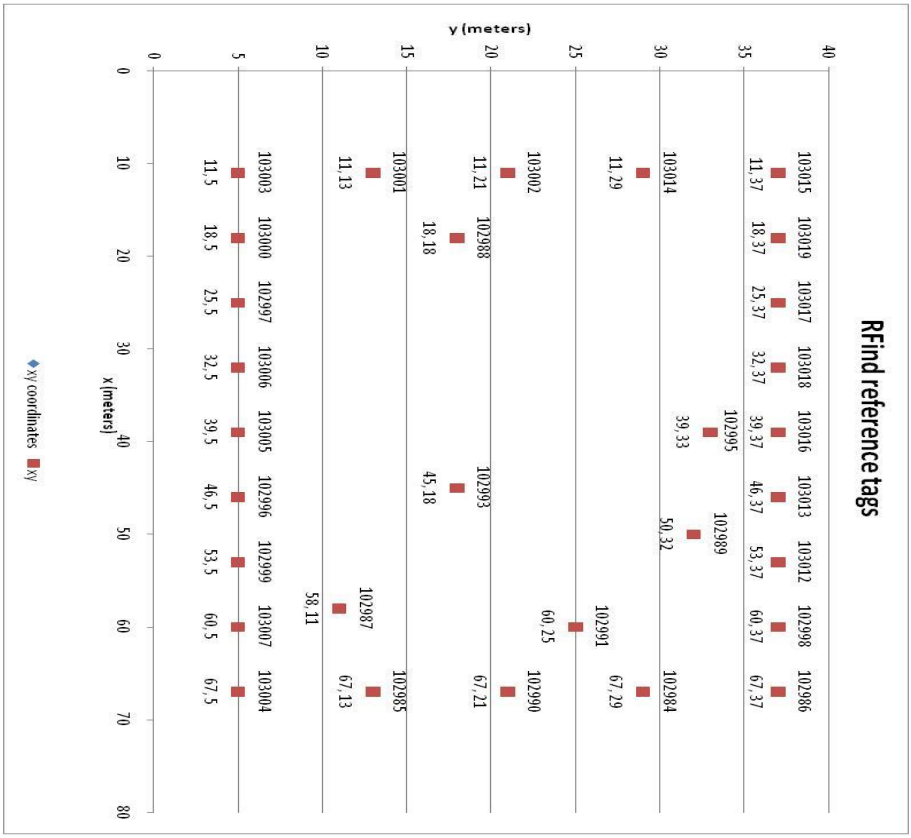
Zhong R.Y., Q.Y. Dai, T. Qu, G.J. Hu, G.Q. Huang, 2013, RFID-enabled real-time manufacturing execution system for mass-customization production, *International Journal of Robotics and Computer-Integrated Manufacturing* 29, 283-292.

APPENDIX A: Metrics Development Matrix

Metrics Development Matrix

Metric Specification				Portrayal Design			Data Collection Plan					Utilization	
Metric	Operational Definition and/or Formula	Purpose of Metric	Metric Owner	Portrayal Frequency	Type of Data	Portrayal Tool	Tracking tool	Data Available?	Data Collection Responsibility	Data Collection Tool(s)	Data Collection Frequency	Implemen-tation Date	Metric Goal
Key Performance Area: Improve the visibility of the internal logistics process													
Location of the vehicle	Coordinates + Area of location (= zone)	Allow a quick view of location and route efficiency	-	Every second	Objective continuous	Spaghetti chart of the last hour / area of location of each vehicle as text	Excel	Yes	-	RFID data	Every second	-	n/a
Status of the vehicle	The status can be: Driving, Waiting, (Un)Loading, Idle or Error	Visualize the occupancy of the vehicle; show defects and other problems	-	Every second / every hour	Objective continuous	Current status as text / Pie-chart which shows the division of work time over the last hour / Bar chart of the occupancy per hour, showing the trend	Excel	Yes	-	RFID data, excel	Every second	-	n/a
Order list progress	Display the current order and progress in the order	Visualize the progress	-	Each time an order is completed	Objective continuous	Display current order as text / display progress in current order	Excel	Yes	-	Order list, excel	Each time an order is completed	-	n/a
Key Performance Area: Increase the efficiency and keep the cost to a minimum													
Overall efficiency	Actual total time per order / expected time per order	Keep track of the overall efficiency of the system	-	Every time an order is completed	Objective continuous	Bar chart comparing actual total time against expected total time for x orders to visualize a trend		Standard time for loading/ unloading is needed	-	RFID data, order list	Every second	-	TBD
Transportation efficiency	Expected transportation time/ Actual transportation time	Visualize the progress of each order, compared to the expected progress at ideal average speed	-	Every second (or 2)	Objective continuous	Graph meter showing the actual driven distance vs. the expected driven distance against time	Excel	Yes	-	RFID data, Shortest path algorithm (excel)	Every second	-	TBD
Average speed	Average speed while Status = 'Driving'	Display the speed efficiency	-	Every order	Objective continuous	Gauge showing the average speed compared against the ideal average speed	Excel	Yes	-	RFID data	Every second	-	TBD
Route efficiency	Length of the shortest possible route / Length of the actual route	Visualize the optimality of the driving route	-	Every second (or 2)	Objective continuous	Spaghetti chart showing the actual followed route vs. the shortest path	Excel	Yes	-	RFID data, Shortest path algorithm (excel)	Every second	-	TBD
Loading efficiency	Standard Loading Time / Actual Loading Time	Detect long inefficient loading methods	-	Every time an order is completed	Objective continuous	Bar chart showing actual loading time vs. the standard time for x hours to visualize trend	Excel	Yes	-	RFID data, order list (standard times)	Every second	-	TBD
Unloading efficiency	Standard Unloading Time / Actual Unloading Time	Detect long inefficient unloading methods	-	Every time an order is completed	Objective continuous	Bar chart showing actual unloading time vs. the standard time for x hours to visualize trend	Excel	Yes	-	RFID data, order list (standard times)	Every second	-	TBD
Load/Unload time variance	Loading time / Unloading time	Detect problems at the loading- or unloading area	-	Every time an order is completed	Objective continuous	Bar chart showing the % difference for x orders to visualize trend	Excel	Yes	-	RFID data, order list	Every second	-	TBD
Overall Utilization	Work time / Total time	Show where utilization can be improved, if too many vehicles are idle or if more vehicles are needed	-	Hourly (or less frequent)	Objective continuous	Bar chart showing the Utilization over x hours to visualize trend	Excel	Yes	-	RFID data, excel	Every second	-	TBD
Percentage loaded	Nbr of kms driven while loaded / total nbr of driven Kms	Discover if the vehicle is inefficiently driving without load	-	Hourly	Objective continuous	Bar chart showing the percentage loaded for x hours to visualize possible trend	Excel	Yes, but difficult	-	RFID data	Every second	-	TBD
Key Performance Area: Increase the reliability of the logistics system													
Lost time percentage	Total lost Time / Total time	Display reliability and show reasons of lost time	-	Hourly	Objective continuous	Pie chart showing the percentage of lost time	Excel	Yes	-	RFID data	Every second	-	TBD
Vehicle reliability	Lost time due to Defects / Total time	Show quality of the used vehicles, quality of maintenance	-	Each time an defect occurs	Objective continuous	Gauge meter showing the Nbr of defects, and a colour-scale which shows performance level / "Defect" warning in status / visual in spaghetti chart	Excel	Yes	-	RFID data	Every second	-	TBD
Mean time to repair	Average duration of a defect	See if improvement in the maintenance department / logistics department is needed	-	Each time an defect occurs	Objective continuous	Graph showing the MMTR of the last x defects	Excel	No, measure manually?	-	RFID data, manual input	Every second	-	TBD
Route reliability	Lost time due to going 'Off track' / Total time	Visualize problems and the places where they occur	-	Each time a routing error occurs	Objective continuous	Gauge showing the Nbr of times vehicle goes off track, and a colour-scale which shows performance level / "Off Track" warning in status / visual in the spaghetti chart	Excel	Yes	-	RFID data	Every second	-	TBD
Picking reliability	Lost time due to wrong deliveries / Total time	Show why mistake happens (no clear order, confusion about the loading- and unloading-points)	-	Each time a picking error occurs	Objective continuous	Gauge showing the Nbr of wrong deliveries, and a colour-scale which shows performance level	Excel	No, how to measure?	-	RFID data, manual input	Every second	-	TBD
Key Performance Area: Increase the productivity of the internal logistics													
# orders picked / hour	Nbr of orders picked / hour	Visualize the productivity of each logistic employee / vehicle	-	Hourly	Objective continuous	Bar chart showing the trend over x hours	Excel	Yes	-	RFID data, order list	Each time an order is completed	-	TBD
# orders picked / Km	Nbr of orders picked / driven Km	Visualize the productivity of each logistic employee / vehicle	-	Hourly	Objective continuous	Graph showing the Nbr of orders picked against the driven kms	Excel	Yes	-	RFID data, order list	Each time an order is completed	-	TBD

APPENDIX B: RFind reference tag layout in the production plant of company B



x (meters)	y (meters)	Location #
11	37	103015
18	37	103019
25	37	103017
32	37	103018
39	37	103016
46	37	103013
53	37	103012
60	37	102998
67	37	102986
67	29	102984
67	21	102990
67	13	102985
67	5	103004
60	5	103007
53	5	102999
46	5	102996
39	5	103005
32	5	103006
25	5	102997
18	5	103000
11	5	103003
11	13	103001
11	21	103002
11	29	103014
39	33	102995
50	32	102989
60	25	102991
58	11	102987
45	18	102993
18	18	102988

APPENDIX C: Match table of theoretical time schedule, RFID data and arrival list

Theoretical Time Schedule					RFID Data				S Arrival List		
Date	Transport number	Departure time from C	From	Day	Time-in/out	Arrival/ Departure	Direction	Skid	Arrival time	From	Skid
9/29/2011	11	22:00	Zuid	Thursday	21:22:01	Arrived at C	South	vh261	20:50	Zuid	vh261
9/30/2011	1	6:30	Noord	Friday	7:48:58	Arrived at C	North	vh358	6:25	Noord	Vh358
9/30/2011	2	8:00	Oost	Friday	6:58:27	Arrived at C	North	vh205	7:35	Noord	Vh205
9/30/2011	4	11:00	Noord	Friday	13:44:09	Arrived at C	North	vh200	11:20	Noord	Vh200
9/30/2011	5	12:30	West	Friday	15:02:57	Arrived at C	North	vh204	13:06	West	Vh204
9/30/2011	8	17:00	Cab Trim	Friday	19:37:13	Arrived at C	North	vh357	17:35	Cab Trim	vh357
10/3/2011	1	6:30	Noord	Monday	6:35:40	To S	North	vh204	7:35	noord	vh204
10/3/2011	2	8:00	Cab Trim	Monday	8:12:32	To S	North	vh200	9:10	Cab Trim	vh200
10/3/2011	2	8:00	Cab Trim	Monday	10:33:54	Arrived at C	North	vh200	9:10	Cab Trim	vh200
10/3/2011	3	9:30	KN	Monday	11:58:35	Arrived at C	North	vh205	10:10	KN	vh205
10/3/2011	4	11:00	Noord	Monday	11:08:14	To S	North	vh207	11:47	noord	vh207
10/3/2011	5	12:30	Noord	Monday	15:03:46	Arrived at C	North	vh262	13:10	noord	vh262
10/3/2011	6	14:00	Oost	Monday	14:04:13	To S	North	vh203	14:50	Oost	vh203
10/3/2011	6	14:00	Oost	Monday	16:43:11	Arrived at C	North	vh203	14:50	Oost	vh203
10/3/2011	7	15:30	Noord	Monday	15:48:01	To S	North	vh200	16:25	Noord	vh200
10/3/2011	7	15:30	Noord	Monday	17:57:37	Arrived at C	North	vh200	16:25	Noord	vh200
10/3/2011	8	17:00	West	Monday	17:10:15	To S	North	vh206	18:00	West	vh206
10/3/2011	8	17:00	West	Monday	18:57:26	Arrived at C	North	vh206	18:00	West	vh206
10/3/2011	9	19:00	Noord	Monday	17:24:36	To S	North	vh205	18:10	Oost	vh205
10/4/2011	1	6:30	Noord	Tuesday	7:52:55	Arrived at C	North	vh262	6:30	Noord	vh262
10/4/2011	2	8:00	Oost	Tuesday	8:20:47	To S	North	vh358	9:10	Oost	vh358
10/4/2011	2	8:00	Oost	Tuesday	10:22:37	Arrived at C	North	vh358	9:10	Oost	vh358
10/4/2011	3	9:30	KN	Tuesday	11:50:22	Arrived at C	North	vh204	9:50	KN	vh204
10/4/2011	4	11:00	Noord	Tuesday	11:00:30	To S	North	vh200	11:19	Noord	vh200
10/4/2011	4	11:00	Noord	Tuesday	13:40:15	Arrived at C	North	vh200	11:19	Noord	vh200
10/4/2011	5	12:30	Noord	Tuesday	12:24:35	To S	North	vh205	13:00	noord	vh205
10/4/2011	5	12:30	Noord	Tuesday	14:48:11	Arrived at C	North	vh205	13:00	noord	vh205
10/4/2011	6	14:00	Cab Trim	Tuesday	14:01:01	To S	North	vh263	14:25	Cab Trim	vh263
10/4/2011	6	14:00	Cab Trim	Tuesday	16:04:03	Arrived at C	North	vh263	14:25	Cab Trim	vh263
10/4/2011	7	15:30	Noord	Tuesday	15:20:13	To S	North	vh358	15:55	Noord	vh358
10/4/2011	7	15:30	Noord	Tuesday	17:53:36	Arrived at C	North	vh358	15:55	Noord	vh358
10/4/2011	8	17:00	Zuid	Tuesday	17:04:26	To S	South	vh357	17:35	Zuid	vh357
10/4/2011	8	17:00	Zuid	Tuesday	19:08:07	Arrived at C	South	vh357	17:35	Zuid	vh357
10/4/2011	9	19:00	Noord	Tuesday	19:57:13	Arrived at C	North	vh206	20:31	Noord	vh206
10/4/2011	9	19:00	Noord	Tuesday	21:21:08	Arrived at C	North	vh206	20:31	Noord	vh206
10/5/2011	1	6:30	Noord	Wednesday	7:37:42	Arrived at C	North	vh204	6:15	Noord	vh204
10/5/2011	1	6:30	Noord	Wednesday	6:24:32	To S	North	vh358	7:15	Noord	vh358
10/5/2011	2	8:00	Oost	Wednesday	8:09:31	To S	North	vh207	9:05	oost	vh207
10/5/2011	2	8:00	Oost	Wednesday	10:27:49	Arrived at C	North	vh207	9:05	oost	vh207
10/5/2011	3	9:30	KN	Wednesday	11:59:49	Arrived at C	North	vh265	10:05	KN	vh265
10/5/2011	4	11:00	Noord	Wednesday	10:58:12	To S	North	vh205	12:05	Noord	vh205
10/5/2011	4	11:00	Noord	Wednesday	13:36:01	Arrived at C	North	vh205	12:05	Noord	vh205
10/5/2011	5	12:30	Noord	Wednesday	12:32:32	To S	North	vh206	13:00	noord	vh206
10/5/2011	5	12:30	Noord	Wednesday	15:04:47	Arrived at C	North	vh206	13:00	noord	vh206
10/5/2011	6	14:00	Cab Trim	Wednesday	14:08:40	To S	North	vh200	14:40	Cab Trim	vh200